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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

AECL PROGRAMS IN BASIC PHYSICS RESEARCH

Programmes de l'EACL pour la recherche en physique fondamentale

G.A. BARTHOLOMEW, G. DOLLING, M. HARVEY and J.C.D. MILTON

Chalk River Nuclear Laboratories Laboratoires nucléaires de Chalk River

Chalk River, Ontario

February 1982 février

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Résumé

Ce rapport décrit, en termes non techniques, le programme de recherche de Chalk River touchant les propriétés fondamentales des noyaux atomiques et de la matière condensée (liquides et solides). On décrit brièvement certains programmes expérimentaux actuellement exécutés, principalement auprès du réacteur NRU et de l'accélérateur tandem MP. On donne un aperçu des études théoriques associées à ces programmes. On mentionne quelques faits saillants d'anciens travaux menés à bien.

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ABSTRACT

This report describes, in non-technical language, the CRNL program of research into the basic properties of atomic nuclei and condensed matter (liquids and solids). Brief descriptions are given of some of the current experimental programs done principally at the NRU reactor and MP tandem accelerator, the associated theoretical studies and some highlights of past achievements.

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1. INTRODUCTION

Canada's nuclear power program taps a source of energy different from that provided by the burning of fossil fuels. The latter is chemical in nature, releasing energy stored in the binding of atoms in molecules. In a nuclear reactor, like Canada's CANDU, energy is released from the tiny, compact core (the nucleus) of the atom itself. In order that the performance of CANDU can be continually improved and more advanced systems evolved, research and development must be carried on in many high-technology areas, such as properties of materials, advanced fuels and system reliability. This work can best be done in a laboratory with a broad range of expertise based upon a thorough understanding of the fundamental properties of atomic nuclei, of nuclear radiations and of the effect of these radiations on materials. One of the functions of AECL's team of basic research scientists is to provide this support in fundamental physics. Through their own research activities, and their good relations with other laboratories throughout the world, they are able to keep AECL up to date on the latest data, latest techniques, latest equipment and latest concepts and approaches in physics and related technology.

Besides providing the background knowledge for the support of CANDU reactors, basic physics research provides a stimulus for new high technology developments. Basic research continually requires the development of new devices, such as accelerators, reactors and radiation detectors, as well as more powerful high-speed computers and more sophisticated theoretical techniques. Satisfying these research requirements extends today's technology to its limits, and beyond. Experience has shown that new developments thus born find their way into industrial usage - often in ways not contemplated when the original demand was made. Thus from physics research needs have emerged new concepts for accelerators for cancer therapy, radioisotopes for medical diagnostics and sensitive radiation detectors with many applications not only in the nuclear industry but also, for example, in oil exploration.

Basic physics research is dedicated to determining the properties of matter of which the whole universe, including ourselves, is created. The research often involves long and painstaking investigations of seemingly inconsequential aspects of nature. Mark Twain once facetiously remarked in Life on the Mississippi: "There is something fascinating about science. One gets such wholesome returns of conjecture out of such trifling investment of fact". He realized perhaps that it is indeed often the little facts that contribute to a deep understanding of nature. The physics research activity at AECL may not always appear to have a direct bearing on the nuclear industry, but it is with the accumulated "facts" that the industry has been built and will continue to grow.

The physics of nature is enormously complex and no one laboratory can hope to examine all aspects. Physics research is a worldwide activity with the free and frequent exchange of information between laboratories an essential part of the success of the whole venture. The underlying physics research carried out by AECL is done mostly in the Physics Division of the Chalk River Nuclear Laboratories (CRNL). The work takes three principal directions:

- experiments to discover and explore properties of the nucleus by using charged particle beams from accelerators, and neutron and gamma-ray beams from research reactors (Section 2),
- experiments to discover and explore properties of condensed matter (solids and liquids) by using neutron beams from nuclear reactors (Section 3), and
- theoretical studies which in part support the experimental work, and in part are studies of the broader, more basic concepts underlying the whole field (Section 4).

