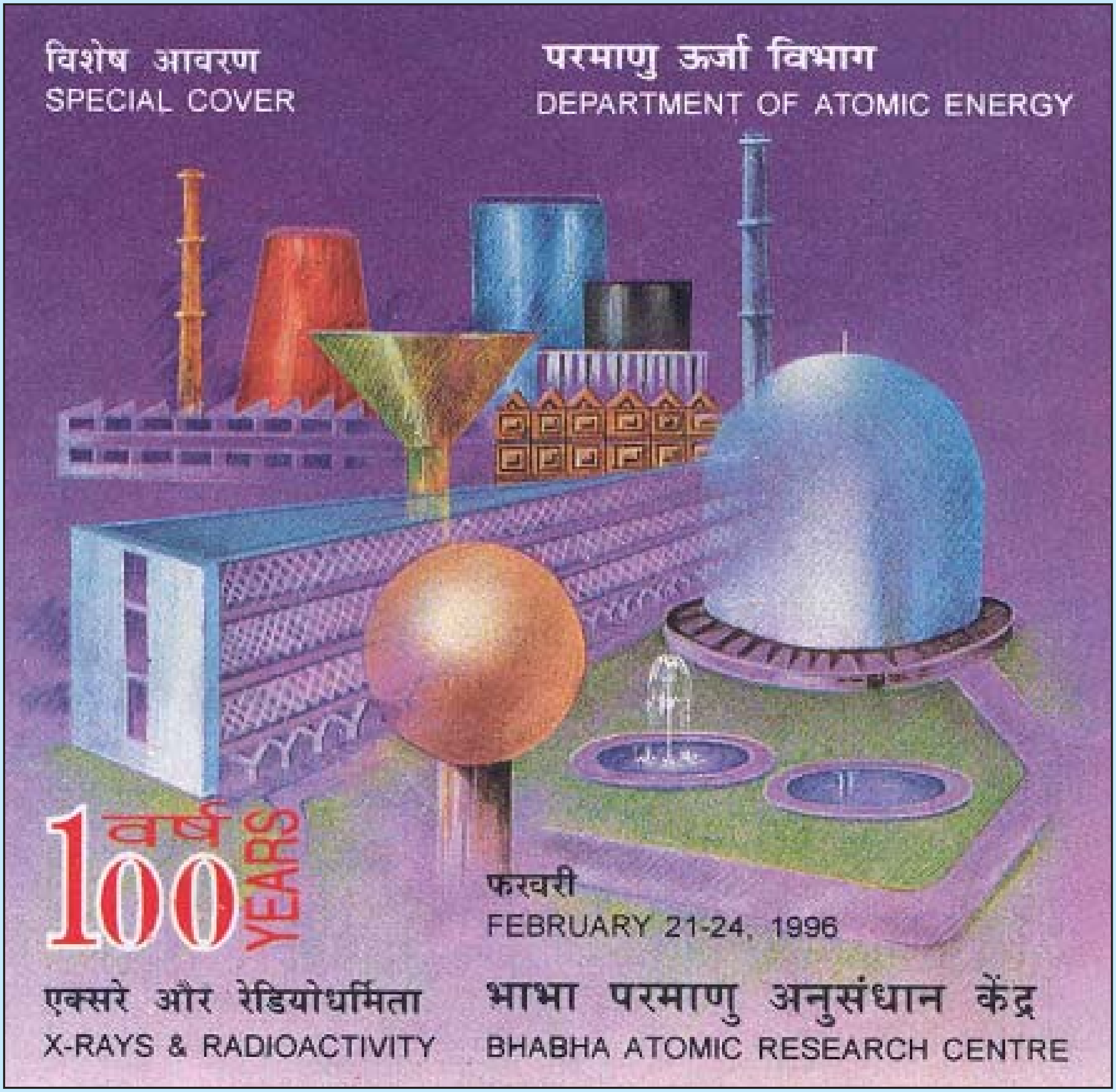
PART 1

PHYSICAL SCIENCES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Physics Relevant to Evolution of Atomic Energy–A Historical Perspective

Observation of natural phenomena with a view to quantifying and systematizing them into definitive patterns, and then exploring possible correlations between them through reasoned inferences is common to all natural sciences. But, amongst natural sciences, physics perhaps, relies the most on unifying observations through deductive reasoning based on a minimal set of what the physicists call as the 'fundamental laws'. Indeed, combining logical reasoning based on such laws to understand natural physical phenomena and thus developing a firm foundation of their subject is the core activity in physics. A sound foundation thus created not only allows physicists to systematize available experimental data but also makes it possible to predict new facts, which can be experimentally verified. In this sense the world of physicists begins with observations and ends with observations, passing through the intermediate stage of "working-thought-model" that best describes the result of rational correlation between observed facts. It would be prudent here to amplify this point through an example. The correlation of planetary motion with the falling bodies at earth's surface offers a good illustration. Johann Kepler in about 1610 gave us the three laws of planetary motion written only as arithmetical relations. Nearly sixty years later Issac Newton converted the experience of falling bodies on earth's surface into formulation of the laws of gravitation and then developed Newtonian mechanics to establish the deeper basis for Kepler's laws. Not only the Kepler laws were thus explained, but also a number of other phenomena and observations could find a rational explanation. In fact, Newton's theoretical formulations resulted in a full mechanistic picture of the universe. The success of Newtonian mechanics also led to attempts to explain many other things in purely mechanistic terms. The motion of mechanical objects was successfully discussed in terms of Newton's equations on both celestial and terrestrial scales. Application of this theory to molecular motion led to formulation of the kinetic theory of gases and after the discovery of electron in 1897, prompted its description also in terms of a Newtonian particle.

After Newtonian mechanics perhaps the best illustration of logically interconnecting very diverse phenomena comes from electromagnetism, which united propagation of light with the functioning of an electrical motor! In 1864, Maxwell showed a connection between the optical and the electrical phenomena. Maxwell's equations could describe the laws governing the emission of radio waves, their reception, flow of current through a conductor as well as displacement current through vacuum, operation of electric motors, transformers etc.

The next important development in Physics to which we would like to devote some space concerns the transition from non-relativistic to relativistic mechanics and classical to quantum physics. The wave nature of light, which had been well established by the diffraction experiments of Young in 1803, required the presence of ether filling up empty space for light to propagate. However, Michelson's experiment in 1887 knocked off the ether hypothesis for ever by establishing that the velocity of light is a universal constant irrespective of the velocity of the source of light. The implications of Michelson's experiment, completely understandable if the postulate of ether is rejected, led Einstein in 1905 to formulate the special theory of relativity. It expressed the mutual equivalence of all inertial systems moving relative to one another. In the theory of relativity a simple universal time does not exist as in Newtonian mechanics. The absolute time of Newtonian mechanics is only an approximation, correct for speeds, which are small relative to the speed of light. The picture of physics built up on the basis of a description of particles and waves in which all physical variables can assume any continuous value is known as Classical Physics.

Let us next turn to the transition from classical physics to quantum physics. The story began with Planck around 1900. His quantum theory, developed to account for the black body radiation, had two essential features, viz. (i) an oscillator can exist only in one of a number of discrete quantum states and to each of these states there corresponds a definite allowed value of energy, and (ii) no radiation is emitted while the oscillator remains in one of its quantum states but it is capable of jumping from one quantum state into another either by absorbing or emitting a quantum of radiation. The emission and absorption of electromagnetic radiation can happen only in discrete quanta, having energy *E* equal to the frequency of radiation (γ) multiplied by a universal constant *h* called Planck constant. This quantum idea was later also used by Einstein to explain the photoelectric effect and with this the dual character of electromagnetic radiation was firmly established. In 1924, de Broglie gave another theoretical idea that matter also has a dual (i.e. particle like and wave like) character. He assumed that the relation between the momentum (p) of the particle and the wavelength (λ) of the corresponding wave is $\lambda = h/p$. In later years, this view was confirmed when electron diffraction by crystals was observed. As Richtmyer, Kennard and Lauritsen, in their famous book "Introduction to Modern Physics" point out "de Broglie did not develop his ideas into an exact theory and had nothing further happened, de Broglie's speculations would doubtless soon have been forgotten". Louis de Broglie's speculation set a German, E. Schrödinger to think and discover precisely how a mathematical theory incorporating de Broglie idea can be constructed. With additions by Born, Heisenberg, Dirac, Pauli, and others, this theory became the highly successful quantum mechanics to which we shall return a little later. Planck's quantum theory was not the only major event that shook physics around 1900; even more interesting experimental facts had been discovered to which we should now pay attention.

Following Roentgen's discovery of X-rays in 1895, Henri Becquerel started studying radiation emitted by Uranium salts. He found that these salts emit a new form of radiation, different from both phosphorescent light and X-rays, which he called, Uranic rays. Further investigations of Uranic rays by Marie and Pierre Curie in 1898 led to the discovery of two new elements, Polonium and Radium. They also showed that besides uranium salts other elements too emitted such rays. They coined the term "Radioactivity", by which the phenomena of this sort of spontaneous emission of radiation has been known ever since. Becqueral, Meyer and Schweidler in 1899 showed that radiations from radioactive substances could be deflected in a magnetic field. Rutherford showed that uranium compounds emitted two different types of rays, one that was unable to penetrate very thin aluminum sheets and the other could travel past even thick aluminum sheets. (Later, these were identified as alpha and beta rays.) In 1900, Villard found a third type of radiation which could not be deflected in a magnetic field but had considerable penetrating power and produced a marked effect on photographic plates, later identified as gamma rays. These discoveries marked the beginning of the field of nuclear physics, which is concerned with the study of properties of nuclei, the tiny objects at the core of atoms and the forces that hold the constituents of nuclei, namely, nucleons, together. It was eventually learned that alpha-rays are just helium atoms without electrons and carry two units of positive charge, that beta rays are fast moving electrons, while gamma rays are very short wavelength electromagnetic radiation.

Soon after the start of the twentieth century, Rutherford and Soddy found that substances like uranium and thorium transmute naturally into other elements by virtue of their radioactivity. Rutherford found that any given amount of a radioactive substance decays at a rate that is proportional to the amount of the substance available at that time. This means that the original amount decays exponentially with time; the time it takes for half the material to decay is known as the half-life.

In 1911, Rutherford's observation of unexpectedly large angle backscatterings when alpha particles hit a gold foil, led him to the theoretical picture of atom as being made up of a small heavy nucleus of Z positive charges and A-Z 'neutral bound pairs of positive and negative charges' surrounded by a cloud of Z uniformly distributed electrons. (That electron is negatively charged had been known since 1898.) However, such "static" model of atom was unacceptable by virtue of Earnshaw's theorem of electrostatics, that implied an unstable arrangement of charges.

In 1913, Niels Bohr developed a dynamic model of the hydrogen atom, involving an electron circulating around a hydrogen nucleus, (which later acquired the name 'proton'). However, Bohr's model posed a different problem, namely the radiation produced by an accelerating charged particle (viz. the circulating electron) according to classical electromagnetic theory implied that atoms would have a life ~ 10^{-8} seconds. To overcome this problem, Bohr also introduced the idea of stable orbits called stationary states. By allowing the electron to emit light only when it jumps between these stationary states, Bohr was able to explain the known energies of light emitted by excited hydrogen atoms. Subsequently, to improve upon Bohr's model, several scientists principally Schröedinger, Heisenberg, Born came up with the formulation of Quantum Mechanics. By late 1930's it was recognized that Quantum Mechanics and Einstein's Theory of Relativity provide a sound conceptual basis for theoretical description of most physical phenomena.

One of the early successes of quantum mechanics in the realm of nuclear physics was to provide an explanation of the alpha decay process. It had been known that alpha decay half-lives are very strongly influenced by the energy of alpha particle. Doubling the energy from 4 to 8 MeV causes the typical half-life to decrease from 10^{10} years to 10^{-2} seconds. Gurney and Condon and independently Gamow, in 1928, provided an elegant explanation of this extreme energy dependence as a quantum mechanical phenomenon. According to classical physics, an alpha particle, held inside the nucleus cannot escape from it due to a potential barrier. However, quantum mechanics does allow the alpha particle to escape by "tunneling" through the barrier, with an energy-dependent half-life consistent with observed data. Interestingly, an understanding of where the beta rays viz. fast moving electrons that emanate from radioactive atoms, actually come from was not clear until Bohr had constructed his atomic model in 1913. From the Bohr's model itself it had become clear that the energies of beta rays are too high and so the electrons cannot have extra nuclear origin. Rather, these must come from nucleus. Similarly, gamma rays are too energetic to have extra nuclear origin and like beta ray, come from the nucleus.

The continuing studies of Rutherford and his co-workers on the interaction between alpha particles and matter led to many striking results like the attenuation of alpha particles while traveling through a target of a certain thickness, and their possessing a rather definite range which is a function of their energy. It was also found that an alpha particle could knock a proton from nitrogen nucleus. While, Rutherford was uncertain about the exact details of what he had observed, he knew that man-made nuclear rearrangement is possible, and that it should be possible to rearrange the nuclear structure of many of the light elements by bombardment with alpha particles. Rutherford and Chadwick bombarded all the light elements with alpha particles and found ten cases where protons were produced. By studying the range of these protons, they determined that in some cases the proton has more energy than the original alpha particle. This indicated that possibly the alpha particle is absorbed by the nucleus, so that energy of ejected proton is largely determined by the instability of the intermediate nucleus. This marked the beginning of a systematic research on nuclear reactions.

Until 1932 little progress was made in the understanding of the internal structure of atomic nuclei. It was taken for granted that these nuclei are composed of protons and electrons, the only particles known at the time. Only when the neutron was discovered in 1932 that physicists could begin to understand nuclear structure. Discovery of the neutron ushered in the field of modern nuclear physics in which nuclei are regarded as composed of neutrons and protons. Later, it was found that a free neutron disintegrates with a half life of 13 minutes into a proton, an electron and a neutrino .

The greatest discovery for development of the concept of Atomic Energy occurred in 1939 when Hahn, Meitner and Strassman observed the phenomena of slow neutron induced nuclear fission in uranium. The fission process produces not only very high energies (around 200 MeV per fission) but also extra neutrons that can cause fission in other uranium nuclei. Thus, fission process can be used to establish a chain reacting system for continuous release of energy. A nuclear reactor is a system where a chain reaction is initiated, sustained and controlled.

In the course of studies of beta rays, it was found that the emitted electrons, unlike alpha rays or gamma rays, do not have a definite energy, but instead exhibit a continuous spread of energies. The paradox was that the average energy release, as measured in a calorimeter, was, definitely less than the maximum electron energy, i.e. the energy difference between initial and final nucleus. W. Pauli proposed that the deficit between the maximum and the actual energies of the emitted electron is carried away by a new particle, which he called a neutrino. When Fermi succeeded in explaining the continuous beta spectrum with its help, this postulate came to be accepted.

In 1956, Reines and Cowan obtained the experimental evidence for the existence of neutrinos. Subsequent work in nuclear physics showed that strongly interacting particles like protons, neutrons, mesons, etc, having a generic name hadrons, have a structure of their own. They were seen to be composed of quarks and gluons. All we know about the size of quarks is that they are too small for us to measure using existing accelerators and experimental methods. So theoreticians treat them as if they were point particles.

Quantum Chromodynamics (QCD) which deals with the study of quarks and their interactions, provides a basis to understand the strong force. As the name suggests, this force is about 100 times stronger than the common electromagnetic force and also has a very small range, of the size of an atomic nucleus. It is commonly believed that the short range of the strong force arises as a consequence of what is called quark confinement, which forces quarks to be permanently locked inside strongly interacting particles (composite) like nucleons. That is, it takes enormous energy to remove a quark out of a nucleon. Counter-intuitively, when it is inside the nucleon, it appears to behave as though it is free. A complete understanding of this phenomena is the object of intense activity.

In the first half of the twentieth century researches in the atomic and molecular spectroscopy brought out need for evolving a microscopic theory of interaction of electromagnetic radiation with atoms and molecules. That laid, in the second half of the twentieth century, the foundations for the growth of what turned out to be a very important area, namely, Quantum Optics. It not only provides tools for investigating several fundamental aspects of the quantum theory but it is basic ingradient for the development of many emerging technologies such as quantum computing and quantum information processing. Its methods have led to the opening up of a new field of research, namely, Atom Optics. Atom optics deals with quantum effects arising due to large de Broglie wavelength of ultra-cool atoms. The required low temperatures are achieved by laser cooling. Bose-Einstein condensation is just one example of the “quantum condensation” observed at low temperature using methods of quantum or atom optics. Quantum optical systems also enable one to observe the non-linear dynamical effects in ideal settings. It is, therefore, not surprising that quantum optics has contributed to research in the area of non-linear dynamics in general and classical and quantum chaos in particular.

In the sections which follow we will take each topic of physics in which DAE institutions have been actively engaged in Research and Development programmes over the past fifty years or so and capture a flavour what have been some of noteworthy contributions accomplished through these efforts. We begin our story with Atomic Physics & Spectroscopy and then turn to Nuclear Physics & High Energy Physics and so on.

Atomic Physics & Spectroscopy

Link P1

The broad concept of atomic hypothesis was introduced in Greek. It said that all material things were made up ultimately of small individual units which Democritus called atoma. However, the atomistic concept of matter lay dormant for long period of time. During sixteenth and seventeenth centuries the scientists favoured the view that matter was not continuous in nature but was made up of particles called atoms (little particles that move around in perpetual motion, attracting each other when are a little distance apart but repelling upon being squeezed into one another).

Atomic physics is concerned with high precision measurements that test our very basic understanding of many-electron systems. Apart from its fundamental interest, study of atomic physics helps better understanding of several features of plasma physics, astrophysics, and chemistry. It encompasses many fields, from detailed study of the atom's interior to experiments that trap and manipulate single atoms, to "atom lasers" - beams of atoms that have the same properties as laser light and many more. While, atomic physics has given us very important fields of nuclear physics and electronics in public domain, the most important benefit has been philosophical rather than technical.

A view of the laser-cooling facility in BARC. The picture shows the magneto-optical trap (MOT) consisting of an octagonal chamber, diode lasers, optics and opto-mechanical components, and diagnostic equipments

Atomic Physics and Spectroscopy

Optical spectroscopy towards the beginning of the last century helped to build basic understanding of atomic structure and led to the birth of quantum mechanics. The bound state problems were investigated to an extent in the earlier days, but the problems in atomic collisions remained beyond reach because of absence of suitable experimental techniques. However, many techniques developed for work on nuclear physics and high-energy physics lately became available for investigations concerning atomic physics. These include; mass spectroscopy, high resolution electron spectroscopy, lasers, computers, accelerators, ion traps, coincidence and phase sensitive detection, ion sources, ultra high vacuum to name a few. Consequently, the last few years have seen some remarkable advances in the understanding of atomic phenomena. It is now possible to isolate atomic systems in traps, measure in coincidence the fragments of collision processes, and by the use of storage rings produce and study multicharged ions; one can look at bulk matter in such a way that the fundamental atomic character is clearly evident. Coincidence studies of atomic collisions, hollow atom, clusters, atom traps, Bose-Einstein condensates, atomic interferometry, density functional theory, atomic physics with anti-matter and surface adsorbates are some of the new directions of research in the field.

In DAE, the work on inner shell ionization of atoms using the Van de Graaff generator marked the beginning of atomic physics activities. This was augmented with the availability of the modified version of the neutron generator. X-ray spectroscopy was the technique primarily used for these studies. Efforts were also initiated towards building low energy electron spectrometers for various atomic collision experiments. Later, activities were initiated in electron scattering, low energy ion-atom / molecule collisions, afterglow studies, beam foil spectroscopy etc. Resonant scattering of electrons at the K-shell edge of C and N, giant resonance in Xenon, threshold measurements and partial cross sections in electron impact ionization of atoms and molecules were some of the notable achievements in the early electron collision studies. The ion translational energy spectrometry which accurately measures interchange of potential and kinetic energies in atomic and molecular species during their collisions brought to light several unique features of dicationic molecular species, which were attracting increasing level of attention world wide. The experimental observation of several of these unique metastable molecular species was complemented by quantum chemical calculations. The inelastic ion scattering studies carried out using a translational energy spectrometer that employed two cylindrical sector energy analyzers with very high resolution revealed a hitherto unknown propensity rule in the transfer of kinetic energy to the internal energy of the collision partners depending on the spatial distribution of electron densities and electron momentum distributions in the colliding partners.

Novel electron collision experiments in combination with conceptually new time-of-flight mass spectrometric techniques provided unmatched accuracies in the measurement of absolute cross sections for the formation of specific positive and negative ions from molecules. A flowing afterglow experiment was built to study low energy atom-radical collisions and positive ion – negative ion mutual neutralization reactions. The products arising from the reactions were diagnosed using fluorescence spectroscopy to study several reactions between atomic nitrogen and various fluoride radicals as well as the reactions between positive and negative ions. A variety of atomic and molecular physics experiments were conducted using the Pelletron accelerator starting with production of near-thermal highly charged ions by colliding fast ion projectiles with gaseous targets of free atoms and molecules. These experiments lead to the study of the formation of highly charged positive molecular ions and their fragmentation pattern and dynamics. In a related study, the influence of electron-electron interaction resulting in simultaneous removal of both the electrons from He and molecular hydrogen targets were investigated in a series of experiments using fast projectiles starting from electrons and protons to various bare nuclei and a systematic relationship of this process with the velocity and charge of the projectiles was derived. Another thrust was the study of the highly excited levels of ions and their radiative lifetimes using beam foil spectroscopy in which energetic ion beams are passed through a very thin carbon foil leading to their collisional excitation. Several ions of charge states starting from single ionization stage to very highly charged stage of ionization and of importance to astrophysics were studied using the beams from the 400 kV accelerator and the Pelletron accelerator.

Another aspect that has been studied is the ion – solid interactions using beams from the Pelletron accelerator. In one class of experiments, the channeling of swift highly charged ions through a single crystal was studied using X-ray spectroscopy to understand the radiative electron capture by the projectiles in their inner shells. These and the efforts to probe the then reported formation of extremely high and transient magnetic field produced during ion – solid collisions, led to another set of experiments in which the dynamics of creation and filling of inner shell vacancies and subsequent polarization effects were studied. These experiments in which the inner shell processes dominate ion – atom collision processes have been developed into a full-fledged program involving X-ray spectroscopy, electron spectroscopy and ion time-of-flight spectroscopy to understand the details of the collision processes with increasing levels of sophistication. Observation of solid – like wake effects in ion collisions on individual C_{60} molecules and interference effect due to the two protons in the hydrogen molecule on the ejected electrons have been some of the recent highlights.

Laser based studies of various atomic and molecular processes have also been carried out. One of these involved the use of lasers to prepare the molecules in known excited states and carry out electron collisions on these excited molecules. These experiments, the results from which have applications in various plasma processes, are aimed at understanding short-lived negative ion states of molecules and the dynamics of their decay as a function of the initial state of the molecule and the incident electron energy. New instrumentation and measurement techniques involving both hardware and software have been created for these experiments and have resulted in several new results in the form of absolute cross sections form excited molecules, details of the negative ion states of molecules and their decay, orientation dependent electron capture by the molecules and control of molecular dissociation.

The experience gained in the study of ionization and fragmentation of molecules in ion collisions led to research in intense laser field interaction of matter- study of ionization and fragmentation of molecules. The electric fields associated here (10^7 Vcm^{-1}) being nearly comparable to the atomic fields induce nonlinear interactions that can no longer be understood from simple perturbative dynamics. They induce nonlinear effects well beyond intuitive expectations. For example, it is possible to remove 6-8 electrons from atoms such as Xenon with photons of about 1.2 eV, effectively inducing non-linear process of about 60th order or more. The strong fields also induce large torques due to the induced dipole moment and align the ensemble of molecules along the electric field vector of the linearly polarized light. This work enunciating the rules and systematics of the alignment has demonstrated the pendulum motion of the molecular dipoles in intense laser fields.

The successful study with the pico-second laser laid the foundation for exploring a new regime of non-perturbative physics using intense femto-second laser fields that are not only equal to the atomic fields but also exceed them. The temporal domain of the alignment as well as the role of polarization of electric field in inducing ionization was studied in a large number of molecules. The large degree of ionization that can be induced in molecules lead to the possibility of producing hot plasmas with condensed matter and studying hot dense plasmas in high field dense matter interactions. Interaction of ultra short laser with solid targets provide a new avenue of laser-plasma physics due to their ability to provide hot dense plasma that are not amenable by any other conventional techniques. These studies initiated in the recent past have brought many a new facets of physics that are directly applicable to technology. Methods to probe the plasma in ultra short timescale were devised and are used to measure the hot electron currents that are produced. Multi-mega gauss magnetic fields, the largest known to the man, were observed recently in these laser plasmas and experiments were carried out to understand the mechanism of their production, their spatio-temporal extents etc. Ability to control the production and evolutions of this pico-second magnetic field bursts are not only of fundamental interest across fields like astrophysics but also of interest to many innovative applications, and efforts towards this continue to be active area of work.

Clusters are nano-sized particles that bridge the gap between bulk matter and the atoms or molecules constituting it. Apart from understanding the evolution of various physical properties from a single atom to bulk matter, the study of clusters is important for some of the unique dynamical processes not seen in single atoms or bulk matter. In this context, a new experiment has been built to study intense laser interaction on atomic and molecular clusters produced in a supersonic jet expansion. In these experiments more than 10 electrons on each of the few ten thousand atoms are removed in femto-second time scale, which is faster than the movement of the individual atoms in the clusters. The loss of large number of electrons creates a cluster of positive ions. The very large positive charge density in the cluster leads to extremely large electrostatic repulsive force on the positive ions and accelerates them to energies as large as MeV. Experiments on these "table-top acceleration" schemes are carried to provide new strategies coupling the laser energy with the hot-dense plasma more efficiently and also to use the polarization properties of the laser to coax the ions to preferably follow the laser electric field. The nano-size clusters are now augmented with micron sized droplets. The droplets produce very different interactions with light and the first results demonstrate that they are best suited to couple the laser energy very efficiently as seen in the more than two orders of magnitude rise in hard X-ray generation.

Spectroscopy

Nuclear energy program introduced the concept of "nuclear purity" where the tolerable impurity (e.g. B, Cd, Gd etc) levels in the fuel were of the order of sub-ppm. For such stringent quality control of nuclear materials, spectroscopy was a natural choice and hence the nuclear energy programme depended heavily on spectroscopy. Having successfully met all the needs of the quality control and certification requirements of a vigor.ous nuclear energy program, spectroscopy research subsequently got diversified into a variety of other areas of advanced research in atomic and molecular physics, notably, atomic and molecular structure and dynamics, high resolution spectroscopy, laser spectroscopy, multi-step and multiphoton ionization spectroscopy, laser cooling and trapping of atoms and optical instrumentation. Advent of tunable lasers in early seventies provided a natural impetus to the growth of the subject and the promise of laser isotope separation made the discipline an integral part of the nuclear fuel cycle. Spectroscopy has also been employed for online monitoring of various industrial processes like the on-line diagnostics of electron beam evaporated refractory metals like zirconium and uranium based on laser absorption and photo-ionisation spectroscopy. Spectroscopy group has made substantial contributions, on their own and also in collaboration with other groups abroad, to two major areas of accelerator based atomic spectroscopy, namely, beam foil spectroscopy and spectroscopy with high energy accelerators (at CERN and GSI).

Many of these studies could be possible because of the development of a number of specialized equipments. These include, remote viewing system for spent fuel examination, 22-channel multi-element inductively coupled plasma (ICP) emission spectroscopy system for nuclear fuel analysis, a 1-meter scanning monochromator system for analysis of rare earths, state of the art time of flight mass spectrometers and precision laser frequency locking system for multi-step laser-photoionisation experiments. Also, for the program carried out optical components, namely the dielectric coated mirrors, lenses, beam splitters etc., were developed.

Quality Control and Certification

Right from the time of construction of CIRUS reactor the task of preparing primary standards for uranium, developing spectroscopic methods using large quartz prism spectrographs and grating spectrographs for analysis of sub-ppm impurities was undertaken. Simultaneously, the reliability of the over-all quality certification was established. The highlight of this programme was the development, for the first time anywhere, of a double beam infrared spectroscopy technique to meet the requirements of on-line and off-line analysis of heavy water. For the isotopic analysis of lithium (Li^6/Li^7) and uranium (U^{235}/U^{238}) based on isotope shifts in the resonance line the necessary development was carried out. Laser enhanced ionization spectroscopy technique for sub-ppb level analysis of sodium in water was also developed.

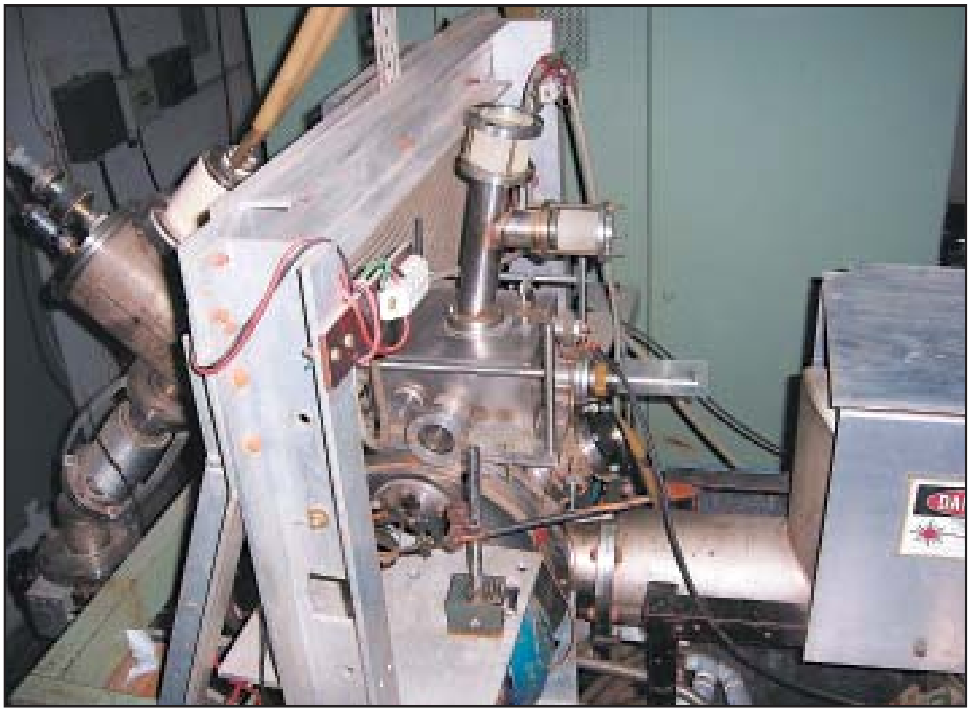
Atomic Hyperfine Interactions

Hyperfine interaction is concerned with changes in the atomic spectra due to nuclear interactions. it gets manifested in terms of isotope shifts (IS) in a chain of isotopes, and hyperfine structure (HFS) in case of a nucleus with non-zero nuclear spin. Measurement of IS and HFS in atomic systems is crucial for many areas of research. In case of lanthanides and actinides, which exhibit a complex energy level structure, IS is a crucial input for analysis of atomic spectrum and assignment of electronic configurations. Very precise measurements of IS and HFS provide nuclear information such as the spin, multipolar moments, deformation and variation in the mean square charge radius in a chain of isotopes. On the applications side, IS and HFS provide the very critical input for development of laser isotope separation technology. Earlier studies on high-resolution atomic spectroscopy were done with indigenously built Fabry-Perot optical spectrometer, which enabled resolution of 1 in 10^6. This equipment has been used to study IS in thousands of spectral lines of lanthanides, Nd, Sm, Gd, Eu, Dy, Er and Yb for unequivocal configuration assignment.

Actinides studied include isotopes of uranium namely, U^{233}, U^{235} and U^{238}. With the introduction of single mode lasers, a number of new laser-based techniques, notably, saturated absorption spectroscopy, polarization spectroscopy, inter-modulated spectroscopy were developed for Doppler-free spectroscopy and were utilized for IS and HFS measurements in uranium isotopes.

Multi-Step and Multiphoton Ionization Spectroscopy

Spectroscopy of highly excited levels, namely, Rydberg and auto-ionization levels, has always interested atomic physicists. Rydberg levels are the hydrogen-like levels of a complex atom and exhibit many interesting properties such as relatively long radiative lifetimes and large dipole moments. The auto-ionizing levels are bound levels above the continuum and as the name suggests they spontaneously decay by ionization process. During the eighties, laser spectroscopists made extensive studies on Rydberg and autoionization levels of uranium and a few lanthanides using multi-step and multi-photon ionization spectroscopy incorporating tunable dye lasers. Information that resulted from these studies was simply colossal. For example, in case of uranium, several hundreds of new levels (in the range 34,000 – 43,000 cm^{-1}), new Rydberg series and hundreds of new auto-ionizing levels (in the range 49960 – 51560 cm^{-1}) were discovered. Several of these new energy levels were important for isotope-selective photoionisation of specific elements; and as a natural extension of these studies, isotopically selective photoionisation of uranium was demonstrated. Apart from direct photoionisation, associative ionization of excited uranium atoms with molecular oxygen was also studied.



Setup for multiphoto ionisation spectroscopy

Molecular Structure and Dynamics

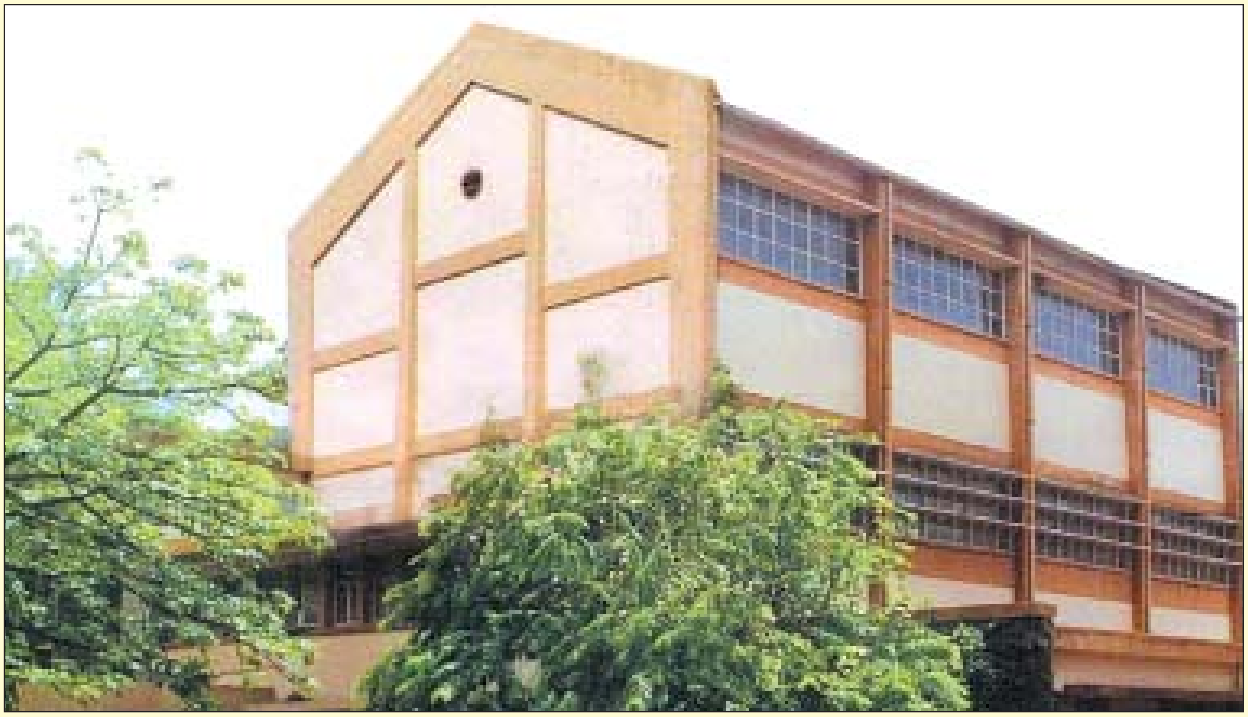
Molecular spectroscopy, conventional as well as high resolution, is of great importance to nuclear energy program as illustrated by the analysis of heavy water. Thus, this technique was extensively used for the very important program of determination of the purity of UF_6 used for U^{235} enrichment. Likewise, spectroscopic methods for analysis of SF_6, used as insulator in high voltage systems for accelerators, were developed and these results came handy when the first laser isotope separation was achieved for S^{34} enrichment.

The expertise gained helped in making several original contributions to the understanding of molecular structures. Prominent among these are Asundi Bands in CO, Mahavir Singh Bands in $MgCl_2$ and the first ever observation of the emission spectrum of the lasing excimer molecule XeCl. High-resolution infrared spectral studies, using tunable diode laser and Fourier Transform Spectrometer, were carried out on a number of asymmetric top and symmetric top polyatomic molecules such as NH_3, NH_2D, CF_3I, CH_3D, C_2H_6, COF_2, CF_4 etc. The research involved was assignment of ro-vibrational transitions, centrifugal distortions, Coriolis interaction, inversion rotation interaction and splitting of rotational level degeneracy. These studies, which are fundamentally important in molecular physics, also provided precision molecular structural parameters for molecules of relevance in isotope separation or development of tunable IR lasers. One of the major achievements of the molecular structure and dynamics studies was the design, fabrication and use of a supersonic, high resolution molecular beam system, which gave considerable insight into the dynamics of supersonic nozzle beams for production of super-cooled molecules such as NH_3, SF_6 and UF_6.

Laser Cooling and Trapping of Atoms

The interest lies in single atom spectroscopy, understanding the collective properties of fundamental quantum systems and the quantum character of translational motion of heavy atoms with potential applications in nanofabrication, microscopy and isotope selective manipulation of atoms. As a first step, development of a magneto-optic trap, which is a widely used robust device to cool and trap neutral atoms, was taken up. The traps have been successfully operated with Rb atoms and cooling the cesium atoms down to ~100 micro Kelvin temperature at CAT and BARC, respectively. The experiments on ultra high-resolution spectroscopy and collision physics of ultra cold atoms are being currently performed. An experimental set up for Bose-Einstein condensation of alkali atoms and to investigate interaction of resonant and near-resonant light with cold atoms is being setup.

Fluorescence image of the cold cloud of atoms (~ 100 million) formed at the centre of the MOT. The cloud has diameter of ~ 1 mm and the temperature of ~ 100 microKelvin



Apsara Reactor Building at Trombay

Apsara Reactor and Surrounding Hall

Nuclear & High Energy Physics

Link P2

Investigations concerning the phenomena of radioactivity, atomic structure, identification of neutron, nuclear radiations and nuclear fission were the subject of intense study during the first half of the twentieth century. In the course of a systematic investigation of nuclear reactions produced by neutrons the formation of $_{92}U^{239}$, an isotope of uranium which does not occur naturally, was suggested. Later, the formation of new elements with atomic numbers 93, 94 ... and so on were discovered. These elements were found to be unstable, decaying with emission of different nuclear particles/radiations and were referred by the general name of transuranic elements. Broadly nuclear physics deals with the structure of nuclei, dynamics of atomic nuclei and nucleaons, processes within or between nuclei, etc. Modern nuclear physics is part of an interdisciplinary field together with high energy physics.

The study of nuclear physics has not only led to a new source of energy but several other important applications. The knowledge gained is also applied to astro-physical and cosmological conditions. It is known that conversion of hydrogen to helium is the source of sun energy. This process is known as fusion and if it can take place in the stars, it is possible to cause it here on earth. While uncontrolled fusion in an Hydrogen bomb has been achieved, the constructive utilisation of the energy released from fusion is now a major field of research endeavour.

Apsara Reactor Pool with Core Trolley

Apsara Reactor Core

Nuclear Physics

The research in nuclear physics was initiated with the 1 MV cascade generator at TIFR and followed up with the neutrons from the APSARA reactor at Trombay which gave it a real momentum. Later, with the commissioning of 5.5 MV Van de Graaff accelerator at Trombay, in the early sixties, pursuit of charged particle based nuclear physics experimental programmes got a boost and many areas of then contemporary interest could be studied. In fact, in the sixties the Trombay 5.5 MV accelerator was the only major facility in the country and it catered even to several users from outside DAE laboratories. This also stimulated the nuclear physics community to plan for a higher energy accelerator and the decision was taken in the late sixties to build a cyclotron of the same design as the one at Berkeley. With the commissioning of the Cyclotron at Kolkata in the late seventies, alphas (energy 25-130 MeV), deuterons (energy 12-65 MeV) and protons (energy 6-60 MeV) became available for studies of nuclear reactions. The studies in early nineties also included the 14 MV Pelletron at TIFR and in the very recent years indigeneously built FOTIA at BARC. In parallel, international collaborations were established with Fermi Lab. and RHIC-USA, CERN-Geneva, GANIL-France, RIKEN-Japan, LNL-Italy. For work, different types of nuclear radiation detectors and some powerful and high quality systems were developed from time to time. Scintillation detectors such as NaI(Tl), CsI(Na,Tl), anthracene, BGO, BaF_2, $CdWO_4$, plastic, silicon based detectors of different types and lithium-drifted germanium detectors, position sensitive gas detectors were produced in large numbers. Recently, a new detector called ENSTAR has been developed for use in the search for η-mesic nuclear matter. This is an exotic nuclear species whose existence has been so far a matter of speculation. This development was undertaken under a collaborative program with Institute fur Kernphysik, Forschungszentrum, Juelich, Germany with an aim to study the reactions: $p + {}^{12}C \rightarrow {}^{3}He + {}^{10}B\eta$, $p + {}^{6}Li \rightarrow {}^{3}He + {}^{4}He\eta$ and $p + {}^{16}O \rightarrow {}^{3}He + {}^{14}N\eta$. Some of the instruments developed for the experimental program include (i) Compton polarimeter for measuring circular polarization of gamma rays, (ii) A single-gap high resolution magnetic beta-ray spectrometer, (iii) A six-gap magnetic spectrometer with 12% transmission, (iv) A thin magnetic lens beta-ray spectrometer. Some of the thrust areas in which the research is being pursued are summarised in Box.

One of the thrust areas of nuclear physics research involves regimes of nuclear structure studies at high temperature (excitation energy) and angular momentum, elastic and transfer reactions. The energetic heavy ion beams from the Pelletron accelerator are used to produce proton-rich nuclei far from the beta stability line. The decay modes of the excited nuclei carry signals from which the nuclear properties like the nuclear shape parameters of the fundamental vibrational modes and effective

Some areas of research in nuclear physics pursued in DAE

- Nuclear reactions near Coulomb barrier.
- Shape evolution of nuclei as a function of angular momentum and excitation energy.
- Mechanism for transfer of nucleons, clusters and intermediate mass fragment emission.
- Entrance channel dynamics in fission.
- Reactions with weakly bound projectiles.
- Non-nucleonic degrees of freedom in nuclear reactions.
- Nuclear reactions near the Fermi energy.
- A statistical model and double-core model for nuclear fission.
- DWBA analysis of transfer reaction data.
- Calculations based on the Nilson model on the stability of deformed nuclei and possibility of stable octupole and triaxial shapes.
- Quasiparticle-phonon coupling model applied to calculate spectroscopic strengths, gamma transitions probability and level schemes.
- Analysis of complex gamma spectra.
- Estimation of transition probabilities.
- Calculation of detailed shell model wave functions.
- Nuclear structure at large angular momentum.
- Relativistic mean field theories.
- Mass formula based nuclear matter properties.
- Heavy ion scattering.

interactions among the nucleons can be deciphered. As the rapidly rotating nuclei are "fast" quantum rotors they offer a unique opportunity to study interplay of many quantum mechanical aspects. For nuclei in the region of mass numbers A~80 and A~110, various properties like changes in moment of inertia, nuclear shapes (shape co-existence), breaking of neutron or proton pairs, interaction of unpaired particles with the rest of the nucleus, changes in the symmetry properties of a nucleus by studying discrete, characteristic gamma-rays in rapidly rotating condition (high spin states) have been investigated. Another interesting phenomenon known as magnetic rotation, resulting from anisotropic arrangement of nucleonic currents in nearly spherical nuclei, has been investigated in Ce and In isotopes.