To understand the significance of the above lines of research it is essential to appreciate some of the problems associated with discovering the properties of objects as minute as atoms and nuclei. Individual atoms are too small to be seen by microscopes using visible light and the nuclei of atoms are several thousands of times smaller still (see Figure 1). To "see" and study properties of atoms in molecules and of the nucleus in an atom one must substitute for ordinary light, kinds of radiation whose wavelengths are better tuned to these smaller dimensions. It turns out that slowly moving neutrons have properties closely matching those required to study the properties of matter in its solid and liquid states (condensed matter). Gamma rays (electromagnetic radiation with extremely small wavelengths - see Figure 1), fast moving neutrons and fast moving "heavy ions" are well suited to "looking at" what is going on inside the nucleus. The human eye is, of course, only sensitive to "visible light" (electromagnetic radiation with a wavelength of about 5×10^{-7} m) and not to these other types of radiations. The scientist therefore has had to develop apparatus that will detect the radiations that impinge on, and emerge from, the matter under study, and methods for interpreting the results in a form that can literally be seen; this can be a picture on a television screen or perhaps a printout from a computer.

Essential to the physics research at CRNL therefore are the radiation beams, and these are at present generated by the nuclear reactors and the MP Tandem accelerator. These facilities are generally in use for 24 hours of every day of the year.

1.1 The NRU and NRX Reactors

The NRU and NRX are research reactors that generate beams of neutrons. Neutrons are part of the fabric of nuclei themselves and are released when a heavy nucleus like ^{235}U breaks up (fissions). Both reactors have a large number of tubes (Figure 2) through the concrete shielding that beam the neutrons

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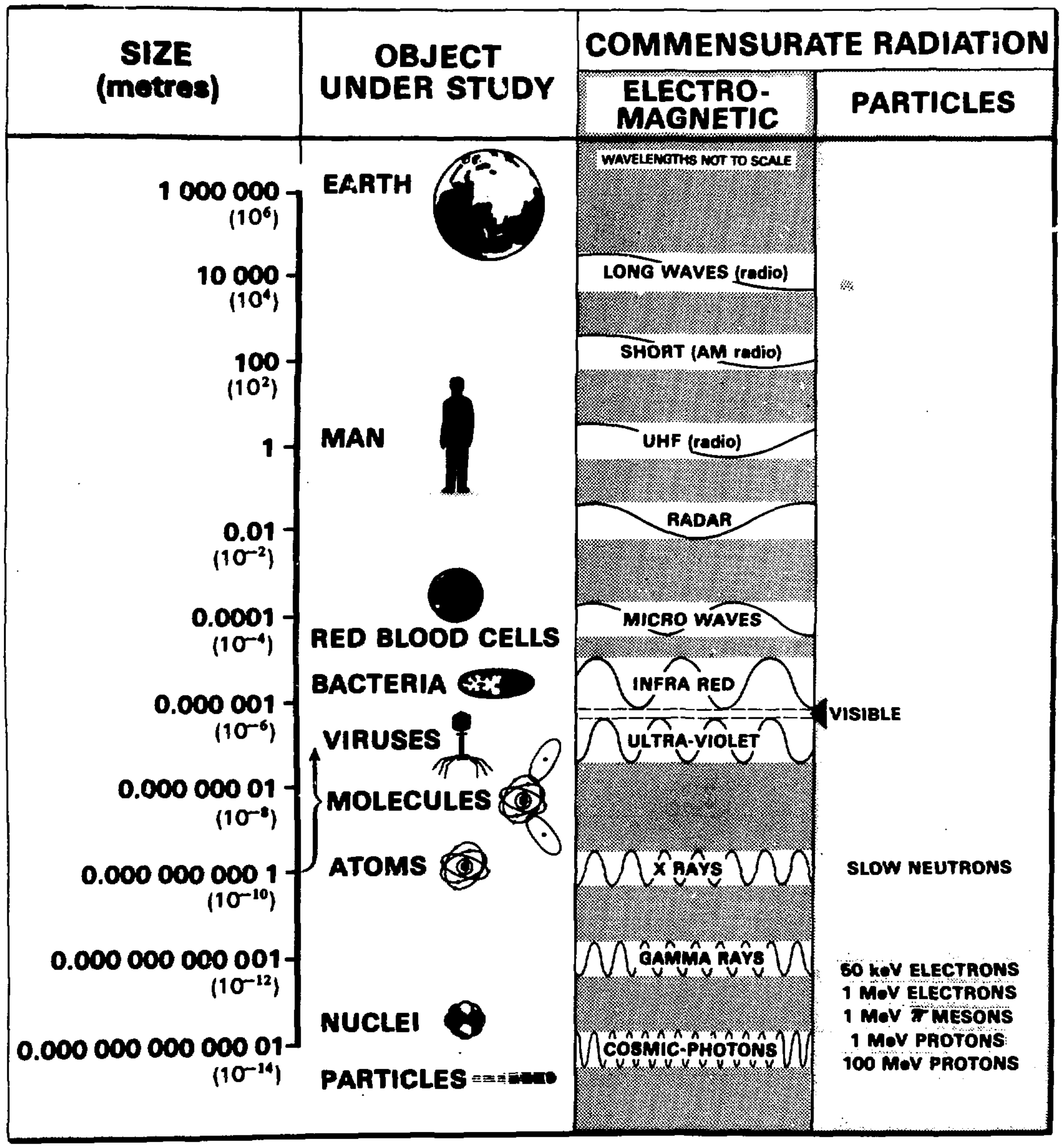

Fig. 1 Sizes of objects and the radiation that can be used to "see" them. Radiation corresponding to any given size can be used to image objects of larger size but not smaller. For example, light can be used to see objects of the size of the virus, bacteria, man, the earth or larger but cannot be used to see things smaller than the virus. To "see" atoms and molecules one must use radiations like X rays or slow neutrons; to see the nuclei of atoms one must use gamma rays or energetic particles.

from the reactor core to the experimental apparatus adjacent to the reactor. The slow neutrons have the long wavelengths appropriate to research on solids and liquids, whereas the faster neutrons have the shorter wavelengths more suitable for probing the atomic nucleus.

Neutrons (both fast and slow), on interacting with a nucleus, can stimulate it to emit electromagnetic radiation (gamma rays) of very short wavelengths (of the order of 10^{-15} m). A facility has been constructed at one of the beam tubes at NRU (a gamma-ray monochromator) that will collect outside the reactor, gamma rays so generated and make them into a "secondary" radiation beam that is also suitable for probing atomic nuclei.

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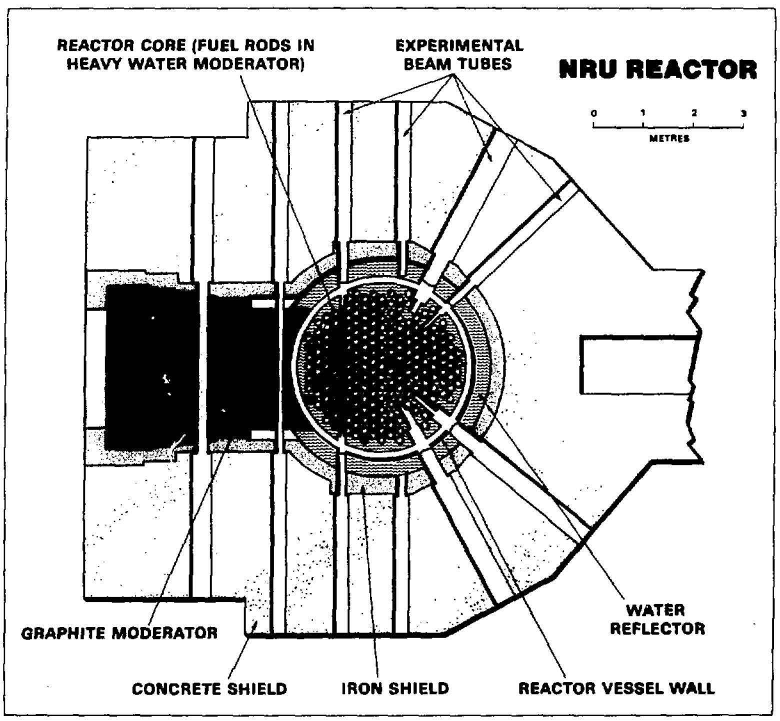