The study of high energy gamma rays (~5 to 35 MeV) emitted by the excited compound nucleus in early decay stages (Giant Dipole Resonance/GDR) has been employed to probe the shapes of hot nuclei in different mass regions 80 to 200. A general feature that emerges from these studies is that the nuclei become deformed, straddling different shapes and orientations at high angular momentum or temperature, irrespective of the shape they assume in the ground state. In the region of mass number ~200, the deformation as well as the triaxiality (departure from the cylindrical symmetry) is seen to increase with angular momentum, whereas at lower mass numbers around ~80 amu the effect of temperature is relatively more important than that of the angular momentum. The results from these experiments have provided important information for understanding the behavior and structure of the nucleus under varied conditions. The fusion process at energies, of projectile as well as target nuclei, close to the Coulomb barrier has also been studied. These experiments have not only been useful in evaluating effect of the internal properties of the interacting nuclei on the fusion process but have also suggested a new method for computing angular momentum of the fused nuclei and its connection with the fusion excitation. The time evolution of nuclear reactions was probed through measurement of ultra-short compound nuclear lifetimes (10^{-17} s) using crystal blocking technique.

In the more recent past, investigations like studies of threshold anomaly in optical potential and the role of fission dynamics in super heavy nuclei formation have been performed. Some other significant research undertaken include: (i) Investigations on the evolution of nuclear structure as a function of angular momentum in deformed rotating nuclei following microscopic many-body approaches like Hartree-Fock-Bogoliubov theory and statistical descriptions for interacting Fermionic systems like nuclei, (ii) Study of high spin states in nuclei, band-crossings, rotation-alignment, signature effects, K-isomers using deformed Hartree-Fock and angular momentum projection. This model successfully describes all these phenomena within the framework of a many-body theory without phenomenological assumptions, (iii) Study of the remarkable magnetic properties of large K bands to substantiate the prediction of high seniority large K isomers up to very high spins, (iv) Super heavy nuclei and the structure of exotic nuclei away from stability-line have been investigated. These have allowed prediction of new magic numbers (spherical and deformed). The nuclear matrix elements for double beta-decay are evaluated using deformed HF and J Projection method, (v) The development of Infinite-Nuclear-Matter (INM) mass formula based on many-body theoretical foundation using generalized Hugenholtz-Van Hove theorem. It treats the nucleus as a quantal many-fermionic system rather than the classical liquid (without any reference to particle number) used in Bethe-Weizsacher-like mass formulae. It extracts the saturation density, binding energy and the incompressibility of INM from a single source, namely nuclear masses. The radius constant r_o so determined agrees with that from electron scattering, leading to resolution of the long standing r_o-paradox. The successful predictions of masses up to and beyond drip lines have the most desired unique features of shell quenching and new islands of stability, (vi) Based on fireball and spectator-participant picture, a model for heavy-ion induced multifragmentation reaction has been developed which includes entrance channel effects, (vii) Development of a diatomic-like molecular model, based on quantum mechanical two-body dynamics (using Morse-like poential) and surface friction model for unified description of both deep inelastic collision and fusion phenomena, (viii) Analytical solution of the deuteron problem by an ingenious way, bringing out new aspects of this classical problem, (ix) Large anomalies of the knockout reactions have been resolved in terms of the shell structure at the direct reaction vertex, (x) In medium heavy nuclei the evolution of nuclear shape and level density as a function of angular momentum and / or temperature has been investigated from the measurements of high energy gamma rays and charged particles, (xi) Measurement of astrophysically important nuclear cross secion of $^{7}Be(p,\gamma)$ reaction using the radioactive ion beam, (xii) Determination of the time scale of fission process, (xiii) Studies concerning the mechanism of fusion initiated with weakly bound nuclei, (xiv) Fusion barrier distribution via quasi-elastic scattering has been determined for ^{11}B, ^{12}C, ^{13}C and ^{209}Bi to investigate the effect of transfer coupling on fusion cross section around coulomb barrier, (xv) Development of a generalized pre-equilibrium fission model to understand fusion-fission dynamics, (xvi) Investigations concerning the 2n cluster and 2n correlated pair transfer in ^{16}O, ^{18}O and ^{174}Yb and (xvii) The value of incompressibility of infinite nuclear matter has been experimentally determined by studying Isoscalar-Giant dipole resonance in nuclei ranging from ^{58}Ni to ^{208}Pb.

Spectroscopic investigations of high spin states have been performed utilizing the Pelletron accelerator facilities and heavy ion beam at VECC. These resulted in the establishment of several new level schemes. The inner-shell ionization cross-sections, vacancy alignment and multiple ionization cross-section studies are being pursued by bombarding targets of high atomic number with heavy ions thereby testing theoretical models describing the atomic system. A novel approach to determine the Croster-Kronig transition probability, f_{23}, has been successfully demonstrated.

A part of the current activity in area of theoretical nuclear physics has shifted to border line areas of nuclear and high energy physics like nuclear astrophysics and quark-gluon plasma, conformal field theory, string theory, etc. Signatures of quark gluon plasma in collisions of heavy nuclei at high energy, phase transitions in hot compressed nuclear systems, microscopic calculations of slow time dependent large amplitude changes like fission have been pursued. With the advent of radioactive ion beam (RIB) facility, novel studies pertaining to signatures of neutron halo are being carried out. In the high energy physics domain, phenomenological studies in the standard model, light front dynamics, super symmetry and black hole studies, and lattice gauge theory are being pursued. The work on neutrino physics has specially addressed outstanding problems dealing with solar neutrinos.

High Energy Physics

High energy or elementary particle physics seeks to understand phenomena at the sub-atomic level and at the highest energies available today. It is recognized as a challenging and frontier area of natural sciences with an aim to discover the fundamental constituents of matter and the laws governing their interaction. The world as we know it today is a result of interactions among these fundamental particles. There are four known fundamental forces. Of these, the best-known force, gravity, is the weakest. The other three forces are the strong, the electromagnetic and the weak. Both quarks and leptons (which are basic building blocks of matter) interact among themselves by exchanging entities called "gauge bosons". The exchange of different types of gauge bosons results in different types of forces. A unified description of the properties of matter and their interactions with respect to strong, electromagnetic and weak forces, is given by the so-called Standard Model of particle physics. The fourth, namely gravity, has eluded unification with the other three. The standard model explains most natural phenomena coming under the purview of these interactions with just one important component missing - a new particle called the Higgs boson. The existence of this particle has been predicted on the basis of theoretical considerations. However, no demonstrable proof of its existence has yet been obtained. One of the most important experimental goals now of elementary particle physics is to discover this exclusive particle. At the theoretical level, an important component of the standard model, which still continues to defy a complete understanding, despite considerable advancement in related fields, is the problem of confinement, that is how quarks are confined within the proton or neutron. In addition, scientists around the world are asking whether there exists something beyond the standard model. The motivation for this question is the fact that the standard model does not specify the magnitudes of the masses of either the quark or the lepton. In particular, it specifies that the mass of certain leptons called neutrinos be zero. It has long been suspected that neutrinos are not absolutely mass-less. Over the last three decades

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experimental evidence from both solar and atmospheric neutrino experiments strongly indicate that neutrinos possess mass. The experiments not only suggest that neutrinos are massive, with small masses, they also indicate that the neutrino flavors mix and therefore show the quantum mechanical phenomenon called oscillations. Pioneering work related to determining various parameters of neutrino oscillations as well as attempts to gain a theoretical understanding of the magnitudes of the neutrino masses has been carried out. Given this overwhelming evidence, considerable effort has been focused on developing theoretical models that could explain the observations in a natural way. Studies of possible CP violating effects and the feasibility of their being observed have also been undertaken. It is exciting to note that generation of neutrino masses is possible in many extensions of the standard model that have been invoked to address different questions. It is of immense importance and interest to study the relative merits of these different options in the light of the current data on neutrino oscillations. At the theoretical level, a new symmetry among the elementary particles such as supersymmetry, or a new unification of the interactions could also lead to new physics beyond the standard model. All these issues have been actively pursued in DAE

Several efforts of both experimental and theoretical nature are ongoing in the area of ultra high energy (up to 10^{21} eV) neutrino physics. The origin of such high energy neutrinos is not understood and several scenarios like pion decay from hadronic collisions, Gamma ray bursts of Active Galactic Nuclei, topological defects and Kaluza-Klein excitations of gravitons are envisaged. The detection of such neutrinos, especially in view of their ill-understood fluxes, necessitates very careful estimation of their interaction with terrestrial detectors. With several new experiments being planned, this is a potential arena for making new discoveries. Concerted efforts are therefore being made to both calculate the standard model cross sections and detection profiles for such neutrinos as well as to judge the efficacy of using such particles as probes for new physics.

The results of collision processes among particles provide us with a major source of information. Hence higher the energy of the colliding particles the deeper one can probe in the distance scale. Consequently, this activity demands building of machines known as accelerators to produce charged particles of higher and higher energies. Thus, the experimental work in this area involves use of major international facilities and working in large collaborating teams. The earliest collaboration between TIFR and CERN started in early sixties for nuclear emulsion based programmes. The first CERN based bubble chamber experiment that TIFR participated in was the 760 MeV/c antiproton experiment in a hydrogen (proton) bubble chamber. Currently, TIFR is participating in a world wide collaboration called Compact Muon Solenoid (CMS) experiment at CERN to look for Higgs particle, which is projected as the originator of mass for all other particles. Various scenarios for the detection of Higgs bosons in the light or lower intermediate mass region ($M_H < 130$ GeV) at Large Hadron Collider (LHC) at CERN and Tevetron at Fermi Lab. have been discussed and it is pointed out that at LHC, one promising signature is that of the isolated two photons. The other promising signature in this mass region is e/μ+bb+a soft jet event. A detailed study of the signal and background has been carried out using parton-level monte-carlos and event generator PYTHIA.

In theoretical high energy physics considerable work is being done all the way from phenomenology to more formal problems onto fundamental issues and mathematical structures: quark models and hadron spectroscopy, sensitive tests of electroweak and QCD theories, CP violations flavor mixing, neutrino physics, Higgs and superparticle searches, grand unification and supersymmetry, higher dimensional theories, superstrings, conformal field theories, lattice methods, problems related to foundations of quantum mechanics.

Pioneering work related to the determination of various parameters of neutrino oscillations as well as attempts to gain a theoretical understanding of the magnitudes of the neutrino masses has been done. While many details of the standard model have been rigorously checked (indeed, much data was used as inputs to this description), some of the major open issues include detailed calculations in the strong sector, understanding the existence of an (almost) exact mirror symmetry in the Universe, and the question of the origin of fermion masses, including that of neutrinos. Investigations concerning the difficult problem of quark confinement have been carried out, both analytically and using numerical techniques. The latter involves studying particle interactions using techniques of lattice gauge theory. Some of the existing techniques had serious lapses, and so new approaches to solve these problems were formulated. The problem of nearly free quarks can be thought of as the case where the quarks have large momenta. In this limit, it turns out that the strong force problem is tractable by using perturbative techniques. Here, questions such as how the properties of the proton are reflected in those of the quarks that constitute it, and conversely, how quarks interact to produce composite particles such as nucleons, can be addressed. Many interesting results obtained in these areas are continuously tested by carefully planned experiments. The standard model does not specify the number of quarks and leptons. It turns out, experimentally, that there are at least three different types of quarks and leptons each, the former making up different types of composite particles called hadrons. It is curious that the presence of the three so called flavors allows for a break-down of a symmetry that makes our universe composed of matter and its mirror-image antimatter. Experimentally, it turns out that this symmetry is broken very slightly. It is not at all easy to understand the origin of this small violation or to device methods that would permit observartion of such violations in different processes. Some of the innovative suggestions that would make it possible to observe this CP violation are now being used in devising ingenous experiments around the world.

Any theory of particles and their interactions must be consistent both with the theory of relativity as well as with quantum mechanics. A consistent mathematical frame-work is provided by what is called a quantum field theory. Quantum Chromodynamics is an example. The formal construction of quantum field theories such as topological field theories and non-commutative field theory, and their study as a tool to understand geometry and topology of space-time is an area in which important contributions have been made. Some of these developments find important applications in quantum gravity as well.

Significant contributions have been made in the area of classical and quantum gravity. This includes the exciting physics of black holes, which are believed to exist in large numbers in the universe. One of their intriguing features is that the behaviour of black holes is analogous to that of a thermodynamic system. When quantum effects are taken into account, they have a “Hawking temperature” as well as entropy given by ‘Bekenstein-Hawking formula’. The next leading correction to this formula has been one of the major contributions. Scattering at Planck scale energies (when gravity becomes as strong as the other fundamental forces), has also been studied. Classical gravity predicts singularities at which physics as we know it, breaks down. This happened at the time of Big Bang and also ‘inside’ the black holes. Some light has already been thrown on how the (loop) quantum gravity ‘dissolves’ the cosmological singularities.

One of the most challenging problems in high energy physics is to obtain a consistent quantum field theory of gravity. While a lot of progress has been made, it is believed that the string theory would be able to address the issues involved. It is also strongly believed that, simultaneously, the string theory will be able to provide a unified description of all forces, including gravity. A lot of work is going on around the world, towards this end. Notable contributions have been made to a number of interesting developments in the non-perturbative aspects of strings. String theories are also described in dimensions larger than those of the known physical world, for reasons of consistency. The extra dimensions are compactified in order to obtain descriptions of the physical universe. The studies of different manifolds for compactification have been done. The application of the holographic principle to cosmology has been discussed. A study of black hole properties in conformal field theories, with a view to study their evolution, has also been done.

Other significant contributions made by the DAE scientists in the area are summarised in the following four Boxes.

Topological defect formation and quark hadron transition

- It is shown that due to non zero pion mass, the baryon (in the Skyrme model) production can be significantly enhanced and may be used as a signal of chiral symmetry restoration.
- A new mechanism has been proposed for the production of defect-antidefect pairs via oscillations of the order parameter field.
- A novel scenario for a first order quark-hadron transition in quark-gluon plasma has been studied. It is shown that this will lead to concentration of baryon number in a narrow beam-like region in center and can be used as a signal for detecting quark-gluon plasma.
- The distorted chiral condensate (DCC) domain formation in relatively low energy collisions is possible only when tempera ture ture reaches Ginzburg temperature but never reaches the critical temperature.
- A novel mechanism for the formation of a very large single DCC domain in heavy ion collisions is proposed.

Chern-Simons term, charged vortices and anyons

- Abelian Higgs model with Chern-Simons term in 2+1 dimensions has charged vortex solutions of finite energy, quantized nonzero flux and charge. These vortices have nonzero angular momentum, which in general can take any arbitrary value. Thus, this is an example of an extended charged anyon.
- Chern-Simon term can also be generated by spontaneous symmetry breaking.
- Charged vortex solutions also exist in SU(N) gauge theory.
- Charged vortex solutions exist in Abelian Higgs model with Chern-Simons term even if the Maxwell term is not present.
- Second virial coefficient is exact in the semi-classical approximation. Within the same approximation estimation of the third virial coefficient in the Boltzmann basis (i.e. by summing over symmetric, antisymmetric as well as mixed symmetry states) was made.
- The ground state energy of three anyons near the fermionic end increases as one goes away from the fermionic end, which is contrary to the naïve expectation.

String theory

- Consequences of holography in black hole physics and cosmology.
- Supersymmetric stable solitonic configurations in string theory.
- Explicit solutions for D-branes in pp-wave background in type IIB string theory.
- Non-threshold bound states of (p,q) string networks dissolved in D-branes.
- Study of cosmology in string theory.
- Properties of two-dimensional string effective action.
- The construction of string theory / supergravity duals of gauge theories, which show confinement.
- Use of adS/CFT correspondence to calculate vacuum expectation values of Wilson loop operators in gauge theories.
- Deriving renormalization group flow and associated c-theorem in four dimensional quantum field theories using the equations of motion of the dual supergravity theory.
- Understanding the spectrum of string theory in the back ground on an anti-de Sitter space.
- Quantum properties of non-commutative theories, which show a curious UV/IR mixing, as well as novel classical properties like the existence of new kinds of solitons.
- Non-supersymmetric systems and tachyon condensation.

Supersymmetric quantum mechanics

- Not only eigenvalues but also the eigenfunctions of the shape invariant potentials can be obtained algebraically thereby extending the oscillator case. It is worth noting that the shape invariant class includes all known exactly solvable potentials, which are found in standard quantum mechanics textbooks. It was also shown that the supersymmetry inspired WKB approximation is exact for shape invariant potentials.
- The most general solvable potentials in quantum mechanics were studied and it was shown that shape invariance, even though sufficient is not a necessary condition for solubility in quantum mechanics. The full classification of shape invariant potentials with translation was also carried out and new potentials displaying shape invariance with scaling were discovered. These potentials have infinite number of bound states and are reflection less.

Quark Gluon Plasma

When subjected to extremes of temperatures or / and densities, nuclear matter undergoes a deconfining phase transition to a new phase of matter called Quark-Gluon Plasma (QGP). Quarks are fermions and Gluons are bosons (carriers of the strong force that bind quarks together into hadrons such as protons or neutrons). Study of color gauge theory (Quantum Chromodynamics) of quark-gluon interaction has shown the critical density to be $n_{cr} = (5 – 10)\ n_0$, where $n_0 = 0.15$ GeV/fm^3 is the density of cold nuclear matter, and the critical temperature to be T_{cr}= 150-200 MeV. This exotic phase of matter certainly existed in the early universe about a microsecond after the big bang. It probably exists even today in the core of massive neutron stars. According to nuclear theoriticians if atomic nuclei are squeezed hard enough under conditions of high pressure and temperature, a QGP will form. There have been some indications of such a phenomenon where conventional matter dissolves into free roaming quarks and gluons. Even so more conclusive evidence for QGP is yet to come. The efforts in this direction are being made at CERN and BNL. Some of the constituent units of DAE are also participating in these global efforts including what is known as A Large Ion Collider Experiment (ALICE) at Large Hadron Collider (LHC) at CERN. This is mammoth undertaking that is a collaborative effort of 83 laboratories from all over the world. This experiment is aimed at looking for the tell-tale signature of Quark Gluon Plasma (QGP). SINP is responsible for the design, fabrication and installation of a tracking station. This tracking station is a multi wire proportional gas detector with segmented cathodes and has a diameter of 2.5 meters with anode to cathode separation of 2.5 mm having an accuracy within 100 microns over the entire detector area giving a position resolution of around 50 microns. The front-end electronics for such five tracking stations is the MANAS chip developed by SINP. Also, SINP is responsible for the fabrication of the graphite and stainless steel parts of the front absorber for the dimuon spectrometer, as well as data interpretation and simulation necessary for the LHC in general and ALICE in particular. For this collaboration, VECC and IOP along with some Indian universities have been responsible for the development of Photo Multiplicity Detectors (PMD). These detectors will also be used for STAR collaboration at Relativistic Heavy Ion Collider (RHIC) at BNL, which is also aiming to study QGP. TIFR has participated in the L3 experiment at the LEP (Large Electron Positron) collider at CERN. A part of the hadron calorimeter was fabricated and contributions were also made in software development and physics analysis. Some areas of major contributions are given in the following Box.

In recent studies of the classical YM system in (3+1)-dimension on a lattice carried out at IPR, the occurrence of chaos has been related to the thermalization of gluons in the deconfined state which may be formed in relativistic heavy ion collisions. Motivated by the numerical findings, a simple calculation has been carried out using quartic oscillators with two degrees of freedom to model YM classical mechanics. This simple model explains qualitatively all the features reported in the lattice simulations where the largest Lyapunov exponent (λ) and the thermalisation time were evaluated numerically. It is shown analytically from the model calculation that λ scales with the 4th root of the energy density. The thermalization process in the analytical model is due to relaxation phenomena associated with the colour degrees of freedom.

The present interest in studying QGP dynamics is driven by the possibility of its creation in ultra-relativistic heavy ion collisions. Because of high collision energies involved, it is expected that, if the plasma is formed, then it will be in a state, which is far away from thermodynamic equilibrium. As stated previously, thermalization has been shown to be intimately related to the chaotic dynamics of a system. To study the chaotic dynamics of a Quark-Gluon plasma in 1+1 dimensions, a relativistic particle-in-cell simulation code – QGP1 has been written. The thermalisation in case of a coloured plasma involves both momentum and colour relaxation. A detailed study of both has been done. All these studies on thermalisation involved were done in 1+1 dimensions. Since in a realistic situation, transverse modes of interaction also plays a significant role, a systematic study of the transverse modes alone (decoupled from longitudinal modes) has also been carried out. It has been found that the equations governing the evolution of transverse modes are similar to the equations for longitudinal modes. The equations are solved approximately using a Multiple time scale method. It has been observed that in the parameter regime where Multiple time scale analysis is valid (when the non-abelian coupling terms are small), a new non-abelian mode appears modulating the frequency of the usual abelian mode. As the non-abelian coupling strength is increased, both frequency and amplitude modulation of the abelian mode are seen. For very large values of non-abelian coupling, chaotic behaviour sets in.

Significant Contributions in the analysis of L3 experiment

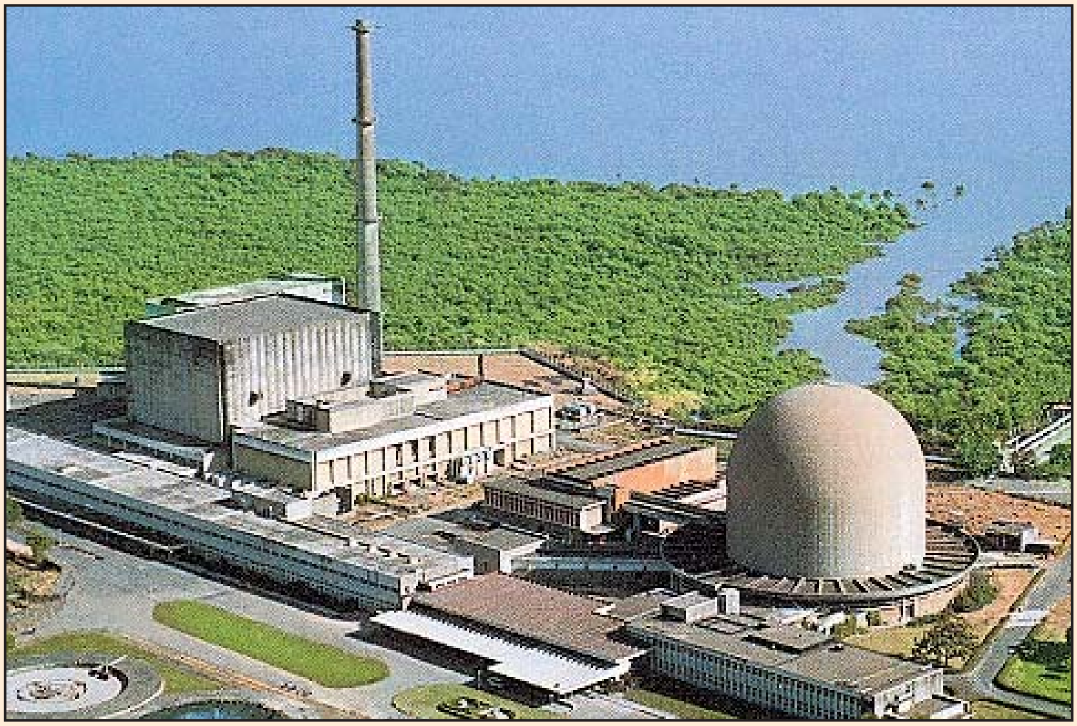
- Lineshape analysis at LEP1 to determine the properties of the Z-boson (mass, partial and total decay widths, couplings to quark and lepton pairs). For all the LEP1 period, TIFR physicists were responsible for this analysis in L3.
- Tagging of Z -> b bbar events and their study. A pioneering technique of applying neural networks to obtain better tagging results was employed by TIFR.
- Study of quantum chromo dynamics in e+e- interactions as LEP energies and determination of the strong coupling constant (alphas) at various energies to study its evolution with energy.
- Search for supersymmetric and Higgs particles.
- Selection of e+e- -> W+W- -> qqqq and qq e nu and e+e- -> ZZ -> qq lepton nu reactions at LEP2 and determination of their cross sections and mass and width of the W.

Reactor Physics

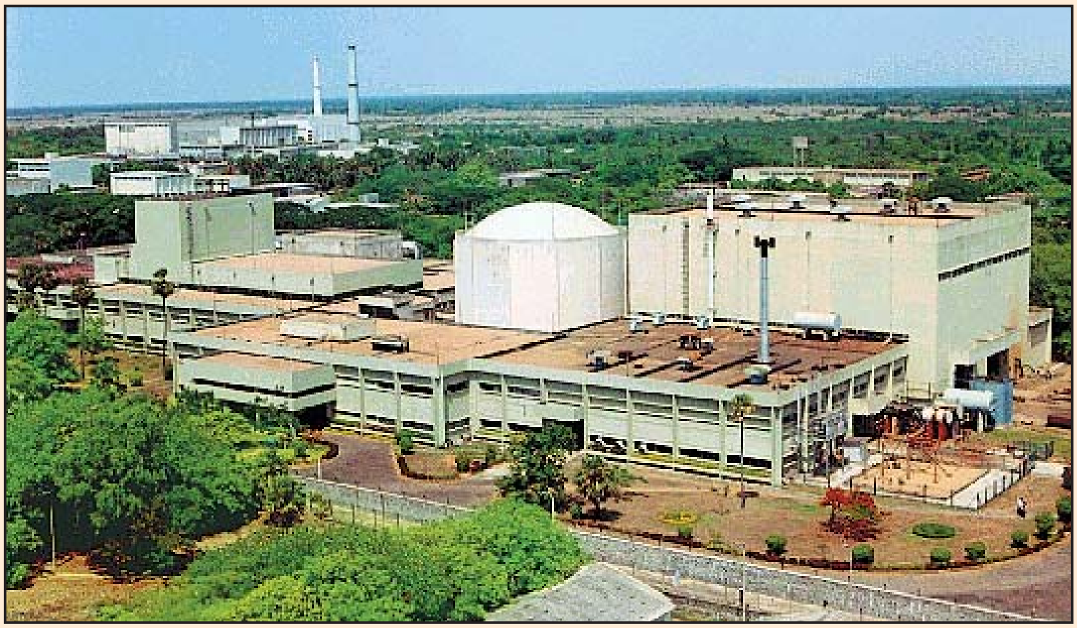
Link P3

The 1939 discovery by Hahn and Strassman that slow neutrons can cause fission of uranium nuclei was a major surprise to physicists, since no one expected that a strongly bound system like a nucleus could be broken up so easily. Soon it was realised that enormous amount of energy is also released upon fission of heavy nuclei. So, if one can create a controlled fission chain reaction, a new source of energy is available to mankind using nuclear reactor. (A nuclear reactor is a system where a chain reaction is initiated, sustained and controlled). Upon fission, the energy is released in various forms, including kinetic energy of the fission fragments, emission of highly energetic photons (gamma rays) and neutrons. Due to the high penetrating power of gamma rays and neutrons, special care is required to ensure safety of personnel working in a reactor area. In addition, some highly radioactive fission fragments having long half-life need to be managed at a later stage. Thus, to design a nuclear reactor, first major issues related to physics of the system must be examined including those dealing with interaction of the emitted radiations with matter and control of the chain reaction.

In this link we summarise the work carried out in the area of reactor physics. The application of nuclear reactors in physics has been summarised under link-P8.



Panoramic view of CIRUS and DHRUVA research reactors at Trombay



Panoramic view of Fast Breeder Test Reactor at IGCAR, Kalpakkam

Reactor Physics

The nuclear processes are potentially far more energetic than chemical processes. For instance, one carbon atom oxidised to CO_2 liberates 4 eV energy, while one radium atom disintegration gives 4.8 MeV. It must be emphasised that highly energetic radioactive disintegrations are not very promising as practical source of energy. At best radioactivity may be utilised to make electric batteries of exceptionally long life. We have seen that fission reaction releases very high energy (around 200 MeV per fission) and that makes it a source of practical energy. The principal isotope of uranium that undergoes fission is ^{235}U and it breaks apart in many ways. Here, the average number of neutrons released per fission is 2.5. This makes it feasible to establish a chain reaction and indeed provides real potentiality of using nuclear fission as a power source. For a self-sustaining chain of fission reaction, it is important that at least one neutron from the first fission produces another fission and so on for the third and subsequent events. Thus, for the physicists it is important to determine conditions under which fission chain can be maintained.

The fission cross-sections for ^{238}U and ^{235}U in case of fast neutrons are roughly 0.02 and 1.2 barns, respectively. Whereas, for slow neutrons these figures are roughly 0.0 and 580 barns, respectively. Natural uranium contains two isotopes namely ^{235}U and ^{238}U with concentrations of about 0.7% and 99.3%. Since, ^{238}U is far more abundant than ^{235}U and hence the neutrons released on fission would have an excellent chance of non-fission capture by ^{238}U. For a self sustaining fission chain it is important that the ratio of the number of neutrons in one generation to the number in the preceding generation called the multiplication factor (k) is maintained equal to unity. It turns out from data on fission cross section that a body of ^{238}U of any amount will be sub critical for fast neutrons, i.e. the value of k remains much below unity. On the other hand, every ^{235}U nucleus that absorbs a high-energy neutron has a great chance of undergoing fission. The k value in this case is simply the number of fission neutrons produced, which is much larger than unity. Since the number of neutrons produced in each generation is much larger than the preceding, the only way to prevent a body of pure ^{235}U from exploding is to break it into pieces so small that more than 50% of the neutrons escape without producing fission.

The importance of reactor core design and the relative concentrations of the two uranium isotopes in the fuel to achieving self-sustaining fission reaction thus cannot be underestimated. In order to take advantage of the very large value for fission cross-section of ^{235}U, it is necessary to slow down the fission neutrons, most of them having energy of ~1 MeV. This is very effectively achieved by scattering them elastically with light nuclides. Both hydrogen and deuterium are, therefore, employed as moderators in the form of water. Hydrogen has a absorption cross section of 0.33 barns and scattering cross section of 38. On the other hand, these figures for deuterium are 0.0005 and 7, respectively. The use of light water as moderator requires enrichment of ^{235}U to the level of ~2.5% for attaining criticality. In contrast, with heavy water as the moderator it is possible to maintain chain reaction with natural uranium as the fuel. Thus, the relative concentrations of ^{238}U and ^{235}U in the fuel to be used are dictated by the moderator used.

Apart from ^{235}U, which is the only naturally occurring fissile material, ^{239}Pu and ^{233}U are also fissile nuclides and are very important materials from nuclear energy point of view. These materials are produced inside a nuclear reactor. ^{239}Pu is formed when a neutron is absorbed in ^{238}U and likewise ^{232}Th gets transformed into ^{233}U.

DAE has been working on the design and building nuclear reactors for different applications and they are classified into research reactors, converter reactors and power reactors.

DAE 3-Stage Programme

The first reactor built at AEET (BARC) used enriched uranium fuel with light water as the moderator. It was commissioned on August 4, 1956 and named as APSARA. Operating at 500 kW it provided neutron flux of 10^{12} neutrons/cm^2/s. The first experiments carried out at the shielding corner related to measurement of slowing down properties of a variety of moderator materials. Fission physics studies were taken up at the thermal column. The neutron beams were used for neutron beam research. The second research reactor CIRUS was built in collaboration with Canadian Atomic Energy Agency and it was commissioned in 1960. The fuel used was natural uranium and heavy water as the moderator. Working at a maximum thermal power of 40 MW, it provides central thermal neutron flux of 6 x 10^{13} neutrons/cm^2/s. On January 14, 1961 the reactor ZERLINA (Zero Energy Reactor for Lattice Investigations and New Assemblies) was commissioned for lattice studies. On May 22, 1972, a zero energy critical assembly called PURNIMA (Plutonium Reactor for Neutronic Investigations in Multiplying Assemblies) was commissioned which employed plutonium oxide as the fuel. DHRUVA, a 100 MW heavy water research reactor of totally indigenous design, became operational in 1985. At the maximum thermal power, the corresponding central flux achieved is nearly 2 x 10^{14} neutrons/cm^2/s. At present, DHRUVA is the main workhorse for neutron beam research programme.

The first stage nuclear power programme utilized natural uranium as fuel in Pressurized Heavy Water Reactor (PHWR) power plants. The generation of physics design capabilities for power reactors was an uphill task. With the help of research reactors viz. APSARA, ZERLINA, CIRUS and DHRUVA, such capabilities have been attained. For the shielding design of the nuclear power plants, the data on attenuation coefficients for different shielding materials were also required. With the help of the research reactors these data banks were also prepared. Using neutron nucleus interaction data obtained from IAEA and the above mentioned data banks, various codes have been developed for the physics design of nuclear reactors, which make us self reliant with regard to designing, operation and up-gradation of our nuclear power plants.

In the design of the present PHWRs, quite a good number of changes have taken place, essentially based on the experience that has been gained with their operation. In the past, for the control of reactor, measure of the reactor power used to be the difference of the coolant temperature across the reactor core. This was possible as no boiling was allowed in PHWR core. After having developed confidence in the measurement of the neutron flux, this signal is being used instead to control the power reactors. This change has led to the up-gradation of the existing design of the PHWRs. By allowing a partial boiling in the core, the same engineering design of a 540 MWe PHWR can give an enhanced capacity of 700 MWe generation. This is quite a significant development from the point of view of the cost of power generation.

The second stage envisages development of Fast Breeder Reactors utilizing plutonium produced in PHWRs. A modest beginning in this direction was made by constructing a sodium cooled Fast Breeder Test Reactor (FBTR) at IGCAR, with a nominal power of 40 MWt, based on the design of the French Reactor, RAPSODIE. The reactor attained its criticality in 1985 and has been in operation at its maximum attainable power level of 40 MWt with a small core. It is the first of its kind in the world to use plutonium-uranium mixed carbide fuel. In 1996, a 30 KWt, ^{233}U fuelled mini reactor called KAMINI was made operational at IGCAR for neutron radiography, neutron activation analysis etc. Comprehensive research and development activities covering the entire spectrum of Fast Breeder Reactor technology is going on to design and construct Prototype Fast Breeder Reactor (PFBR) of 500 MWe.

India has huge thorium resources and hence the third phase of our nuclear power program is designed keeping this fact in mind. Thorium is converted to ^{233}U by irradiation in PHWRs and FBRs. An advanced heavy water reactor (AHWR) is being developed to expedite transition to thorium based systems. The reactor physics design of AHWR is tuned to generate about 75% power from thorium, and to maintain negative void coefficient of reactivity under all operating conditions. This task requires to generate relevant data for thorium and ^{233}U. This work has to be carried out by DAE exclusively as no other country in the world possesses such vast resources of thorium and consequently have no interest in performing such a study. A critical facility is being built at Trombay, which will enable generation of physics data required for design and operation of reactors in the third phase.

Several aspects of physics related to design and operation of various reactors were studies. These included measurement of nuclear cross-sections, evaluation of different types of systems viz. thermal, light water and fast reactors, reactor analysis techniques, physics of resonance region, reactor kinetics etc. Initially, reactor physics design methods were based on four-factor formula and 2 group diffusion theory. These methods were based on French and Canadian recipes that existed in the early days. Subsequently, design studies on natural uranium, heavy water moderated, organic cooled reactors were undertaken. With the availability of the 27 group and 69 group libraries of the cross-sections, the development of more accurate multi-group multi-dimensional transport theory methods was emphasized. Various codes namely MURLI, CLUB, SUPERB, PHANTOM-CMESH were developed for reactor lattice calculations. In-house fuel management of Boiling Water Reactor at Tarapur was taken up from 1976 onward. A versatile code called COMETG was developed to calculate the cycle length, power distributions and hot spot factors. Computer code TRIVENI was developed for calculations of PHWRs

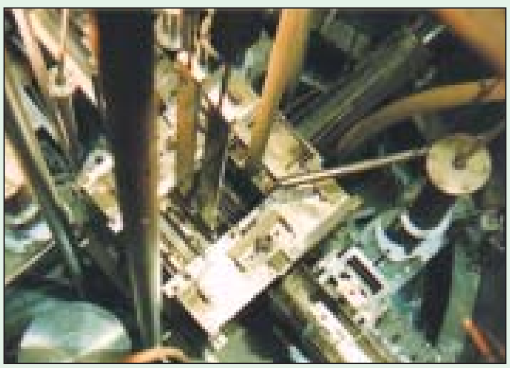
ZERLINA reactor was mainly used to investigate buckling of a sub-critical lattice by substitution technique and comparison of data with the theoretical computations / validations and adjustments of codes. In this technique the lattice under test forms one of the zones of a two-zone critical system, the second zone consisting of a lattice whose properties are known. The reference core is well studied by measuring the 3 D neutron flux distributions for buckling and intra cell parameters e.g., fine structure flux in the cell, the Westcott spectrum parameters, fast fission factor, initial conversion ratio etc. All the DHRUVA reactor lattice physics measurements were carried out in this reactor. Here, the core could be easily changed to obtain different configurations. It was possible to create a thermal column having a well thermalized neutron flux, by removing few peripheral fuel rods. The thermal column served as the reference while measuring neutron spectrum parameters. A facility called batch addition / removal system that could add / remove a small but accurate quantity of heavy water was also provided. The fuel used was in the form of natural uranium metal of 3.56 cm diameter and 243.8 cm length covered with 1 mm thick aluminum sheath – ZA rod. A maximum of 80 ZA rods could be suspended from tank top in the heavy water, which acted as both moderator and coolant. The moderator was provided a cover of dry Nitrogen gas. The maximum operating power was restricted to 100 watts, which corresponded to a thermal flux of about 10^8 n/cm^2/s at the core centre. Lattice pitch could be easily changed by re-arrangement of girders placed on the tank top from which fuel was suspended. The reactor consisted of an aluminum tank of inner diameter 228.6 cm surrounded by 73.5 cm thick and 300 cm high radial reflector with 7 cm annular gap in between the tank and reflector. A 1.5 mm thick cadmium shutter operated in the gap.

ZERLINA was also used for experiments on the modeling of neutron absorbing / producing assemblies. The experiments were carried out on few such assemblies proposed for the PHWR program. For example, plutonium boosters were studied extensively in ZERLINA. Reactivity worth and fine structure flux distribution inside the boosters and flux perturbations in the core were measured and compared with calculations. This reactor also played an important role in the development of measurement techniques, inter-calibration of neutron activation foils made of alloy materials and standardization of counting setups and procedures all aimed at improving the measurement accuracies.

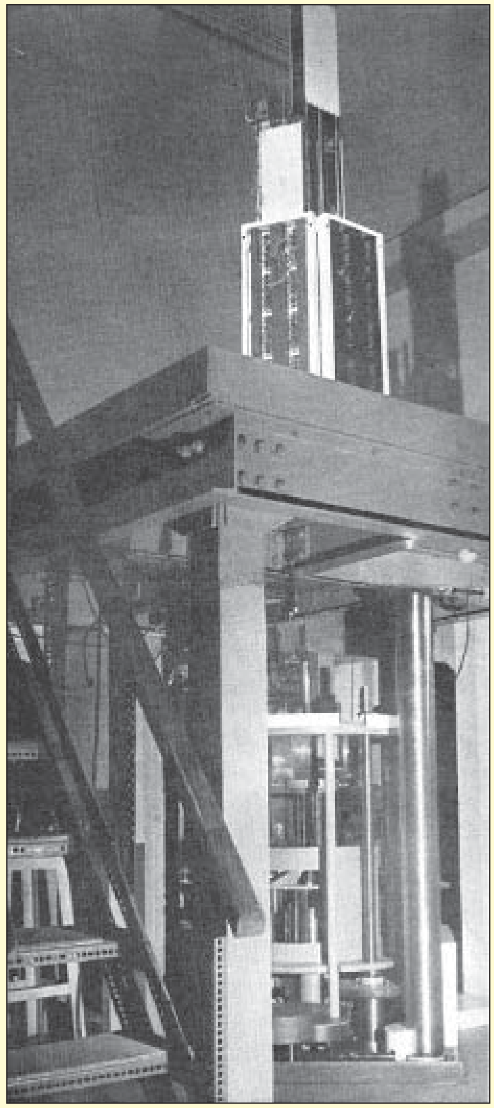
The plutonium fuelled zero power fast critical facility (PURNIMA-I) was designed to carryout reactivity worth measurement, neutron lifetime measurements and determination of the parameters for the proposed Pulsed Fast Reactor. It used about 20 Kg of plutonium in the form of oxide as fuel and was reflected by copper/steel. In the next stage of the work (PURNIMA-II) the first ^{233}U(uranyl nitrate solution) fuelled and beryllium oxide reflected zero power reactor was built. Here, the fissile solution was contained in a cylindrical zircalloy core vessel, which was surrounded by 300 mm thick BeO reflector. The critical mass varied in the range 400 – 600 grams. Due to the inherent alpha-activity of ^{233}U, the solution handling equipment was positioned inside a pair of glove boxes. This reactor was used to obtain inputs for the construction of PURNIMA III, which was later renamed as KAMINI reactor at IGCAR, Kalpakkam. With the commissioning of KAMINI, which is a totally indigenous effort, DAE has entered the third phase of reactor physics and technology development, which is via the thorium route.

Significant work done in the area of reactor physics

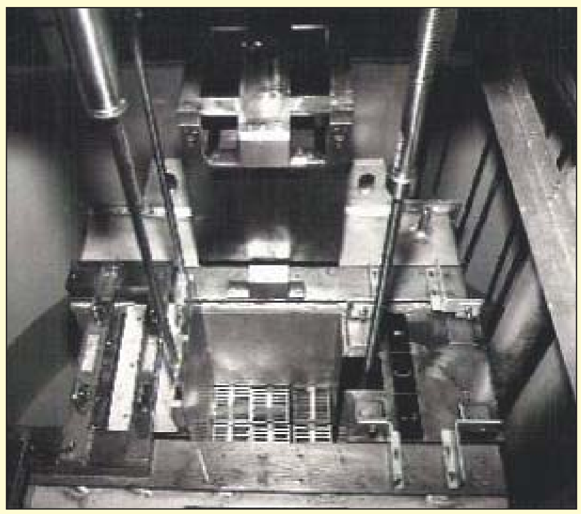
- Theoretical calculations of neutron scattering in BeO and the associated experimental investigations.
- Neutron transport theory, thermalisation, resonance phenomena and reactor kinetics.
- Development of MURLI, CLUB, SUPERB, PHANTOM-CMESH codes for lattice calculations.
- A versatile code called COMETG was developed which allowed calculation of cycle length, power distributions and hot spot factors comparable to those of original designers (GE).
- Computer code TRIVENI developed for core computations of PHWRs.
- Computer code FARCOB developed for core computations of FBRs.
- For Dhruva reactor lattice physics measurements of buckling, intracell parameters, optimization of D_2O scatterer thickness in through tubes and all aspects related to gadolinium nitrate liquid poison tube system.
- Investigations concerning plutonium boosters for PHWR program were made. Reactivity worth and fine structure flux distribution inside the boosters and flux perturbations in the core were measured and the data compared with calculations.
- The experiments pertaining to optimization of shielding design for the proposed 500 MWe prototype fast breeder reactor as well as the advanced heavy water reactor have been carried out at APSARA.
- Development of a code TRISUL for core calculations of thorium based reactor.



Top view of KAMINI reactor



PURNIMA-I facility



Inside view of PURNIMA-III core

Accelerator Physics

Link P4

One of the avowed aims of research in physics is to understand the nature of the fundamental constituents of matter and interactions between them. Once this is known it would be possible to understand how the universe came into being and how it keeps functioning the way it does. It becomes necessary therefore to smash atoms and nuclei at great speeds so that they would break apart into their constituents and reveal their secrets. Particle accelerators help achieve this goal. These machines give high energy to subatomic particles, which then collide with targets. Out of this interaction come many other subatomic particles that pass into detectors. From the information gathered in the detectors, physicists can determine properties of the particles and their interactions. The higher the energy of the accelerated particles, the more closely we can probe the structure of matter. Accelerator physics deals with problems concerning designing, building and operating particle accelerators of various types and with different intended applications.

As developmental programmes in this area are quite expensive and the variety is rather large, in-house work has been focused only on some application specific accelerators, while for the activities requiring very high energy particle accelerators, DAE is utilising many of the facilities available in the world under collaborative programmes.