Fig. 2 Plan view of the NRU reactor showing the penetration of experimental beam tubes through the concrete and iron shields to the region of high neutron flux in or near the core. Tubes of different sizes and locations with respect to the core are provided.

The NRU reactor began operating in 1957. It provides about a factor of ten increase in neutron intensity (flux) over the older NRX reactor at CRNL (operating since 1947) and hence is the favoured reactor with which to perform physics experiments. The neutron flux of the NRU reactor is exceeded by only a few other research reactors in the world.

1.2 The MP Tandem Accelerator

The MP Tandem accelerator provides a wide variety of ion beams suitable for the study of atomic nuclei. An ion is the name given to an atom or molecule from which some electrons have been removed or to which some have been added so that the electric charges of the orbiting electrons do not exactly cancel the positive charges on the nuclei. Fewer electrons lead to an overall positive charge and hence to "positive ions": more electrons lead to an overall negative charge and hence to "negative ions". In the MP Tandem accelerator (see Figure 3) a negative ion beam is generated in the ion source by adding electrons to slowly moving atoms (sometimes combined in molecules). These negative ions are attracted (and accelerated) to the positively charged central terminal of the Tandem. In the central terminal some electrons are stripped from the negative ions, thus turning them into positive ions. The positive ions are now repelled (with further acceleration) through the second half of the Tandem from the still positively charged terminal. Outside the Tandem the fast moving, positive ions can be steered to the various experimental areas where their special characteristics are exploited for the study of atomic nuclei.

The present MP Tandem accelerator is but the latest of a series of ion accelerators at CRNL. The first (1952-1960) was a vertical Van de Graaff that had a single accelerating section with an electrostatic potential up to 3 million volts which could provide a useful beam of light ions (mainly protons). This was superseded by an EN Tandem (1958-1967) with 5 million volts on the central terminal. The EN was the first of the Tandem accelerators to be delivered to any laboratory in the world and could accelerate useful beams of heavy ions (e.g. of carbon and oxygen). This in turn was replaced in 1967 by the present MP Tandem then with 10 million volts on the central terminal. Modifications in 1972 upgraded the MP Tandem to 13 million volts on the central terminal and further modifications in 1974 improved the stability of the machine to make it one of the most reliable in the world. At present the laboratory is in the process of upgrading the heavy ion facility by the addition of a superconducting cyclotron (see Section 2.6) which will further accelerate the present ion beams that emerge from the MP Tandem. The proposed Tandem/cyclotron facility will provide useful beams of heavy ions from lithium (mass 7) to uranium (mass 238).