Panoramic view of the Synchrotron at CAT

Accelerator Physics

The important discoveries in the early era of modern physics came from study of nuclear reactions produced by bombardment with alpha particles. However, alpha particles could cause disintegration of only light elements. The alpha particle scattering experiments of Rutherford had clearly shown the distance of closest approach when an alpha particle is directly aimed at a nucleus is directly proportional to the charge of the target nucleus as well as that of the alpha particle and inversely proportional to the kinetic energy of the alpha particle. The light elements thus can be easily disintegrated due to their small nuclear charge, while heavier elements cannot be. To disintegrate the latter it is essential to use particles having more energy, less charge or both. Protons are not ejected by radioactive atoms, but they are easily formed by ionizing hydrogen. They have half the charge of alpha particles and should be able to disintegrate heavy nuclei if endowed with enough energy. Besides, they can be accelerated by causing them to fall through a potential difference. Likewise, other charged particles can also be accelerated. It is then obvious that higher the energy of the colliding particles the deeper one can probe in the distance scale and hence there has been interest in building accelerators of higher and higher energies. Although, originally such machines were constructed to probe structure of atoms, later they found applications in several other areas of science, industry and medicine.

Different schemes to accelerate charged particles have therefore been employed, from time to time, to meet specific objectives. In order to measure the cross-sections for (n,α), (n, 2n), (n, p) and (n, d) reactions, a 400 keV Cockcroft-Walton accelerator for neutrons as external beam was built in 1958. Also, the generic type of machine invented by Lawrence and Livingston known as cyclotron was developed in 1960. The internal beam current of 3-4 MeV protons was optimized to 70 mA and the external beam current at the target was nearly 0.1 mA. This machine was used to investigate the level schemes of several nuclei ^{51}Mn, ^{85}Y, ^{96}Tc, ^{96}Nb, ^{97}Rh, ^{103}Ag, ^{107}In and ^{113}Sb, which were included in the Nuclear Data Tables. The external beam was mainly used in experiments on Coulomb excitation of low-lying levels and $(p, n\,\gamma)$ reactions. Need for higher energies saw commissioning of a 1 MV Cockcroft-Walton accelerator in 1953 and a 5.5 MV Van de Graaff accelerator a few years later. In the late sixties the construction of a variable energy cyclotron was undertaken at Kolkata. A decision to construct synchrotron radiation source at CAT was taken in early eighties. During the nineties, the 14 MV Pelletron accelerator facility was installed and also a 450 MeV synchrotron source was developed. In the year 2000, an indigenously developed 6 MV terminal voltage Folded Tandum Ion Accelerator (FOTIA) was commissioned. A superconducting linear accelerator (LINAC) has been indigenously developed to boost energy of the heavy ions emerging from the Pelletron. Phase I of the LINAC booster (3 modules) was commissioned in September 2002. All its critical components like e-beam welded resonator cavities, RF control electronics, cryogenic distribution, beam transport etc. were designed and developed in-house.

These successively more powerful machines, per force, led to a fair amount of development of accelerator physics and technology. A beneficial fall out of this activity was in the building of accelerators for industrial applications of radiation processing such as surface irradiation of fruits and vegetables, curing of paints & coatings, making of heat shrinkable foils, paper pulp irradiation, irradiation of PMMA films, surface sterilization, disinfestations of seeds, cross linking of small cables and wires. Facilities for commercial use of such applications have now been setup at New Mumbai and Indore.

The Large Hadron Collider (LHC) is the largest particle accelerator under construction at European Organization for Nuclear Research (CERN) in Geneva. LHC will accelerate and collide proton beams with energy of 7 TeV as also heavier ions up to lead. This would allow investigations of basic constituents of matter and also study of the conditions, which had prevailed at the beginning of the universe, just prior to the formation of basic particles. LHC will be installed in the existing 27 km circumference tunnel about 100-m underground straddling the Swiss-French border. Under a cooperation agreement, signed in March 1996, DAE is required to develop and supply some of the components of LHC. These include; detectors and associated electronics, superconducting sextupole and decapole magnets, LN_2 Tanks, precision magnet positioning system jacks, engineering studies for cryogenic distribution line interconnects, vacuum system design for long beam transport lines for beam dumps etc.

For large scale and long time production of nuclear power in the future two very important issues must be addressed. They involve breeding of fissile ^{233}U from thorium and reduction of technical complexities of geological repositories for storage of long-lived high-level radioactive wastes. This calls for good amount of basic research on accelerator driven sub-critical systems (ADSS) and the associated nuclear processes. This activity has been initiated and would be a major area of thrust in future. The ADSS concept has the inherent versatility of having any desired level of neutron density in the reactor core by varying the high energy proton beam from external accelerator without any risk of run away conditions of super criticality. Further, ADSS is convenient for breeding of fresh fissile ^{233}U from its thorium blanket zone at the reactor periphery. This needs thermal or fast neutrons at lower flux level of ~10^{14} neutrons/cm^2/sec so that formation of undesirable ^{234}Pa can be minimised. Simultaneously, one can ensure fast neutrons at a higher flux (~1.5 x 10^{15} neutrons/cm^2/sec) at the central core of ADSS to transmute the long lived fission products like ^{129}I, ^{135}Cs, ^{99}Tc and ^{93}Zr into either short lived radio-nuclides or harmless stable isotopes. The highly radiotoxic transuranic elements generated in uranium fuelled thermal reactors constitute only1.0 percent of nuclear waste. However, after 1000 years their combined radioactivity would be 20000 times that due to fission products. These can be completely incinerated as nuclear fuel in the high flux fast neutron core built around the spallation neutron source. The broad road maps for ADSS development program has been identified and work on sub-systems/components including materials of construction has been initiated.

Variable Energy Cyclotron

One way of accelerating a charged particle is to subject it to higher and higher potentials. Alternatively, this can also be achieved by using comparatively lower voltages and subjecting the particle to it over and over again. A cyclotron is based on this latter principle. The machine consists of two chambers called “D”s which are of semi-circular shape and are so positioned that there exits a gap between the two. A magnetic field perpendicular to the plane of the D’s forces ions into a circular path. The angular velocity of the moving particle is independent of its translational velocity. Between the D’s an alternate potential is applied whose frequency is so chosen that the charged particle emerging out of a D experiences an attractive force in the direction of the opposite D. As a result of the acceleration, the radius of the circular path keeps increasing and by subjecting the particle to an applied voltage repeatedly it can be accelerated.

The cyclotron at Variable Energy Cyclotron Centre (VECC), Kolkata is based on the Berkeley 88 (where 88 stands for the diameter of the magnet pole pieces in inches) design. It enables acceleration of protons from 6-60 MeV, deuterons from 12-65 MeV, alpha particles from 25-130 MeV and heavy ions up to a maximum energy of 130 Q^2/A MeV. A 400 kW radio frequency system provides acceleration. The chamber, which has a volume of 28 m^3, is evacuated to a pressure of about $1x10^{-6}$ Torr with the help of two 0.889 meter oil diffusion pumps. The accelerator incorporates an electron cyclotron resonance (ECR) heavy ion source. Here, the ionizing electrons are accelerated using a 6.4 GHz microwave source. Since an ECR ion source is a large device, the ions are externally injected into the cyclotron as opposed to an internal source. The source is capable of producing large variety of very heavy ions, including those of metallic elements at about 10 – 20 kV potential. There also exists an isotope separator on line (ISOL) facility to study the properties of very short-lived nuclei that are far from the beta stability line.

To extend the energy regime of heavy ion beams further, construction of a superconducting cyclotron was undertaken in the 8th 5-year plan. This cyclotron would provide heavy ion beams with energies up to 80 MeV per nucleon which is almost 3 times the capability of VEC + ECR source combination. The heart of this cyclotron is a large superconducting coil operating at liquid helium temperature i.e. around 4.5 K. For a magnetic field of about 6 T in the gap, the stored energy in the coil is 22 MJ. A large cryogenic system for production and circulation of liquid helium and liquid nitrogen to various parts of the cyclotron poses a formidable technological challenge. The technology of other cyclotron systems such as radio frequency, power supplies, vacuum, injection, extraction, etc. need to be driven to cutting edge in view of the compactness of the cyclotron capable of delivering higher energy beams. The research facilities for nuclear physics, materials science, chemistry, biophysics etc. have been planned. The superconducting cyclotron facility will be available for research towards the end of 10^{th} plan period.

Top view of the main magnet frame of superconducting cyclotron under assembly

Folded Tandem Ion Accelerator

This is basically an electrostatic accelerator. But the D.C. terminal voltage accelerates the ions using tandem principle involving two stages as opposed to a single one. The use of the term ‘folded’ in its name is because the ion beam is folded by 180° using a bending magnet after the first stage of acceleration and then it is re-accelerated in the second stage through another accelerating tube placed by the side of the first one. The source for the charged particles generates negative ions that are initially accelerated to low energies in a short horizontal section. These low energy negative ions are

Superconducting coil winding facility

Superconducting coil for cyclotron

then bent through 90^o using a 70^o injector magnet followed by a 20^o electrostatic deflector into the vertical accelerating column. In the first stage, the negative ions are accelerated towards the positively charged high voltage terminal situated at the top of the accelerator. The high electric potential at the terminal is achieved by continuous transfer of charge to the terminal by means of the pellet chain system. Inside the terminal, the ions pass through a stripper in the form of a thin carbon foil or a small volume of gas. The fast moving ions lose electrons while passing through the stripper and acquire positive charge. The average positive charge of the ion depends upon the type of the ion and its energy. The resulting positive ions now get bent through 180^o by the magnet placed inside the terminal and then enter the second or high-energy stage of acceleration where the high positive voltage of the terminal acts repulsively on the positive ions. The final energy of the ions, which have acquired a positive charge of n units, will be (n+1) eV, where V is the terminal voltage. Typical final energies at the maximum terminal voltage are 12 MeV for protons, 18 MeV for alpha particles, and 66 MeV for calcium ions of the 10^+ charge state. The accelerated ions coming out of the high energy accelerating tube are focused by a magnetic quadrupole triplet and then gain momentum analyzed by the 90^o dipole magnet, located on the ground floor and adjacent to the 70^o injector magnet. Since, the ion mass is already selected by the 70^o magnet in the injection system, the analyzing magnet is used only to select particular energy of the beam. The analyzed beam is then guided to different experimental beam lines through the quadrupole triplets and the switching magnet. The high voltage column section is located on the first floor of the accelerator building. This column is 0.965 meter in diameter, and 5.7 meter in height. It consists of six modules, each with a voltage rating of 1 MV. The modules are made from laminated alumina ceramic and titanium metal insulating posts, stainless steel hoops and separator plates. One insulated (perspex) rotating shaft, rotating at 1450 RPM, runs to the terminal from the base of the column, to drive the local 5 KVA alternator which provides electrical power to the 180^o magnet, foil changer, quadrupole doublet, pumps, etc., located inside the terminal. The accelerating tube is made of short sections, which are bolted together. Three sections together make up one module rated at 1 MV. Each tube module is made of titanium metal electrodes and ceramic insulators coupled together with aluminium bonded joints. There are in all 18 such sections in each accelerating tube. The terminal, which is charged to a high voltage by the charging chain, is a highly polished stainless steel dome consisting of a cylinder (of 0.965 meter diameter and 0.482 meter height) covered by a hemisphere of 0.965 meter diameter. It is located at the top of the column. The stripping system uses either a thin carbon stripper foil or a gas stripper, and is located inside the terminal. When the negative ions reach the stripper they lose electrons and acquire several units of positive charge. Since carbon stripper foils have limited lifetime, there is a foil changer, which allows 120 foils to be kept ready for use. The charging system in FOTIA utilizes a chain of alternate metal cylinders (pellets) joined by nylon links. The chain is rotated by an induction motor at 600 RPM. The pellets are stainless steel cylinders of 3.2 cm diameter and 3.2 cm height. The charging is done by electrostatic inductor and the maximum charging current exceeds 50 mA. This continuous transport of charge results in the build up of high voltage at the terminal. The voltage gradient in the high voltage column and accelerating tube is achieved by corona needles. The column has 18 gaps in each module, while the accelerating tube has 33 gaps. The accelerating column is housed inside a large pressure tank filled with insulating gas, sulphur hexafluoride (SF_6), at a pressure of about 90 psi, in order to prevent electrical discharge of the high voltage terminal. The accelerator tank is a giant pressure vessel of 7 meter in height and 2.4 meter in diameter. It has a total internal volume of about 32 cubic-meters, and it weighs ~ 12.5 tons. The gas handling system serves to transfer the SF_6 gas from the gas storage tank to the accelerator tank or vice versa and also to maintain the gas purity by circulating it through an activated alumina drier. The entire system is thoroughly leak tested and SF_6 monitoring is maintained continuously. The whole accelerator operation is controlled through a PC based system, which is designed as a network of PCs with a front-end interface using CAMAC instrumentation. All the PCs use QNX real time operating system. The system is designed to control and monitor the parameters like current and voltage applied to various components, the status control, the status read of the instruments, the quality of the beam, etc. Communication of the parameters in the high voltage areas (located in terminal and ion source deck) to the CAMAC instruments is through the fibre optic telemetry system. The system uses a multiplexing-demultiplexing technique to communicate several parameters through a single fibre optic cable. The Terminal Voltage Stabilization system developed enables a voltage stability of ±2 kV at terminal voltage of 2.5 MV.

In the first phase, three experimental beam lines are developed. The beam coming out of the analyzing magnet can be diverted to any of these beam lines by means of a switching magnet. A big new experimental hall has also been built, where it is planned to set up five beam lines. Each beam line will have at least a quadrupole, a beam profile monitor and a Faraday cup to focus, monitor and measure the beam respectively. While, the experimental set up including the detectors, pre-amplifiers, power supplies, etc., is kept inside the beam hall, the data

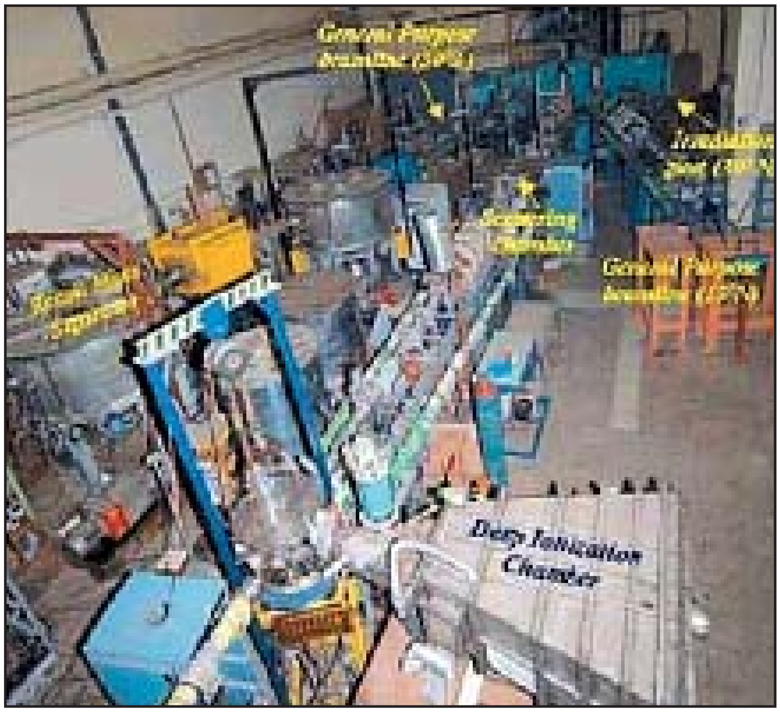
Beam lines at FOTIA

signals are collected at the control room through the patch panels which interlink the beam hall to the outside. In FOTIA, the ions extracted from the SNICS-II negative ion source have to travel a distance of ~35 meters before they reach the experimental target. Since the charge exchange cross sections for heavy ions are very large it is necessary to minimize the residual gas pressure and maintain ultra high vacuum (UHV) in the accelerator tubes and rest of the beam transport system of the accelerator. The UHV is also required to reduce the loss of beam intensity and spread in energy of the ion beams due to collisions of the ions with the residual gas molecules present due to poor vacuum. A distributed pumping system having eight pumping stations maintains UHV in the whole accelerator up to the switching magnet. A vacuum of 1×10^{-8} Torr is achieved in all the beam extractions.

The FOTIA facility is being utilized for nuclear physics, material characterization and modification, biological investigations etc. For material characterization PIXE, RBS and ERDA facilities are available. For irradiation of living cells for radiation biological investigations, proton beams of energies 3 to 5 MeV are taken out in air through a 20 micron titanium foil.

Experimental Facilities Developed Around the 14 MV Pelletron Accelerator

The accelerated heavy ions from the pelletron are transported into the experimental hall through a five port switching magnet. In order to carry out investigations in frontier areas of nuclear physics, several state of the art experimental facilities have been set up at the end of the beam lines. They include; Separator for Heavy Recoil Ions (SHRI) for heavy ion fusion measurements, high efficiency segmented gamma arrays based on HPGe for high spin spectroscopy and based on BaF_2 for high energy gamma emission and GDR studies, one meter diameter general purpose scattering chamber for fission and charged particle measurements, large area position sensitive ionization chamber for fission and charged particle measurements. Gamma arrays based on BGO and BaF_2, charged particle arrays based on phoswich and neutron arrays based on plastic scintillators are some of the other major experimental set ups. Energetic heavy ions are also used for radiochemistry, condensed matter physics, atomic physics, materials science and accelerator mass spectrometry programs. Liquid helium cryostat with superconducting magnet has been set up for condensed matter studies. With the superconducting LINAC booster scheduled for completion in 2005, a new experimental hall has been built to purse nuclear physics programmes based on higher energy heavy ions to be available from the combined pelletron and LINAC operation.

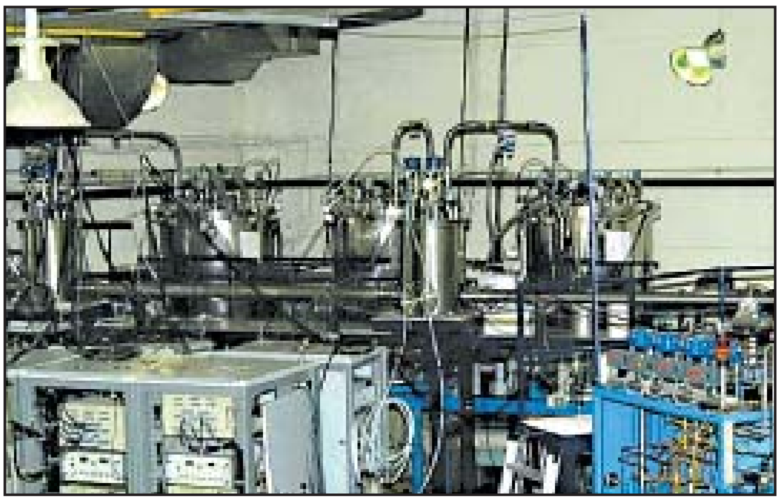


Beam lines setup at Pelletron

BaF_2 and BGO detector setup for high energy gamma rays detection

Development of a Superconducting LINAC Booster for the Pelletron

A superconducting linear accelerator (LINAC) has been indigenously developed to boost energy of the heavy ions emerging from the Pelletron. Phase I of the LINAC booster (3 modules) has already been commissioned. All critical components of LINAC booster like e-beam welded resonator cavities, RF control electronics, cryogenic distribution, beam transport etc. have been designed, developed and fabricated.



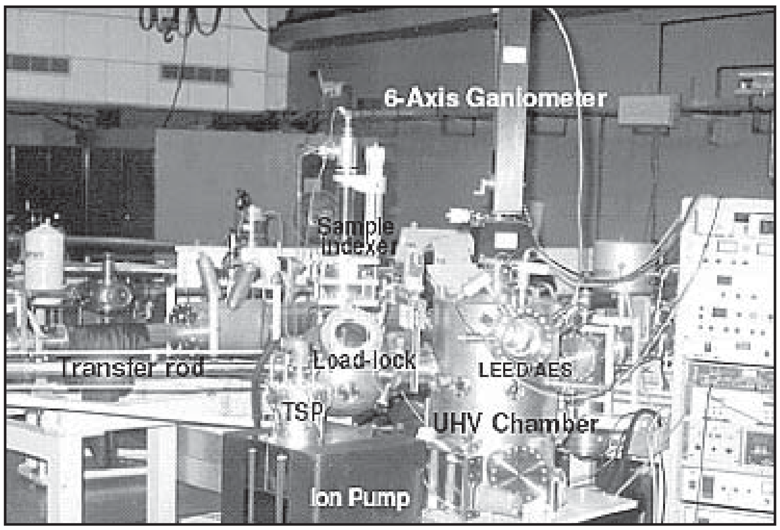
Superconducting linear accelerator

Experimental Facilities developed around the 3 MV Tandem Pelletron Accelerator

The 3 MV Pelletron accelerator facility, in its original configuration was purchased with two ion sources - one sputter ion source for generating all sorts of negative ions from solid targets and an RF ion source for generating ions of H and He which are needed for majority of the analysis techniques using low energy ion beams. A two port 45° magnet was provided for mass analysis at the injection stage. At the high energy end there is a 90° bending magnet for selection of the right mass and charge state for the energetic ion relevant for the experiment.

This has a mass resolution of 0.1%. The switching system at the end of the analyzing section has a seven port switching magnet with a ME/z^2 value lying between 18 at ±45° to 151 at 0°. The initial configuration consisted of only two beamlines at 45° and -15° looking downstream from the switching magnet. One of the beam lines has been incorporated with an octagonal, general purpose scattering chamber with facilities for carrying out most of the analysis work such as RBS, Channeling, PIXE, NRA etc. with light ions. For channeling measurements, a high vacuum compatible, five-axis sample manipulator is provided. The beam line also has a raster scanner system, capable of scanning an MeV beam over a six inch wafer, and a chamber with facilities for sample positioning.

Another beam line is dedicated to surface studies. A custom built Ultra High Vacuum chamber (with a base pressure ~10^{-10} Torr) is provided with a Four-grid Reverse View LEED and Auger system which is capable of showing surface structure together with a capability of chemical analysis using Auger Electron Spectroscopy. For in-situ sample deposition, it has two Knudsen cells and for sputter cleaning of the sample there is an Ar ion gun. A UHV compatible 5-axis sample manipulator with heating and cooling facility is provided for sample orientation and positioning inside the chamber for RBS/ channeling measurements. A load lock chamber attached to the UHV chamber is used for sample introduction into the UHV chamber.



Surface physics beamline showing the UHV chamber with a 6-axis ganiometer for ion channeling studies

A microbeam facility of about 2 µm beam size, has been set up along the 45° direction. It has the joint capability of taking X-ray scans as well as depth and element sensitive charged particle scans using PIXE and RBS techniques. The system, which is unique of its kind in the country, can generate a multi-elemental map over a typical area of ~100 µm. In one of the studies the microbeam facility has been used to characterize Au samples, (Au_4Si) island structures grown on Si(111) as well as Si(100).

Presently, the injector section has a cathode sputter ion source, a 45° spherical electrostatic analyzer (ESA), a 90° wide pole analyzing magnet and a bouncer tube with off-axis Faraday cups to measure stable isotope current (for mass 9 or 13 depending upon whether one is carrying out ^{10}Be or ^{14}C measurements) for radiation dating. In addition the analyzing section includes off axis cups for measuring the stable isotope (^{9}Be, ^{13}C etc.) current at the high-energy end.

Another beamline incorporates a 15° cylindrical ESA erected along a 15° port of the switching magnet for rare isotope measurements. The ESA, in combination with the 90° analyzing magnet selects the rare isotope uniquely without any interference from other ions.

With the facility it has been possible to get $^{14}C/^{12}C$ ratio with error less than 1% in samples. The system has also been used to date some FIRI (Fourth International Radiocarbon Intercomparison) samples with dates 4.4 ky and 11.7 ky. The measured dates are found to be in close agreement with consensus data.

The fourth beamline with large area (~1m in diameter) scattering chamber was setup for nuclear physics work. This has facilities to place several detectors on two movable planes making any angular distribution measurement easy. The detector planes can be moved with motorized control from outside. The chamber being large is fitted with a motorized lifting arrangement of the top flange for opening and closing. The exit end of the chamber is provided with a tapered nylon tube sealed with a ~2 µm thick kapton foil. This enables X-ray imaging of museum related samples, with awkward shapes using 2 MeV proton beams. Several rare museum related samples have already been studied for composition based on which they can be dated quite accurately.

Microbeam facility

AMS beamline. The 15° cylindrical ESA is located before the chamber

Synchrotron Radiation Sources

Charged particles such as electrons on acceleration emit electromagnetic radiation or photons. Accordingly, electrons also emit electromagnetic radiation while moving on a curved path because a change in the direction of motion is a form of acceleration. If electrons become relativistic i.e. their speeds approach very closely to the speed of light, the number of photons and their energy increase dramatically. The emitted radiation is highly intense, confined in narrow cone and is polarized. It has a broad spectrum ranging from infrared to X-rays. This spectrum is characterized by a wavelength called critical wavelength. In the power spectrum, half of the radiation power is emitted below this wavelength and the other half above this wavelength. The brightness of synchrotron radiation sources in vaccum ultra violet (VUV) and X-ray region is several orders of magnitude higher compared to conventional sources.

A synchrotron radiation source is an electron storage ring designed and operated specifically for the purpose. It consists of bending magnets, quadrupoles and sextupoles. Bending magnets are used to bend the path of the electrons to keep them moving on a circular orbit, quadrupoles to keep the beam well focused within a certain cross-section and sextupole magnets for correction of chromatic effects arising due to a finite though small energy spread of the electrons. The magnets are arranged in a periodic way and the circumference can be divided into many identical parts each having the same arrangement of magnets. Each part constitutes a unit cell or a super period and the arrangement of magnets in this cell defines the lattice of the accelerator. The circulating electrons emit synchrotron radiation in bending magnets and insertion devices. The characteristics of the radiation particularly the spectrum from the insertion devices are different from those of the radiation from bending magnets. The insertion devices used in these sources are wigglers and undulators. Both of these devices provide transverse alternating magnetic field along the straight path of electrons, which cause them to periodically accelerate inwards and outwards giving rise to a series of local radiation sources. The radiation from wigglers have characteristics similar to bending magnet radiation with the difference that the spectrum of radiation is shifted and the intensity is enhanced in proportion to the number of poles. In undulators, electrons undergo feeble deflections; the radiation from these devices has sharp peaks at certain wavelengths. The intensity of the radiation at these wavelengths becomes much higher and increases as the square of the number of undulator periods.

Besides the magnets, the storage ring has radio-frequency (RF) cavities in which the electromagnetic field oscillate at a frequency, which is multiple of the revolution frequency of the electrons in the ring. These fields replenish the electron beam's energy lost due to synchrotron radiation. Because of their oscillating nature, they also divide the electron beam into bunches which are responsible for the pulsed time structure of synchrotron radiation. In order that the radiation is available to users for a sufficiently long time extending to few hours, the air pressure in the beam chamber in which electrons move is maintained below 10^{-9} Torr.

Due to its unparalleled characteristics, synchrotron radiation has emerged as a powerful tool for research in several areas such as materials science, chemistry, biology, medicine and semiconductor technology. Two such sources namely INDUS-1, a 450 MeV electron storage ring for production of VUV radiation and INDUS-2, a storage ring of 2.5 GeV for X-rays were planned.

Synchrotron Radiation Source - INDUS-1

It consists of a 20 MeV microtron, a 450 MeV synchrotron and a storage ring INDUS-1. The electrons are generated and accelerated to 20 MeV in the microtron. After extracting the beam from the microtron, the beam is transported to the synchrotron through Transfer Line-1 (TL-1). A long pulse of 1 ms is injected into the synchrotron and its energy is increased from 20 MeV to 450 MeV. After acceleration to 450 MeV, the electrons are extracted from the synchrotron and transported to the storage ring INDUS-1 through the Transfer Line-2 (TL-2). This process of production, acceleration and injection is carried out every second till the stored current reaches 100 mA in the storage ring. In the storage ring, the electron beam keeps circulating for a long time emitting synchrotron radiation continuously in the dipole (bending) magnets.

Microtron

The microtron is designed to give a 20 MeV electron beam with a current of 25 mA in pulses of 1µs duration at a repetition rate of 1-2 Hz. It is a classical microtron having a dipole magnet of 1.4 m diameter, which produces a magnetic field of 1.8 kG with a uniformity of 0.2% over a diameter of 0.8 m encompassing 22 orbits of accelerating electrons. The acceleration occurs in a microwave cavity energized by a 5 MW pulsed klystron at 2856 MHz. A LaB_6 pin of 3 mm diameter mounted on a flat face of the cavity is used as the electron emitter. The electrons emitted from the emitter are accelerated to 20 MeV in 22 orbits. The vacuum maintained in the microtron is better than 10^{-7} Torr.

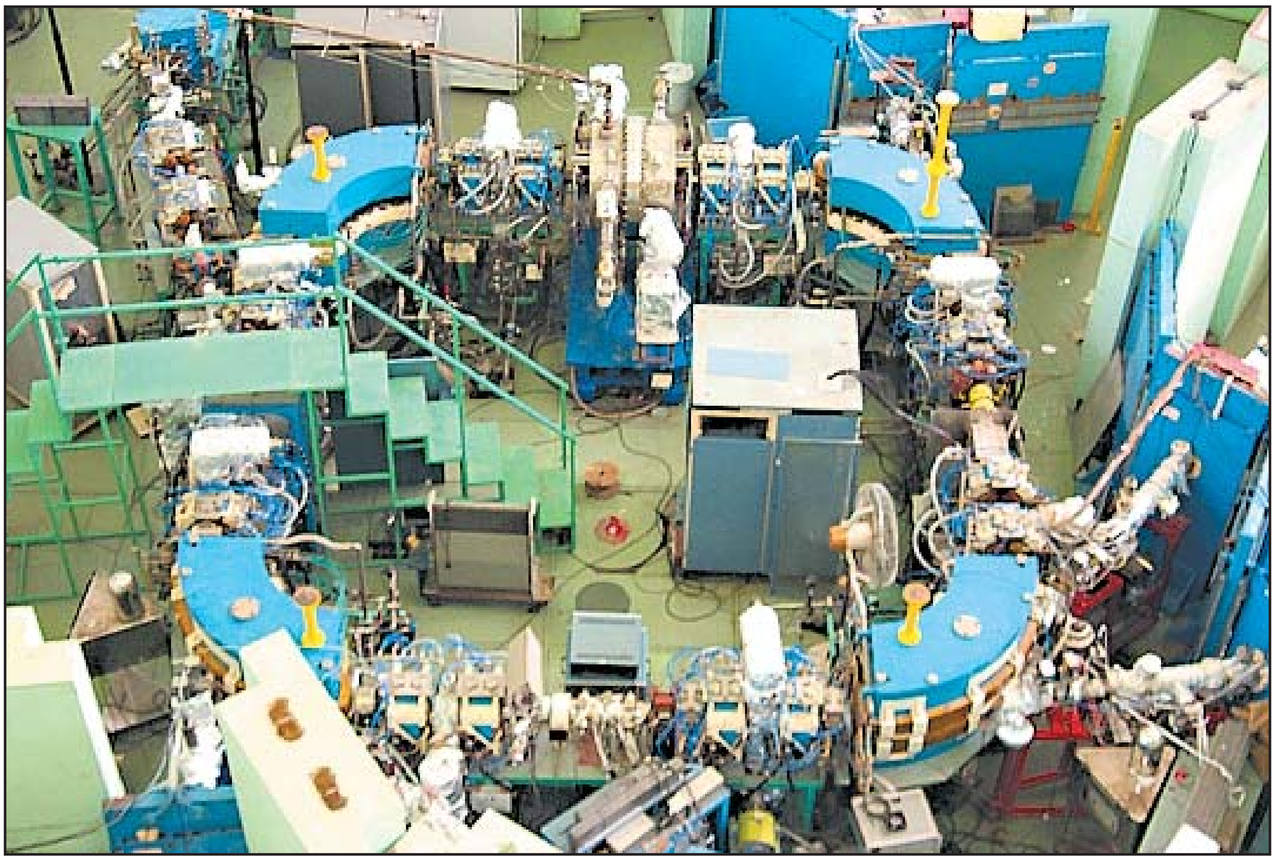
The microtron and part of transfer line-1

Synchrotron

The beam from the microtron is transported to the synchrotron through transfer line, which has a length of about 14m. The magnetic lattice of the synchrotron consists of 6 superperiods, each consisting of a dipole magnet to bend the electron beam on a circular path and a pair of focusing and defocusing quadrupole magnets to keep the beam well focused in radial and vertical planes. The maximum magnetic field of the dipole is 1.32 T. The circumference of the synchrotron is 28.44 m. The electrons are injected into the synchrotron by adopting a multi-turn injection scheme, which employs three injection kickers at a repetition rate of 1 Hz. A compensated bump producing a maximum amplitude near the injection septum is produced using three injection kickers. After injecting the beam, the electrons are accelerated to 450 MeV in nearly 200 msec following a linear ramp using an RF cavity operating at 31.619 MHz. Fields in the dipole, quadrupole and steering magnets are synchronously increased during the acceleration. The energy for acceleration and to replenish the loss due to synchrotron radiation is provided by the RF cavity. Since the cavity frequency is thrice the revolution frequency of the electrons in the synchrotron, three electron bunches are formed during acceleration. The accelerated beam is extracted by deflecting it by a fast kicker magnet having a rise time 45 ns. As the separation between two bunches is 30 nsec, during the extraction process, one out of three bunches is lost and two bunches are extracted and then transferred to the storage ring Indus-1. This process is repeated every second till a required current is achieved in the storage ring. The vacuum pressure in the synchrotron is in the 10^{-7} Torr range. The synchrotron was commissioned in April 1997 and a maximum accelerated current of 11mA was achieved.

Storage Ring

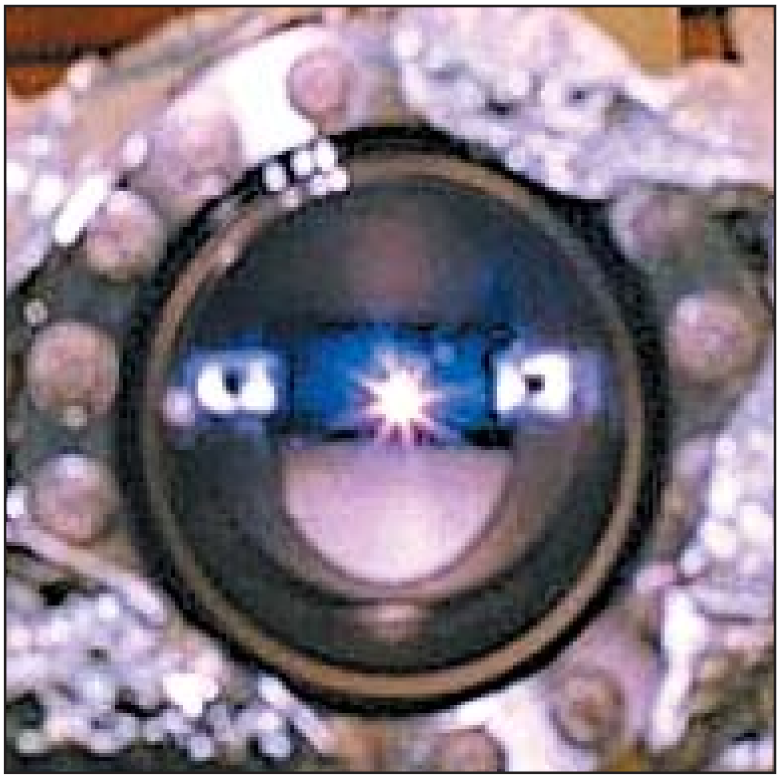
The storage ring is designed to provide radiation in the range 30 - 2000 Å. It is a small ring having a circumference of 18.96 m. The critical wavelength of the radiation emitted from its four 1.5 T bending magnets is 61 Å. A 3 T wiggler is planned in this ring to provide the radiation of critical wavelength 31 Å.



The storage ring Indus-1

The magnetic lattice of the ring consists of 4 superperiods, each having one dipole magnet with a field index of 0.5 and two doublets of quadrupoles. Each superperiod has a 1.3 m long straight section. Two such straight sections are used for beam injection; one section accommodates the septum magnet and the other diametrically opposite to it accommodates a pulsed kicker magnet. Of the remaining two straight sections, one is used to accommodate an RF cavity and the other, a 3 Tesla wiggler to be installed later. The natural chromaticity of the ring, which arises due to different focusing of different energy particles is corrected using a pair of sextupoles in each superperiod. The circumference of INDUS-1 ring is two third of the synchrotron. The RF frequency of 31.619 MHz provides the electron beam with the additional energy equivalent to the energy radiated by it in the form of synchrotron radiation. It thus keeps the electrons moving in a fixed orbit with a fixed energy. In order to achieve a beam lifetime of a few hours, the pressure in the vacuum chamber in the presence of 100 mA electron beam is maintained better than 10^{-9} Torr.

INDUS-1 was commissioned in early 1999 with a maximum accumulated current of 161 mA. The accumulated current was subsequently increased up to 200 mA.



Light from an SR port of INDUS-1

Almost all of the subsystems of INDUS-1 were designed, fabricated and installed in house though the private industry also lent a helping hand in building a few components. INDUS-1 is thus a totally indigenous effort.

INDUS-1 Beamlines

INDUS-1 has four bending magnets of field 1.5 Tesla and radius of 1 meter. Each bending magnet vacuum chamber has two ports at 10^0 and 50^0. Beamlines can be drawn from only three bending magnets as the fourth magnet is close to the injection septum magnet. From these three bending magnets, it is possible to tap six beamlines. At present four beamlines are operational. Two more beamlines are in advanced stage of their commissioning.

The Toroidal Grating Monochromator (TGM) beamline is designed taking 10 mrad as horizontal and 5 mrad as vertical divergence from bending magnet DP2 of INDUS-1. The premirror is a toroidal mirror to focus the SR beam on to the entrance slit of the monochromator with a vertical deflection. The beam is incident at 4.5^0 to the mirror surface. This mirror is gold coated and has a demagnification ratio of 2:1. The monochromator used in this beamline is a toroidal grating monochromator (TGM) type. The entrance slit of the monochromator can be changed in horizontal direction from 0.4 mm to 3 mm in four discrete steps, whereas the vertical slit is adjustable from 0.0 to 1.8 mm continuously. The deflection angle at the grating is 162^0. The three interchangeable gratings (200, 600 and 1800 lines/mm) would cover the wavelength from 40 Å to 1000 Å. The average spectral resolution for this wavelength range is 500. The post mirror is also a toroidal type to refocus the monochromatic beam on to the target, which is kept at a distance of 1.8 meters from the center of the mirror. The demagnification ratio is 1:1. The typical spot size is 1 mm (h) x 1 mm (w). The experimental station on this beamline is a multipurpose reflectometer. It operates in the vacuum of 1×10^{-8} Torr and has a two-axis goniometer with an independent and coupled rotation of a sample and a detector with an angular resolution of 2.5 mdeg. In between the beamline and the reflectometer a differential pumping station is installed as the beamline is under a vacuum of 10^{-9} Torr. It is possible to set the reflectometer in either s or p polarization geometry. The detectors that are used are either Si or GaAsP photodiodes.

Using this beamline, angle dependent reflectance measurements in the soft X-ray region on etched silicon and silicon dioxide wafers and float glass in the wavelength range 80 - 200 Å and soft X-ray reflectivity measurements on Mo/Si multilayers have been performed.

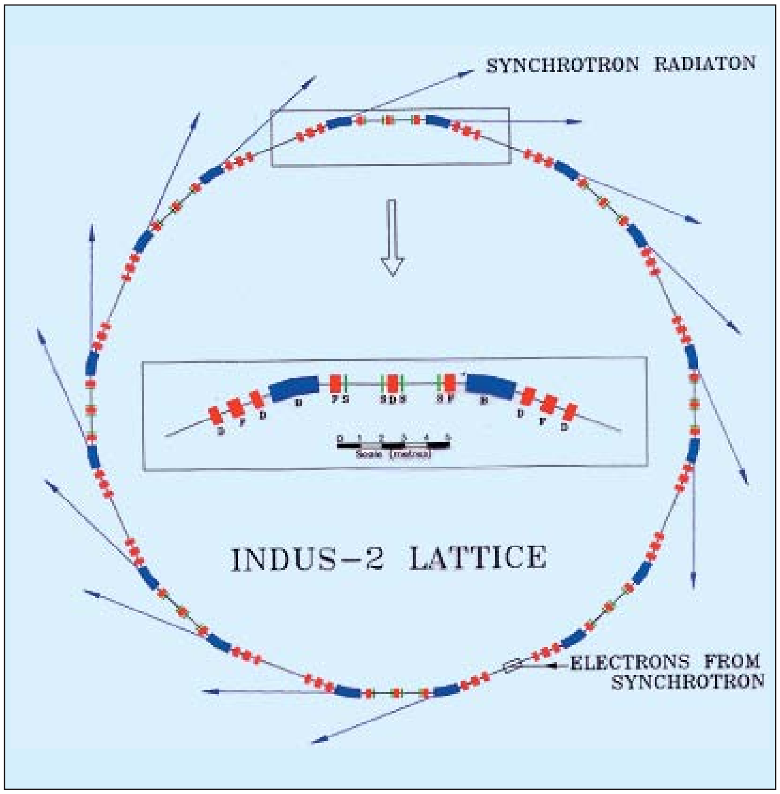
Reflectometer setup

INDUS-2

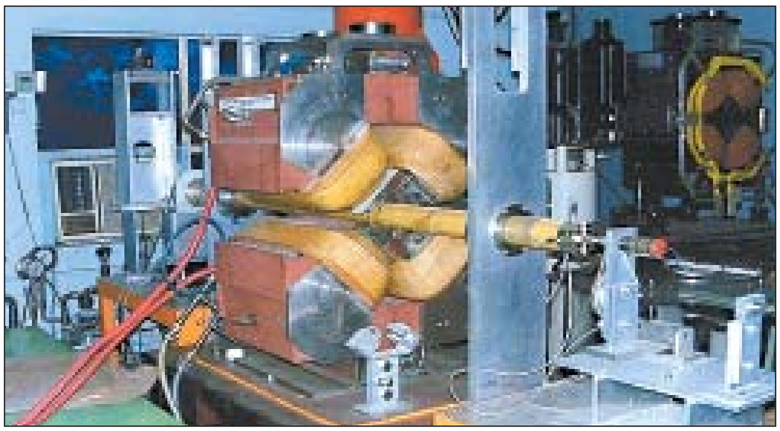
It is an electron storage ring with beam of 2 - 2.5 GeV which is adequately high to produce powerful X-rays from the bending magnets and wigglers. The critical wavelength from the bending magnets, high field wiggler (5T) and multipole wiggler (1.8T) at 2.5 GeV will be 2Å, 0.6Å and 1.6Å, respectively. The storage ring has a circumference of 172.4 m and consists of 8 unit cells (or super periods) each providing a 4.5 m long straight section. Its unit cell has two 22.5° bending magnets, a triplet of quadrupoles for the control of dispersion in the achromat section, two quadrupole triplets for the adjustment of beam sizes in the long straight sections and four sextupoles in the achromat section for the correction of chromaticities. Of the eight 4.5 m long straight sections, one will be used for beam injection and two for RF cavities and the remaining five for insertion devices. Presently, the installation of two wigglers has been planned of which one will be a 5T wavelength shifter and the other a multipole wiggler of 1.8T. The remaining three straight sections are left unused for future developments, essentially to keep pace with new developments or new insertion devices. In bending magnet sections, the radiation ports will be provided at 5° and 10° from the edge of the magnet facing the electron beam. Therefore in one superperiod, four ports will be available for tapping radiation from the bending magnets. In addition, there would be five ports for tapping radiation from insertion devices. These ports will be provided on the bending chambers facing the insertion devices.

Beamlines on INDUS-1

Beamline	l – range	Mono-chromator	Organ-isation	Status
Reflectivity TGM	40-1000 Å	TGM	CAT, Indore	Operational Nov. 2000
Angle Integrated PES	60-1600 Å	TGM	IUC, Indore	Operational Nov.2000
Angle Resolved PES	40-1000 Å	TGM	BARC, Mumbai	Operational Dec.,2002
Photo-physics	500-2500Å	Seya-Namoika	BARC, Mumbai	Operational Mar. 2003
High resolution VUV	400-2500 Å	Off-plane Eagle	BARC, Mumbai	Under constrution
Photo absorption (PASS)	100-700 eV	SX700	BARC, Mumbai	Under constrution



Magnetic Structure of INDUS-2



Quadrupole magnet for INDUS-2

The electron beam extracted from the synchrotron will be injected into INDUS-2 in the horizontal plane. For injection into INDUS-2, the synchrotron will accelerate electrons to voltages in the range 600 - 700 MeV. The synchrotron will provide two bunches each of about 1ns duration and separated from each other by nearly 30 ns with a repetition rate of 1-2 Hz. After injecting several pulses at 600 - 700 MeV to accumulate 300 mA current, the beam will be accelerated to 2 - 2.5 GeV by slowly increasing the magnetic field of the bending magnets. The beam will be injected in the horizontal plane via two septum magnets (one thick and another thin one) by a multi turn injection process in one of the 4.5 m long straight sections by employing a compensated bump which will be produced by means of four pulsed magnets.

Dipole vacuum chambers for INDUS-2

FOTIA column and the tank

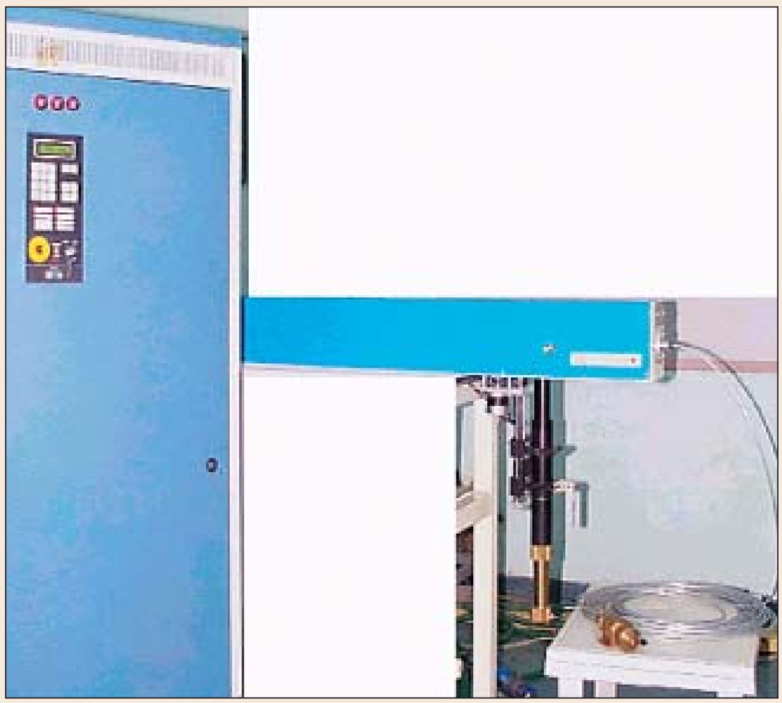
Low and high energy beam lines in FOTIA

Laser & Plasma Physics

Link P5

We have seen that the accelerators are very important for the programmes of DAE, whether they are in the area of basic sciences or applications. Amongst, several applications of accelerators being pursued by DAE, Accelerator Driven Sub-critical System is perceived to be useful from the viewpoint of augmenting our nuclear power programme. The Department is also pursuing other energy related R&D programmes viz on Inertially Confined Fusion through using high power lasers or magnetically confined plasma at CAT and IPR, respectively. The neutrons produced from laser induced fusion can be used for production of energy through fission in sub-critical multiplying blanket of fissile material. Laser based techniques can be expected to play a useful role in future in our nuclear fuel cycle covering isotopic separation (because of inherently high selectivity that the laser beam technique offers) and photon induced nuclear reactions (involving extremely intense lasers). The latter has become a recent and expanding field of research with potential applications in transmutation of nuclear waste and production of isotopes.

A 20 kW CW CO_2 Laser System



A Nd:YAG laser system for industrial applications

Laser & Plasma Physics

LASERS (light amplification by stimulated emission of radiation) are sources of coherent electro-magnetic radiation with wavelengths ranging from far infrared to X-rays. They differ from conventional sources in that the phenomenon of stimulated emission and the characteristics of laser resonator together provide great control on the properties of the light emitted. Because of their high intensity and great coherence, many new phenomena have been observed and exploited. For instance, at high intensities material response becomes nonlinear, allowing exchange of energy between different laser beams. This makes it possible to convert a laser beam into a coherent light beam of different frequency. Nonlinear frequency conversion has allowed the generation of vacuum ultraviolet radiation as short as 35.5 nm in wavelength. Nonlinear optical processes also allow the study of ultra-fast physical, chemical and biological processes which occur in the pico-second and subpico-second regimes.

Many engineering applications of lasers arise from their ability to deliver energy in a highly controlled manner, providing unprecedented accuracy and precision in heat treatment. High power lasers are finding increased use in drilling, cutting, welding and the surface hardening of metals, ceramics and composite materials. Currently, the use of lasers for biomedical imaging and diagnosis is attracting considerable interest. Towards this purpose it is necessary to investigate the photo-biological effects of laser irradiation on living organisms and to explore the use of laser induced fluorescence spectroscopy for cancer diagnosis. Lasers have been used to make atoms stationary or to identify impurities at the level of one part in more than a billion.

In recent years, lasers are finding increasing use in nuclear physics research. Two specific areas of interest are (i) high resolution optical spectroscopy of atoms to probe the properties of the atomic nuclei and (ii) studies on photon induced nuclear reactions which become possible because of extremely large intensities (~10^{20} Wcm^{-2}) available with the very recent laser systems. The interaction of such an intense radiation field with a target results in the creation of a relativistic plasma and in production of high energy particles and radiations which can trigger nuclear processes such as (γ,n), (p,n), (p,α) and photo induced nuclear fission and heavy ion fusion. This application of lasers is rather recent and the research field termed as photo-nuclear physics is growing fast.

The application of lasers in isotope separation is of much interest in nuclear fuel cycle because of inherently high selectivities. Some important examples include: enrichment of uranium, removal of U^{232} from thorium fuel cycle, extraction of precious metals like rhodium or palladium, isotopic tailoring of structural materials like zirconium or burnable poisons like gadolinium. Laser induced fluorescence (LIF) and resonance ionization spectroscopy have been established as the ultra sensitive techniques for trace analysis. Ion traps may be used for increasing the sensitivity of detection for existing laser spectroscopic techniques which are already more sensitive and fast compared to dosimetric techniques. LIF or other laser spectroscopic techniques also find useful application in diagnostics of high temperature fusion plasmas for detection of fuel or impurity species with spatial and temporal resolution leading to density and velocity profiles of atomic and ionic species. Laser spectroscopic techniques are also applicable in pollution and atmospheric monitoring, analysis of materials etc.

Lasers are finding increasing role in bio-medical applications such as detection of abnormal tissue condition or presence of toxic elements, photo-dynamic cancer therapy, less invasive surgical techniques, DNA sequencing and for fundamental understanding of biological processes at sub cellular and sub picosecond levels.

Research on various aspects of laser physics and technology was undertaken in real earnest during the sixties. Initially, lasing action in different media viz. solids, dyes and gaseous was *investigated. Besides, theoretical work on nonlinear optics, laser assisted plasma generation and its diagnostics was also taken up. Various sub-systems required for building up high power laser systems the associated power supplies and the electronic controls were developed in-house. A high power laser system with YAG(Nd) as the oscillator and Nd-glass as an amplifier was developed during the seventies as a first step towards undertaking research on laser assisted fusion. Considering the fast growing applications of lasers and the expertise gained it was decided to develop industrial applications in a major way at a new center. Thus, the Centre for Advanced Technology (CAT) was established at Indore during the eighties. Since then this activity has been pursued both at BARC and CAT with well-defined objectives. The current activities are very wide ranging having applications in science, industry and medicine, as shown in following Box. Integrated development of lasers and sub-components is an essential step for exploiting the potential of lasers based applications. In this regard, a wide variety of laser sources have been developed and their performance is being continuously improved.*

The development centered around He-Ne, CO_2, N_2, Dye and solid state lasers in the early days. Stidies of non-linear optics were also pursued. These helped develop laser sources in the wavelength ranges not covered otherwise. The He-Ne lasers up to 50 mW power, CW CO_2 lasers up to 450 W and pulsed (TEA) form with a peak power of 100 MW, electron beam controlled CO_2 laser with pulse energy of 100 J, N_2 lasers of 1 MW (50 - 100 Hz, 8 ns), Ar-ion of few watts (CW or tunable), Nd:YAG of EO Q-switch, 5 MW, 10 ns, Nd:Glass of 50 J, 5 ns chain were developed during the early period. One of the important applications of the lasers developed in those days was for laser based spectroscopy including laser Raman spectroscopy, high resolution atomic spectroscopy, laser optogalvenic spectroscopy, multiphoton ionization spectroscopy, laser spectroscopy for trace analysis. Spectroscopy and chemistry of laser photo-dissociation products, laser produced plasmas were also pursued. In addition, picosecond time resolved fluorescence studies by time correlation technique, nanosecond time resolved absorption (UV, visible), quantum fluctuations, phase conjugation, squeezed states etc. also evoked interest. Now more attention is paid to developing more powerful lasers for basic physics research as well as for industrial and medical applications.

Laser physics related activities

- Laser sources (Nd:YAG, Nd:Glass, CO_2, N_2, Excimer, Dye laser, Cu-Vapor), Optical Limiting, Laser Cooling and Trapping of Atoms, Nonlinear Optics with Nano- structured Materials, Pulsed Laser Deposition, Biomedical Applications of Lasers **(CAT)**.
- Laser sources (Dye lasers, CO_2, N_2, Cu-Vapour, Ar-ion, Excimer, Nd:YAG, Nd:Glass), Non-linear optics, laser spectroscopy, laser plasma and diagnostics, laser materials and laser processing **(BARC)**.

Diode-Pumped Solid-State Lasers

Development of high-power diode arrays allows use of highly efficient diode lasers for pumping solid-state lasers. Previously lamp-pumped solid-state lasers have been a standard method of delivering high power laser beams, but at the cost of low efficiency and poor reliability. The combination of diode arrays and solid-state laser technology makes it possible to realize high power diode-pumped solid-state lasers (DPSSL) which are highly efficient, compact and truly portable for applications ranging from research & development, industrial processing to medicine.

The use of diode pumping minimizes heating of the gain medium, thus maximizing the average power available from a given gain volume. Depending on the experimental conditions, lamp pumping generates up to four times more heat than diode pumping at the same level of power delivered to the upper laser level. In contrast, efficiency of DPSSL is at least an order of magnitude higher than lamp pumped lasers. The other inherent advantages of DPSSL are high average output power simultaneously with very good beam quality and better pointing and amplitude stability.

100mW Single Mode DPSS IR Laser at 1064 nm

One such, a 100 mW of stable single mode IR laser in a standing wave cavity, where a coated 3 at % doped Nd:YVO_4 crystal with 0.5 mm thickness is end pumped by a fiber coupled laser diode beam was built. This operated in Single Longitudinal, Single Transverse and Single Polarization (linear) modes. The IR output was circularly symmetric with M^2 = 1.00 and the linearly polarized beam had more than 1:10,000 polarization ratio. The lasing threshold was around 70 mW and the slope efficiency was ~40%. The laser produced stable SLM up to 125 mW at an absorbed pump power of 394 mW.

End-Pumped Intracavity Doubled Nd:YVO_4 Laser

High power fiber coupled diode lasers giving more than 15 W output power at 808 nm have been developed. Using this pump laser, a highly efficient V-cavity based intra cavity doubled green laser has been developed. The system consists of fiber coupled diode laser, Nd:YVO_4 crystal and KTP harmonic converter. The output from a 600 micron fiber coupled diode laser beam is collimated and focused to a spot size of 300 micron. This is on 1.1% doped Nd:YVO_4 crystal mounted on a water cooled copper enclosure for efficient heat removal.

The resonator consists of V-shaped folded design with Nd:YVO_4 and KTP on either side of the resonator. The KTP crystal is cut for Type-II phase matched, high reflective coated for 1064nm and high transmission coated for 532 nm. The important feature of the folded resonator is by adjusting the individual arm length the spot sizes on the Nd:YVO_4 and KTP can be independently varied. This allows efficient operation by mode matching on the Nd:YVO_4 crystal and optimum spot size on KTP crystal for maximum harmonic conversion. The maximum CW green power of 2W has been achieved for the absorbed pump power of 9W.

High Power Nd:YAG Laser in Side-Pumping Geometry

The important systems include multi-hundred watt Nd:YAG laser for material processing application and the intra cavity doubled high average power green laser generating more than 50 W for pumping dye lasers. In side pumping approach, generally 1-cm diode laser bars capable of emitting 30 W-50 W are used. Depending upon the length of the rod there are many diode bars kept side-by-side to form a linear stack (horizontal stack) of suitable emission length. Many such linear stacks are mounted around the laser rod in an axially multiplexing scheme. Several pumping schemes using the side pump geometry are in use. Of these, the simplest one is to go for Nd:YAG rod of sufficient doping and cross-section to absorb the pump light to greater extent in single pass itself. A laser rod of 5 mm diameter and 100 mm length mounted coaxially in a quartz flow tube for water cooling, and pumped by a total of 15 numbers of 50 W laser diode bars gives more than 215 W of CW power at a diode pump power of 700 W. The slope efficiency and optical-to-optical efficiency are 37% and >30%, respectively.

Using low power pump module an A-O Q-switched system with intra cavity KTP crystal has been developed to generate green power of more than 18 W at a repetition rate of 8kHz. The cavity uses a V- type geometry described earlier. One end mirror is a curved mirror with HR coating at the fundamental, whereas the other end mirror is a flat mirror with dual HR coating for 532 nm and 1064 nm.The folding mirror of 200 mm ROC and coated HR at 1064 nm but HT at 532 nm allows the green beam to transmit. The KTP crystal used was 10 mm long and Type-II phase-matched at 80°C temperature. The KTP crystal was placed near the flat mirror. The optical-to-optical conversion efficiency was more than 10%.

Laser Isotope Enhancement

Laser based technologies can be employed for isotope enrichment of various elements of interest. So both atomic vapor laser isotope separation (AVLIS) and molecular laser isotropic separation (MLIS) were tried. Iinitially, sulpher isotopes of masses 32 and 34 were separated by multi-photon dissociation of SF_6 using a TEA CO_2 laser. A molecular beam setup with heating arrangement was used for studying photo-dissociation of molecules with an on-line quadrupole mass spectrometer. This was followed by studies on uranium bearing molecules. Infrastructural facilities for UF_6 based MLIS setup for supercooling of molecular vapor to a few Kelvin and the line tunable CF_4 laser were developed. In parallel, AVLIS approach was also pursued. For this, an evaporation system with electron bombardment heating to generate atomic vapor and copper vapor laser (CVL) pumped –dye lasers were set up. CVL lasers operating at 510.6 nm and 578.2 nm and providing an average laser power of 20 W at 6 KHz repetition rate were used to pump dye lasers which provided tunable output from 570 nm to 680 nm. Uranium atomic vapor was selectively ionized using dye laser output for one color, two color and three color and the ions so generated were collected by an electric field. Plasma plumes of boron oxide produced by Nd:glass laser of 30 ns duration and 10^{10} Wcm^{-2} was electrostatically analysed. Energy distributions of B_{10} and B_{11} isotopes were found to be different thus enabling their enrichment.

Optical Limiting

Motivated by the need to protect sensitive detectors and imaging devices from damage arising from exposure to intense laser pulses of nano-second or shorter duration, optical limiting properties of fullerenes, carbon nano-tubes, carbon particles and semiconductor doped glasses were examined. For C_{60} solution, it is shown that apart from reverse saturable absorption, thermally induced refraction and scattering play a major role. As a consequence, thermo-optic properties of the solvent are expected to be important and experiments showed that the optical limiting performance could be significantly enhanced by choosing a suitable solvent. For suspensions of absorbing particles, it was found that particle size is an important parameter and that the larger particles generally result in more efficient limiting. Sharp changes in optical limiting behavior of CdS_xSe_{1-x} doped glasses were observed as the laser wavelength scanned the band edge. An important parameter of an optical limiter is its response time. The performance of a thermal defocusing optical limiter was theoretically analyzed in the transient regime i.e. when the laser pulse duration is comparable to the acoustic transit time to determine its response time.

Non-linear Optical Processes

Considering the importance of developing coherent sources at wavelengths not covered by existing lasers, non-linear optical processes were studied. Using a tunable infra-red source based on stimulated electronic Raman scattering of dye laser radiation from potassium vapor it was seen that optical non-linearities. in conjugated organic molecules were examined. It was seen that a judicious substitution can result in a large increase in non-linearity for aza-derivatives of symmetrical cyanines. Feasibility of generating 16 mm radiation by difference frequency generation (DFG) was explored and quasi-phase matching of three wave mixing was studied in detail. The picosecond laser was used for non-linear optical studies in condensed phase. Several techniques like degenerate four wave mixing and Z-scan techniques were used to study several classes of organic and inorganic materials. The structure property relations and optimization of the nonlinear interaction coefficients were determined.

Nonlinear Optics with Nano-structured Materials

Nano-structured materials provide a way to increasing effective interaction between photons by concentrating the electronic density of states (quantum confinement) and by increasing the local electromagnetic field (dielectric confinement). Investigating nonlinear optical processes in semiconductor nano particles have shown that in the pico-second regime, even for photon energies well below the absorption edge, nonlinear optical response is dominated by two-photon absorption and consequent absorption and refraction by the free carriers generated. Nonlinear absorption, nonlinear refraction (Z-scan), optical Kerr effect and degenerate four wave mixing experiments were performed for determining time resolved non linear response. A single shot method Y-scan was also developed for studies with samples having relatively short life. All these experiments were performed with active mode locked Nd:YAG and Nd:glass lasers. Using negative feedback significantly higher stability was obtained in pulse to pulse energy, temporal duration and spectral modulation of mode-locked laser pulses. Avalanche transistor based Marx bank stacks generating 1.5 nsec step pulses of over 3.5 kV were developed for reliable intracavity single pulse switch out of mode-locked pulses. To achieve this, theoretical and experimental study of avalanche break down mechanism of transistors was conducted. It was shown that fast high voltage step pulse in a Marx Bank circuit is generated due to a current mode “second breakdown” of these transistors. This process is entirely different from the mechanism of break down of spark gaps, which is attributed to voltage multiplication across each spark gap in each successive stages of a Marx Bank circuit. The circuit has operated for more than 10 million shots at 20 Hz repetition rate without transistor failure.

Interpretation of optical response of nanoparticles requires a reliable estimate of their energy levels and eigen functions. These were investigated theoretically in the effective mass approximation and by empirical tight binding method.

Finite size effects on electronic and vibrational spectra of nanoparticles were investigated using Raman Spectroscopy and photoluminescence spectroscopy. These techniques were used on a variety of materials including semiconductor nanoparticles embedded in glass, nanoparticles deposited on a substrate by Langmuir-Blodgett technique, ZnSe epilayers deposited by pulsed laser deposition and C_{60} films before and after damage by swift heavy ions. Spectral line-shape analysis and other optical spectroscopy techniques specially the surface photo voltage spectroscopy were used to establish optical characterization strategies for III-V semiconductor nano-structures to be prepared by metal organic vapor phase epitaxy (MOVPE) technique.

Biomedical Applications of Lasers

Fluorescence from human tissues offers a promise of sensitive, early diagnosis of some types of cancer. Further, this can be done in-situ obviating the need of surgical removal of a part of the tissue, as also in near real time. For this purpose, a laser based system suitable for clinical deployment was developed and put into active use in the Government cancer hospital at Indore to screen patients for cancer of oral cavity. Different optical techniques for biomedical imaging are also being developed. Time gated imaging utilizing stimulated Raman scattering was used to image bar charts with spacing of up to 100 µm through 1 cm thick intralipid solution having a scatter-ing coefficient of ~3 / mm. Topographic and tomographic images of transparent objects with resolution of ~ 10 µm was achieved by free space optical coherence tomography. Depolarization of light in turbid medium was examined for probable use in optical imaging.

Effects of UV and visible light on cell cultures and animal models were studied to develop sensitive therapeutic applications of lasers. These demonstrated that in addition to the reported bactericidal effect laser irradiation can induce changes in the proliferation of the epidermal cells, and can also lead to stimulation of macrophages both of which influence the rate of wound healing.

Photodynamic effects of exogenous photosensitizers on cellular cultures and animals were also studied. Some of the photosensitizers being used for studies on cellular cultures and animal models have been prepared and characterized in house. These showed photodynamic inactivation of cells of epithelial origin like carcinoma of cervix cells using merocyanine 540 and of antibioticresistant strains of Pseudomonas. This provided the impetus for pilot studies on photodynamic therapy of tumor bearing animals. The application of laser beams to study molecular dynamics has most recently been extended to probe isolated cellular – level motion in biological systems.

Plasma Physics

Plasma, often described as the fourth state of matter, has been posing challenging problems to experimenters and theorists. Consequently, physics of thermal plasma, laser plasma, magneto hydrodynamics, high temperature magnetically and inertially confined plasmas, coherent emission of high power electromagnetic radiations by relativistic electron beams and on other high power devices has been extensively studied. The program, which started with small scale laboratory experiments, has now evolved as the thrust area at various units viz. CAT, SINP, BARC, while Institute for Plasma Research (IPR), Gandhinagar is fully committed to this development. The highlights of plasma related activites pursued by DAE constituents are given in the next Box. From this summary it follows that the thrust is on technology development and inertial confinement studies at CAT and BARC and around tokamak at IPR and SINP.

Activities at CAT

When a high intensity laser pulse is incident on a target, the material is rapidly ionized, producing high temperature, high density plasma. Importance of such plasmas may be understood from the temperature of hundreds of million degrees, densities approaching solid density, and pressures of up to billions of atmospheres which mimick conditions existing in the core of the sun.

Special emphasis of research in this area was thus related to laser driven inertial confinement fusion, generation of high brightness thermal and coherent X-ray radiation and its applications. Simultaneously, equation of state of matter at extremely high pressures and laser plasma interaction at ultrahigh intensities were also investigated. A number of high power laser systems delivering peak powers in the range of few gigawatts (10^9 watt) to one terawatt (10^{12} watt) in pulses of a few nanosecond (10^{-9}s) to a few hundred femtosecond (10^{-15}s) duration were, therefore, developed. These include a 4-beam Nd glass laser chain, delivering single laser pulses of up to 100 J (3 ns duration) per beam. One of these beams was used to generate black body radiation inside hollow microsphere of gold. The laser beam illuminates the inner wall of the gold cavity, and heats it to a temperature of about one million degrees, generating very intense thermal soft X-ray radiation. This enables looking at the behavior of matter under condition of intense thermal radiation and extremely high pressure shocks. A Terawatt (called T^3) Nd: glass laser system was developed to carry out studies of laser matter interteraction at ultrahigh intensities (~10^{17} W/cm^2). The plasma produced at these intensities acts like a miniaturized ultra fast X-ray source (size ~ one hundredth to one tenth of a mm) of high energy photons (~MeV), and charged particles of tens of keV to MeV energy ranging from protons to ions of heavy elements of very high degrees of ionization (e.g. in excess of 50 for gold). These have many potential applications in nuclear and material sciences. Single pulse peak X-ray brightness of these plasmas is much higher than that of any other laboratory source. Hence, they are used in single shot X-ray contact microscopic imaging of living biological cells with high spatial resolution, and ultra fast diffraction studies of materials.

Diagnostic of laser produced plasmas, in general, pose unique problems in view of their small size and small duration on one hand, and very high temperature and density on the other. In order to study dynamic evolution of these plasmas, a variety of plasma and X-ray diagnostic systems with high spatial resolution of ~10 mm and temporal resolution of ~few Pico seconds (10^{-12}s) were developed. Various aspects of laser plasma interaction in the laser intensity range of 10^{11} - 10^{13} W/cm^2, including absorption and back reflection of laser light, hot electron generation, dependence of mass ablation rate and ablation pressure on target atomic number and laser intensity, radiation energy transport, lateral smoothening of the effect of non-uniform laser illumination on ablation pressure profile, dynamics of ablatively accelerated targets, shock propagation through thin foils etc. were extensively studied. A strong foundation for taking up a comprehensive program on development of high intensity lasers and laser plasma interaction studies was thus laid. Some important investigations made in the area of laser plasma interaction are summarised in Box.

Plasma physics related activities

- Laser driven inertial confinement fusion, generation of high brightness thermal and coherent x-ray radiation and its applications, investigations of equation of state of matter at extremely high pressures, and laser plasma interaction at ultrahigh intensities. **(CAT)**

- Theoretical investigations on plasma dispersive properties, transport coefficients in a magnetic field and dielectric behavior at different frequencies and MHD relaxation states with minimum dissipation in toroidal magnetic configuration systems. The high temperature plasma research addressing wide variety of problems. **(SINP)**

- Experimental and theoretical research in plasma physics with emphasis on the physics of magnetically confined hot plasmas and non-linear plasma phenomena. Development of different facilities for plasma studies, plasma processing and applications **(IPR).**

- Theoretical and experimental investigations related to thermal plasmas, laser plasmas and MHD. Plasma diagnostic. Design diagnostics. Design and development of a 5 MW (thermal) MHD experimental plant. Development of plasma torches and electron beam equipments for cutting/welding/spraying, melting or evaporation applications **(BARC)**.

Some important investigations on laser-plasma interaction

- Increase in soft X-ray yield through opacity optimization of copper-gold mix-Z plasmas.
- Harmonic generation from solid surfaces
- Non-thermal population distribution and X-ray line intensity enhancement in plasma expansion in back ground gases.
- Equation of state through impedance mis-match technique.
- Effect of pulse duration on X-ray conversion efficiency.
- X-ray emission from laser heated gas-puffs and clusters.
- Analysis of isotopic enhancement in laser ablated plumes.
- Numerical simulations of laser driven shocks.

Activities at SINP

In the early years, experimental plasma physics activites centered around duoplasmatron ion source, penning ionization gauge and developing rf diagnostics using impedence probe. An electron beam was assembled with the duoplasmatron to initiate beam plasma interaction in a magnetic field and to form a negative hydrogen beam as a first step towards creation of neutral beams. Theoretical studies revolved around the non-linear distribution function and its effects on varieties of resonant behavior of a plasma. Experimental activities in high temperature plasma centered around a Tokamak machine. High temperature plasma research activites mainly addressed to such problems as (i) accessibility criteria of low –q regime of operation, (ii) anomalous ion heating mechanism in low-q operation, (iii) study of unique behavior of soft X-ray sawtoothing activity in normal q operation, (iv) study of fluctuations in edge regime, (v) study of the runaway electrons in the startup of low-q discharges and in helicity injection in runaway dominated discharges, (vi) study of drift like instabilities, (vii) simulation of low to high confinement mode by edge biasing and (viii) study of anomalous current penetration. Currently, the theoretical work in the area of MHD relaxation states with minimum dissipation in toroidal magnetic configuration systems is being pursued.

Activities at IPR

Initially, some basic experiments in toroidal assembly (BETA) such as the study of low frequency instabilities, vortex formation, effect of shear on turbulence were performed. For this purpose, a setup comprising of vacuum chamber with base pressure of 10^{-6} Torr, limiter to limit the plasma from the stainless steel vacuum vessel wall, a DC power supply, 16 toroidal field coils to produce magnetic fields up to 1 kG and lasting for 1 sec duration was developed. Radially movable Langmuir probes at various azimuthal locations with current to voltage converters and voltage followers formed the basic diagnostic tool for measuring fluctuations and plasma parameters. Other diagnostics used were Rogowskii coil, magnetic probes, microwave interferometry, various retarding potential analyzers, Faraday cups and mach probe. Also, in some experiments a 210 KJ capacitor bank was employed to produce 5.0 kG field for a duration of 40 ms. Subsequently, a major experimental facility tokamak ADITYA was built. The plasma is formed by an electrical breakdown in an ultra high vacuum toroidal vessel and a current is inductively driven in the plasma. As the plasma temperature rises the efficiency to heat the plasma drops. Hence, to further raise the temperature of the plasma to fusion grade, auxiliary heating schemes are used. Various sophisticated tools are also developed for plasma diagnostics.

ADITYA has a major radius of 0.75 m and minor radius of the plasma is 0.25 m. A maximum of 1.2 T toroidal magnetic field is generated with the help of 20 toroidal field coils spaced symmetrically around the toroidal vacuum vessel. ADITYA is operated with a transformer-converter power system. Plasma discharges of duration ~100 ms and currents ranging from 80 - 100 kA at toroidal field of 8.0 kG are being regularly studied.

It incorporates cleaning facilities such as Pulsed Discharge Cleaning (PDC) and Electron Cyclotron Resonance (ECR) discharge cleaning. The diagnostic tools used to measure plasma parameters are (i) Langmuir probes to measure plasma parameters and turbulence at the edge of the plasma, (ii) Multi chord microwave interferometer system for measurement of temporal and spatial plasma density profiles, (iii) Soft X-ray pin hole camera to measure plasma temperature in the core of the plasma, (iv) Thomson scattering for temperature measurement, (v) ECE diagnostic for temperature profile measurement and (vi) Laser blow-off diagnostic. The plasma is monitored with a grazing incidence monochromator (GIM, 10 - 600 nm), a normal incidence spectrometer (NIM, 100 - 300 nm) and a visible spectrometer (VIS, 300 - 800 nm). The auxiliary heating systems used to increase the plasma energy content during discharge include: (i) A 200 kW ion cyclotron resonance heating system operating between 20 - 45 MHz, (ii) A 100 kW system operating at 3.7 GHz and (iii) A 28 GHz, 200 kW gyrotron based electron cyclotron resonance heating (ECRH). The ECRH system is meant for use during initial break down of the plasma as well as heating at a later stage. With the help of this system pre-ionization is achieved which enables initial breakdown of the plasma with lower loop voltage. Experiments on edge plasma fluctuations, turbulence and other related experiments were conducted to have better understanding of fluctuation-driven anomalous transport of particles and heat. This is of paramount importance in modern fusion devices. An experiment concerning the effect of lithium conditioning on the discharges is underway. The presence of lithium during experiment is established by spectroscopic measurements. Initial results show an increase in the H-alpha radiation and decrease in the hard X-rays. The newer activities on which the work is being pursued have been listed in Box.

Newer activities at IPR

- Steady State Superconducting Tokamak (SST-1) Experiment
- Pulsed Power Experiments
- Large volume plasma device
- Free electron laser
- Simulation studies
- Facilitation centre for industrial plasma technology (FCIPT).

Steady State Superconducting Tokamak (SST-1) Experiment

The current emphasis is to address physics and technology issues related to steady state tokamaks and so called advanced tokamak configurations. Some of the questions, which will be addressed, pertain to the energy, particle and impurity confinement during steady state operation. Plasma disruptions and vertical displacement episodes will also be studied. Non-inductive current drive would sustain the plasma current during steady state. Different aspects of current drive will also be studied. Since we will have long duration plasma, lot of heat will be removed by components near the edge of the plasma. Various aspects of these problems are being studied during the fabrication and integration of SST-1.

SST-1 is large aspect ratio (ratio of the major radius to the minor radius of the plasma) tokamak configured to run a double/single null, elongated, triangular plasma, with a pulse duration of 1000 sec. The maximum toroidal field of 3 Tesla would be produced at the center of the plasma. A plasma current of 200 kA is envisaged. To accommodate larger plasma current the plasma would be shaped with the help of a set of poloidal magnetic field coils appropriately positioned around the plasma. Superconducting (SC) magnets are deployed for both the toroidal and poloidal field coils in SST-1.

A total of seventeen large volume high field superconducting toroidal field magnets, nine solenoidal superconducting poloidal field magnets and seven resistive OFHC copper wound magnets of various sizes are employed in SST-1. Nearly 22000 kilometers of 0.86 mm diameter NbTi/Cu strand weighing approximately 10,000 kg have been used in the form of a Cable-in-Conduit-Conductor (CICC) along with nearly 5000 kg of SS 304L. Approximately 2000 kg of indigenously developed and cryo-compatible (Bisphenol-A based) insulation system have been used as the insulation of the superconducting magnets. All the superconducting toroidal field magnets have been shrunk-fitted into CNC machined 'D' shaped SS 316 LN casings and nearly 10,000 kg of SS 316 LN material has been used for the fabrication of the casing. Similarly nearly 5000 kg of Oxygen Free High Conductivity Copper has been used for the manufacturing of the seven resistive magnets. These figures give an idea about the magnitude of the job undertaken.

SST-1 deploys a fully welded ultra high vacuum vessel, made up of 16 vessel sectors having ports and 16 rings with D-shaped cross-section, which will be welded in-situ during the SST-1 assembly. The LN_2 cooled radiation shields are deployed between the vacuum vessel and the SC magnets as well as SC magnets and cryostat, to minimize the radiation losses. The auxiliary heating systems are based on high power CW radio frequency (RF) and high energy CW neutral beam injection (NBI) technique. The application of three different high power radio frequency (RF) systems to additionally heat and non-inductively drive plasma current is made to sustain the plasma in steady state for a duration of up to 1000 sec. It will also have a high power NBI system for these purposes. The ion cyclotron resonance frequency (ICRF) (RF) system has the range of 22.0 to 91.0 MHz. A novel feature of the system is the CW high power operation with active water cooling. Lower hybrid current drive (LHCD) system having operating frequency of 3.7 GHz is based on two 500 kW, CW Klystrons with four outputs. The Electron Cyclotron Resonance Heating (ECRH) system is based on a 200 kW, CW gyrotron at 82.6 GHz.

In order to develop SST-1, a wide variety of specialized tasks have been successfully accomplished which include: Neutral beam injector, cryo-condensation pump having pumping efficiency of 10^5 l/s for D_2 at 4.2 K yielding a specific pumping speed of ~ 7 l/s/cm^2, electroforming of OFHC copper on a similar base, 80kV compact post insulator; jointing between Cu-Cr-Zr and SS 316 l by explosive bonding, vacuum brazing for the fabrication of heat transfer elements (HTE), fabrication of 20 m^3 vacuum vessel, 160 V / 100 A discharge power supplies with fast turn On and turn Off AC-DC converters, 490 kW (14 kV, 35 A) regulated high voltage power supply, development of VXI based data acquisition system, development of 16 channel multiplexer cards for the 700 channels of data acquisition, development of a computer controlled movement system for the neutral beam power dump.

Pulsed Power Experiments

Experiments related to development in the field of magnetised target fusion and production of powerful soft X-ray that can drive D-T pellet implosion are being carried out. Some of the significant developments made in this regard are (i) A 44 kV capacitor bank, capable of delivering currents up to 3.6 million amperes with rise times of 5-10 ms, (ii) 120 kilojoules capacitor bank, (iii) An 8-stage prototype of a Marx bank yielding up to 230 kV with a rise time of 250 ns and this is being upgraded to 20 stage to yield 1 MV at an energy level of 6 kilojoules and (iv) A 22 kilojoules plasma focus experiment suitable for both hydrogen and deuterium gases to serve as a test bed for neutron, hard X-rays and high speed imaging diagnostics.

Some other useful applications contemplated for the pulsed high energy sources developed are pulsed underwater electrical discharges for rock fracturing generation of shock/pressure waves and converting thin metallic foils into high-velocity jets, capable of penetrating 10 mm thick aluminum plate with potential applications in oil / gas well exploration. Also, for the large scale application of this technology the development work on compact pulsed-power sources, Tesla Transformers, fast opening and closing switches using exploding wires/foils and diagnostics for pulsed RF and microwaves has been carried out.

Large Volume Plasma Device

The system consists of a large cylindrical vacuum vessel of ~ 1.5 m diameter and a length of 4.0 m. A hot cathode of 1.0 m diameter forms a uniform plasma on the axis.

It has a axial field of ~ 30 gauss. Relatively high density of 10^{12} cm^{-3} after glow plasma is formed in the system. Results from Plasma Hysteresis show that in LVPD, accumulation of negative space charge due to enhanced ion transport occurs over a broad range of parameters, leading to consistent observation of smooth current transition and absence of plasma hysteresis.

Simulation Studies

Suitable codes and parallel computer systems have been developed to simulate various experiments. They include: A three-dimensional hydrocode to model shock waves and high strain-rate fracture phenomena and coupled with a 2-D finite element code allows detailed modeling of exploding foil switches; A three-dimensional time-dependent code for modeling electromagnetic experiments and also to calculate the radar cross-section of complex objects; A parallel computer consisting of 15 Pentium-IV (2.4 GHz) machines connected through a Gigabit ethernet switch for modeling Plasma Torch systems.

Facilitation centre for industrial plasma technology (FCIPT)

The properties of equilibrium and non-equilibrium plasma have been exploited for the some commercial applications mentioned in Box.

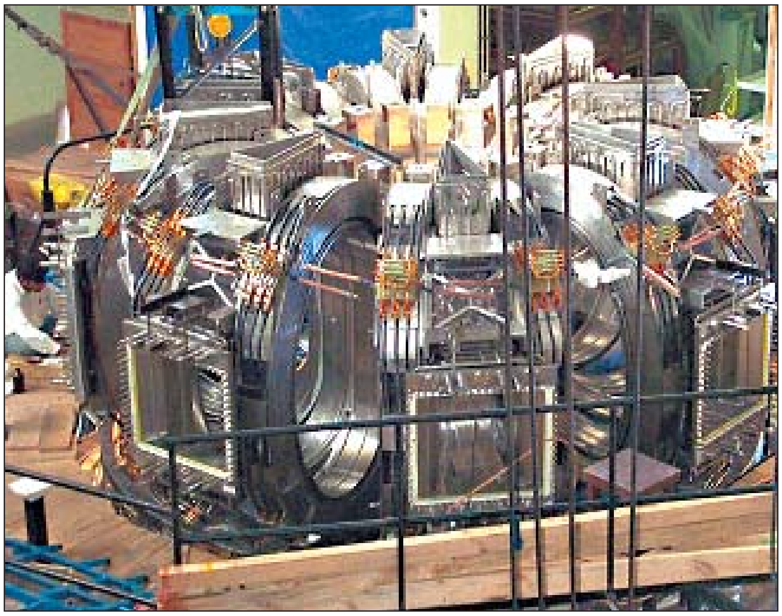
Commercial applications of plasma technology

- Plasma nitriding process for metal hardening.
- Protective barrier transparent coating on large mirrors for the telescope.
- Plasma etching on different types of irregular shaped polymers so as to improve the adhesion between the polymer surface and the colored lacquer coating applied on to it by spray method.
- Medical waste pyrolysis.
- Optimization of plasma nitriding parameters for 18Cr/10Ni steel used for hydropower component.
- Plasma source ion implantation (PSII) technique for low energy Argon and nitrogen implantation in solid surfaces.

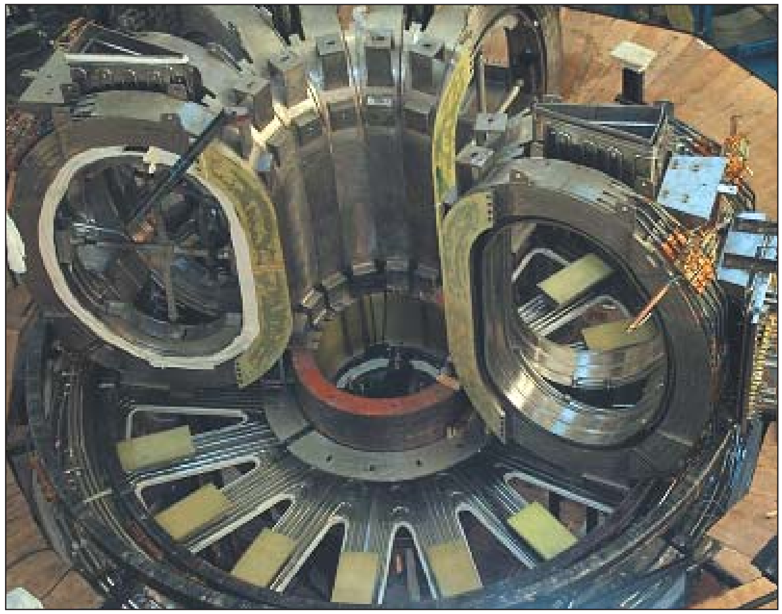
Some important contributions made in respect of plasma and non-linear physics are listed in the following Box. The first observation on intermittency was made in ADITYA tokamak and latter verified by other groups in fusion devices.