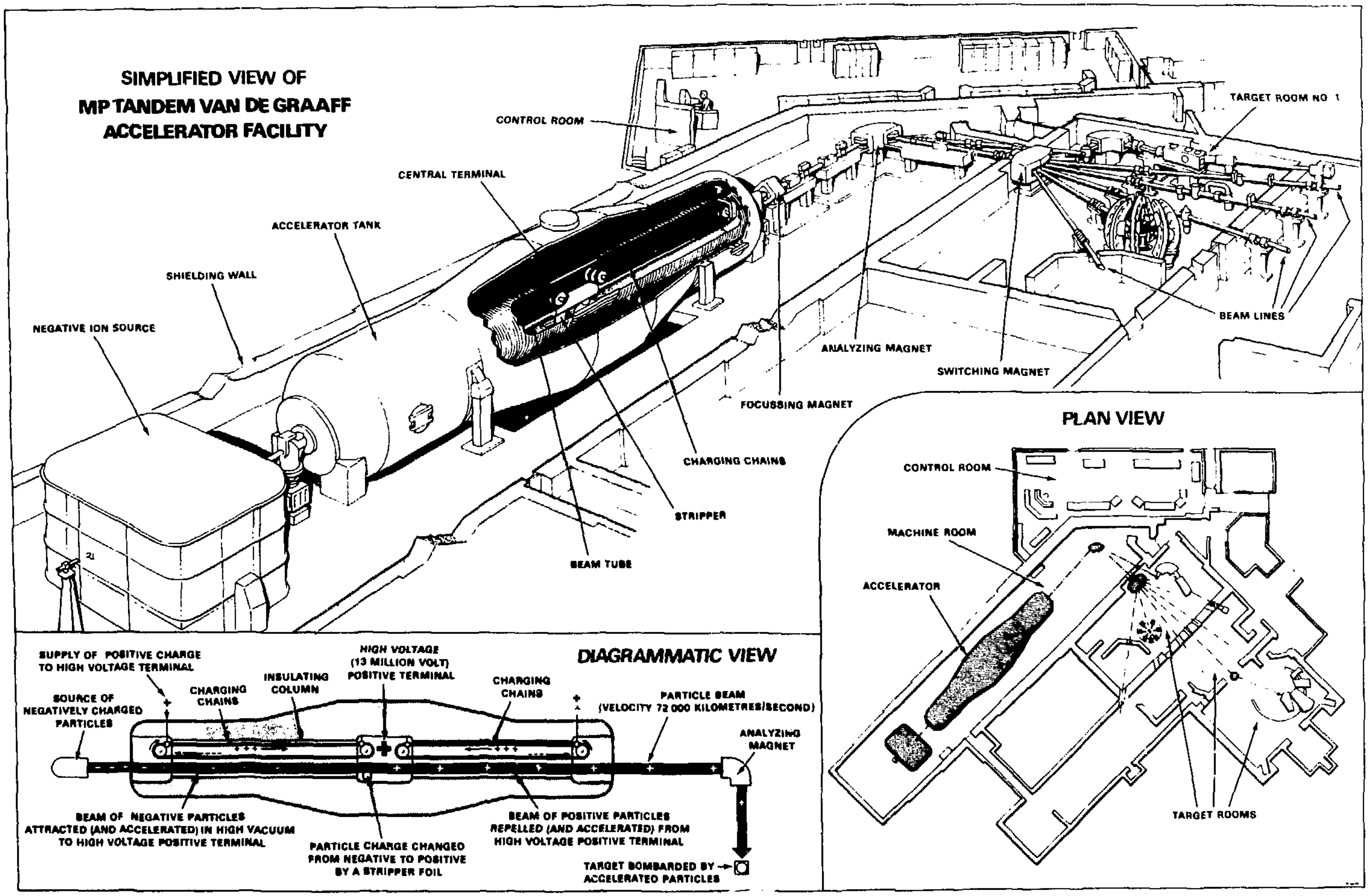

Fig. 3 The MP Tandem is an electrostatic accelerator in which a high voltage is developed on a central terminal by moving "charging chains", see lower left-hand diagram. The particles (atoms) to be accelerated start off in an ion source at the left where they have been induced to take on an excess electron so that they are temporarily "negative ions" which are then attracted to the positive terminal thereby gaining energy. In the terminal the extra electron and some of each atom's own electrons are stripped off so that the ions become positively charged and are then repelled by the terminal gaining further energy. It is this two-way acceleration that leads to the name Tandem. The other diagrams in the figure show the layout of the whole facility.