Significant contributions in the field of Plasma physics

- Intermittency and structures in plasma turbulence
- Rayleigh-Taylor instability and structures in BETA
- Effect of shear on turbulence:
- Linear and nonlinear properties of Whistler waves and EMHD turbulence
- Waves in dusty plasmas
- Non linear systems with delay
- Quark Gluon plasmas (QGP)

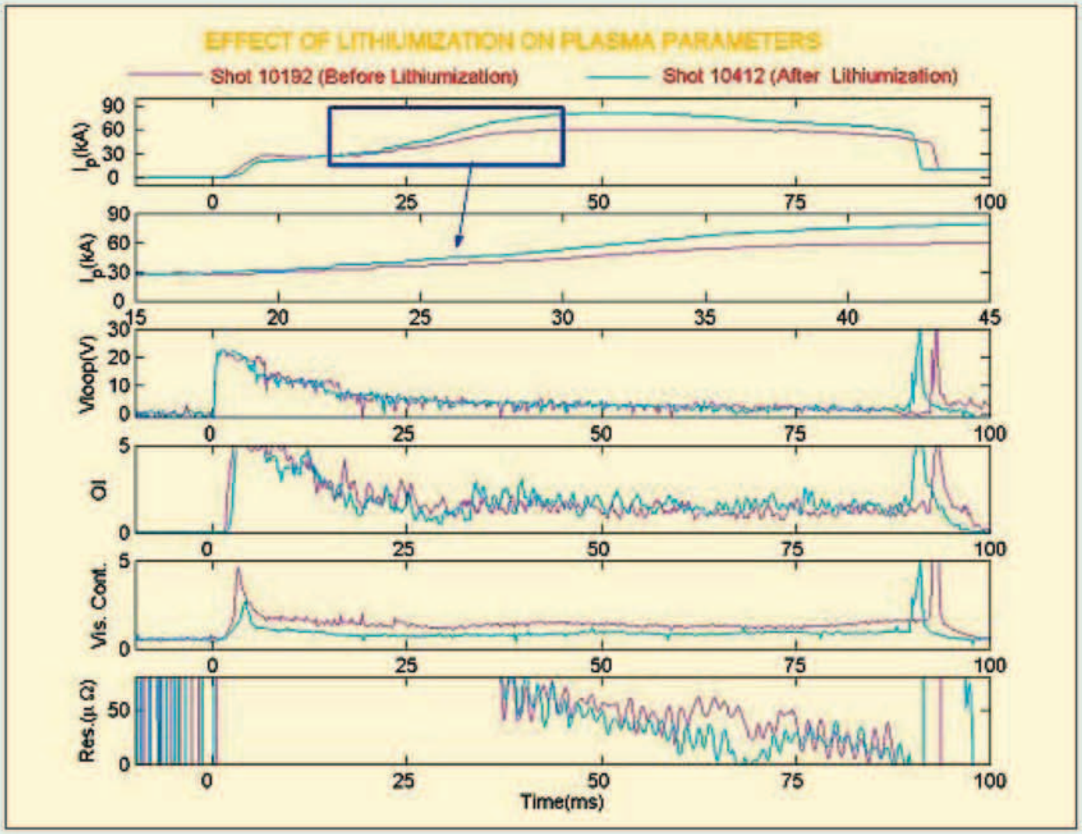


Assembly of machine modules in progress



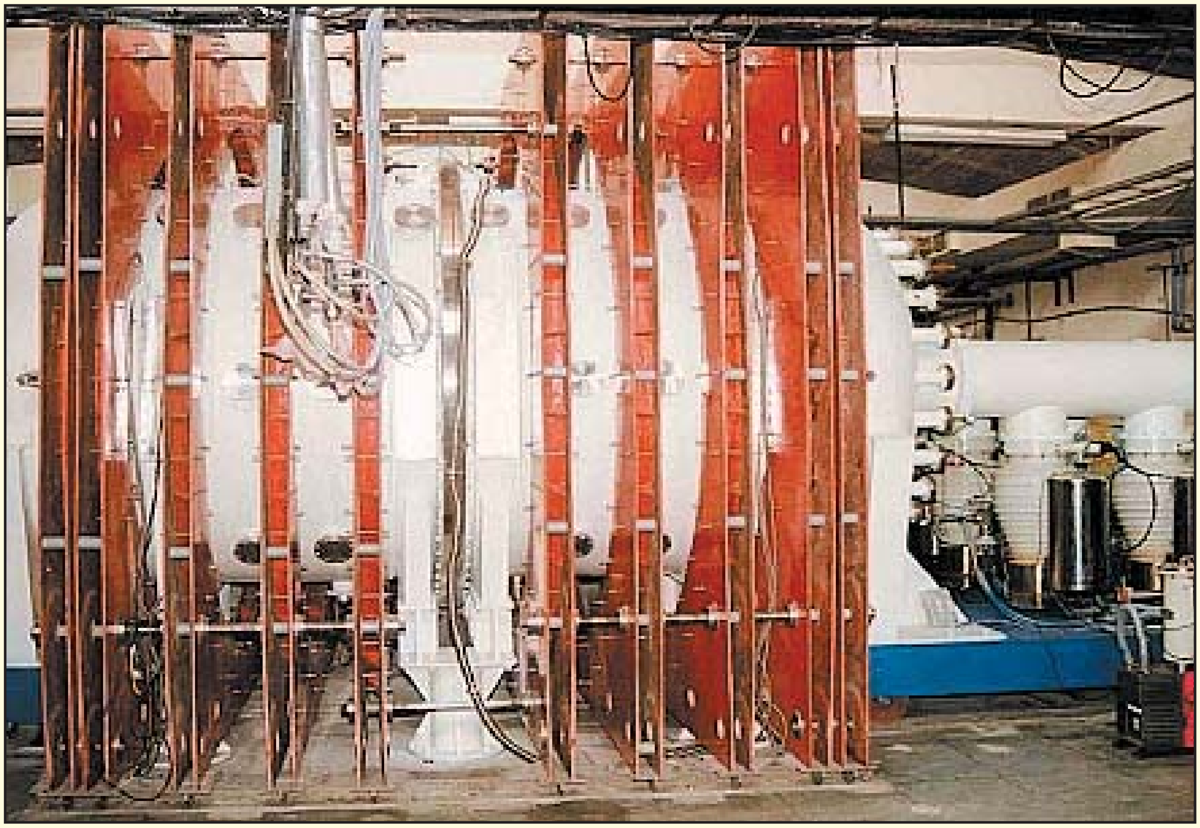
Assembly of four machine modules on TF supporting

Panoramic view of tokamak ADITYA



ADITYA Discharge before and after Lithiumization

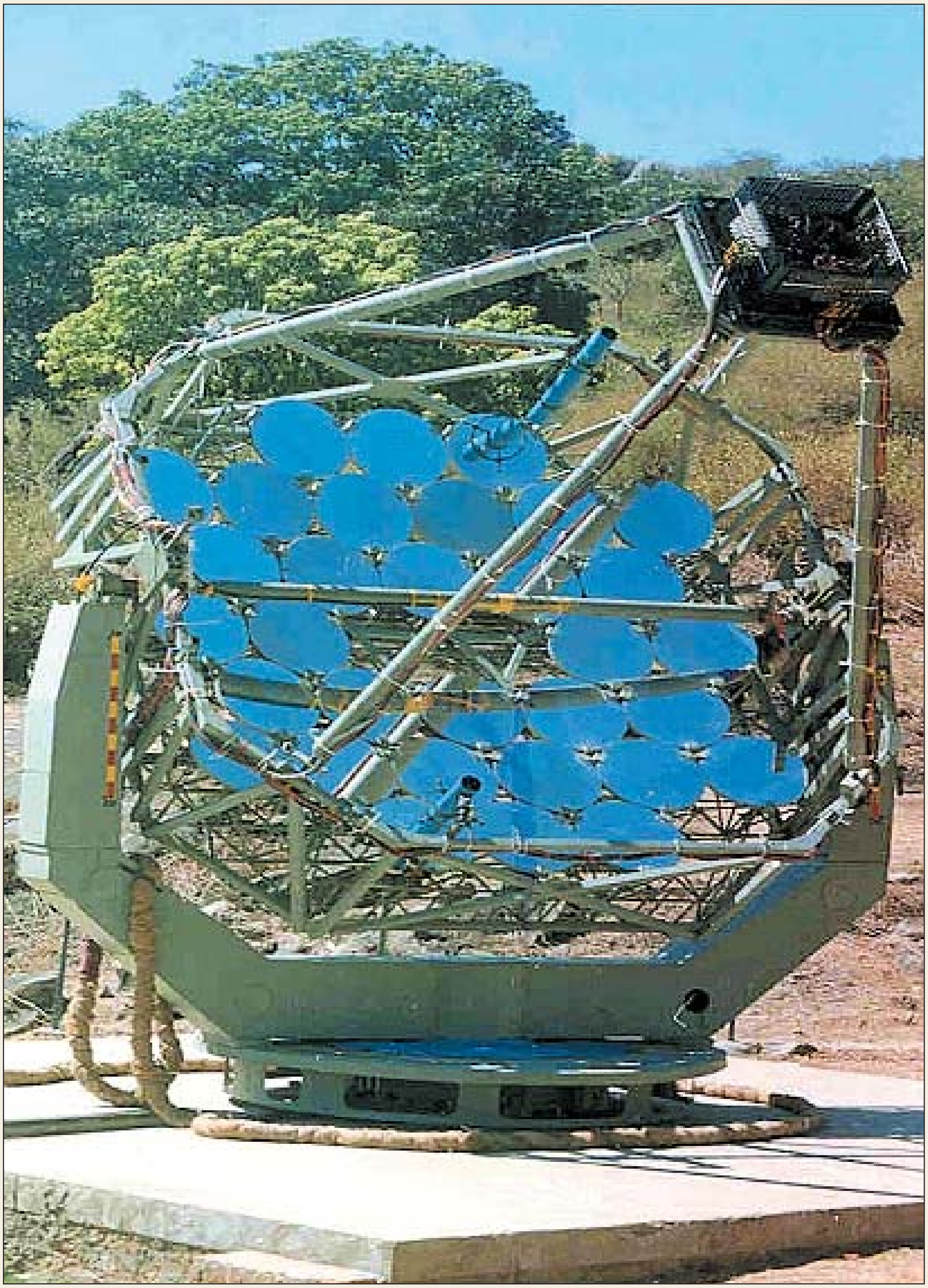

5 MW ion source in operation (ion + neutral) during test run


A view of LVPD machine

Astronomy, Astrophysics and Gravitation

Link P6

The intense activity that goes on in the universe provides a very unique opportunity to study wide variety of astrophysical problems concerning source of cosmic/gamma radiations, hydrodynamics, nuclear astrophysics, laser physics, atomic physics, particle physics,and general relativity to name a few. All stars derive their energy through thermonuclear fusion of light elements into heavy elements. High temperatures are needed so that mutual electrostatic repulsion between fusing nuclei is overcome through high collision velocities. The minimum temperature required for the fusion of hydrogen is 5 million degrees. Elements with more protons in their nuclei require higher temperatures. For instance, to fuse carbon it requires a temperature of about 1 billion degrees. It must be mentioned that such extreme temperatures / energies are not achievable with the available accelerators. The strong stellar winds in the atmosphere of certain stars are like the throat region of a rocket nozzle, where the hot gases rapidly expand and cool. This can produce non-equilibrium states with more gas particles occupying upper energy levels (than lower energy levels) and population inversion resulting in lasing action. Consequently, study of such stars opens up the opportunity to understand plasma recombination and lasing processes which is of practical interest.



The country's first imaging gamma ray telescope TACTIC (TeV Atmospheric Cerenkov Telescope with Imaging Camera) set up at Mt. Abu, Rajasthan has successfully detected steady gamma ray emission from the Crab Nebula and episodic emissions from two extragalactic sources Mkn 421 and Mkn 501. Operating at a energy threshold of about 1 TeV . The telescope can detect the Crab gamma ray emission with a 5s significance in ~ 25 hours of observation

Astronomy, Astrophysics and Gravitation

Astronomy has been at the forefront of research in basic sciences since early times and Indian astronomers have all along contributed to this human endeavor. In the fifth century Aryabatta calculated planetary positions and more recently Sawai Jai Singh of Jaipur built 5 large observatories referred to as Jantar Mantars at Delhi, Varanasi, Jaipur, Mathura and Ujjain. During the last century, rapid developments have taken place in Astronomy and a number of new windows have been opened to the universe. Sophisticated ground and space based detector systems operating over a wide band of the electromagnetic spectrum have been deployed to understand the origin and evolution of the universe around us.

Astronomy and Astrophysics activities within the country have been fostered by DAE through various research programmes at TIFR and BARC. Initially emphasis was mainly on Radio Astronomy and X-ray Astronomy. Later gamma-ray astronomy work was started with the establishment of high altitude laboratory at Gulmarg.

The first major radio astronomy facility, the Ooty radio telescope (ORT) was set up at Udhagamandalam in the Nilgiri Hills in Tamil Nadu in 1970. It consists of an off axis parabolic cylinder 530 m long and 30 m wide operating at a frequency of 326.5 MHz. The reflecting surface is made of 1100 thin stainless steel wires running parallel to each other for the entire length of the cylinder and is supported by 24 steerable parabolic frames. The equatorially mounted telescope is installed on a hill which has a natural slope of ~ 11° which is close to the local latitude. The ORT has been used for determination of the brightness distribution of a large number of weak and distant extragalactic radio sources. It has also been used in very long baseline interferometric (VLBI) observations in conjunction with large radio telescopes abroad. Over the last 30 years, it has produced many important astronomical results on radio galaxies, quasars, supernovae, pulsars and the interstellar and interplanetary media. One of the most successful observational programs carried out for many years at Ooty was to determine the angular structures of hundreds of distant radio galaxies and quasars by the technique of lunar occultation. The application of this unique database to observational cosmology has provided an independent support for the Big-Bang model of the universe. The telescope is currently being used mainly for the study of pulsars, radio recombination lines and interplanetary scintillations.

The giant metre-wave radio telescope (GMRT) which is the world's largest aperture synthesis radio telescope at metre wavelengths, was commissioned at Khodad, about 80 km north of Pune in 1998. It consists of 30 fully steerable parabolic antennas each of 45 m diameter. 12 antennas are located in a compact central array of 1 km x 1 km area and the remaining 18 are placed along the 3 arms of an approximately 'Y' shaped configuration spread over an area of about 25 km in diameter. The telescope operates in 6 frequency bands around 50, 151, 235, 327, 610 & 1000-1400 MHz with angular resolution ranging from ~ 60 arc sec to ~ 2 arc sec. The telescope is a very sensitive aperture synthesis array at low frequencies and has been made using an innovative design (Stretched Mesh Attached to Rope Truss), which has resulted in substantial reduction in its weight. Its central compact array and the long arm antennas provide good sensitivity for detecting large diffuse objects and high angular resolution needed for small objects. Signals from all antennas are brought together in optical fibres and correlated to form one large telescope. It is being used for a variety of astrophysical studies such as the detection of red shifted 21 cm line radiation representing the epoch of galaxy formation, pulsars, supernova remnants, diffuse emission from nearby galaxies, giant radio galaxies, distant active galactic nuclei, quasars and the Sun. Predicting the presence of proto-galaxies or proto-clusters of galaxies made up of clouds of neutral hydrogen gas before their gravitational condensation into galaxies by detecting the well known radio line emitted by *neutral hydrogen at a frequency of 1420 MHz is of fundamental astrophysical importance and can provide very important constraints to the theories of formation of galaxies and clusters. GMRT is expected to be an ideal instrument for the study of pulsars because of a large collection area of the telescope, which can lead to a substantial increase in the number of pulsars known in our galaxy. Because of the strong gravitational field associated with the pulsars, such systems form excellent laboratories for testing gravitational theories such as Einstein's General Theory of Relativity. Detection of extremely minute changes in the pulse arrival times from a group of pulsars can also lead to the detection of a weak background of gravitational radiation believed to have been generated by asymmetries in the very early universe. Investigations concerning (i) how large scale structures in the universe at the early times, especially the important structures known as damped Lyman- clouds, which are known to contain the bulk of neutral hydrogen at* $z \simeq 3$ *can be detected using GMRT and (ii) how the study of background light in the meter wave range at* $z \simeq 3$ *epoch can reveal the matter distribution at early times have been investigated.*

The experimental work in X-ray astronomy started at TIFR soon after detection of the first extra solar X-ray source Sco X-1 in 1962, with the use of balloon borne instruments sensitive in the 20 –100 keV energy band. A national balloon facility was established at Hyderabad in 1969 and over the years hundreds of balloons with scientific payloads have been launched from this facility. There are some unique advantages of conducting hard X-ray and gamma-ray studies from India. The flux of primary cosmic rays over Hyderabad is only about one-fifth of that at other launch stations in the world from where most balloon flights are conducted. The flux of secondary particles and X-rays and gamma-rays of atmospheric origin produced by the interaction of cosmic rays is also correspondingly low. This low background, in the presence of which one has to detect the feeble signal from cosmic sources is a major advantage in conducting hard X-ray and gamma-ray observations from India. In addition, many bright sources like Cyg X-1, Crab Nebula, Sco X-1 and Galactic Centre are also observable from Hyderabad due to their favorable declination. Gamma ray astronomy and far-infrared studies have also been conducted using balloon borne instruments. The infrared astronomy group at TIFR successfully carried out far infrared studies in the 100 - 500 micron wavelength using a balloon-borne 1m aperture telescope. A gamma ray experiment was also flown onboard the first Indian satellite Aryabhatta launched in 1975. An all sky monitor to detect transient sources and study the time variability of steady X-ray sources in the energy range 2 – 20 KeV was fabricated and launched onboard the second Indian satellite Bhaskara in 1979. Subsequently, an updated Indian X-ray astronomy experiment (IXAE), was flown onboard IRS-P3 satellite in 1996. Following the success of IXAE work was initiated on the development of a dedicated Indian astronomy satellite named 'ASTROSAT' which is proposed to be launched by 2006. This new state of the art satellite will be configured for multi-wavelength observations of celestial sources. Three different types of X-ray instruments which will be suitable for the study of X-ray pulsars over a very wide energy band are presently at various stages of development.

Cosmic ray studies at ultra high energies are being carried out at the Cosmic Ray Laboratory in Ooty using the GRAPES (Gamma Ray Astronomy at PeV Energies) series of experiments. These experiments deploy detectors for recording electrons (e^-, e^+) and muons (m^+,m^-) in a cosmic ray shower. The GRAPES II consists of 100 x 1m^2 scintillators for detecting electrons and a large 200 m^2 area water Cerenkov detector for muons. GRAPES III comprises 270 x 1m^2 scintillation detectors and a 600 m^2 area muon detector to record muons above 1 GeV energy. The muon detector uses 3700 large 600 cm x 1 cm x 10 cm proportional counters deployed in four layers. The main aim of the experiment is to study the nuclear composition of primary cosmic rays around the knee region (10^{15} to10^{16} eV) and also to investigate the relationship between muon multiplicity and the shower size. Several observations on the electrons, muons and hadrons in air showers at energies ~ 10^{15} eV have suggested that the primary cosmic ray flux may be getting enriched in heavier nuclei with increasing energy. This conclusion, though in conflict with some other observations, particularly, on the characteristics of the Cerenkov radiation in showers, has very significant implications for the nature of galactic sources generating and accelerating particles to ultra high energies. The results from the analysis of data collected with GRAPES on the muon multiplicity distributions seem to provide support to the hypothesis that the energy spectra for the heavier elements in the primary flux tends to be the flatter relative to the spectra for lighter nuclei at energies ~ 10^{15} eV.

Research activities in Very High Energy (VHE) gamma ray astronomy commenced in 1971 with the setting up of an atmospheric scintillation experiment for detection of gamma ray emission from supernova explosions and primordial black-hole evaporation. The experiment deployed 3 closely-spaced, vertically oriented, large area photomultiplier tubes, two of which were provided with wide band optical filters to restrict their response to wavelengths ~ 300 – 450 nm while the third was provided with an optical filter which permitted photons with wavelength ~ 450 – 600 nm to preferentially reach it. The most important result from the Gulmarg wide-angle experiment was based on a time series analysis of the atmospheric Cerenkov pulses recorded by it from the direction of the Cygn X-3 indicating a 4.5 s significance excess in the orbital phase region ~ 0.6. Although, several candidate fluorescent events were recorded by the Gulmarg system, only upper limits were derived for the gamma-ray bursts of supernova origin because of limited time overlap with other observatories. These efforts were consolidated with the commissioning of the multi-element first generation atmospheric Cerenkov telescope in Gulmarg in 1985 for observation of gamma ray source candidates in the TeV energy domains. During the 5 years of its operation, the telescope observed some interesting phenomena in the X-ray binary systems Cyg X-3 and Her X-1. An important result from the Gulmarg telescope was the detection of a TeV signal from the prototype cataclysmic variable AM – Herculis. The signal was found to be modulated with the characteristic 3.4 h orbital period of the system and an outstanding feature of the light curve was its striking morphological resemblance to the circular polarization curve of the source.

Presently, VHE gamma-ray studies in the country are being carried out by TIFR and BARC. The TIFR has set up a Cerenkov wave front sampling telescope at Pachmari referred to as PACT (Pachmari Array of Cerenkov Telescopes) which deploys 25 telescopes, each consisting of 7 parabolic mirrors mounted on a single equatorial mount, over an area of about 8000 m^2. The event arrival direction is determined with an accuracy of ~ 0.25^0 by timing the onset of the Cerenkov wave front at different light collectors with better than 1ns time resolution. Further rejection of the residual cosmic ray background is done by using a series of promising new data cuts based on the lateral distribution of Cerenkov photons at the array elements. An Observatory has also been set up recently at Mt. Abu, Rajasthan by BARC for the study of Celestial bodies in the TeV (10^{12} eV) energy band using the Cerenkov imaging technique. The country's first imaging gamma ray telescope TACTIC (TeV Atmospheric Cerenkov Telescope with Imaging Camera) set up there has successfully detected steady gamma ray emission from the Crab Nebula and episodic emissions from two extragalactic sources Mkn 421 and Mkn 501. Operating at the energy threshold of about 1 TeV, the telescope can detect the Crab gamma ray emission with a 5 s significance in ~ 25 hours of observation. Some important contributions made in this area are summarised in the next Box.

Some important contributions

- Large volume of lunar occultation data collected by the Ooty radio telescope has provide independent support for the big-bang model of the universe.
- Low frequency continuum mapping in the Galactic plane is important for identification of supernova remnants and for studying the intervening inter-stellar matter. After detailed mapping of a number of galactic sources, the GMRT observations confirmed some of these as super nova remnants.
- The IAXE observed random and regular X-ray variability over a wide range of time scales from the galactic micro-quasar source GRS-1915+105. Quasi periodic oscillations with luminosity dependent frequency in the range of 0.62-0.82Hz were also observed from the source.
- The muon multiplicity distribution data collected by the GRAPES array supports the hypothesis that the energy spectra for the heavier elements in the primary cosmic ray flux tends to be flatter than the lighter nuclei at energies ~ 10^{15} eV.

- The atmospheric Cerenkov pulses recorded by the Gulmarg wide-angle experiment from the direction of Cygn X-3 indicated a 4.5σ excess in the orbital phase region ~0.6.
- The Gulmarg gamma ray telescope detected a TeV signal from the prototype cataclysmic variable AM-Herculis .
- The flaring activity of the active galactic nuclei Mkn 501 picked up by the TACTIC imaging gamma ray tele scope in early 1997. This was the first concurrent multi-observatory detection of a TeV gamma ray source.

The design of the 21m diameter stereoscopic MACE (Major Atmospheric Cerenkov Experiment) telescope proposed to be set up at Hanle, Ladakh, is presently being finalised. This telescope will deploy two high resolution imaging Cerenkov telescopes for gamma ray studies in the sub TeV energy range. With an expected energy threshold of about ~30 GeV, this telescope will cover the important gap between the satellite and ground based observations in the field of VHE gamma ray astronomy.

A multi-institutional program for comprehensive research in the upcoming area of neutrino physics has recently been initiated by TIFR. A working group has been formed to assess the feasibility of establishing an Indian Neutrino Observatory and two possible sites for the observatory have been identified.

One of the interesting observational facts known about the universe is that it is expanding. So at earlier times, it must have been hotter and more compact. At sufficiently early stages, it must have been hot enough for the elements hydrogen and helium to be ionized. As the universe expanded from this hot state, it cooled and at some stage ions and electrons combined to form neutral atoms. Once this happened, there were few electrons left and the mean free path for photons became very large. The spectrum of these photons is thermal with an effective temperature of 2.7º K, and these constitute what is known as the Cosmic Microwave Background Radiation (CMBR). It is known that CMBR is remarkably isotropic, with variation in temperature being less than one part in 10^{-5}. This level of isotropy is surprising, particularly as in the standard Big Bang model these photons are coming from regions that are not causally linked. Hence, one has to look for mechanism for making different parts of the universe causally look alike, or believe that the initial conditions for our universe are very special. Inflation is one mechanism that can link different parts of the universe causally, and hence allow for homogenization. It is hypothesized that the universe underwent very rapid expansion at a very early stage, and that everything we see originally came from a causally connected region. This alleviates the problem of an isotropic universe to some extent, and also predicts that the universe must be very closed to flat. Inflation also provides a straight forward mechanism for generating small perturbations, and these account for the tiny anisotropy that is observed in CMBR. The tiny perturbations in the CMBR that are barely observable grow via gravitational instability to form large structures like galaxies and clusters of galaxies. The study of formation and evolution of these structures is an active area of research. Scientists in HRI are involved in work on inflation, numerical simulations on forma-tion and clustering of galaxies, and in making theoretical pre-dictions for the Giant Meter-wave Radio Telescope (GMRT) in popular scenarios of galaxy formation.

Recent developments in cosmology have touched almost all aspects of the subject; from determination of cosmological parameters, to observations of evolution of galaxies and their spatial distribution. The former specifies the background universe and the latter describes the evolution of density fluctuations in this background. Evolution of density fluctuations is probed in many ways, from observations of anisotropies in the CMBR at $z \simeq 1100$ to observations of galaxy distribution at $z \simeq 5$ and below. Two major surveys to determine the distribution of galaxies at $z < 0.3$ are underway. Of these, the 2dF galaxy red-shift survey is the largest red-shift survey at present with more than 50,000 galaxy red-shifts. There is an accompanying survey for quasars that has observed nearly 10,000 quasar red-shifts in the range $0 > z < 3$. This has been made possible by 2 degree Field (2dF) multi object spectrometer that allows observers to obtain spectra of 400 sources simultaneously. Another major survey being carried out is the Sloan red-shift survey, which will measure 10^6 galaxy red shifts in the coming years. This survey will also measure 10^5 quasar red-shifts and provide high quality sky maps for one steradian of the sky. Test runs of this survey have already led to the discovery of many bright, high red-shift quasars and also a new type of dwarf star.

The evolution of density fluctuations and its implications for the observed distribution of high red-shift galaxies have been studied. Using numerical simulations of structure formation, it is found that observations of spatial distribution of galaxies at high red-shifts can be used to determine the differences in clustering of galaxies and dark matter.

The tools for simulating evolution of density fluctuations have been developed. The focus has been on developing N-Body codes that can be parallelised without a significant loss of speed. The tree and the multi-pole methods are found more promising than other techniques. In these methods, the gravitational force of distant structures is truncated at some multi-pole and higher moments of the distribution are ignored. Also, a faster code for numerical simulations of gravitational clustering Tree-PM code, which is amenable to parallelisation and remains efficient even in highly clustered situations has been developed.

The properties of dense stellar objects have been investigated by adopting relativistic mean field theory for nuclear matter and chiral color dielectric model for quark matter. Masses, radii, rotational properties etc of these objects are computed after solving Tollman-Openheimer-Volkov equation. The calculations show that these dense stellar seem to have quark matter cores. The properties of these objects are quite similar to the properties of pure neutron stars. Their radii are about 10 km and masses are of the order of solar mass.

Theoretical work on approximate weak interaction rates, which are important at the collapse stage of type-II supernova has been carried out.

Gravitation and other Feeble Forces

The studies on gravitation and other feeble forces have been carried out at TIFR to address the following fundamental questions experimentally: (i) Does Gravitation respect the Principle of Equivalence?, (ii) Does G, the Newtonian Gravitational Constant vary with cosmological time?, (iii) Does the Gravitational force law depart from the Inverse Square? and (iv) Is there a halo of massive neutrinos surrounding the Galaxy?. To answer each of these questions the torsion balance has been used in a novel way. The driving force came from the realization that the torsion balance as a torque-transducer has large measures of untapped sensitivity, and that the primary means to release this latent sensitivity lay in ideas of symmetry. While most of the thrust has been towards understanding the nature of Gravity, there lay a clear perception that these queries were close also to basic issues in particle physics. This made it natural in later years to concern itself with questions in the then emerging field of non-accelerator particle physics.

The development of an ultra-sensitive torsion balance, a state-of-the-art optical lever for interrogating the torsion balance, sensitive low-noise techniques for the measurement of temperature and magnetic field, could be possible because of the technological advances made by, especially with regard to ultrahigh vacuum, thermal and magnetic-field metrology, and precision machining. A special underground laboratory for conducting delicate mechanical experiments was designed and set up at Gauribidanur, Karnataka (not far from the Seismic Array Station of BARC), at a rural site specially chosen for the low ambient micro-seismic noise as well as in variations/ fluctuations in gravitational gradients.

A series of important contributions, limiting the strength of new intermediate range forces weaker than gravity was made. The existence of a “Fifth Force”, viz., a possible coupling to nuclear isospin with a strength 1% of gravity, was effectively ruled out. Further results placed the (then-) tightest limits on “fifth-forces” coupling to a variety of charges, including nuclear isospin, B-L, and phenomenological spin-dependent charges. Some of these results have been improved subsequently, but the basic sensitivity of the torsion balance as an acceleration transducer remains one of the best in the world.

In recent years, work on building up a very sensitive test of the Equivalence Principle, one of the cornerstones of the General Theory of Relativity is being done. Present sensitivities, at a part in 10^{11} are comparable with those of earlier measurements of Dicke and Braginsky, but major improvements are expected in the near future. The work on the design of a cryogenic torsion balance has been taken up: this is challenging, but the payoff is a significant reduction in noise, and consequent improvement in basic sensitivities of the torsion balance. One area where this is planned to be used is in a search for deviations from the inverse-square law of Gravitation at ranges less than 1 millimeter, with implications for recent speculations originating in string and other higher dimensional theories.

Giant Metre-wave Radio Telescope (GMRT) is the world's largest aperture synthesis radio telescope at metre wavelengths. It was commissioned at Khodad, about 80 km north of Pune in the year1998

Condensed Matter Physics

Link P7

Condensed matter physics is the field of physics that deals with the macroscopic physical properties of matter. In particular, it is concerned with the "condensed" phases. The classical study of the condensed matter physics (CMP) was primarily concerned with the measurement of macroscopic properties of solids like mechanical, optical, thermal and electrical. However, the modern study is primarily concerned with the microscopic properties and since the time quantum mechanics has been applied to it, there have been several important advances. In this state, matter possesses certain unique properties that makes these materials ripe for practical applications that would not be possible otherwise. For example, a superconducting material is extremely useful for construction of very high field magnets. Liquid crystals have found use in many walks of life and have become very visible in the world around us.

Every DAE institution has a programme on CMP for the reason that the breath of the subject is immense and application regime is vast. Different DAE institutions have developed strengths in different areas of CMP (BARC: neutron, X-rays & light scattering, high pressure physics, superconductivity, magnetism, crystallography, soft matter, molecular dynamics, electronic structure, computational CMP; TIFR: low temperature physics, superconductivity, magnetism, semiconductor physics, theoretical CMP; IGCAR: Defect CMP, high pressure physics soft matter, superconductivity, etc.; CAT: superconductivity, non-linear optics; IOP: theoretical CMP, surface physics; HRI: theoretical and computational CMP; IMSc: theoretical superconductivity). To this diverse base, CMP research using synchrotron source at CAT has now been added.

Panoramic view of the neutron spectrometers at Dhruva reactor, BARC. The facilities existing are powder and single crystal diffractometers for crystal structure determination, Hi-Q diffractometer for structural studies in amorphous and liquid systems, polarization neutron spectrometer for magnetic scattering studies, for small angle neutron scattering (SANS), quasi-elastic scattering studies (QENS), inelastic neutron scattering studies

Condensed Matter Physics

Condensed matter physics deals with a bewildering variety of phenomena, which have been constantly culminating in the growth of new physics, new devices or enhancing the performance of known devices. The importance of this branch of physics to the nuclear program was realized from the very beginning since preparation materials suitable for applications under high radiation fields required in depth understanding of the mechanisms of radiation damage. Also, interaction of ionizing radiations with solids was one of the important ways of detecting radiations present in the environment. Another very important reason of promoting this physics was the application of thermal neutron beam obtained from a nuclear reactor to investigation of structure and other properties of solids. Research that started with the interaction of radiations with solids was further expanded to substantiate some of the results. The high level expertise developed over the years then enabled undertaking investigations in frontier areas of condensed matter physics. While, reviewing the present state of work in this field, it is only appropriate to begin with neutron beam related research (NBR) as it has remained a major area of investigation till date.

The neutrons have high penetrating power, unique sensing capabilities of light atoms among heavier atoms, capabilities of exchanging energies in almost similar magnitudes as their normal energies. They form excellent magnetic sensors in view of their magnetic moments. In addition they have widely varying cross-sections as one goes from one isotope to another across the periodic table. On account of these properties they carve out a special niche for themselves among all available probes of solids and liquids. In order to carry out neutron scattering studies the first nuclear reactor APSARA was built at Trombay in 1956 which provided a neutron flux of 10^{12} neutrons/cm^2/s at the central region. The first experiments at APSARA related to measurement of slowing down properties of a variety of moderator materials. Thus, with the commissioning of APSARA work on neutron scattering also started. Later, this activity shifted to CIRUS (40 MW), which became available in 1960 and then to the present research reactor DHRUVA that is a 100 MW natural uranium reactor with peak thermal flux of 1.8×10^{14} neutrons/cm^2/s. This reactor was designed and built based on indigenously developed know-how and materials. The reactor has tailored features for NBR like recessed cavities for installing neutron spectrometers close to the core, cavities for installing neutron monochromators and neutron guides in the biological shield, tangential beam tubes and large diameter beam tubes for installing cold and hot moderators. In addition, it is possible to take cold neutron beams from the reactor into a large adjoining hall by using shielded neutron guides.

Neutron Beam Research

The first home built single crystal neutron spectrometer was setup at APSARA in 1957. Total cross sections of a few elemental solids were measured using this spectrometer. The thermal neutron spectrum as diffracted from a variety of single crystals was also studied. These measurements led to the observation of neutron double Bragg scattering for the first time. Some of the other experiments carried out using this instrument were study of shape of thermal neutron resonance in indium metal. The broad resonance could be explained on the basis of Debye spectrum of phonons in the materials.

A large variety of neutron spectrometers were designed and developed initially at CIRUS and subsequently at DHRUVA to carry out research in neutron crystallography, magnetic diffraction, phonon spectroscopy and to study dynamics in liquids and molecular systems. The facilities that exist presently at DHRUVA reactor include those for powder diffraction, single crystal diffraction for crystal structure determination, Hi-Q diffractometer for structural studies in amorphous and liquid systems, polarization neutron spectrometer for magnetic scattering studies, for small angle neutron scattering (SANS), quasi-elastic neturon scattering (QENS) and inelastic neutron scattering studies. The 1-D and 2-D position sensitive detectors (PSD) and the associated electronics required for this development were developed. The QENS spectrometer also has vertically curved monochromator for focusing of neutrons and it is installed on Tanzboden (air-cushion) facilitating easy maneuverability. Some of the interesting and landmark experimental investigations made using these facilities at CIRUS and DHRUVA are listed in the next Box.

The facilities developed for neutron beam research (NBR) have been declared as the National Facility for Neutron Beam and hence are available to a wider community of condensed matter physicists. In addition to these, the facilities at Variable Energy Cyclotron (VEC) at Kolkata and the INDUS-1 synchrotron at Centre for Advanced Technology (CAT), Indore have also been made available to universities by setting up the Inter-university consortium for DAE facilities (IUC-DAEF) in collaboration with the University Grant Commission.

Some Important Experimental Neutron Beam Research

- Determination of crystal structure of amino acids.
- Study of nature of hydrogen bonding in hydrogenous crystals, flexibility of hydrogen bonds and their relevance to biological systems.
- Measurement of phonon dispersion relations in Be, Mg and Zn.
- Investigations of Kohn anomalies in Zn.
- Molecular reorientation studies in NH_4 halides by Time-of-Flight technique and by filter detector spectrometry.
- Development of high resolution inelastic scattering techniques like difference filter technique.
- Polarized neutron diffraction from ferrites, heusler alloys etc.
- First observation of non-collinear Yafet-Kittel type of ordering in a mixed ferrite.
- Nature of anharmonicity in librational potential in molecular systems.
- The first measurement of phonons in an ionic molecular crystal.
- Determination of crystal structure of high temperature superconductors.
- Determination of magnetic structure of a number of systems in the temperature range of 10K-300K.
- Small angle scattering studies of micelles and surfactants.
- Inelastic scattering studies of phonons in minerals, magnetic materials, high T_c superconductors etc.
- Study of reorientational motions in various ‘molecular’ systems by high-resolution quasielastic neutron scattering.

Facilities available for IUC-DAEF programme

1. Neutron Spectrometers installed at Dhruva, BARC
   - A single crystal spectrometer with an Eulerian cradle.
   - A Triple axis spectrometer.
   - A polarized neutron spectrometer.
   - Two powder diffractometer with 1D position sensing capability.
   - A high momentum transfer diffractometer with multiple 1D position sensing detectors.
   - An air-cushion based high resolution quasi-elastic spectrometer.
   - Two small angle scattering spectrometers.
   - A neutron relectometer.
2. The beam lines on INDUS-1 at CAT, Indore.
3. The ion accelerators at VEC, IGCAR and IOP.

In order to complement the investigations on NBR pursued at BARC, work has also been carried out employing other techniques viz. X-ray diffraction, Mossbauer spectroscopy, Compton Scattering and Raman spectroscopy. The X-ray diffraction group has investigated structure of nucleic acids, large bio-molecules and proteins. The Mossbauer investigations on many magnetic systems have been made. High resolution helium and argon ion based laser Raman spectrometers were developed to carry out Raman spectroscopy work. In addition to supplementing work related to neutron investigations in systems like $LiKSO_4$, independent programs related to orientational dynamics of molecules in liquids, resonance Raman spectroscopy from semiconductors, dynamics of molecules in liquid, resonance Raman spectroscopy from semiconductors, organic systems, nanocrystals, quantum dots and high-pressure investigations were also taken up. Liquid crystals and other systems were investigated by techniques of laser Brillouin spectroscopy of high resolution using Fabry-Perot echelon, differential thermal analysis, X-ray diffraction etc.

In order to be self-sufficient in interpreting experimental data, theoretical investigations have also been part and parcel of the program. Some of the notable contributions made are listed in Box. Computer Simulation studies to supplement the theoretical lattice dynamical calculations and neutronic experimental investigations of complex solids have also been carried out.

Some notable theoretical investigations carried out at BARC

- The study of group-theoretical aspects as applicable to external modes of crystals.
- Determination of interactive potentials, lattice dynamical calculations and molecular dynamics simulations in many ionic molecular solids, minerals, cuperates and negative expansion materials.
- Pauli anticommutation.
- Observation of non-cyclic phases and separation of geometric and dynamical phases.

The activities carried out at TIFR from early days are summarised in the following Box. A number of sophisticated equipments like NMR, ESR, NQR spectrometers were developed in the early days to carryout frontline investigations in condensed matter physics. Installation of the Pelletron accelerator also gave a boost to interdisciplinary research in condensed matter physics using nuclear probes and hyperfine interaction related techniques. In particular, extensive studies on the formation and stability of magnetic moment on d/f ions embedded in different metallic hosts could be carried out for a number of probes e.g. Fe^{54}, Rh^{100}, Mo^{94} leading to salient results like the observation of giant *4d* magnetic moment on Rh atom in Pd and Pt metal and the elucidation of moment stabilizing influence of ferromagnetic host spin polarization.Compared to a conventional Kondo type antiferromagnetic spin polarization that always increases spin fluctuation and hence destabilizes the magnetic moment, ferromagnetic polarization of the host conduction electrons has been shown to suppress spin fluctuation rates and hence a more stable magnetic moment. Another important milestone was the successful demonstration of Kondo behavior of Fe impurities in Ag nanoparticles. Compared to Fe in bulk Ag, a ten-fold increase in the magnitude of Kondo temperature T_k in the nanoparticles was shown. Employing PAC technique, studies of static and dynamic spin correlation in uranium based heavy fermion systems showed a clear indication that the manifestations of “heavy fermions” viz. enhancement of electronic specific heat, can arise from dynamic spin correlation between uranium atoms without any enhancement of electronic mass.

Some of the early activities at TIFR

- Nuclear Magnetic Resonance and the Knight shift in metals.
- Studies on alkali halides.
- Measurement of ultrasonic attenuation in solids.
- Synthesis of nano materials using the sol-gel route.
- Transport properties of noble metals with magnetic impurities.
- Ferromagnetism and spin glass effects in PdAuFe and PdAuMn based systems.
- Elucidation of the oscillatory nature of the conduction electron polarization in rare earth inter-metallics and Heusler alloys.
- Phonon softening in ferroelectrics.
- Phenomenon of valence fluctuations in rare earth intermetallics (such as $CeSn_3$).
- Magnetic phase transitions.
- Valence fluctuation and hybridization properties of intermetallics $CeRh_3B_2$ etc.

A new concept of 'latent symmetry' was introduced in the recent past, which may have important implications for the theory of phase transitions in crystals as also for the symmetry and macroscopic properties of composites in general. Another possible application area is in the domain-average engineering of ferroic materials. The central idea is the unexpected extra symmetry, which can arise sometimes when two or more identical objects are combined to form a composite object in a specified way.

In order to understand soft modes and structural phase transition in systems like $BaTiO_3$ and $SrTiO_3$, a simple one dimensional field theoretic model with anharmonic terms up to the sixth power of the displacement of the atom was proposed at IOP. The equations of motion for such a field theory were solved exactly and many intricacies of structural phase transition were explained. Inspired by this excursion into the domain of nonlinear physics, a study was also made of the classical dynamics and thermodynamics of the double Sine-Gordon field theory and shown that the free energy and the first two correlation functions can be analytically obtained at several temperatures.

The work on characterization of materials using Mossbauer spectroscopy, nuclear magnetic resonance, nuclear quadrupole resonance and electron paramagnetic resonance techniques has been pursued from mid fifties onward. The equipments for all these techniques were developed in-house. Besides the experimental work, theoretical work on electronic band structure calculations and the study of paramagnetism of 4d and 5d transition metal ions was also carried out. In the recent times activities are progressing in electronic structure of disordered systems, transmission properties in disordered open quantum systems, level spacing distribution studies in 1d disordered systems, surface properties like chemisorption, surface reaction and catalytic activity of transition metals and their alloys. Quantum renormalisation group systems and to study the magnetic and superconducting regimes in the phase diagram of Hubbard models. The other important areas of current investigations are mentioned in Box. SINP is also actively pursuing research in surfaces, interfaces and clusters is also being actively pursued. Facilities available for this work include DC/RF magnetron sputter coating units, Langmuir-Blodgett trough and spin coating units for the preparation of single and multi-layered / non-metallic, metal-organic and polymer; a 200 kV isotope separator and ion implanter and grazing X-ray scattering, scanning probe microscopy, secondary ion mass spectrometer, bombardment induced light emission spectroscopy setups.

Some current areas of research at SINP

- Statistics of fracture of brittle solids and linear polymers in porous media.
- Quantum Ising glass.
- Dynamic transition and hysteresis in magnets under oscillating and pulsed fields.
- Transport properties like resistivity, Hall voltage and thermo-electric power of different high temperature superconductors.
- Colossal magnetoresistance in magnetic systems.

Superconductivity

The phenomena of vanishing electrical resistance and expulsion of magnetic flux in certain metals / alloys below a certain temperature (known as transition temperature - T_c) has been fascinating physicists and technologists for over eighty years. It is known that electrons pair up in superconductors and that such Cooper pairs are responsible for the properties of superconducting materials. It was found that such pairing occurs in a surprising way in a material called Sr_2RuO_4. The study of this material teaches us many things about superconductivity. The discovery of superconductivity in yttrium barium cuprate above liquid nitrogen temperature (77K) in 1987 was singular in the history of science. The high temperature superconductivity (HTSC) was expected to have applications in many areas. Therefore, work on Nb-Ti magnets was undertaken in the eighties, which was essentially for the accelerator program. In order to test the performance of superconducting wires / bundles, a short sample test facility was developed. Prior to the discovery of HTSC, basic studies in this area had mainly focused on magnetic properties of the superconductors. Work on HTSC has been rather broad based focusing on different aspects of synthesis of bulk materials and investigating their structural, electrical, magnetic and thermal properties. In addition to the deposition of thin films, thick films of these materials were also prepared to facilitate construction of devices at a later stage. Single crystal growth of $YBa_2Cu_3O_x$ and $Bi_2Sr_2CaCu_2O_x$ materials was carried out and the grown crystals were used to investigate any possible role of the dislocations as the pinning centers. The presence of superconductivity in a wide variety of quaternary borocarbide and boronitride compounds was discovered. Study of coexistence, competition and interplay between superconductivity, magnetic order and spin/charge density waves in strongly correlated electron systems has been carried out. A mechanism was proposed for the normal state c-axis resistivity of the high-temperature layered cuprates. This mechanism is a particular case of the quantum Zeno effect, namely the suppression of transition between two weekly coupled Hilbert spaces due to strong interspace coupling to environment. The calculated normal state c-axis resistivity follows the metallic-like temperature dependence of the ab-plane resistivity at high temperatures, while at low temperature it exhibits a non-metal like upturn. This mechanism admits d-wave pairing. Work has also been done towards understanding the mechanism of superconductivity in the recently discovered series of superconducting compounds, the cobaltates.

Experimental Work using SQUID

SQUID magnetometer enables measurement of tiny magnetic moments (as small as10^{-6} emu) in a variable magnetic field and temperature environment. This facility has been extensively used to understand the vortex phase diagram in the mixed state of type-II superconductors and various magnetic systems. In the mixed state, flux penetrates the superconductor in the form of quantized magnetic vortices each carrying a flux equal to 2.01×10^{-7} Gauss cm^{-2}. The vortices interact with each other by a repulsive interaction and arrange themselves into a triangular lattice. However, vortices are free to move when a current is passed. Vortex motion causes dissipation. Crystalline defects or quenched disorder present in the superconducting material trap the vortices and arrest the motion of vortices thereby dissipation. This phenomenon known as pinning, which is crucial for high current applications of superconductors, disturbs the vortices from their mean positions. Further, thermal energy makes vortices fluctuate about their mean positions. The interplay between the vortex-vortex interaction, thermal energy and the vortex-defect interaction is responsible for a variety of phases of vortex matter, such as vortex solid, liquid and glass phases. Some important contributions in the understanding of the vortex solid or Bragg Glass phase to vortex glass phase transition or order-disorder transition have been made. This transition is identified by a rapid increase in the magnetiztion hysteresis measured using the SQUID magnetometer. However, a pronounced metastability and history dependence in the state of vortex matter near the transition makes it difficult to access the equilibrium state experimentally, without which the nature of the underlying therodynamic transition is not possible. Theoretical models proposed provided a systematic under-standing of the metastable behavior. More importantly, they also suggest an experimental procedure to reach a unique and unambiguous equilibrium state and compute thermodynamic equilibrium magnetization across the order-disorder transition. It has been demonstrated that the transition is of the first-order in nature.

Theoretical Developments on the Critical State Model

Bean had proposed a model for describing irreversible magtization behavior of hard type II superconductors. Solutions of the model could be obtained only in some simple cases.

There were also difficulties of non-uniqueness of the solution when fields are applied in succession in two different directions. To obviate these difficulties a criterion namely – the minimum flux change criterion has been suggested. This is analogous to the variational principle in quantum mechanics in the sense that the criterion can be used to select a more realistic solution among a variety of available solutions. Using these ideas a number of nontrivial problems involving magnetization of hard type II superconductor samples have been solved. An exact expression for the surface current density on a cylindrical conductor of arbitrary cross section that produces a uniform magnetic field in its interior has been obtained. Prior to our work, the only result available was for cylindrical surfaces of elliptical cross section given by Landau and Lifshitz. An extensive use of this result to examine cylindrical samples of hard type-II (potentially useful) superconductor vis-a vis their magnetization has been made. In particular, the scope of available solutions of the critical state model to a much wider class that includes cylindrical samples of arbitrary cross section and subjected to an external field in any general direction has been enlarged.

Studies in MgB_2

Large scale calculations (40 atoms per cell) on hole-doped derivatives of MgB_2C_2 have predicted that they are good candidates of the MgB_2 family for achieving high temperature superconductivity. Doping studies on MgB_2 have been carried out using a home built, novel 50 bar-pressure locked apparatus, which prevents the loss of volatile Mg. These include, experiments on electron doping of MgB_2 with C substitution at the B site, and hole doping with Li/Cu substitution at the Mg site. From these studies, it is seen that T_C shows a universal behavior as a function of the electron count, with T_C remaining unchanged for electron count lower than that in MgB_2 and precipitously dropping for electron count greater than that in MgB_2. These results have great implication on the comprehensive theoretical understanding of the electronic structure and the mechanism of superconductivity in this material.

Mesoscopic Systems

Several aspects of mesoscopic systems have been investigated. In particular, several surprising effects related to persistent currents or circulating currents in the presence and in the absence of Aharonov Bohm flux in open systems have been investigated. It may be noted that they have no analogue in closed or isolated systems. Some of these effects include (i) directional dependence of persistent currents in the presence of a transport current, having important bearing on the symmetry property of the mesoscopic rings (ii) current magnification effect or circulating currents in the absence of magnetic field, but in the presence of a transport current flow (iii) existence of persistent currents simultaneously due to two non-classical effects, namely Aharonov-Bohm effect and quantum tunneling. Extension of these effects in the presence of the Aharonov-Casher flux has also been considered. Further, several phenomenological models of dephasing in mesoscopic systems have been considered. The studies on stochastic resonance and dynamical hysteresis have been extended to the quantum domain. Finally, a unified treatment for the general theory of molecular motors has been given with special emphasis on their efficiency and energy.

High Pressure Physics Research

The most basic effect of high pressure in materials is compression, which in turn brings about a reduction in the inter-molecular distances. For example, using a diamond anvil cell in the laboratory, one can squeeze a material to almost one third of its initial volume, in contrast with a few percent volume reduction broughy about by temperature variation. With the large and reproducible compression achievable in laboratories, one can change the intermolecular forces by almost two orders of magnitude higher than what is possible with the variation of temperature. Therefore, the high pressure investigations provide a very stringent test of the fundamental understanding of the materials. In addition the information obtained can be very useful for understanding several issues relating to geophysics, astrophysics, plasma and also is a vital input into hydrodynamic calculations for nuclear safety, fission/fusion energy systems, hyper velocity impacts and weapon development. At the fundamental level, broadly the information obtained from high pressure, static and dynamic, experiments can be termed as equation of state - with or without phase transitions. When there are phase transformations, with the simultaneous usage of theory, one can deduce additional insight about the mechanism of such changes. From mid-seventies much work has been carried out to investigate, both experimentally and theoretically, the physics of materials at high pressures. Many materials, such as metals and alloys, inorganic and organic compounds have been investigated. For most diamond cell experiments the shifts in the ruby fluorescence (R) lines are used as pressure sensor. However, under shock loading these lines shift quite differently and depend on the shock propagation with respect to crystal direction. Response of the ruby R-lines to external deformations was formulated and consistently explained with the help of a theoretical framework based on the microscopic strain to which the Cr atom in ruby is subjected.

At BARC, special emphasis has been laid on equation of states (EOS) studies, and the high pressure phase transitions related to these EOS, particularly those based on the first principle electronic structure and molecular dynamics (MD) simulations. The work on actinide thorium has for the first time shown that the contribution of 5*f*-states through hybridization is essential for stabilization in face centered cubic (FCC) structure at normal pressure and temperature conditions.

Experimental techniques developed for high pressure work at BARC, IGCAR and CAT

- Design and development of diamond anvil cells.
- Dynamic gas gun facility.
- High temperature high pressure laser heating facility.
- Raman scattering facility using diamond anvil cell.
- High pressure, Mossbauer, optical-absorption and resistivity facilities incorporating diamond anvil cells.
- Angle dispersive X-ray diffraction incorporating diamond anvil cell and imaging plate and CCD area detectors.

Further, the calculations showed that the high pressure induced FCC to BCT transition near 80 GPa in Th is due to the descending of unoccupied 5*f*-band through the Fermi level. For use in large-scale simulations, the parallelization of the electronic structure and *ab initio* MD computer programs on parallel processors were developed. The parallelization is important for carrying out calculations on some of the strategically significant actinides, which occur in many phases, some of which have more than 30 atoms per unit cell. The parallelized computer code for electronic structure calculations for crystal approximant to a quasicrystal with 162 atoms per unit cell have been used.

The axial ratio anomaly in zinc near 10 GPa pressure was predicted theoretically as due to an electronic topological transition (ETT). This generated world-wide interest on this subtle phenomenon, both experimentally and theoretically, leading to controversies as experimentally the observation is sensitive to the pressure transmitting medium, and theoretically the axial ratio anomaly is sensitive to the **k**-vector sampling for the integration over the Brillouin zone. A non-zero temperature electronic structure computer code to study the dependence of ETT on temperature in Zn was implemented. Large scale calculations (with 115,000 **k**-point sampling), along with the data of X-ray diffraction experiments with synchrotron source, pointed out the significance of the universal EOS in obtaining signatures of subtle transitions, and thus provided a new method to identify ETT. Due to the inadequacy of the energy bands based on the density functional theory to represent the interacting quasiparticle states, the studies on Zn included calculations by Green's function screened coulomb (GW) method to verify ETT.

The routines to calculate shock Hugoniots were developed using the first principle results. The calculations were carried out for copper and uranium, to corroborate with the laser shock data obtained at CAT. A routine to obtain the embedded atom type potentials for metals using *ab initio* results was developed. These quasi-*ab-initio* potentials would be useful for large scale MD simulations – including high pressure melting studies by 2-phase method, shock simulation, *etc.*, both of which have been carried out with these potentials for copper.

The *ab initio* phonon frequency calculations with harmonic approximation carried out for Zn showed that the anomalies observed near 18 GPa in the resistance and phonon frequency variations under pressure are due to phonon assisted ETT. The *ab initio* phonon simulations along with non-zero temperature electronic structure calculations have been used in evaluating thermal contributions of ions and electrons, respectively, to the free energy and hence to pressure in the shock Hugoniot calculations.

It has been shown that hcp structure of rhenium is stable up to 1 TPa, which is an important result as Re is used as gasket material in high pressure cells. For the technologically important material beryllium, it is shown that hcp to orthorhombic structural transition does not occur, in contrast to the inferences of some experiments.

Elemental Si is known to undergo several phase transitions under pressure. But the observation of a reversible phase transformation from beta-tin like tetragonal phase to a primitive hexagonal phase at ~ 16 GPa, was shown to be displacive, driven by the softening of a vibrational mode. The mechanism postulated that this transformation would take place through an intermediate orthorhombic phase. This intermediate phase has since then been observed in tin alloys, which undergo a similar phase transformation. In a closely related problem of Cd and CdHg alloys, transforming from the body centered tetragonal phase to a hexagonal close packed structure, the transition was shown to arise from two coupled order parameters viz., shuffle and homogeneous strain. Similar ideas were further extended to understand hexagonal phase to cubic phase in cadmium sulfide, observed under shock as well as static pressures.

While most materials show crystal-crystal phase transformation under high pressures, there are several materials, which become amorphous under high pressures. $LiKSO_4$ was one of the first compounds studied which showed irreversible amorphization and since then several compounds, such as $FePO_4$, GeO_2, and many other compounds showing negative thermal expansion have been shown to amorphize when compressed. This kinetically favored state was shown to arise from the steric hindrance encountered on the way to the higher density crystalline phase. In contrast, for the quartz structured $AlPO_4$, it was shown that this compound instead undergoes a reversible crystal-crystal phase transformation at variance with much acclaimed memory glass effect.

Carbon nanotubes are exotic materials, which can be viewed as being formed of folded graphite sheet such that its diameter is of the order of a few nanometers and axial dimensions of several tens of microns. These tubes naturally grow as bundles. With the help of high pressure X-ray diffraction investigations of single wall carbon naotubes it was shown that these tubes retain their two dimensional translational order till ~ 9 GPa beyond which the lattice periodicity vanishes. These results superceded all other results which found this transition at ~ 2 GPa. In addition, it was shown that these tubes act as coupled elastic tubes. The investigations of Fe-filled multi wall carbon nanotubes showed that interfacial compound Fe_3C and nanotubes undergo a coincident phase transformation at ~ 9 GPa, much unlike the bulk Fe_3C.

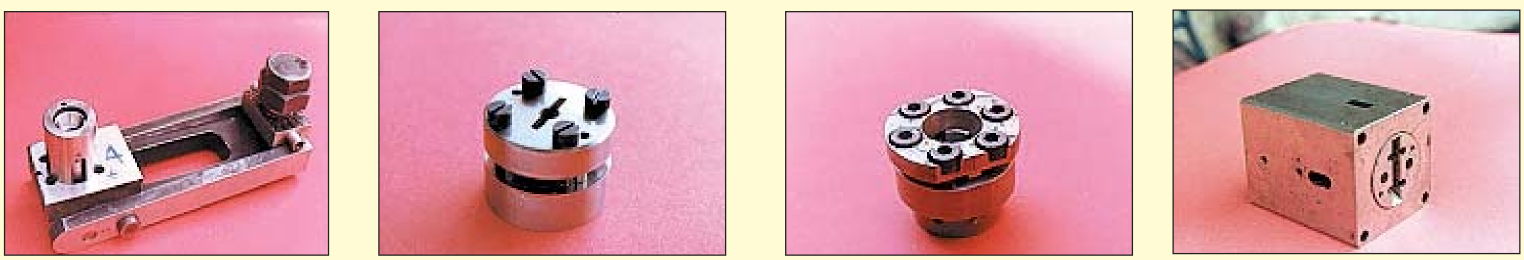
The combination of theoretical computations and experiments has been very useful in understanding the mechanism of several phase transformations. In particular, classical molecular dynamics simulations, which are essentially based on time evolution of an ensemble of interacting particles, have been used to connect to experimental observables like diffraction and inelastic neutron scattering pattern. It was shown for the first time that the crystal structure of the high pressure phases can be determined even though only limited data is available for these phases.

At IGCAR, pressure induced structural transformations in solid C_{70}, $AgGaSe_2$, ZrW_2O_8, $ThAl_2$ etc have also been investigated. In case of C_{70}, it has been shown that the development of orientational order leads to a sequence of phase transitions: the free rotor hcp/fcc phase going over to long axis aligned distorted hcp / rhombohedral phase and eventually to a completely aligned monoclinic phase. These orientational ordering transitions are considerably influenced by the application of pressure in these soft plastic crystalline solids. At elevated pressures, when the inter-fullerene distance becomes comparable to the on-ball carbon-carbon distance, transformations to amorphous carbon and diamond like structures are seen. When high pressure is applied along with high temperature, a reaction between parallel double bonds of the neighbouring molecules results in the formation of novel polymeric structures. A large number of systems including negative thermal expansion materials such as zirconium tungstate have been found to exhibit pressure induced amorphization. It was earlier believed to arise due to kinetic hindrance of equilibrium phase transitions. However, detailed Raman studies have shown that pressure-induced amorphization could also arise, if a decomposition of the compound into mixture of dense-packed daughter phases is kinetically constrained. The observation of Pressure Induced Amorphization (PIA) at ambient temperature in negative thermal expansion material ZrW_2O_8 and decomposition into mixture of ZrO_2 and WO_3 at high-pressure and high-temperature confirms the validity of the new model of pressure-induced amorphization. In the case of $ThAl_2$ a systematic sequence of structural transitions from cubic hexagonal orthorhombic tetragonal structures with increase of pressure and this can be rationalized in terms of electronic structure calculations as arising due to the increasing delocalization of f-electrons with pressure.

High temperature-high pressure laser heating facility

Direct conversion of graphite to a "Diamond-Like" phase using the LHDAC facility at at 14 GPa, with CO_2 laser power of ~15 watts. (a). black graphite sample under high pressure inside the DAC, (b). the shining laser heated zone of the pressurized graphite sample, and (c). formation of the translucent diamond-like phase after heating

Gas gun facility



1 2 3 4

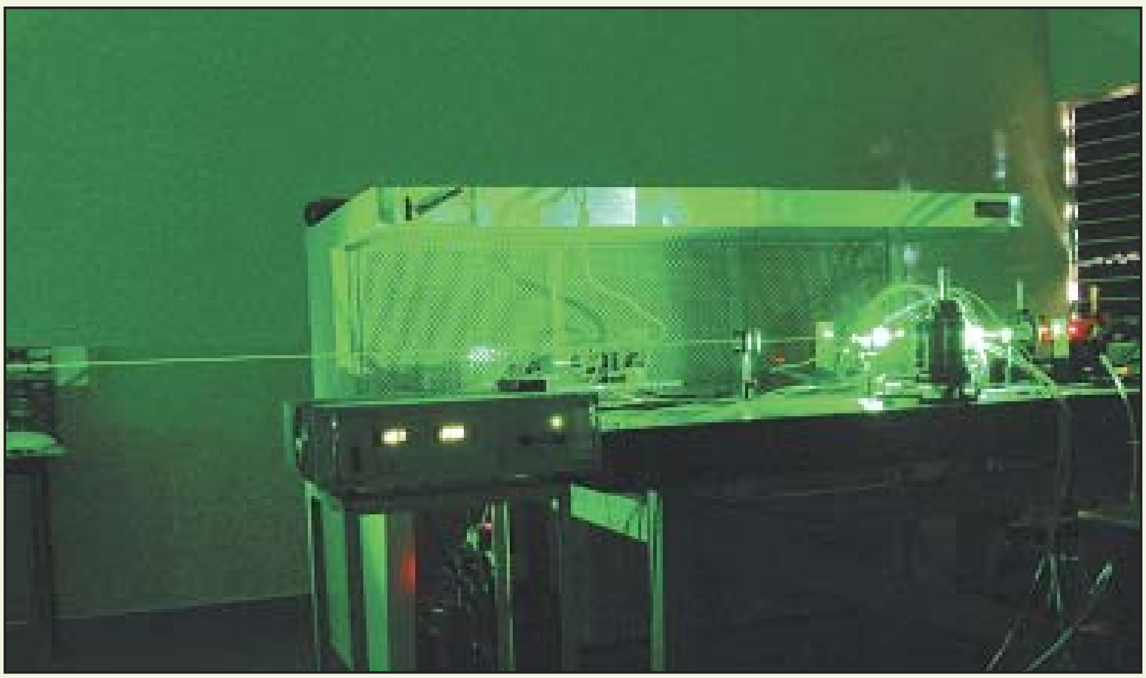
Various designs of diamond anvil cells (DAC) developed
(1. Modified Mao Bell DAC, 2. Miniature clamp type DAC, 3. Bassett DAC, 4. Modified Merrill Bassett DAC)

Materials Science

Link P8

Research on new and advanced materials has become a ‘technology push driven’ process rather than ‘market needs driven’ process. Semiconductors, metals, ceramics and polymers constitute the four corners of a ‘tetrahedron’that form the building block of materials science. The connecting edges and faces of this tetrahedron represent the various artificial solid/solid interfaces having novel properties. Such single interfaces, called hetero-junctions, and multiple interfaces, called multi-layers or super-lattices have interesting applications in materials science as well as in microelectronic devices. In these areas of technological interest, atomic scale changes can lead to very large changes in the macroscopic properties. Atomistic simulation plays a crucial role in designing new materials, that will cater to the need of our reactor, radiation detectors & sensors, laser, or semiconductor device oriented programmes. For static as well as dynamic simulation in nanometer length scale, the recent advances in the techniques of density functional electronic structure calculations have opened up new channels which were previously inaccessible to the condensed matter and materials science community. Starting from first principles local density calculations, it is now possible, for example, to (a) design alloys, such as transition metal aluminides, with desired strength-cum-ductility, (b) synthesize artificial multi-layers and super-lattices of metals, semiconductors and ceramics with tailored properties, (c) understand the novel cohesive, electronic and optical properties of clusters and nano-particles. Each of these areas have potential technological applications.

UV excited luminescence in some optical crystals



KTP crystal producing second harmonic of 1064 nm emission from YAG(Nd)

Materials Science

Materials are crucial to the nuclear programme. Hence work in this area has been intensely carried out from the very beginning. During the initial phase, the main emphasis was on developing a number of special materials including nuclear fuel, special alloy tubes to contain fuel pellets, moderators to slow down fission fast neutrons, neutron absorbers for controling the fission process, materials for detection of nuclear radiations and dose assessment etc. Consequently, development of preparatory methods and conditions for synthesizing materials exhibiting desired features (structure-property correlation) engaged much attention. Simultaneously, effects of radiations on these materials (radiation induced changes / damage) were determined. The expertise gained and the infrastructure created helped subsequent development of many different types of materials to keep pace with developments in such diverse fields as lasers, scintillators, superconductors, high temperature ceramics, radiation resistant glasses, polymers, nanoparticles, to name a few. They have been prepared in different forms viz. bulk (single crystals / polycrystalline), wire or thin / thick films.

Rapid advances in the understanding of the physical process and technology of bulk single crystal growth as well as thin / thick film deposition during the past forty years has led to development of several important technologies such as lasers, microelectronics, medical scanning/imaging, communication, automation, process control etc. To understand some fundamental properties of materials single crystals or films of newer materials and improved quality are always needed. Likewise, crystals of newer materials or those of the known materials but of improved quality, performance and sizes are key to development of newer applications or better technologies.

Performance characteristics of different crystal ingots of a given material prepared under more or less identical conditions are often found to show large variations. This fact can be attributed to a number of factors such as, (i) the technique and preparatory conditions employed, (ii) purity of the starting materials used, (iii) stoichiometric deviations, (iv) simultaneous presence of more than one phase etc. The formation of lattice defects which act as quenchers is mainly governed by the method of preparation and the preparatory conditions employed. While, a particular material may be prepared in a number of ways, the selection of the one that produces an end product of better crystalline purity is important. The lattice defects of concern here are the dislocations, precipitates, point defects, cracks etc. The presence of impurities in the lattice is invariably of serious concern. Very often the impurity levels do not have to be very large to give rise to frequently observed crystal coloration in optical crystals. The crystal coloration has a detrimental effect on the luminescent properties of the crystals. In the case of mixed oxide crystals, the constituent oxides may have quite different vapor pressures at the processing temperatures and consequently the composition of the grown crystal deviates from stoichiometry. The stoichiometric deviations are invariably detrimental to crystal property of interest. The situation gets further complicated if more than one phase are present in particular ingot.

Single Crystal Growth

Different technologies for growing single crystals by solution, melt and vapor deposition methods are being constantly developed at BARC and CAT. Besides, development of techniques for characterisation of major / minor fractions of the raw materials and crystal ingots alike, as also their structural and specific properties such as luminescence, scintillation, lasing, electrical, optical & non-linear optical properties has been an integral part of this activity. Essentially, crystals of materials required for detection of nuclear and infrared radiations, spectroscopy work and laser technology have been developed. In addition, single crystals of some high temperature superconductors viz. $YBa_2Cu_3O_x$, $Pb_{0.5}Sr_{2.5}Y_{0.5}Ca_{0.5}Cu_2O_y$ and $Bi_2Sr_2CaCu_2O_x$ have been grown for studies aimed at understanding basics of high T_c superconductivity. The technology for single crystals of alkali and alkaline earth halides (NaCl, KCl, KBr, LiF, CaF_2, BaF_2) and Ge up to a diameter of 50 mm for use as transmitting optical windows or scintillation detectors (NaI(Tl), CsI(Tl, Na), CaF_2(Eu), BaF_2) has been brought to the level where regular and reliable production can ensue. Technology for production of NaCl, KCl, KBr crystals up to 130 mm diameter has also been developed. The necessary crystal growth equipments for all the above activities were designed and developed in-house. Also, the crystals of $Bi_4Ge_3O_{12}$ up to 50 mm diameter and 70 mm length have been grown for use as heavy scintillators. Other heavy scintillators produced include materials like $CdWO_4$, $PbWO_4$ and $ZnWO_4$.

Crystals of $Y_3Al_5O_{12}$(Nd) have also been grown and used for the development of laser rods of diameters up to 6 mm and length of 60 mm. Laser crystals of $Gd_3Ga_3Sc_2O_{12}$(Nd, Cr) and Al_2O_3(Cr) have also been produced. Single crystals of $NH_4H_2PO_4$, KH_2PO_4 of sizes up to 60 x 60 x 200 mm and $LiNbO_3$ of 30 mm diameter and 45 mm long have been grown for the fabrication of second harmonic generators or electrooptic modulators. The other non-linear optical materials on which the work is being currently carried out are b-BaB_2O_4, $KTiOPO_4$, LiB_3O_5 and $Li_2B_4O_7$. These were grown by employing top seeded solution growth technique and the equipments required for this were developed in-house. Single crystals of pyroelectric $Pb_5Ge_3O_{11}$ and $(NH_2CH_2COOH)_3H_2SO_4$ have been grown for the development of energy / power meters for pulsed laser beams. Crystals of $PbMoO_4$ up to 40 mm diameter have been grown.

Significant contributions made in crystal growth and characterization

- Modified Bridgman Stockbarger technique.
- Development of a novel technique for the melt growth of alkali halide crystals up to130 mm diameter.
- Development of technology for the growth of scintillation grade NaI(Tl) crystals.
- Detection of minute amount of deviations from stoichiometry in optical crystals.
- The role of microstructure of the melt/solution in crystallization process.
- Origin of cracking in crystals.
- Energy transfer process in crystals.
- The effect of impurities on the growth and performance of crystals.

Neutron Transmutation Doping

Fabrication of silicon based devices requires crystals with excess electron conductivity (n-type). This can be achieved by controlled addition of phosphorous ions as dopants. Such n-type Si crystal were grown by Czochralski method from a melt that contained the required amount of the dopant concentration. Variation in dopant homogeneity in the CZ-crystals is about 200%. Such a crystal is suitable for fabrication of low power devices but not for high power applications. The requirement of uniform distribution of dopant in silicon is important only if a finished device has to operate at uniform current density. On the other hand, all the devices produced from the same ingot must have reproducibility. In order to overcome this dichotomy, the technique of neutron transmutation doping (NTD) of the float zone grown silicon crystal has been developed. Variation in dopant concentration observed here is less than 5%. The advantage of NTD technique is that the overall crystal defect density is very small and carrier life times are very large. Natural Si has three stable isotopes namely Si^{28}, Si^{29} and Si^{30}. Si^{28} has 92.2% abundance and low thermal neutron absorption cross-section. Si^{29} has 4.7% abundance, low thermal neutron absorption and produces stable Si^{30} isotope.

Si^{30} isotope has 3.1% abundance and on neutron absorption produces an unstable isotope Si^{31}. This decays into P^{31} by beta emission. P^{31} is a stable isotope of phosphorous and is the desired dopant in silicon crystals. The range of neutrons in silicon is very large. Therefore, irradiation produces crystal ingots of highly uniform dopant concentration.

CIRUS research reactor was used for NTD-Si investigations. In this regard, a detailed study concerning neutron fluence control, the radial and axial distribution of the thermal flux, nuclear heating of the ingot, induced radioactivity, radiation damage and thermal annealing of the irradiated ingot was carried out.

Accelerators Based Materials Research

The accelerators were originally built for basic nuclear physics research. Subsequently, however, their utility for developing newer materials of interest came to light. High-energy ion beams are proving to be very versatile tools for modification and engineering of materials properties besides providing powerful techniques for analysis of materials. Impact of energetic ions gives rise to displacement of lattice atoms from their equilibrium positions and the consequent defect production. Relaxation of these irradiated regions can result in non-equilibrium phases and structures that cannot be obtained using conventional thermal methods. Such materials have some interesting properties. The inherent non- equilibrium nature of the ion implantation process allows introduction of any atomic species in any matrix without being limited by solubility constraints. If the species thus introduced is insoluble, it precipitates out as nanoclusters under suitable annealing conditions. Further, ion irradiation of mutlilayers of thermally immiscible systems results in ion-induced intermixing leading to novel metastable phases including nano-scale granular structures. In addition to the process of implantation and irradiation, ion beams from an accelerator were also used for characterization of these materials using the techniques of Rutherford Backscattering Spectroscopy (RBS), Ion channeling, Particle Induced X-ray Emission (PIXE) and Neutron Activation Analysis. An accelerator based materials research program has been pursued using a 150 kV ion accelerator, a 400 kV ion implanter and a 2 MV tandem accelerator. Studies in the field of metallic glasses, hydrogen in metals and phase instabilities during irradiation were carried out Significant research contributions in this area include identification of solid argon bubbles, two dimensional argon clusters, effect of the dynamics of implanted hydrogen in metals, radiation induced amorphization and radiation induced segregation in alloys etc. PIXE technique was also used for determination of trace levels of toxic heavy elements in Cheyyar river in Kerala.

Thin Films

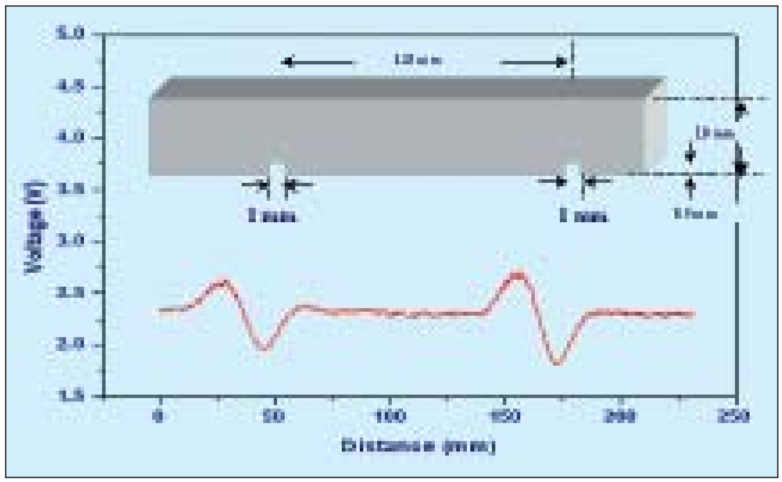
Thin films can exhibit significantly different properties due to small thickness, large surface to volume ratio and their physical structure. At times it is possible to modify properties of these films by controlling the growth process. Moreover, it is possible to obtain non-equilibrium metastable phases in thin films that would not be achieved in monolithic bulk material. This approach was used for a variety of applications ranging from gas sensors, semiconductor lasers, superconducting quantum interference device (SQUID), multiplayer coatings for optical applications, etc. SnO_2 film based sensors for the detection of hazardous H_2S and H_2 have been developed. Thin films of high temperature superconductors have been prepared by sputtering, laser ablation and molecular beam epitaxy (MBE) techniques. An important investigation carried out in this regard was the doping of films with silver. Films exhibiting critical current densities of the order 10^6 A cm^{-2} at 77K were produced. The effect of silver doping in thin films of 123 material, the deposition behaviors of individual constituents of 123 in both metallic and oxide forms by MBE has been studied. In thin films, the high T_c and CMR materials were juxtaposed together to study spin injection devices. Also, chemical vapor deposition of intermetallic and ceramic for coating purposes has been carried out. Some investigations carried out with thin films of different materials are summarised in the next Box.

Significant contributions made in production of thin films and their characterization

- Electrical properties of ultra thin TiO_2 films on SiC hetrolayers.
- Electrical properties of Ta_2O_5 films deposited on ZnO.
- Electrical properties and conduction mechanism in ultra thin ZrO_2 films on SiC hetrolayers.
- Structural, vibrational and phase transition studies of single crystal surfaces and thin epitaxial layers on surfaces employing X-ray Standing Wave technique.
- Epitaxial nanostructures of Ge and Ag on silicon surfaces. For Ag islands grown on n-type Si, single electron tunneling behavior has been observed.
- Ion-beam induced surface smoothing below ~ 50 nm length scale.
- Diffraction, standing wave, reflection and resonance enhancement experiments carried out on layered synthetic microstructures, thin polymer layers and epitaxial nanostructures using synchrotron X-radiation at HASYLAB, Germany.
- The growth of high quality lead titanate (an excellent ferroelectric) directly on silicon wafers for microelectronic applications.
- Thin films of bismuth ferrite that show simultaneous ferroelectric and magnetic properties.
- Laser ablated oriented thin films of MgZnO and Cd ZnO prepared and band gap variation was demonstrated.
- Pulsed laser deposition of crystalline thin films of high band gap semiconductors ZnSe and ZnO has been investigated. Considerable intermixing of ZnSe and GaAs at the interface has been inferred by exploiting several characterization techniques.

The work to develop SQUIDs based on Nb and $YBa_2Cu_3O_x$ superconductors has been pursued. A Josephson tunnel junction consists of two relatively thick superconducting electrodes (ex. niobium films, about 200nm thick) separated by an extremely thin tunnel barrier (ex. AlO_x, about 2nm thick). Josephson effect can be used to develop SQUID sensors, which have emerged as the world's most sensitive detectors of magnetic flux. A DC SQUID sensor consists of a closed loop of a superconductor interrupted by two Josephson junctions. Typical area of a SQUID loop is 100µm by 100µm while that of the Josephson junction is less than 5µm by 5µm. The device is made using micro-fabrication techniques similar to those used in the fabrication of large scale integrated circuits. A typical fabrication process involves 4 to 8 mask levels depending on the complexity of the device layout. The first high quality Josephson junction realized was of the type Nb/AlO_x/Nb and in the year 1995 this know-how led to the development of the DC SQUID sensor based on Nb and $YBa_2Cu_3O_x$ superconductors with characteristics comparable to the international benchmarks.

Low frequency SQUID sensor developed at IGCAR enables detection of defects that are difficult to detect using conventional eddy current techniques owing to skin depth limitations. The figure below shows the applicability of the SQUID to detect defects in a metallic sample.



Semiconductors

The initial emphasis of research on semiconductors was on development of large size silicon based discrete bipolar devices like rectifiers, thyristors and then of small scale integrated bipolar circuits and hybrid thin film circuits. An ambitious programme was initiated in the mid 1970's to design and fabricate NMOS and CMOS very large scale integrated circuits, to be in step with similar activity in the rest of the world. Several test chips were designed, fabricated and tested. Crucial in this effort was a detailed study of the MOS gate insulators and metal and polycrystalline silicon electrodes. Setting up of a microprocessor application laboratory, development of LSI mask layout software, use of process, device and circuit simulation software are some of the significant milestones in this work. More recently, silicon based MEMS development has been undertaken.

An important result in the area of semiconductors was the discovery of the importance of hydrogen dilution in the preparation of amorphous silicon hydrogenated alloys to enhance material stability. This is now the standard recipe used worldwide in the manufacture of hydrogenated amorphous silicon based devices. In studies with III-V compound semiconductor devices, the early emphasis was on material growth by Liquid Phase Epitaxy and defect spectroscopy using optical and electrical probes. This was followed in the mid- eighties by establishing Metal Organic Vapor Phase Epitaxy to grow and study low dimensional systems – with emphasis on strained quantum wells of systems based on GaAs, InP and their alloys and Al GaAs alloys. Consequently, a wide variety of lasers from 730 nm – 1600 nm were grown and processed at TIFR. A femtosecond laser laboratory was set up and ultra fast optoelectronic phenomena in semiconductor nanostructures like Quantum wells, wires and dots studied. Currently, research on semiconductors is broadly concentrated in development of opto-electronic materials and devices based on III-V compound semiconductors and organic semiconductors, optical and electrical spectroscopy, and study of ultra fast phenomena.

Using first-principles LMTO (linear muffin-tin orbital) method in supercell geometry, we have given a theoretical explanation for the orientation dependence of Schottky barrier heights in A- and B-type $NiSi_2$/Si(111), which was demonstrated, experimentally in Bell Laboratories. The same theoretical prescription was applied to explain the nature of chemical bonding in metal/oxide-ceramic interfaces e.g. MgO/Ag(100), as well as the geometry and band offset in insulator/semiconductor interface like CaF_2/Si(111). The supercell prescription has subsequently been utilized, in conjunction with a generalized version of "Force Theorem", to investigate the relative stability of hexagonal (nH, n=2,4,6,8) diamond polytypes (which can be looked upon as homo-interfaces). Detailed total energy calculations have revealed that these closely competing polytype structures can not be achieved as high pressure phases of the normal cubic diamond. In fact, 4H diamond polytype has been synthesized using low pressure route (viz. laser-induced reactive quenching at a liquid-solid interface), and its interband transitions have been found to agree with the XPS energy loss data.

More recently, work on dilute magnetic semiconductors that have generated tremendous interest due to their possible spintronics applications in magnetic recording, storage and sensor applications is being pursued. Nonmagnetic semiconductors, III-V, II-VI, as well as several oxides and perovskite families, when doped with 3d transition metal atoms, show half-metallic behavior and under appropriate conditions show ferromagnetism. GaN doped with 5% Mn is the first successful example that shows high Curie temperature (near or above room temperature). This system is therefore conceived as a promising candidate for room temperature semiconductor spintronics where one can exploit electron-spin as an added degree of freedom over and above its charge. First-principles density functional electronic structure investigation has been carried out on Wurtzite structured $Ga_{1-x}Mn_xN$, in order to establish that the magnetic moments localized at the Mn sites couple ferromagnetically with significant magnetic moment ~$3.5m_B$.

Nano Materials

Various technologically important properties can be substantially improved by reducing the particle size. For example, a number of normally unstable or metastable crystallographic phases can be stabilized using the nanoparticle route. Another example is the demonstration of improved light emission (photoluminescence), photoconductivity and non-linear optical properties using a nano composite of two different but structurally similar semiconductors and substantial enhancement of laser induced X-ray emission from metal surfaces at nanocrystalline surfaces. Other technological applications of the nanostructured materials are in the areas of sensors, catalysts, machinable ceramics and coatings. Exotic properties of nanostructured materials arise because of two fundamental differences with respect to the bulk. First, presence of large fraction of atoms on grain boundaries modifies mechanical properties of the nanophase materials. Second, absence of lattice periodicity beyond the nano-grain of a few nm size leads to confinement of charge carriers and phonons within the nanoparticles. Confinement of these elementary excitations results in dramatic changes in the optical and vibrational properties. To realize the enormous potential of nano materials technology, it is essential to obtain a detailed understanding of the behavior of different classes of applicable materials when the system size is reduced to 5 - 50 nanometers. Thus, the smallest possible size of a ferroelectric memory element, below which it ceases to show ferroelectric property, has been determined. This is very important since the next generation of computer memories is expected to be based on ferroelectrics. In analogy with the quantum mechanical problem of particle in a box, confinement of electrons and holes within a semiconductor nanoparticle of a few nm size results in discrete energy levels both in the conduction and valence bands. The resulting increase in the band gap depends on the particle size. This idea has been exploited to achieve band-gap engineering by playing around with particle size. A blue shift of the absorption edge, arising from the increased band gap, is observed for selenium nanoparticles. In the case of metal nanoclusters dispersed in insulating hosts, surface plasmons are found to cause absorption in the visible range, the width of plasmon resonance being related to the size of the nanoparticles. In direct gap semiconductors such as cadmium sulfide, photoluminescence arising from radiative transition is also found to show a blue shift. The confinement of electrons and holes within a small region of space can also increase the probability of radiative recombination, resulting in more efficient optical processes. Several fold increase in the photoluminescence efficiency has been found both in selenium and cadmium sulfide. These results point to the potential applications of nanostructured semiconductors as efficient radiation detectors. Similar to the confinement of charge carriers, phonons are also confined within the nanoparticle. This restriction on the spatial extent of the phonon, via a relationship of the uncertainty type, results in a spread in the wave vector of the zone center optical phonons leading to broadening of the Raman line shape. Phonons with large dispersion possibly exhibit more broadening. For example, in wurtzite crystals polar phonons have much more dispersion than the nonpolar phonons. This indeed has been found for phonons of different symmetries in nanocrystalline zinc oxide.

A number of innovative techniques for synthesis of nanomaterial such as, vacuum thermal decomposition, microemulsion-mediated reactions, sol-gel process, rapid liquid dehydration, high pressure sputtering, etc. have been worked out. The nanostructured materials suitable for applications in liquid chromatography and as alcohol sensors have been grown. The processing details of a high-grade yttrium iron garnet material for microwave and lead zirconate titanate for piezoelectric transducer applications were worked out. Besides, nanocrystalline selenium, ceramic oxides and metal nanoclusters have been prepared. Control over precipitation rate of elemental selenium in a viscous polymer solution was achieved by changing its viscosity by adding/removing the solvent. This method results in 3-4 nm selenium particles dispersed in polyacrylamide host. The synthesis of nanocrystalline oxides is achieved through the programmed vacuum thermal decompositions of corresponding carbonates and nitrates. Here, the final temperature of the programmed heating is selected just above the decomposition temperature to yield oxide nanoparticles.

Other Materials

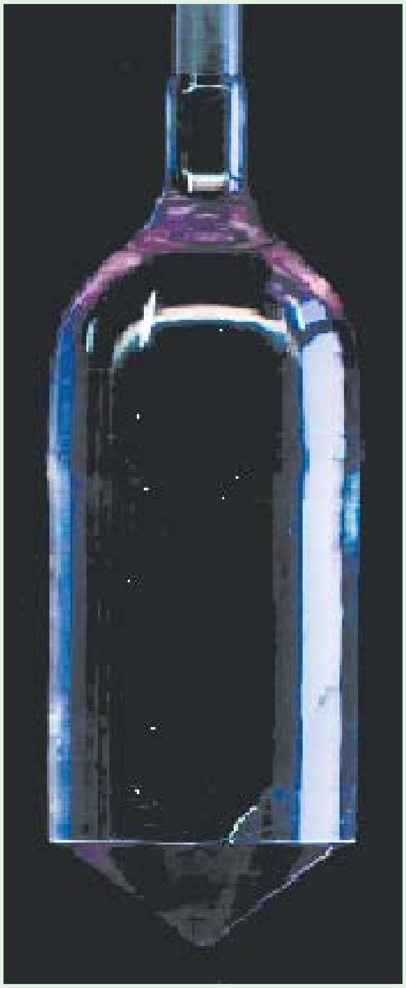
Processing and characterisation of many materials categorised as the structural materials, nuclear fuels and functional materials has been an important activity and being pursued over long period of time. Some of the work carried out is listed in the next Box.

1.7MV Tandetron accelerator along with the ion irradiation and ion beam analysis experimental setup installed at 10 degree beam line for materials research

Significant achievements in the field of materials

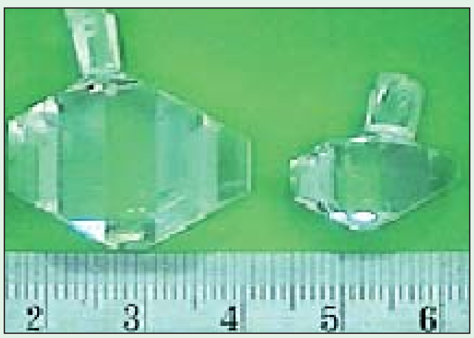
- Characterization of high temperature fracture behavior of nuclear structural materials.
- Compatibility study of mixed carbide fuel with SS-316 clad tube at high temperatures.
- Preparation and characterization of borosilicate glass for nuclear waste immobilization. Structural aspects of mixed oxide glasses, zirconium based metallic glasses and nanocrystalline materials.
- Development of different ceramics viz. Zirconia Based Nano Ceramics, Ferroelectric Ceramics, Dysprosium Titanate Based Ceramics, Zirconia Ceramics, Gadolinium Aluminate based ceramic, Magnesium Aluminum Silicate Machinable Glass-Ceramic, Silicon Carbide Ceramics, Bioceramics for Reconstructive Orthopaedic Surgery.
- Microstructural characterization and mechanical property evaluation of aged Alloy 625.
- Hydride induced embrittlement of zirconium alloy pressure tubes.
- Diffusion of hydrogen through thin walled SS-316 tubes.
- Multi-scale material modeling in fracture.
- A model for fracture of disordered materials.
- Studies on high temperature and surface properties of iron aluminide intermetallic.
- Computer Simulation of the Early Stages of ordering transformation in alloys.
- Ordering transformations and microstructural evolution in Ni-V Alloys.
- Stress corrosion cracking of zircaloys in iodine vapor.
- Corrosion evaluation of an Extremely Corrosion Resistant Alloy.
- Effects of hydrogen on the corrosion behavior of a Duplex stainless steel under slow strain rate test condition.
- Inter-comparison of irradiation growth behavior of annealed seamless and seam welded zircaloy-2 calandria tubes.
- Heat shrinkable sleeves and other components of Ni-Ti shape memory alloys.
- Stainless Steel Based Shape Memory Alloys.
- Beryllium metal and BeO manufacturing technology.
- Metallurgical investigation of aluminium clad of Dhruva fuel.
- Development of molecular magnets.
- Investigations on thermoelectric materials.

Systems for the single crystal growth of fluoride materials under high vacuum conditions

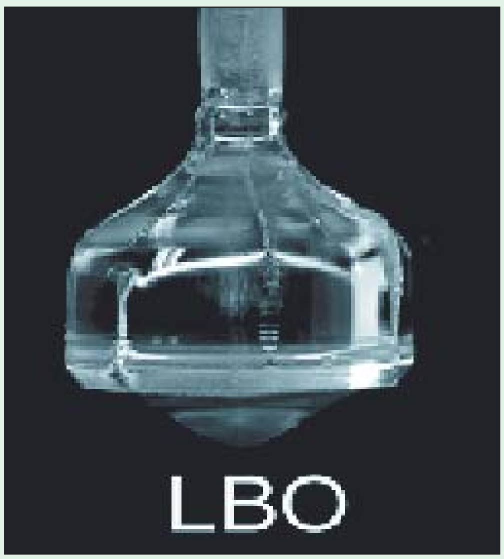


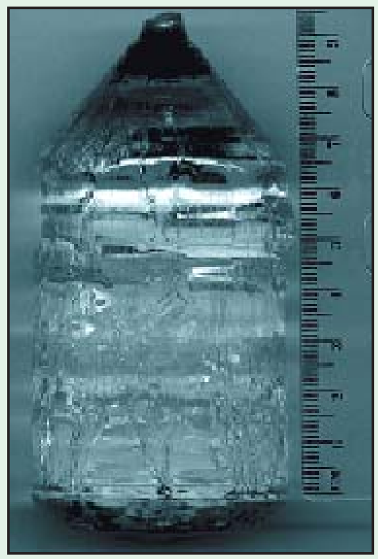
Nd:YAG crystal boule

↑**ZWO**



KTP ↑





BGO ↑

Single crystals of different materials developed for the detection of nuclear radiations or laser technology

Theoretical Physics

Link P9

The research in theoretical physics started as a support provider for the main mandate of DAE, which is the development of atomic energy for various national needs. However, as often happens, the activities in one area catalyze interest and growth in many related areas. The story of the growth of different kinds of theoretical activities in DAE is no different. Such a diversification, however, is in tune with the wider mandate of DAE, which is to develop new technologies and promote basic sciences. Thus, whereas the nuclear reactor related work led to research in the transport theory and the numerical methods (see link-P3), the search for more powerful mathematical methods for various purposes led to the trail of Feynman path integrals. The need to harness nuclear fusion energy has been responsible for our interest in the areas of plasma physics and fluid dynamics (see link-P5). The availability of neutron beams from experimental nuclear reactors established groups devoted to the study of material property by neutron scattering (see link-P7). Those groups subsequently made important contributions even to fundamental aspects of quantum mechanics involving, what is called, the geometric phase of a quantum mechanical wave function.

$T \sim a^{3/2}$ (Kepler's 3rd law)

Newtonian

$F = d(mv)/dt$

$F = G\, m_1\, m_2 / r^2$

$F = (1/r^2) \exp(-\, r / r_o)$ ← nuclear force

$F = q\,(E + v \times B)$ ← Lorentz force law

Maxwell's Equations

$\nabla . E = \rho / \varepsilon_o$

$\nabla . B = 0$

$\nabla \times E = -\,\partial B / \partial t$

$c^2\, \nabla \times B = j / \varepsilon_o + \partial E / \partial t$

Bohr → $m\, v\, r = n\, h / 2\pi$

$E = m\, c^2$ (Einstein)

$\lambda = h / mv$ ← de Broglie

$m = m_o / \sqrt{1 - v^2 / c^2}$ [Relativistic]

Heisenberg → $\Delta t\, .\, \Delta E \geq h \backslash 2\pi$ & $\Delta x\, .\, \Delta p \geq h \backslash 2\pi$

$ih/2\pi\; \partial\psi / \partial t = -\; h^2/2m\; \nabla^2 \psi + V(r,t)\, \psi$ ← Schrödinger

Theoretical Physics

Feynman Path Integrals

Our intuition tells us that, under a given force, a material particle will follow a definite path or trajectory. That indeed is the prediction of the theory founded by Newton, which is referred to as the 'classical theory'. It provides a way of finding a particle's trajectory when all the forces are known. However, certain experimental observations in the microscopic world, during late nineteenth and early twentieth century could not be adequately explained on the basis of tenets of Newtonian mechanics and with it of statistical mechanics. To resolve this problem a new theory, the quantum theory, was propounded. This introduced some counter-intuitive ideas. One of them being that, under the influence of a given force, a particle need not follow a definite path. Rather, at the subatomic level if the same task is repeated for the same particle under the influence of the same force, the results of different experiments are not necessarily the same and, therefore, it is more mean-ingful to talk of averages, instead of outcome of individual trials.Quantum theory aims at predicting only the average outcomes of, in principle, infinitely many experiments all performed under the same conditions. It is like predicting the outcome of results of tossing a coin: If an unloaded coin is tossed several times, we cannot predict whether the result of a particular toss will be the appearance of its head or its tail. However, we can say that, under a very large number of trials, half of the times the result will be tails and on the other half of occasions it will be heads. In general, the probabilistic nature of outcome of statistical events is described by a probability distribution function, which only tells the probability of occurrence of a particular event. In quantum theory the probability distribution is to be obtained from what is called the wave function of the system. A wave function is an abstract entity that represents averages of experimental observations.

Feynman related the abstract wave function with a classical observable, the particle trajectories. He considered a particle traveling from one point to another under a given force. Classical theory ascribes a definite path or trajectory joining those points on which the particle is predicted to move. In contrast, quantum theory does not associate any definite trajectory with the motion of the particle. Feynman postulated that the particle can follow with equal probability any trajectory joining the two points. He gave a prescription relating the quantum mechanical wave function with an integral of a function over all paths joining the two points. That relation has come to be known as the Feynman path integral. The method of Feynman path integral, though intuitively appealing, is mathematically hard to carry. Theoretical work in the area of Feynman path integrals is concerned with analytically evaluating challenging problems as exactly as possible.

Quantum Optics

The microscopic theory of interaction of electromagnetic (e.m.) radiation, like light, with atoms and molecules has been of fundamental importance in the development of foundations of physics as well as in numerous applications. For example, on the one hand, it was instrumental in laying foundations of the quantum theory which revolutionized physical sciences. On the other hand, it led to development of lasers whose revolutionary impact on technological progress is there for all to see. Since developing lasers and their applications to evolve new technologies contitutes an integral part of the nuclear program it is necessary to understand the microscopic theory of interaction of the electromagnetic radiation with atoms and molecules.

Quantum Optics deals with these microscopic aspects. It is being applied also in the technologically important area of interaction of the e.m. radiation with quantum dots and quantum wells. In quantum optics, light is treated, not as a wave as in the classical theory of radiation, but as a quantized entity. A familiar consequence of quantization of radiation is the concept of photon. It states that the e.m. radiation is a collection of indivisible quanta called photons. It is ironical that despite having *given birth to the quantum theory, the need for this concept of quantisation of light is still a matter of debate! Alternative theories have been advanced to do away with the need for quantization of light. Though the two theories may make identical predictions in some situations, it is the situations where they make dramatically different predictions, which warrant experimental scrutiny. Unfortunately, conditions required for such testing situations are generally so difficult to achieve that a realistic experiment always leaves room for ambiguities in interpretation of the results. Nevertheless, the need for quantizing light is generally an accepted fact. Some major problems of interest in quantum optics are as follows and the important contributions made are summarized in the next Box.*

(i) Search for such effects, which cannot be explained without quantization of light. Some effects which are of common interest are squeezing, anti-bunching, sub-Poissonian photon number distribution, collapse and revival of oscillations of an electron between two bound states in an atom in a high-Q cavity (that is a cavity in which the rate of loss of the electromagnetic field is very small as compared with the rate at which energy is exchanged between the field and the atoms) and so on. The problems that are encountered in this regard are of proposing new schemes which give rise to one or more quantum properties. The contributions made have been mainly related to interaction of atoms with the electromagnetic field in a high-Q cavity.

(ii) Like in the problems concerning collectively dissipating systems, finding analytical solutions of quantum optical equations is often mathematically challenging. Several problems involving cooperative dissipation in free space or in a cavity have been solved. New models for realizing quantum effects in wave-mixing in a cavity have been proposed. Whereas some of those solutions have been instrumental in providing new insight in to the respective phenomena, others have provided new approaches to solving equations occurring in quantum optics.

(iii) The question of identifying truly quantum effects is not limited to the electromagnetic field alone. It concerns other systems as well. For example, though the issue of what characterizes a truly quantum behavior of the electromagnetic field is settled, it is still debatable for several other systems. The focus of attention in this regard has been two-state systems like a collection of spin-1/2s and the two-level atoms.

(iv) The concept of coherent states of the electromagnetic field has been of importance in quantum mechanical formalism. An issue of interest has been the extension of that concept to other systems.

(v) The quantum optical systems provide means of implementing the operations for realizing quantum computing and quantum information processing.

Dissipation

(i) An exact equation for the density matrix of a system of harmonic oscillators interacting with a bath of oscillators was derived and solved. The exact equation provides a rare insight into how irreversibility arises from reversible equations.

(ii) The master equation for the density matrix of a system of N two-level atoms dissipating collectively into the environment while being driven continuously by a monochromatic laser (in other words, the problem of resonance fluorescence from N two-level atoms) was solved exactly for its steady state.

(iii) The analytically exact steady state solution of the master equation to describe the statistical properties of atoms and of the radiation from a collection of N two-level atoms driven by a monochromatic laser while dissipating in to a broad-band squeezed reservoir has been derived.

(iv) Analytical solution of the master equation for an atom interacting with the field inside a high-Q dissipating cavity.

(v) Non-cooperative interaction is not a necessary condition for observing the optical bistability. It was shown to occur involving only collective interaction between atoms and the field if the dipole interaction between the atoms and their detuning with the applied field is taken into account.

Study of quantum effects in cavity quantum electrodynamics

(i) An experiment involving nature of oscillations between two levels of an atom traversing a single-mode high-Q cavity was proposed to look for the signature of quantization of light. It emerged that the oscillations will be sinusoidal if the field is not quantized but would exhibit the phenomenon of collapses and revivals if the field is quantized. The significance of the proposed experiment lies in the fact that it can distinguish the nature of light on the basis of only qualitative features of time evolution of a particular observable.

(ii) A model system exhibiting quantum interference effects between two channels of transitions between two atomic levels leading to wave mixing in a cavity was introduced and solved analytically exactly. The model involved Raman transitions between atomic levels.

(iii) It was shown that quantum resonances in the four-wave mixing susceptibility are exhibited only if the field is quantized. However, peaks corresponding to quantum resonances are suppressed in the tail of other peaks, which is expected even when the cavity field is not quantized. The quantum peaks show up only when some other dissipation mechanism, like collisions of the atom under observation with other atoms is taken into account. Like the Bloombergen resonances in free space, the collisions have also been found to give rise to some additional resonances even in four-wave mixing in a cavity. Those additional resonances have no relationship with the atomic transitions. Similar findings were reported for the process of six-wave mixing in a cavity.

(iv) First ever studies of wave-mixing in an atom in a laser-cooled trap were initiated.

Micromaser (a phenomenon in cavity quantum electrodynamics)

(i) A complete study of the stroboscopic theory of micromaser in a high-Q cavity under the condition of regular pumping was undertaken in collaboration with the University of Essen.

(ii) The first complete study of the theory of micromaser for arbitrary pumping statistics and arbitrary efficiency of the detectors used for finding the state in which an atom exits the cavity.

Theoretical formalism of quantum optics

(i) Extension of the concept of coherent states of the electromagnetic field to other systems, such as the two-level systems, has been carried using one or the other of the three defining properties of those states of the e.m. field. Whereas those three defining properties are equivalent in the case of the e.m. field, they generally lead to different results when applied to other systems. A definition of coherent states, which incorporates all the three defining characteristics of the e.m. field coherent states was proposed.

(ii) A definition of squeezing in terms of the quantum error in the process of measurement has been proposed.

(iii) The Bell's inequality provides a sufficient, but not necessary, condition for identifying non-classical states (the states possessing properties which can not be explained in terms of classical probability theory) of two two-level atoms. That inequality has been used to show that any pure entangled state of a system of two two-level atoms is non-classical. The issue of characterizing non-classical states of even two two-level atoms in a mixed state has been largely unresolved. A necessary and sufficient condition to identify whether a given state, pure or mixed, of a system of N two-level atoms is non-classical has been formulated.

Classical and Quantum Chaos

Once the initial position and velocity of a particle is specified, Newton's laws determine its trajectory uniquely. One expects that if the initial position and the velocity of the particle is changed by a small amount then the trajectory will also change by a small amount. However, it is found that under certain conditions, a small change in the initial position and/or the velocity of the particle makes the new trajectory depart from the older one by an amount which is exponential in time (that is to say the separation between the old and the new trajectory varies as a^{kt} where t is the time, a is greater than one and k is positive). Imagine such a situation for a particle in a bounded region, say, in a box and let the initial condition be only slightly uncertain. Since, under the given situation, a small uncertainty in the initial condition leads to trajectories exponentially separated in time and the particle has only a finite region to move in, it can do so by visiting every part of the region. Such a motion is termed chaotic. Conditions under which chaotic motion occurs and the properties of such motion are of immense interest in many disciplines of science. In fact, the interest in such type of motion owes its origin to studies of atmospheric changes in relation to weather forecast.

The above description of chaos is about a classical motion. The question is: Is there anything in a quantum mechanically described motion that is similar to classical chaos? That question arises because the description of chaos, as given above, is in terms of trajectories whereas, as stated before, there is no concept of a trajectory in quantum theory. The problem of quantum chaos is to identify distinguishing characteristics of the quantum motion under conditions in which corresponding classical motion is chaotic.

There are mainly two approaches to investigating this problem of quantum chaos. One is the so-called semi classical method and the other is the method of random matrices. The semi classical approach seeks to look for distinguishing features in the quantum motion. In this method, the concept of trajectories is incorporated in the quantum theory in an approximate way.

The random matrix approach is based on certain observations about statistical properties of the allowed energies of a quantum system when the corresponding classical system is chaotic. For, remember that we are talking about chaos in a system. Though, according to classical theory, the possible values of energy of a system constrained to move in a finite region, are distributed continuously, the allowed values of its energy in the quantum description are spaced discretely. The quantity of interest in the theory of random matrices is the set of numbers constituted by the difference between neighboring energy values. It is observed that those numbers are distributed randomly if the corresponding classical motion is chaotic. The distribution function of those numbers, which gives the number of times any number is repeated in the given set, is also known and is found to be related with certain symmetry properties of the system. It is found that the distribution function is the same as that of the spacing between nearest eigenvalues of a matrix, called a random matrix, having random numbers as its elements such that the matrix has the same symmetry properties as the dynamical system. Why is there such a relationship between the distribution of the spacings between the eigenvalues of a random matrix and that of the spacings between the allowed energies of a quantum dynamical system, which is classically chaotic, is still an open question.

The problems in quantum chaos involve identifying new characteristics of quantum motion which are classically chaotic, and studying the semi classical motion or the statistical properties of the allowed energies of specific systems. Those studies require heavy computation. The theory group in BARC has been involved in the study of chaos by both the above mentioned methods. Some important contributions of the work in BARC in this regard is outlined in Box below.

Work carried out on classical and quantum chaos

1. The concept of determining approximate quantum energy levels using classical information owes its origin to Niels Bohr. While the Hydrogen atom could be quantized using his semi classical recipe, the Helium atom posed a problem. It is now known that the existence of chaos proves to be a stumbling block in the semi classical quantization of Helium. Over the last 35 years, semi classical quantization methods have been developed with the help of this new understanding and the main ingredient of this theory are the classical periodic orbits - invariants that live for ever.

A semi classical quantization method was developed that uses arbitrary classical trajectories rather than the periodic orbits which are hard to compute. It has been used to determine the quantum energy levels and eigen functions of a particle in 2-dimensional enclosures of various shapes. In certain cases, this is the only semi classical method that works successfully.

2. While the volume of the accessible classical phase space determines the number of quantum levels to a lowest order approximation, classical periodic orbits provide the first correction.

It has been shown that degeneracies in the action of periodic orbits can give rise to statistical properties of the quantum levels that do not necessarily reflect the nature of the underlying dynamics contrary to the then existing picture of universality classes.

3.We were amongst the first to study the statistical properties of classical periodic orbits and showed that the fluctuations in the classical length spectrum of periodic orbits are connected to the quantum eigenvalues.

4. A model of a spatially extended system consisting of chaotic elements interacting with their neighbors above a threshold (trigger) was developed and has been successfully used since to design logic gates and eventually a chaos-assisted computer.

5. A model of non-linearly interacting spins exhibiting chaos in its classical description and its quantum eigen value spectrum exhibiting statistical properties same as those of one or the other of the three universality classes of the random matrices under different conditions on the interaction has been developed.

Infrared Spectroscopy of Solid Hydrogen

Solid hydrogen and its isotopic varieties typify the simplest molecular quantum crystals and present unique opportunities for the study of lattice dynamics and intermolecular interactions in the condensed phase. The special appeal of solid hydrogen (H_2 and its isotopic species) to spectroscopists stems from the fact that the gas phase property of quantized molecular rotation persists in the solid down to 0° K, with little change. Also, the spectral line width in the crystalline phase is significantly narrower than the Doppler-limited gas phase spectral line width. This is a direct consequence of the extreme weakness of anisotropic intermolecular forces, on the one hand, and the small moments of inertia of the molecules, on the other. The extremely weak intermolecular forces are the result of a near spherical molecular charge distribution and the relatively large nearest neighbor distances (~3.8 Å) in the solid at not too high pressures.

Because of the symmetry requirements on the total wave function, including the nuclear spin, homonuclear diatomic molecules such as H_2 and D_2, exist in two quasi-metastable ortho and para modifications, which in many experiments can be regarded as distinct, stable molecular forms. The ortho-H_2 modification refers to molecules with total nuclear spin angular momentum quantum number T=1 and rotational angular momentum quantum number J odd (the so called "antisymmetric" levels), and para-H_2 to T=0 and J even (the "symmetric" levels). On the other hand, ortho-D_2 corresponds to T=0 or T=2 and J even, while para-D_2 to T=1 and J odd. At low temperatures at which solid samples have to be necessarily studied, only the J=0 and J=1 levels are appreciably occupied and the solid can be regarded as a mixture of molecules in the spherically symmetric J=0 and the flattened or elongated J=1 states. Since techniques have been developed which make possible experimentation on H_2 and D_2 solids with any desired ortho-para concentration ratio, these solids offer unique opportunity to study the anisotropic interactions and molecular orientation phenomena. The HD molecule is, of course, heteronuclear and hence there is no para or ortho modification of HD. All the molecules in solid HD are normally in the J=0 state.The homonuclear molecules like H_2 and D_2 do not have a permanent dipole moment and therefore pure rotational and vibrational electric dipole transitions in the free state are symmetry forbidden. However, these molecules exhibit an infrared spectrum in the condensed phase, which arises from the electric dipole moments induced by the multipolar interactions among the molecules. Since the spectrum results from the multipole field-induced dipole moment which is the property of a pair of molecules, not only transitions due to single molecules but also simultaneous transitions of individual molecules in a H_2 pair upon absorption of one photon, are observed. Also, the induced dipole moments, among other things, depend on the order of the multipolar induction as well as on the intermolecular separation. As the intermolecular separations are constantly being modulated by lattice vibrations, it is natural to expect lattice modes to get coupled to the inner vibrational excitations in the individual molecules.

Infrared absorption of solid hydrogen typically consists of two parts: relatively sharp features, termed as "zero-phonon lines," each accompanied by broad absorption contours on the higher frequency side, called "phonon branches." The sharp lines are interpreted to be transitions among the levels associated with the internal degrees of freedom of one molecule (single transitions) or at least a pair of molecules (double and triple transitions) without any phonons being involved in the process. The accompanying broad bands represent combination tones in which the absorption of a single photon excites an internal transition in one or more than one molecule with the simultaneous creation of phonons in the crystal. Some major contributions to this field are summarised in the next Box.

To obtain intensity expressions for single transitions in solid hydrogen, one needs to obtain the total moment induced by a molecule in the entire crystal, through its multipolar field. Similarly, in case of double transitions one first considers intensity due to a pair of molecules and subsequently the total intensity is obtained by summing over the entire lattice. As a result, intensity expressions for single and double transitions involve specific kinds of lattice sums. Crystals of solid hydrogen, both of pure species and of ortho-para mixtures, have invariably a close-packed structure in which each molecule is surrounded by twelve molecules at an equal distance R_0 from the central molecule. There are two different close-packed structures, *viz.,* the hexagonal closed packed (*hcp*) structure and the face centered cubic (*fcc*) structure. Solid hydrogen exists in the *hcp* structure at relatively higher temperature (T>4 K) whereas it exists in *fcc* structure at lower temperatures (T < 4K). The required lattice sums for both the crystal structures were computed.

Contributions to understanding of infrared spectrum of solid hydrogen

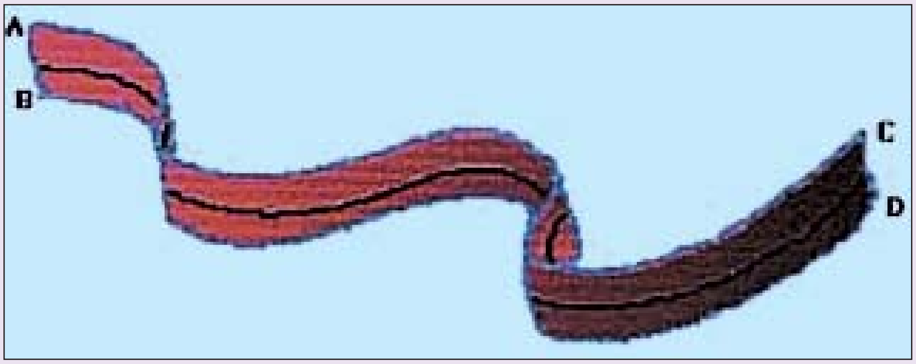
- Derivation of general and special expressions for the integrated absorption coefficients of all types of zero-phonon single and double transitions in solid H_2.
- Derivation of theoretical expressions for the integrated absorption coefficient of various zero-phonon single and double transitions in heteronuclear isotopic variants of hydrogen in condensed phase.
- Prediction of a new kind of double transition in the spectra of solid HD, HT and DT, where the rotational energy of one molecule changes by three quanta and the rotational energy of another molecule simultaneously changes by at least three quanta. Derivation of expressions for the integrated absorption coefficients of various zero-phonon double transitions involving homonuclear-heteronuclear pair of hydrogen molecules (H_2–HD, D_2–HD pairs, etc) in condensed phase.
- Calculation of theoretical intensity hinges on the knowledge of the ro vibrational matrix elements of the multipole moments, and of polarizabilities. ro vibrational matrix elements of the multipole moments up to rank 11, and of polarizabilities for all isotopic variants of hydrogen molecule calculated from first principle.

Mathematics

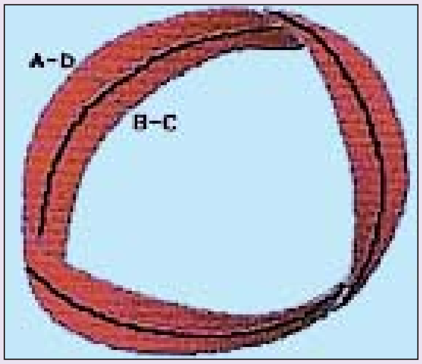
Link P10

Most physical laws are expressed in the form of quantitative mathematical relationships between some physical properties. Often physicists make models to understand nature. Any model is primarily meant to quantitatively interrelate various properties and thus arrive at laws that govern natural phenomena. In this way theoretical physics gets linked to mathematics to pave way for comprehending things around us. To fully master methods of theoretical physics, skills in mathematical knowledge are an advantage.

Topologist's twist !



Strip with edges



Twisted to form Möbious band without any edge between two sides

$e^{i\theta}$ = Cos θ + Sin θ ←Relates algebra to geometry

{ $e^{i\pi} + 1 = 0$ this relates the five fundamental constants of mathematics }

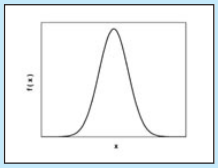
Number theorists delight !

Fermat's last theorem, found in his notes written circa 1637, without proof but with a claim to the proof. It was finally proved in 1994. It states that if n is an integer greater than or equal to three, then the equation

$$x^n + y^n = z^n$$

cannot be satisfied for integral values of x, y and z

Can we do without a Gaussian (normal) distribution ……… ?



$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-x^2 / 2\sigma^2)$$

mean = 0,

variance = σ^2

Mathematics

It is well-known that mathematics plays an important role in the development of science. Physical lawa are represented in terms of various equations. Mathematics helps in finding right solutions for these. There is also another crucial role of mathematics in science, which is not as well recognized by the wider community. Mathematics in its abstract form provides a basic framework in which scientific truths can be conceived, formulated and analyzed far more effectively. Concepts such as numbers, roots, primes etc. in arithmetic, length, area, angles etc. in geometry, which we now take for granted, are mathematical creations from another era. It is intriguing to note that it was only a few hundred years ago that such profound techniques as calculus and coordinate geometry, which are now so vital to the scientific culture, were created.

The subject of mathematics has continued to develop in recent centuries, creating a variety of new concepts, understanding their inter-relationships in the form of various theorems, developing new techniques by which more mathematical truths can be discovered. Many of these have found important applications in sciences as well as in other human endeavors, while alongside the pursuit of mathematics in its purest form as a quest for mathematical truths continues with vigor.

The School of Mathematics at TIFR has made several advances, contributing in a major way to the worldwide progress in various branches of mathematics. Applied and applicable areas of mathematics were developed at the Ban-galore Centre, set up in collaboration with the Indian Institute of Science. Other institutions of the DAE, especially the Institute of Mathematical Sciences (IMSc), Chennai, and Harish-Chandra Research Institute (HRI), Allahabad, have also developed as mathematical centres of international standing. The areas of mathematics pursued at our Institutes, with high levels of expertise, cover a broad spectrum in the contemporary international mathematical scene. They include Algebra, Algebraic Geometry, Number Theory, Topology, Differential Geometry, Lie Groups, Differential Equations, Harmonic Analysis, Functional Analysis, Mathematical Physics, Combinatorial mathematics and other related areas.

Algebra

The usual operations of addition, multiplication of numbers etc., that we are all familiar with, form the basis of Algebra. At an advanced level however one is not talking of the usual numbers alone, but also of more general abstract entities, equipped with operations which correspond to the above usual ones, and satisfy similar laws: groups, rings, modules, ideals, fields, vector spaces, algebras, are some of the basic objects in contemporary algebra. The theorems about these structures have, at a foundational level, to do with solving a variety of equations in unknown variables, or in some instances concluding non-solvability. However, many important theorems in the area primarily seek to explore the properties of the structures, which in turn would improve our overall understanding of the issues involved.

In the sub-area known as commutative algebra, work was done at TIFR in the study of singularities of algebraic equations and interrelations with affine geometry. Study of what are called projective modules has seen vigorous activity, inspired by a conjecture of Jean-Pierre Serre and its resolution by Quillen and Suslin in the early seventies; the developments have implications to questions on the so called complete intersections (relating to minimizing the number of equations needed in certain contexts), efficiently generating ideals in commutative rings etc. Many algebraists at TIFR have contributed to the progress on the topic. A conjecture of Forster on the number of defining equations of curves, and a conjecture of Bass on existence of unimodular elements in projective modules were established.

A counterexample to a quadratic analogue of Serre's conjecture was found at TIFR. This led to a new area of research on quadratic spaces and new insights into some classical questions on division algebras and connections between the structure of quadratic spaces and the geometry of varieties over various fields. Brauer groups and Galois cohomology are some of the invariants on which important results were obtained.

Groups, which constitute one of the simplest algebraic objects, play a role in a wide variety of contexts. Apart from the standard groups of numbers the notion encompasses models for symmetries of an object, either physical or abstract (like those of an equation). In recent years work is being done at HRI on some problems in the theory of groups and group rings.

Algebraic Geometry

Just as the circle, ellipse, parabola etc. in a plane can be thought of via algebraic equations, more intricate geometrical forms can be conceived in terms of more elaborate algebraic structures. This is the general scheme of Algebraic Geometry. The geometrical forms involved need not be 'visual' figures in two or three dimensions, or even their analogues in higher dimensional Euclidean spaces, but can be primarily conceptual, not admitting a realization in the Euclidean spaces in general. Various concepts in Algebraic Geometry, such as the vector bundles, play a fundamental role in the formulation of various principles in theoretical physics. In recent decades Algebraic geometry is being used in various applied problems, such as pattern recognition.

Since the early years of the School of Mathematics at TIFR, Algebraic Geometry has been a major area of pursuit, involving the largest number of members in the School. Foundations for the study of the moduli of vector bundles over curves were laid at the School. The construction and study of vector bundle moduli and moduli spaces over a variety of geometric objects, deformations of moduli, development of new techniques to deal with various questions in the area, etc. has held the TIFR group at the forefront of research in this topic. In recent years this topic is also pursued at HRI, and interesting contributions have been made.

Fundamental work was done at TIFR in the study of actions of algebraic groups on projective varieties, known as Geometric invariant theory. The theory of 'standard monomials' developed at TIFR in the seventies for the study of Schubert varieties and linear systems turned out to be very fruitful. In a remarkable development a notion called Frobenius splitting came to be introduced at TIFR, which together with the observation that homogeneous varieties are Frobenius split, solved several outstanding questions in the area. The study of Schubert varieties, which lies at the cross-roads between geometry, representation theory and combinatorics, is also pursued at IMSc, where recently a conjecture of Kreiman and Lakshmibai was settled, paving the way for further progress in the topic.

A class of objects called Abelian varieties have proved to be of much significance, both from geometrical and arithmetic standpoint. David Mumford had developed a theory of theta functions providing an algebraic approach to studying linear systems on abelian varieties. These ideas were pursued by algebraic geometers at TIFR, extending Mumford's theory, and establishing various interesting results.

Study of properties of algebraic surfaces has been another major activity at TIFR. A well-known conjecture of C.T.C. Wall was proved and various generalizations were obtained. A problem of Zariski on the dimension of certain complete linear systems on a smooth projective surface was also another highlight. Pursuit of various other problems in that area yielded rich dividends.

One of the outstanding open question in algebraic geometry concerns understanding of singularities, of algebro-geometric forms called varieties. (A simple case of singularity in a geometrical form can be seen in the shape of a leaf, at its tip or the point where it is connected to the stem). Desingularisation, classification of singularities into different types, are some of the crucial features of the theory. Algebraic geometers at TIFR have evinced keen interest in the topic and made several important contributions clarifying various points. Study of algebraic cycles on varieties is another fundamental topics in Algebraic Geometry. This involves what is known as algebraic K-theory. Study of Chow groups, construction of Gysin maps, settling various cases of a conjecture of Hodge, which has provided a direction to the topic, are some of the highlights of the work at TIFR on this topic.

There is also a vast area of Algebraic Geometry having interplay with questions in Number theory, especially Diophantine equations. This area is extensively pursued at IMSc, and deep results have been obtained in the theory.

Algebraic Geometry is an area with a direct interface with several areas outside the domain of pure mathematics. The area has a vibrant interaction with theoretical physics, especially string theory. The direction is pursued by some algebraic geometers at IMSc and TIFR. An algebro-geometric viewpoint opens up new possibilities in cryptosystems. Some recent research at IMSc has led to a more algorithmic formulation of some basic objects in algebraic geometry, enhancing the scope in this direction. The area is also being pursued at HRI.

Number theory

Properties of numbers have fascinated humankind since times immemorial. Certain simple notions in number theory like prime numbers and composite numbers continue to be of great importance both from a theoretical standpoint, as well as applications in cryptosystems etc. Several simple-looking questions, such as whether every even number can be written as a sum of two primes (Goldbach conjecture is that this is possible) have puzzled generations of number theorists. Another statement known as Fermat's last theorem, concerning powers of integers, was settled only in the year 1994 by Andrew Wiles using elliptical functions, after two and half centuries of its original formulation.

Number theorists at our institutions have been keenly pursuing various problems in number theory. A long-standing problem known as Waring problem, about writing each natural number as a sum of powers, was settled in a collaboration involving IMSc, continuing from some of the work done earlier at TIFR.

A function called the Riemann zeta function, and a conjecture about the set of points where it vanishes, called the Riemann hypothesis, play an important role in the study of primes numbers. The study of the zeta function has been pursued at TIFR since its early years, and is also pursued at IMSc over a long time. State of the art results concerning the zeros of the functions have come out of these efforts, all along.

The general theory concerning solutions of equations in integers is known as the theory of Diophantine equations. Sometimes, when there are no integer solutions, there is interest in 'approximate' solutions and the theory concerning these is known as Diophantine approximation. Along with solutions in integers, in certain problems there is also interest finding solutions, which are prime numbers. Number theorists at TIFR have made important contributions on many questions involving these themes. The theory of linear forms in logarithms is also a related theory on which sustained development has taken place at TIFR. Visibility of lattice points is a related topic on which some interesting results have been obtained by our number theorists at IMSc and HRI. Important work is also done at our Institutes on recursive sequences, transcendental numbers, exponential sums etc.

The topics in Number theory indicated above fall under what is known as Analytic Number Theory. Number theory also has many other major branches, distinctive in the questions addressed (though at the core they all concern properties of numbers) and techniques applied. Modular forms and automorphic forms are some notions, which played a very important role in twentieth century mathematics, and continue to be of immense interest. Several number theorists at TIFR and HRI have contributed to the development of the area, and there is a strong group, which continues to pursue it.

Algebraic Number Theory is another important branch of Number theory. There is a long-standing conjecture and a general program proposed by Langlands, relating algebraic number theory to representation theory, which has been a driving force in the area. Pursuing the topic our mathematicians have proved several interesting theorems on various aspects of the theory.

Topology

Topology is often nicknamed as 'rubber sheet geometry'. Familiar physical objects, like cups, balls or doughnuts, if they were made of (very elastic) rubber can be transformed by stretching or compressing the parts, but without tearing or pinching anywhere, into forms which would appear quote different from the original (a doughnut can be turned into a cup and vice versa!). The new forms nevertheless retain something of the original, and the objects cannot be changed to another one at will; some things for instance may be more 'knotted' than others. Understanding the principles involved in this, in a mathematical setup, is the subject of Topology. An elaborate paraphernalia has developed especially over the last century to get a grasp of various phenomena that can occur. While some themes rely upon extended intuition, others involve associating to topological spaces, objects from algebra, analysis etc. to grasp the topological features.

Considerable work was done at TIFR on various themes in topology on three-dimensional manifolds and also various other topics such as the study of intersection homology. Recently, at IMSc results have been obtained on the algebraic topological invariants associated with certain spaces with rich geometric properties, known as toric varieties.

Differential Geometry

While Algebraic Geometry pursues the quest of understanding geometrical forms via an algebraic framework, which corresponds at a basic level to understanding structures through polynomial equations, Differential Geometry draws upon the ideas of Calculus to pursue geometry. The underlying frameworks for the study of geometry have to be correspondingly different. A differentiable manifold is a basic object formulated for the purpose, which at an intuitive level corresponds to surfaces and higher dimensional analogues, equipped with intrinsic sense of directions and directional derivatives at its points. Analogues of the idea of distance in the usual Euclidean geometry are also introduced, in terms of what is called a Riemannian metric, which in turn gives rise to the notion analogous to straight lines (geodesics), planes, curvature etc. The study of differentiable manifolds with various additional structures, and various operators like the Laplacian operators associated with them, has proved to be of fundamental importance from an intrinsic mathematical point of view as also physical and engineering applications.

The work carried out at TIFR on the so called Index theorems stands out in the area. Work was also done at TIFR on various other themes in the area, including study of the heat kernel, combinatorial study of Pontriagin classes, Einstein-Hermitian connections, harmonic maps, construction and study of new geometric invariants etc.

Lie Groups

A class of groups introduced by Sophus Lie in 1873, and known after him as Lie groups, have proved to be very influential in many branches of mathematics as well as in physics. Though conceived originally as a tool for studying symmetries of differential equations, they have acquired an independent stature of their own, as fundamental objects modeling geometry and group structure together in a harmonious way. Just as geometry is pursued through algebraic or differential calculus techniques, Lie groups have analogues called algebraic groups, studied using techniques of algebraic geometry. While the original Lie groups are modeled over real numbers, and are 'continuous' in a visual sense, in recent decades there has also been a lot of interest, on account of applications in Number theory etc., in their analogues modeled over what are called non-Archimedean fields, which are highly disconnected. Along with Lie groups interest lies also in understanding their subgroups. A class of subgroups often arise from an 'arithmetic' structure, like the subgroup of integers in the group of real numbers, and are of special interest.

Lie groups and arithmetic subgroups, and more general discrete subgroups, has been subject of much research at TIFR, with path-breaking results. A major part of the work on what is known as the congruence subgroup problem came from the TIFR school. Important results were also obtained on rigidity, arithmeticity, and other geometric and group theoretic properties of discrete subgroups of Lie groups as well as algebraic groups.

Lie groups have a natural interplay with Geometry. The theory of Lie groups was also applied at TIFR to prove various results of geometrical significance. Recently, the notion of a "dynamical type" of transformations of the geometries was introduced at HRI, and interesting consequences were deduced.

Various properties about the structure of Lie groups were also proved at TIFR. It turns out that a crucial way to understand a group is to understand its 'representations'. Proof of a conjecture of Langlands on concrete realization of discrete series representations was one of the major highlights of the early years. This led to sustained work and valuable results on geometric as well as intrinsic questions in the theory.

Associated to a Lie group there is also a more algebraic object called the Lie algebra and the representations of these are crucial to the study of the subject. This leads to interesting objects such as Kac-Moody algebras, toroidal algebras, quantum groups, and significant contributions have been made at TIFR to this theme. Recently, this theme is also being pursued at HRI. A long-standing conjecture of Parthasarathy, Ranga Rao, and Varadarajan was proved, at TIFR, leading to further progress in the area. Significant progress was also made towards proving a conjecture of Kazhdan and Lusztig. Representation theory has also been studied at TIFR over fields of positive characteristic.

Dynamics, Ergodic Theory, Probability

There are various models adopted in the study of dynamics, a common one being to consider a 'space' equipped with suitable structures like topology, geometry etc., together with a transformation of the space, and understand what happens after large number of iterations of the transformation. Depending on the transformation (which may be viewed as a physical rule at a micro level) the asymptotic behavior (which corresponds to macro manifestations) can differ quite dramatically. Various concepts like ergodicity, mixing etc. are known to distinguish various kinds of asymptotic behavior. In the place of discrete time model as above, continuous time models are also considered.

The study of Lie groups and their homogeneous spaces at TIFR led naturally to study of dynamics on these spaces. Formulation of certain conjectures on the behavior of a class of flows called unipotent flows, and the initial work on it at TIFR, has been the basis of some landmark progress in the area, to which members of TIFR have also continued to contribute on a major scale. This approach and the work done at TIFR have had remarkable consequences to certain long-standing problems in Number theory.

Various other dynamical systems were also studied at TIFR from ergodic theoretic and dynamical point of view, and the results were applied in Geometry, Lie groups theory, Number theory etc. A class of multi-parameter symbolic systems were also studied at TIFR, and a conjecture of Kitchens and Schmidt was established in part, and disproved in general.

Dynamics can also be thought of in terms of 'random' transformations, the classical example being of a drunkard's walk. Here the movement is not governed by a physical rule, but can be analyzed in terms of probabilistic laws, such as going in different directions being equally probable at any given instant. This point of view calls for a study of iterates of random transformations, associated to probability measures on groups. The theme is pursued at TIFR since the mid-eighties, and important results are obtained on the problem of embeddability of infinitely divisible probability measures, decay of concentration functions, the central limit problem, Levy's measures etc..

Differential Equations

A differential equation is an interrelation involving an unknown function, say on a domain in a Euclidean space, and the rate at which it changes in various directions; e.g. equation of motion of a particle in a force field; in this example, and also in many contexts, one of the coordinates represents time. Differential equations arise naturally in a variety of contexts, in sciences such as physics, astrophysics, biology, chemistry, as well as in social sciences such as economics, sociology etc. which makes the theory a crucial part of applied/applicable mathematics. The task then is to get an understanding of the function, from the interrelation. While in some cases it may be possible to solve the equation and determine the desired function in an explicit form, very often this is not the case, especially for what are called Nonlinear differential equations. The aim then is to try to get as much information as possible, on the behavior of the function, numerical estimations etc. Differential equations are considered also on manifolds (surfaces and their higher dimensional analogues).

The area is being pursued at TIFR since the mid-seventies when a special programme was started in collaboration with the Indian Institute of Science, at Bangalore, to promote applicable mathematics. Infusion of modern techniques in the addressing various questions in the area, via systematic efforts, was one of the main aims of the programme.

The TIFR group at Bangalore, which has also spread over the years to TIFR Mumbai and IMSc, has made important contributions in the area of Nonlinear differential equations, via application of modern methods of functional analysis. Homogenisation of eigenvalue problems, controllability and long term behavior of vibrations of thin elastic structures like shells and rods, application of finite element techniques in the study of various equations, have been some of the major themes in which important contributions have been made. A conjecture of J.~Smoller on breaking of symmetry was established by combining techniques of bifurcation analysis with knowledge from Morse index theory, and counterexample was given to a conjecture of St. Venant in elasticity theory. There has also been considerable work on hyperbolic equations and conservation laws.

For differential equations on manifolds, the effect of the geometry of the manifold on the so called critical Sobolev exponent was investigated, and a conjecture of Lin and Ni on the existence of positive solutions was established at TIFR Bangalore. Problems in the spirit of 'isoperimetric problems', like the classical fact that for a fixed perimeter the disc has maximum area, were addressed at IMSc and interesting results were proved.

A longstanding paradox in atmospheric sciences, called the Ramdas paradox, on the minimum temperature occurring slightly above the ground, was resolved at TIFR Bangalore.

Analysis (other areas)

As a branch of mathematics Analysis is an area, which in a general sense is an outgrowth from Calculus, though in some of the later avatars the roots in Calculus are almost irrecognisable; (in this context, the use of the term Analysis is not in the general sense of analyzing). Just as the subject of Algebra has a lot more than solving equations, Analysis has a lot more than understanding equations involving Calculus, viz. Differential equations, though the latter is indeed a part of Analysis. There is a whole variety of branches of Analysis, depending on the nature of techniques, and historical branching off of thematic pursuits, etc. Real analysis, complex analysis, harmonic analysis, functional analysis, operator theory, probability theory etc.

Significant work was carried out at TIFR over the years in many branches of Analysis. Extensive work has been carried out at IMSc on Operator algebras, relating specifically to what are called sub-factors, a notion introduced by Vaughan Jones. A finite list of numerical invariants to characterize Hopf algebras is a major highlight of the work. Work is being done in Harmonic Analysis at HRI, relating to the Heisenberg groups.

Mathematical Physics

As we mentioned earlier, various branches of mathematics have close connections with physics. The extensive studies in Algebraic Geometry at TIFR led also to work on topics in mathematical physics. Notable contributions were made in the study of quantum field theory, gauge fields, and connections between Jones-Witten theory and the theory of moduli of vector bundles. In some recent work on mathematical quantum mechanics at IMSc, new uncertainty relations for entropies of observables were obtained and a connection of the theory with the Riemannian hypothesis in Number theory was noted.

Discrete Mathematics

There is considerable interest, in our computer age, in a variety of structures on finite sets. The broad area is termed as Discrete mathematics. Finite geometries, designs, graphs, coding, are some basic mathematical objects of interest in computer science, electronics and communication theory. The area has been pursued at TIFR since the seventies. Embedding problems, proof of a conjecture of Ryser on the so called lambda-designs, classification of graphs with eigenvalue at least -2, construction of optimal unidirectional codes, algorithmic generation of large designs, a protocol for full duplex communication in high-speed network, are some of the highlights of the work. An improved bound was given for the diameter of a hypercubic network, used in parallel processing.

Logic and Concurrency

The research carried out has made some of the earliest contributions and demarcated the technical issues involved. The central understanding, emerging from this work, that global specifications typically lead to undecidability in the context of partial order based models, and that local (structural) specifications lead to decidable logics, is an important contribution in the area. Subsequent work has followed up on this understanding with specific proposals for local specifications and technical results on them using temporal logic and using automata theory. The axiomatization and decomposition theorems obtained here are among the few such results in this area.

While logics of action, time and knowledge have been separately well studied, the interaction between these notions makes for many theoretical difficulties. The work carried out here combines techniques from different areas (knowledge theory and concurrency theory) to offer suggestions as to how these difficulties may be managed. In the process, the class of transition systems identified here has found applications in areas like foundations of game theory. The work on control synthesis has made significant contributions to the study of sequential and distributed controllers, and in particular, has characterized the class of architectures with decidable synthesis problems.

The work on generalizing automata theory to series-parallel posets shows that techniques for string and tree languages can be combined without too much difficulty to work for languages of series-parallel posets. The hard part of combining this "hierarchical" structure with communication remains.

The work on the broad question of when fixed point logics capture complexity classes was carried out. This leads to a finer understanding of certain issues in descriptive complexity, especially in the use of generalized quantifiers as a descriptive mechanism.

Algorithms and Data Structures

Efficient algorithms have been given for the Vertex Cover and MaxSat problems, respectively. These are significant for the following reasons. The work on Vertex Cover was the first to break the 2^k bottleneck to determine whether a given graph on *n* vertices has a vertex cover of size *k*. The algorithm takes $O(\{1.324718\}^k k^2 + nk)$ time improving on the earlier bound of $O(2^k n)$ time. This triggered further similar work on this problem and other NP-complete problems like MaxSat. The current best bound for Vertex Cover stands at $O(\{1.271\}^k + nk)$.

The work done on the maximization version of MaxSat as well as the question of whether at least *k* clauses of the given formula can be satisfied, for a given *k* gives the current best bounds.

A succinct representation for binary trees has been applied to get improved space efficient representation for general Planar graphs, and Suffix trees, the popular indexing structure, and for *k*-ary trees.

In addition, the work on parameterized complexity of finding hereditary properties, succinct dynamic binary trees representation and the parameterizing complexity of MaxSat and MaxCut above the guarantee deal with new and crucial issues in some of the classical problems, which will find many interesting applications.

It has been shown that a simple heuristic based on growing BFS trees can solve a generalized (vertex) partitioning problem almost surely over random instances. Even very special cases of this partitioning problem include well-known NP-complete problems like *k*-coloring, finding a good bisection, etc. Similarly, a simple greedy heuristic has been shown to almost surely find a constant factor approximation to the maximum size induced acyclic subgraph of a given digraph. In the worst case, this problem is not approximable within a ratio of O(ne) for some constant e >0. These results add further evidence to the general trend where several combinatorial problems which are "very hard" to solve with respect to the worst-case measure are solvable in polynomial time by simple heuristics on typical (random) instances.

Computational Complexity

The work on exploring determinants and matchings is a significant and cohesive body of work. Combinatorial techniques have been used to develop elegant new algorithms for computing determinants and pfaffians, to analyze existing algebra-based algorithms for these problems, extract combinatorial insights, and to use properties of the new algorithms in constructing matchings in large classes of graphs. Part of the significance lies in the fact that the underlying problems (notably computing determinants) are fundamental and are very well-studied in the literature; yet this work contributes new knowledge to the understanding of these problems.

The research on reductions to sparse sets and p-selective sets is a significant contribution to the area. In particular, a question on p-selective that was open for several years was solved and this spurred subsequent research.

The work on derandomization and resource-bounded measures presents the first derandomization result for AM based on a hardness assumption, by extending the Nisan-Wigderson result. This was followed up with subsequent research on derandomizing AM. The derandomization result to answer questions in resource-bounded measures has been applied.

The research in learning theory, where an enhanced version of Angluin's exact learning model was introduced, is a novel contribution as it provides a "complexity-theoretic" classification of concept classes according to their exact learnability. The work on the lowness of group-theoretic problems for hard counting classes gives a rich collection of natural examples for the counting classes SPP and LWPP.

Seismology

Link P11

Seismology deals mainly with study of earth's vibrations caused by earthquakes. However, with the advent of nuclear weapon testing around the middle of the twentieth century, seismology acquired a new dimension. It was found extremely useful in monitorring, locating and identifying these tests. With this began the era of modern seismology, which required precise recording of various seismic waves, their analysis and interpretation of the recorded data. Application of advanced methods of signal detection, acquisition, communication, analysis and interpretation methods used in many strategic applications like radar and sonar and allied fields found their way to seismology. That is why modern seismology deals with many of the frontier areas of research in communications, computer science, instrumentation, signal processing methods, numerical modeling methods and imaging, in routine and real- time seismic monitoring systems. Array seismology was one of the off shoots of this development, where interplay of all these fields exists and is still regarded as powerful tool to police small and big nuclear tests. The interest of DAE in seismology has not only been with regard to monitoring the nuclear tests but also in carrying out the site selection for the nuclear installations.

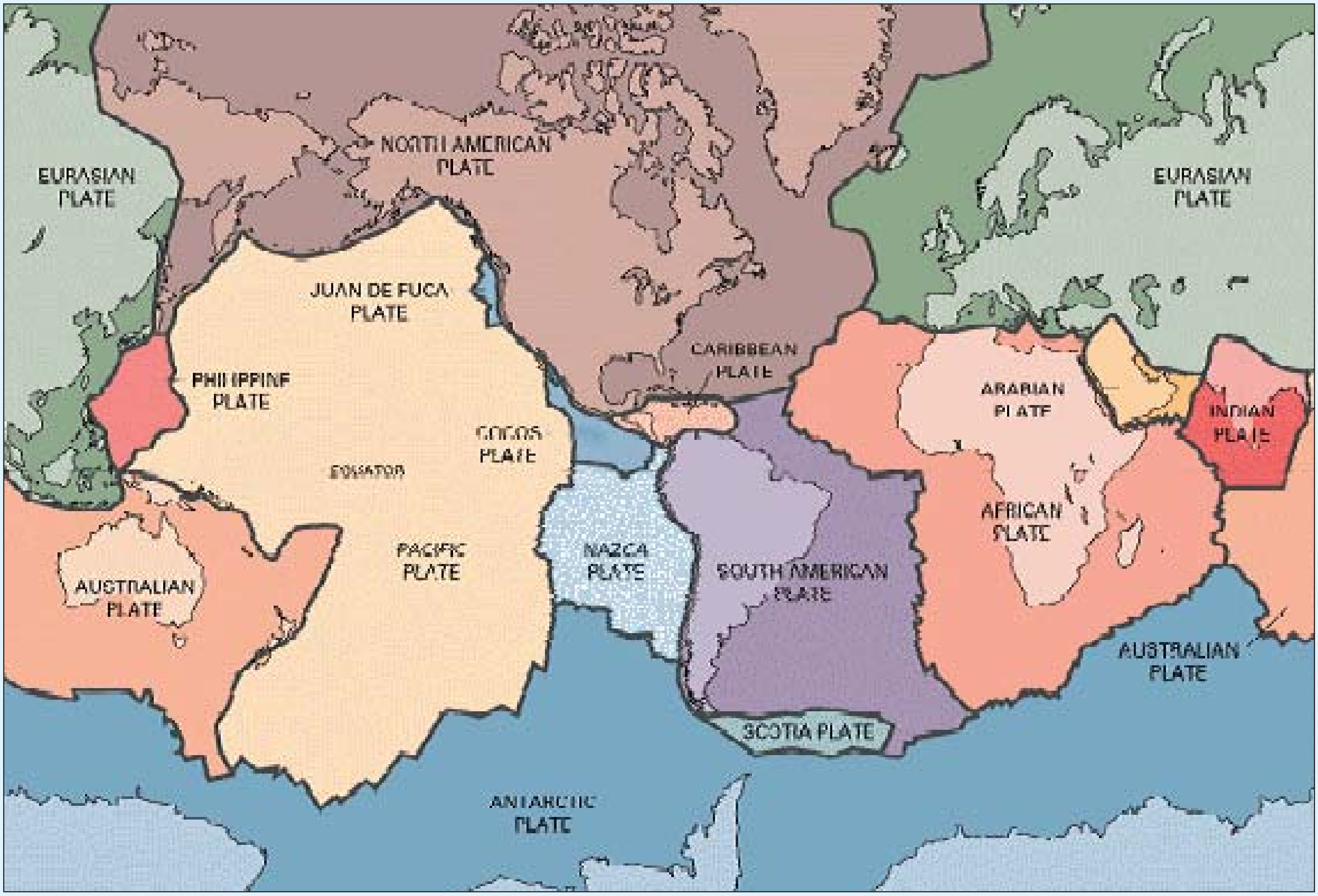


Plate techtonics

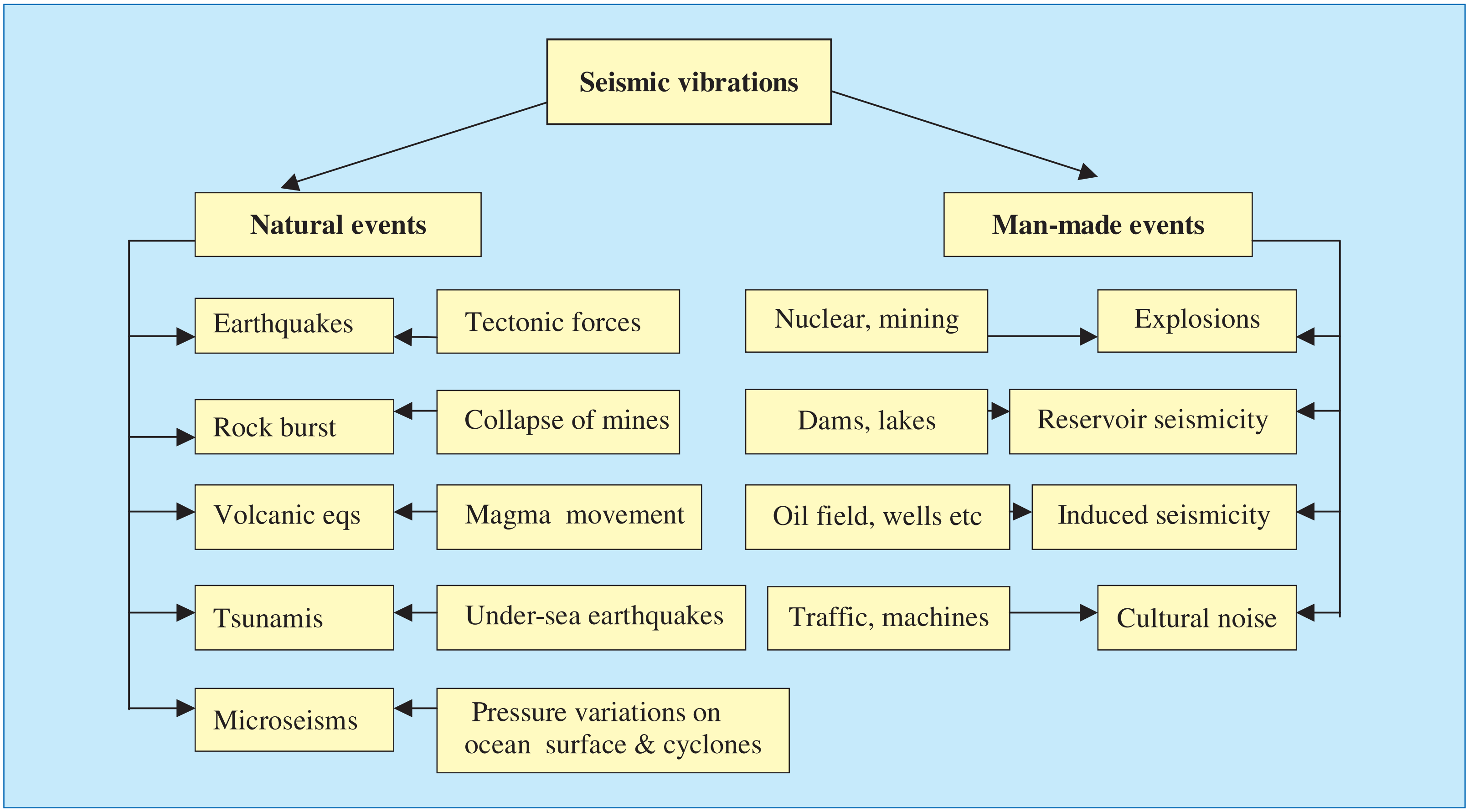
Seismology

A sudden movement or fracturing within the earth's lithosphere, followed by the series of shocks generated by this movement is known as earthquake. The point at which the earthquake originates is known as the seismic focus or hypocenter and the point on the earth surface directly above this is the epicenter. Seismology is the branch of geophysics concerned with the study of earthquakes. The understanding of the causes of earthquakes and modeling the structure of earth and physical processes, which generate earthquakes, form the major part of seismology. A common model of the earth is described as consisting of three main parts, the crust, the mantle and the core. The crust together with the solid outer parts of the mantle down to a depth of about 100 km forms the lithosphere. Below the lithosphere is the astheno-sphere, a region of relatively low strength. The theory of plate tectonics propounds that the earth's lithospheric layer is broken into mainly a dozen or so large and small fragments called plates (as shown in the adjoining figure), which move relative to each other with an average speed of a few centimeters per year due to convection process at depth. The differential motion between these plates is the cause of earthquake activity, which is mostly confined along the plate boundaries. Earthquakes result from a build-up of these stresses within the rocks until they are strained to the point beyond which they will fracture.

An earthquake generates three major kinds of seismic waves viz. compressional (P), shear (S) and surface waves. P and S waves together are called body waves because they can travel through the body of the earth unlike the surface waves, which propagate along the surface of the earth. The particle motion for the P waves coincide with the direction of wave propagation as is the case with ordinary sound waves. For the shear waves, the particle motion is at right angles to the direction of wave propagation. The P wave velocity is about 1.7 times of the S wave velocity which means that the P waves will appear before the S waves in seismic records. Surface waves are mainly of two types. One of the wave type is characterized by a retrograde, elliptical particle motion in a vertical plane coinciding with the direction of wave propagation, called the Rayleigh waves. The other kind of surface wave, called Love wave, has particle motion perpendicular to the direction of wave propagation. The love waves are the result of the horizontal stratification of the crust. Surface waves travel slower than P and S waves therefore they appear after S waves in seismic records. Another kind of seismic wave that propagates in a crustal wave guide in the continental lithosphere is known as Lg or the surface shear wave whose energy departing downwards is wholly reflected back into the crust. The radiation pattern of Lg waves is more isotropic than that of P and S waves.

The measure of the total energy released by an earthquake is called its magnitude. As there are different modes of generation and propagation of seismic waves, several magnitude scales were developed depending on the type of wave and the distance at which it is observed. Generally magnitude is proportional to the logarithm of energy and hence it is proportional to the logarithm of the signal amplitude. Among various magnitude scales, the prevalently used magnitudes are namely body magnitude, surface wave magnitude and moment magnitude and local magnitude widely known as Richter magnitude.

The sources of seismic vibrations can be classified into two categories viz. natural sources and man-made sources. The details of different types of seismic events are given below in the flow chart. When a strong earthquake occurs it gives rise to seismic waves, which causes the shaking we feel. Seismic waves lose much of their energy while traveling over large distances. However, sensitive detectors such as seismometers can respond to the waves emitted by even the smallest earthquakes or man-made events generating ground vibrations of the order of few nanometers. When these detectors are connected to a system that produces a permanent recording, they are called seismographs.



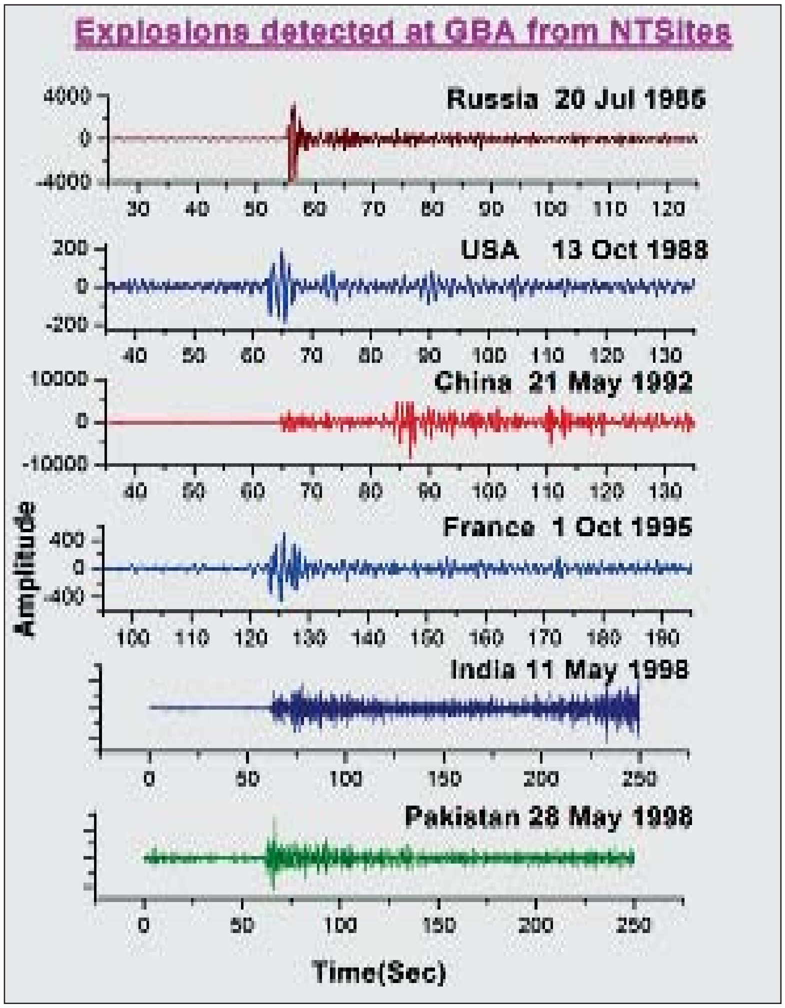
There are various types of seismometers, but they are all based on the fundamental principle that the differential motion between a free mass (which tends to remain at rest) and a supporting structure fixed to the ground (which moves with the vibrating earth) can be used to record seismic waves. Modern seismograph stations can record seismic waves in orthogonal directions, one for vertical ground motion and other two for East-West and North-South components. Besides three component instruments, clocks are an important part of a seismograph system. Modern seismographs use broad band seismometers with bandwidths 300s/30s to 0.02s and using a high dynamic range digital system with 24 bit resolution to acquire the data by computers and computer networks. The transmission of the data from field to local data center and communication between data centers are done through digital telemetry using wireless links, dialup lines and VSAT links. The olden day clocks have made the way for the modern day GPS timing systems.

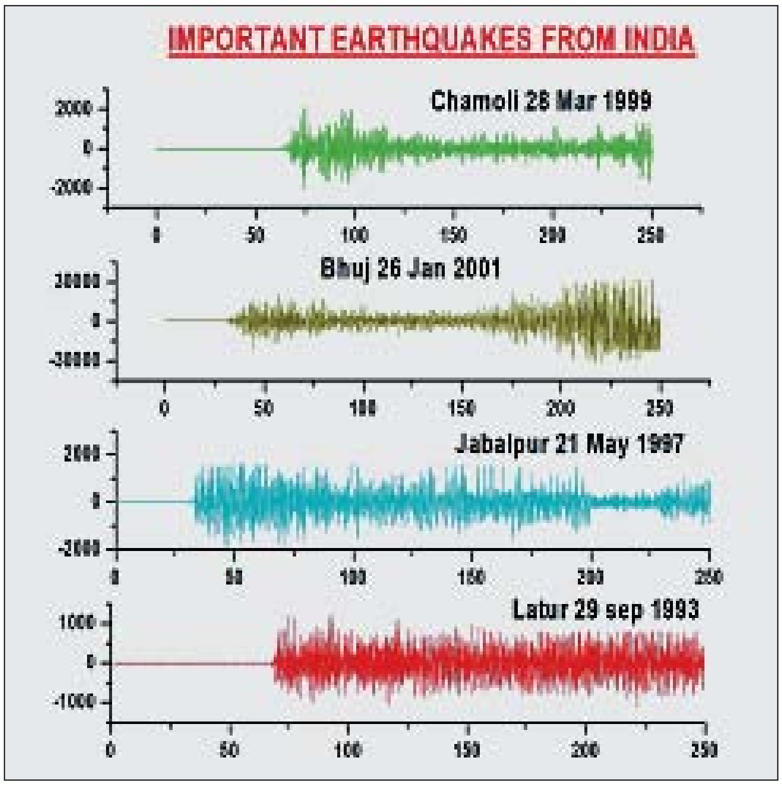
Seismological research carried out in DAE may be broadly classified into (i) theoretical seismology and (ii) computational seismology. The research work pertaining to theoretical seismology includes; elastic wave propagation studies in irregular boundaries; study of wave propagation in medium with non-welded contacts; attenuation and dispersion of Stonely waves; reflection, transmission and attenuation of elastic waves at loosely bonded interface of elastic half spaces; generation of synthetic seismograms; and microscopic model of a fracture to describe an earthquake process. In the field of computational seismology, various state of the art techniques have been developed and used. These include spectral analysis of seismograms for studying seismogram characteristics; auto-regressive modeling of time series for signal analysis, high resolution spectral analysis and source function determination; artificial neural networks (ANN) for signal detection and identification, wavelet and spectrogram analysis for moving spectral estimation; fractal dimension approach of modeling seismic noise and signals to facilitate signal detection; array processing methods using linear and non-linear beaming techniques for enhancement of signal to noise ratio and to study slowness of seismic phases and internal structure of the earth; identification of nuclear explosions from earthquakes using multiple parameters; hypocentral estimation methods based on arrival times of P as well as later phases; fault plane solutions of earthquakes using global data; Lg wave attenuation studies and development of magnitude scale based on RMS amplitude of Lg waves; seismicity studies of regions around Gauribidanur array and Delhi; crustal modeling using seismic signals; site characterization studies; precursory analysis of rock bursts at KGF mines; micro tremor surveys and risk analysis for NPP sites. In the course of the above research work, different software programs developed have been listed in the Box below.

Different software programs developed for seismology

- Online signal detection and event location software for seismic arrays, networks and three component stations.
- Source identification software based on multiple parameters.
- ANN and fractal based programs for event detection and identification.
- Spectrogram and wavelet analysis programs.
- Programs for generating synthetic seismograms from different seismic sources.
- Linear and non-linear beam formation programs for determining earth structure and for online application.
- Offline signal analysis programs.

A short period seismic array to detect, locate and identify nuclear explosions was installed at Gauribidanur, Karnataka, India (GBA) in 1965 by DAE in collaboration with UK Atomic Energy Authority (UKAEA). Small beginning made at that time has grown with in-house technological developments to state of art seismic array conforming to international standards. At the inception, seismological activity of DAE was primarily to monitor and do detailed analysis of seismic signals generated by earthquakes and underground explosions occurring world over. The waveforms of some explosion signals and major Indian earthquake seismograms recorded at GBA are reproduced below, respectively.





The work related to seismic instrumentation began with the installation of FM cable telemetered short period seismic array at Gauribidanur, followed by the development and implementation of wireless FM telemetry system. Later, the Gauribidanur array incorporated FM to digital converters. Recent significant developments are the design and installation of digital wireless telemetry and VSAT based data communication systems. In this regard, PC based data acquisition, communication, and online event detection and location systems have been developed. Micro-controller based systems are being developed for high dynamic range digital acquisition, timing system, event detection and some specific applications. Prototyping and fabrication of short period seismometers and microbarographs have also been successfully carried out in the department. In house software packages were developed and implemented for the above applications.

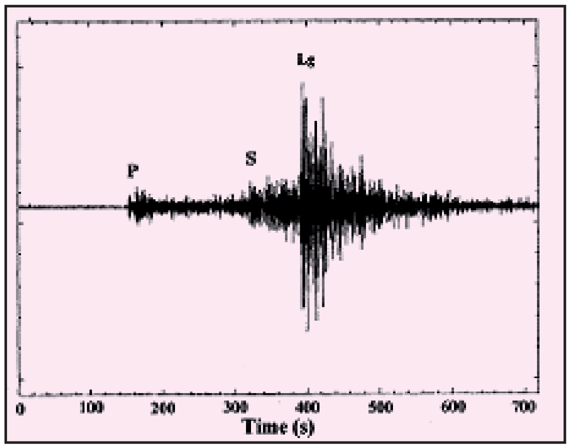
During the past forty years, besides performing round the clock vigil, the seismology group in DAE has also undertaken several collaborative projects both at National and International levels.

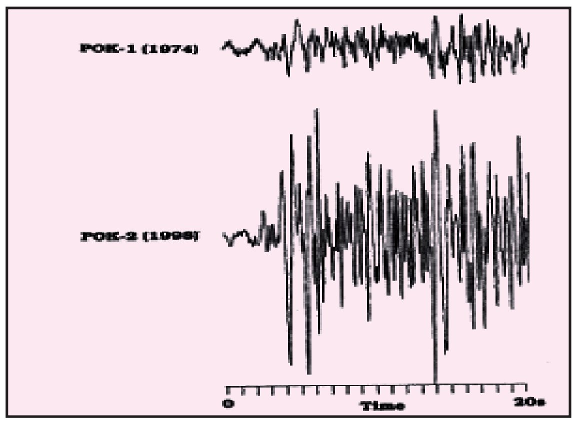
Collaborative work

- Rock burst monitoring systems (RBM) for monitoring the strata stability were installed at Kolar Gold Fields (KGF) Karnataka, Champion Reef mines and at Northern Fold region close to Mysore North Fault to monitor and to study mining induced microseismicity and mine safety.
- A radio telemetered seismic network was setup at Bhatsa to study reservoir induced seismicity.
- Micro earthquake monitoring was carried out at Gulbarga and some other sites in Karnataka after the Latur earthquake of 1993.
- Consultancy for seismic instruments was provided to a UNESCO project for establishing a regional seismological network in south east Asia [1975-1980]. The project work involved setting up over 30 stand-alone systems in Philippines, Thailand, Indonesia and Malaysia.

Pokhran-I & II

Accelerometer array, geophone array and stand alone seismic stations were set up to measure ground motion parameters of May 18, 1974 and May 11-13, 1998 Indian nuclear explosions. Strong Lg and Rayleigh waves were observed at several in-country stations from May 18, 1974 (POK1) and May 11, 1998 (POK2) Indian nuclear tests. The magnitude of POK2 based on regional Lg wave data was obtained as 5.47. A comparison of Lg waves at GBA corresponding to POK2 with that of POK1, gave a yield ratio of 4.83 between these events, which is very near to the value of 4.46 obtained from the differences in *m*b values between POK2 and POK1. The seismogram of POK2 recorded at GBA and the comparison of P-waves from POK1 and POK2 are shown below. Analysis of regional Rayleigh waves provided a *M*s value of 3.56 for POK2. The yield estimates of POK2 from the teleseismic, regional and close-in seismic data were found to be consistent with those obtained from the post-shot radio-chemical measurements.





Radiation Physics and Protection

Link P12

In nature we encounter different kinds of radiations, like charged particles, neutrons and electromagnetic waves covering a fairly wide spectrum of energies. If a radiation is capable of knocking off one or more electrons from chemical species, it is referred to as ionizing radiation. Various types of ionizing radiation produce nearly similar effects, albeit with varying magnitudes. Exposure to such radiations may be voluntary (medical examination, sun exposure) or involuntary. Ionizing radiations and radioactive materials have always been features of our environment. Even so, as our senses do not see them directly, we were unaware of their existence until X-rays were discovered. Both the harmful and beneficial effects of X-rays and similarly of radiations from radioactive materials, became known within a few years of their discoveries. This knowledge matured with time and it became clear that living tissues in human body can be damaged by ionizing radiations. While the body can repair the damage (if the exposure is not too severe or widespread for nature to heal), due to the potential risk of radiation injury, it is important to keep the exposure below an acceptable level. The primary objective of radiological protection is to provide appropriate standards of protection for plant personnel and general public for different types of radiations. It is like handling petroleum products (that are highly inflammable) or using high voltage electricity. While both these, may have some attendant risks. But by following specific guidelines and proper technology all deleterious effects can be effectively kept under check.

"Radioactive materials and sources of radiation should be handled in the Atomic Energy Establishment in a manner which not only ensures that no harm can come to workers in the Establishment or anyone else, but also in an exemplary manner, so as to set a standard which other organizations in the country may be asked to emulate"

H.J. Bhabha

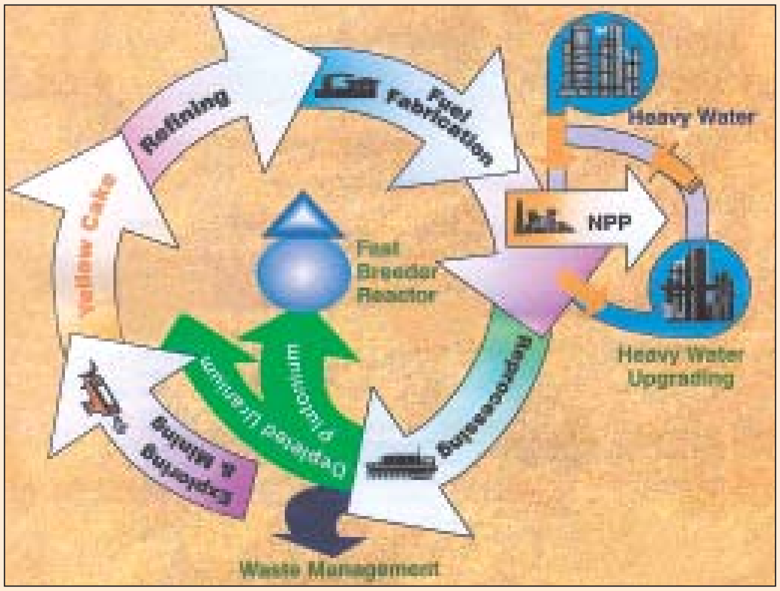
Feb. 27, 1960

General principles followed for radiation protection.

- No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the detriment it causes.
- The exposure due to any particular source, for which the number of people exposed and / or the magnitude of individual doses are not certain, should be kept as low as reasonably achievable taking the economic and social factors into account.
- The exposure of individuals resulting from the combination of all the relevant practices should be subjected to dose limits, or to some control of risk in the case of potentially hazardous exposures. These are aimed at ensuring that from these practices no individual is exposed to radiation risks that are judged to be unacceptable in any normal circumstances. Since, not all sources are amenable to control by action at the source it is necessary to specify the sources to be included as relevant before selecting a dose limit.

Radiation Physics and Protection

Ionizing radiations have been present in the environment since antiquity because of naturally occurring radioactive minerals remaining from the very early formation of the planet. Radioactivity is thus present everywhere, in the air, on the ground and even under it, in the water and even inside our body. Also, we are continuously exposed to ionizing radiation that come from outer space and pass through the earth's atmosphere - so called cosmic radiation. In addition, there are sources of man made ionizing radiation. Almost all of these are related to the process of producing nuclear energy.



Nuclear fuel cycle

The normal process of generation of nuclear power involves negligible risk of exposure to general public. However, fall out from nuclear weapons explosions and other accidents world wide do contribute to the total exposure to general public. Second source of exposure is related to the application of X-rays or radioactive substances in medicine. The applications of radioactive materials in industry either for radiography or as a tracer constitute the third source of radiation exposure.

The ionizing radiation that we are mainly concerned in the field of atomic energy from the health hazard point of view are beta particles, alpha particles, gamma rays, X-rays and other energetic charge particles and neutrons. The type of health effect depends upon the amount and duration of radiation exposure. Two broad categories of exposures viz. (i) those associated with long term, low level exposure and (ii) short term, high level exposure or acute exposure may be considered. Two basic types of injuries can occur in an individual exposed to significant dose of radiation. The first type is confined to the exposed individual. This is known as somatic damage. The other type, called genetic damage, may be passed on to the subsequent generations. Human body does possess the ability to repair the damage provided the damage occurs over a sufficiently long period of time and its extent is not unmanageable. Nuclear industry endeavours to ensure that the bodily repair processes are allowed to carry out their job efficiently. This is done by ensuring that no individual, woking personnel or member of the public, receives an unmanageable and hence dangerous dose.

The health hazards from acute exposure to ionizing radiation usually appear quickly. They include burns and radiation sickness, which causes premature aging or even death. The symptoms of radiation sickness include: nausea, weakness, hair loss, skin burns or diminished organ function.

The exposures are classified as external or internal depending on whether the source of radiation is outside or inside the body. Further, exposure may be to the whole body (often the case with external exposures) or it could be selective to some part of the body as is often the case when radioactive substances are inhaled or ingested. A health physicist has to analyze the potential for and effects of internal and external exposures. Because of their limited power of penetration external exposure to alpha or beta radiations are not of great concern. However serious damage can occur due to exposure to alpha radiation in case of open wounds and beta when in contact with the skin or eyes. In general, the most hazardous radiations are gamma rays, X-rays and neutrons, which can *travel long distances and penetrate entirely through the body. With neutrons it is the indirect result of various possible interactions. Thermal or slow neutrons undergo (n, γ) reactions with several body elements, particularly hydrogen. The gamma radiation so produced then cause ionization. Another process involving slow neutron is N^{14} (n, p) C^{14} reaction, in which case the protons emitted have a considerable ionization effect. It may also be noted that C^{14} is itself a beta emitter. The effect of fast neutrons is essentially due to the production of recoil protons by the impact of neutrons on hydrogen in the body. The fast protons thus produced cause ionization in their paths.*

The general health hazard of ionizing radiation from ingested or inhaled radioactive materials are essentially the same as due to exposure from an external source. However, even a very small quantity within the body can produce considerable injury. This is more so if the radio nuclide tends to concentrate in specific cells or tissues that are highly radiosensitive. The assessment of hazard of any radio nuclide inside the body is based on its biological half life which is the time taken to decrease to half of its initial value due to elimination by biological processes. A combination of the biological and the radioactive half lives then determine the total radiation dose. The nuclide having short radioactive half life and a comparatively long biological half life cause relatively greater internal hazard. Short radioactive half life means the greater rate of energy release, while long biological half life means that active material resides for a long time in the body and hence the cumulative dose becomes high. Iodine-131 is a typical example of this type. It has a radioactive half life of only 8 days but the biological half life is about six months because iodine is rapidly taken up by the thyroid gland from which it is eliminated slowly. Consequently, the presence of this radio nuclide in the body can cause serious health hazard. The other radio nuclides of major internal dose concern are Ra^{226} and Pu^{239} (alpha emitter) both of which have very long radioactive and biological half lives as they are deposited in the skeleton. Strontium-90 (a beta emitter), which is produced on fission of U^{235} and Pu^{239} also has a half life of 28 years. Thebiological half life is about ten years and consequently it causes serious health hazard. The factors that can lead to inhalation or ingestion of radio nuclides are listed in the Box below.

Possible sources of inhalation of radioactivity

- Presence of volatile radio nuclides viz. tritium, carbon-14.
- Industrial processes such as incineration that could release radio nuclides to the air or generate residues such as ash.
- Mishandling of radioactive materials.
- Dust from radioactive soil.
- Presence of radon gas in the environment.

Possible sources of ingestion of radioactivity

- Drinking of radioactively contaminated water (polluted ground water).
- Working with radioactive soil.
- Food plants that take up certain soil radioactivity.
- Consumption of fish from contaminated water bodies.
- Direct contact with active water (bathing, swimming) etc.

The absorbed dose of any ionizing radiation is defined as the amount of energy imparted to matter by ionizing particles per unit mass of the irradiated material. In the next Box, certain terms used in radiological protection have been defined.

The biological damage caused by different radiations is very different even when the body absorbs the same amount of energy from each type.This brings into focus the relative biological effectiveness (RBE) of different types of ionizing radiations. The RBE factors have been listed in the Box.

Definition of certain terms used in radiological protection

- **Exposure:** The act or condition of being subjected to irradiation. It could be either external or internal.

- **Dose:** A measure of radiation received or 'absorbed' by a target. The quantities termed as absorbed dose, organ dose, equivalent dose, effective dose, committed equivalent dose or committed effective dose are used, depending on the context. The fundamental dosimetric quantity in radiological protection is the absorbed dose D, which is the energy absorbed per unit mass and is given the name gray (Gy).

- **Equivalent Dose:** It is the absorbed dose averaged over a tissue or organ (rather than at a point) and weighted for the radiation quantity that is of interest. The radiation weighting factor (w_R) is selected for the type and energy of the radiation incident on the body or, in the case of sources within the body, emitted by the source. The equivalent dose in tissue T is given by $H_T = S\ w_R.\ D_{T,R}$ where $D_{T,R}$ is the absorbed dose averaged over the tissue or organ T, due to radiation R. The unit of equivalent dose is joule per kilogram with the special name Sievert (Sv).

- **Effective Dose:** The effective dose is the sum of the weighted equivalent doses in all the tissues and organs of the body. It is given by the expression $E = S_T\ w_T.\ H_T$. The tissue weighing factor w_T accounts for the different sensitivity of organs to radiation. The unit of effective dose is the joule per kilogram with the special name Sievert (Sv).

- **Annual Limit of Intake (ALI):** The intake by inhala tion, ingestion or through the skin of a given radio nuclide in a year by the reference man which would result in a committed dose equal to the relevant dose limit. The ALI is expressed in units of activity.

Relative biological effectiveness (RBE) of different types of ionizing radiations.

Radiation	Relative Biological Effectiveness
X-ray, gamma ray, beta ray	1
Thermal neutrons	2-5
Fast neutrons	10
Alpha particles and high energy ions	10-20

In DAE, activities on all aspects of radiological safety covering entire nuclear fuel cycle operations have been pursued. The scope and objectives of radiation protection in DAE are listed in Box.

Radiological Safety Activities Scope and objectives

- Radiation protection and surveillance of all nuclear related activities, encompassing the entire nuclear fuel cycle including nuclear power generation.
- Radiation protection and surveillance of different medical institutions, industrial units, research and academic institutions, both under the Government as well as privately managed units.
- Personnel monitoring services for radiation workers in the country.
- Environmental monitoring of radiological pollutants and study of radioactivity and conventional pollutants in food, water, industrial products etc.
- Development of methodologies, techniques, calibration and standardization for detection and measurement of radiation and radioactivity.
- Safety related matters in the design of nuclear facilities and other institutions using radiation sources or radiation generating machines.

Methodologies and Techniques for Individual Dose Assessment

Assessment of internal dose is carried out by performing bioassay (urine analysis, faecal analysis, breath analysis) and whole body counting coupled with modeling of bio-kinetics of radio nuclides. Due to tropical conditions, the daily intake of fluids by an Indian is more than that for ICRP (International Commission for Radiological Protection formed in 1928) reference man. Hence, ALI and derived air concentration values have been worked out taking this aspect into account. The methods developed for the internal dose assessment due to different radio nuclides are summarized in the next Box.

Assessment of internal dose

- Due to actinides (U, Pu, Am) and pure beta emitters (tritium, Sr-90): through the analysis of excreta (urine, faeces etc.) using radiochemical methods.
- Due to tritium: through analysis of urine.
- Due to Th and Ra body burden: Evaluation of low levels through the measurement of thoron and radon in breath.
- Due to various fission, activation products and radio pharmaceuticals: through whole body counting.
- Due to actinide depositions in lungs and other body organs: Assessment of low levels through whole body scanning using scintillation and semiconductor detectors.

The devices used for measuring external dose are summarized in the following Box.

Assessment of external dose

- $CaSO_4$(Dy) thermoluminescent dosimeter badges and, Quartz fibre direct reading dosimeter for X, γ and β rays.
- Film badges for X, γ and β-rays and thermal neutrons.
- Semiconductor diode detector for day to day control of dose due to X and γ-rays.
- Solid state nuclear track detector (SSNTD) for fast neutrons.

Environmental Surveillance

The pre-operational and subsequent regular environmental radiological surveillance of all nuclear energy related installations is important to meaningful and effective radiation protection. This is essentially to setting appropriate limits for radiation exposure to general public. In pre-operational phase of a facility, a detailed measurement of radioactivity in different environmental matrices viz. air, water, fish, silt, sediment, soil, goat thyroid, milk, grass, vegetables, fruits, crops, meat and other dietary items is carried out covering a 30 km radial distance around a nuclear plant. The number and type of samples and sampling frequency is optimised for each site on the basis of the nature of operating facilities, utilisation of local natural resources, existence of population clusters and related demographic data. In the operational phase, continuous monitoring of external radiation levels in the environment is regularly carried out to assess contribution, if any, due to release of radioactivity from the plant. For quick assessment of radioactive contamination over a large area, aerial gamma spectrometry systems have been developed which can be deployed in a vehicle or aircraft. Besides, environmental radiation monitors deployable in a vehicle or railway coach have been developed for simultaneously acquiring data with 3D positional coordinates using global positioning system. For meteorological measurements an instrument called sound detection and ranging (SODAR) is developed. The system can probe the atmosphere up to a height of about one kilometre.

Ten monitoring stations are built across the country which provide quick on-line information on the status of radiation in the environment either natural or due to fall-out. The Germon integrated system installed at these stations consists of particulate beta-gamma air monitor for radon and thoron daughter products and long-lived activity monitoring and environmental gamma dose monitors (based on GM counter, plastic scintillator and high pressure ionisation chamber). Each station also includes large volume air sampler, dry and wet deposition measuring system, facility for periodic analysis of milk samples for Cs^{137}. The software developed for the PC based system allows continuous collection and analysis of the data.

Instrumentation for characterising aerosols in the environment and workplace are developed. Underlying physical processes are studied including simulation of aerosol behaviour and transport under reactor containment, special effects of electrical charge on particles in radiation environment, role of aerosols in the modulation of the solar radiation etc.

For accident dosimetry, geological dating or surface dose mapping, the IR stimulated luminescence studies in samples containing quartz and feldspar are performed.

Modeling Studies

A variety of modeling studies have been performed which pertain to two broad areas namely; (i) atmospheric modeling and (ii) hydrological modeling. Different models developed are summarized in the next Box.

Monazite Survey Project

Dosimetric measurements are being carried out as a part of epidemiological studies in the natural high background radiation areas of Kerala. The estimation of external gammas in the dwellings and outdoor regions is carried out using thermoluminescent dosimetery. The twin cup radon / thoron dosimeters are used for estimation of inhalation doses.

Countrywide Radon / Thoron Mapping

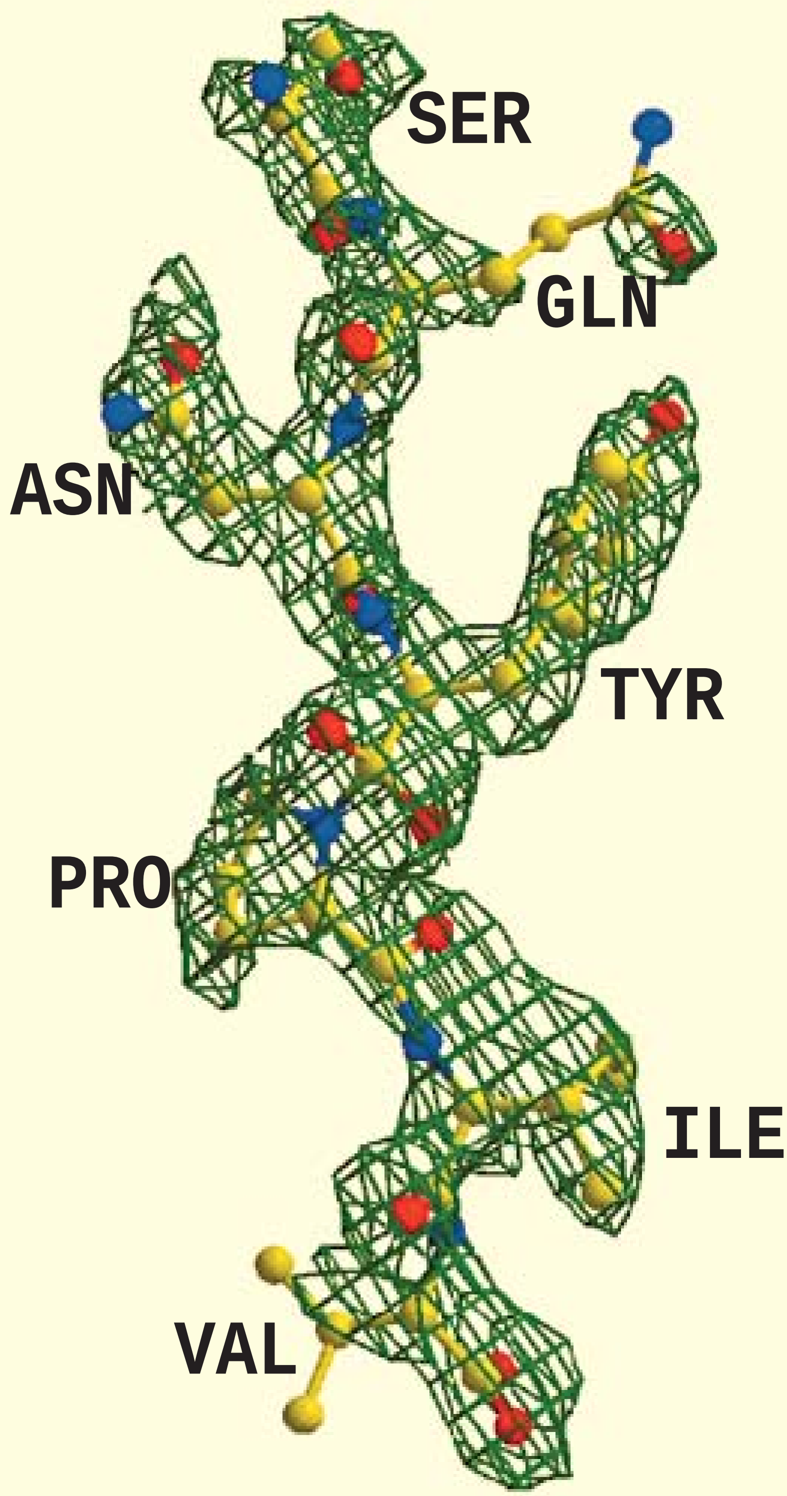
This study aims at generating the map of natural background inhalation exposures due to radon and thoron and their progeny across the country. For this monitoring, a twin-cup passive dosemeter system based on solid state nuclear track detectors was developed.

Radiation Standards

The measurement of the type, energy and intensity of radiation is very important from the point of view of radiation protection. Consequently, maintaining of standards and their continuous updating is an important activity. The standards developed include primary standards like $4\pi\beta\gamma$ coincidence system, free air ionization chamber, manganese sulphate bath assembly and Fricke dosimeter.

Modeling studies

- Three dimensional complex terrain model for environmental impact assessment for routine releases of radioactivity into the atmosphere from nuclear reactors.
- Particle trajectory model for computing the concentration of radio nuclides and corresponding gamma dose on a spatial and temporal scale.
- Land Sea Breeze Model for obtaining the sea breeze/ land breeze circulation over plain terrains.
- Gaussian Plume Model for evaluation of atmospheric dilution capacity for routine and unplanned radioactivity releases by nuclear reactors.
- For long-term safety assessment of radioactive disposal facilities as well as radioactive liquid effluent release practices over the hydrological domains.
- The Continuous River Release Model and the Continuous Coastal Release Model for evaluating the impacts of routine releases of radioactive liquid effluents and sewage effluent discharge.
- Shallow Land Burial Model and Risk Evaluation Model for Safety Assessment for assessing the safety performance of near surface radioactive disposal mode, type of disposal facility and geohydrology of the site.
- Deep Geological Repository Model - migration of radio nuclides from vitrified high-level radioactive waste disposed off in geological repositories.



Reaction intermediate in HIV-1 protease-substrate complex