1.3 Collaboration

As stated in the Introduction, scientific research is international. CRNL scientists go to other laboratories both in Canada and abroad to use specialized equipment and to learn new techniques. CRNL in turn welcomes visiting scientists who have a standing invitation to use the research facilities and interact with the in-house researchers. To illustrate the degree of collaboration that takes place, about 60% of the operating time on the MP Tandem is used on experiments involving visiting scientists and, in these experiments, the visitors contribute 40% of the personnel. At the NRU reactor, out of some dozen beam tubes in continual use, four are exclusively allocated to university scientists who have set up their own equipment and run their own experiments. In addition many visitors collaborate on the experiments initiated by CRNL physicists at the reactors.

AECL encourages the transfer of basic scientific knowledge by sponsoring conferences and by sending its scientists to speak at conferences and to work and lecture at other laboratories throughout the world. In return AECL benefits by a flow of seminar speakers through its laboratories and an active summer program involving both senior scientists and students. AECL scientists present the results of their basic scientific research in the open scientific literature. Titles of some highlight papers are given in Section 6 to illustrate the diversity of subjects that have been studied.

2. NUCLEAR PHYSICS RESEARCH

2.1 Basic Principles

Atoms may be likened to miniature "solar systems" made up of negatively charged electrons orbiting like planets around a positively charged nucleus, their "sun". Nuclear physics is the study of that central nucleus.

Although the orbiting electrons of an atom determine its chemical properties, it is the nucleus that contains most of the mass - actually more than 99.9%. Nuclei are some 10,000 times smaller than the atom yet atoms themselves are so minute as to be unobservable with a conventional microscope. To put this into a more imaginable perspective, if the nucleus were the size of a baseball, the diameter of the outermost electron orbits in the atom would be about one kilometre, yet it requires a hundred million atoms in a row to span one centimetre.

As stated in the Introduction and illustrated in Figure 1, the small size of the nucleus means that rather energetic radiation beams must be used to study its structure. Electromagnetic radiation (gamma rays) with a wavelength 1 million times shorter than that of visible light is one example of such a beam. Neutrons (see Section 1.1) or ionized atoms (see Section 1.2) are also good probes. The essence of an experiment is to bombard a target nucleus with a radiation beam and then use specialized equipment to observe the emergent radiations, their energies, their directions and speeds, and whether they appear promptly or are delayed. Extensive theoretical analysis is often required to recreate the nature of the miniature event that led to the complex phenomena observed.

2.2 The Fundamental Nuclear Model

We can picture the nucleus as a close packing of two types of particles - the neutrons and the protons - which are commonly called nucleons. Each nucleon has a mass about 2000 times that of an electron. The neutrons have no electric charge and each proton carries a positive charge equal in magnitude to the negative charge on one electron. It is the number of protons in the nucleus that determines the number of electrons in the atom, which in turn distinguishes the elements in nature - one for hydrogen, two for helium, ..., eight for oxygen, ..., ninety-two for uranium. Because neutrons have no charge they can be added to or subtracted from the nucleus without changing the number of electrons. Different "isotopes" of the same element are characterized by different numbers of neutrons in their nuclei.

If the nucleus were only influenced by the electric force, its constituent protons would repel each other and cause the nucleus to fly apart. There is, however, another force that acts to bind the nucleons together. Although this "nuclear force" is stronger than the electric force when the nucleons are close, it is weaker when they are far apart. The balance of these forces is such that no nucleus with more than about 100 protons is stable, since protons on opposite sides are too far apart for the nuclear force to be effective and the repulsive electric force becomes dominant. This is why only about 100 elements are found in nature.

Although the number of neutrons does not affect the charge of a nucleus, the delicate interplay of the forces defines an optimum number for any given number of protons. Isotopes with near this optimum proportion lie near the bottom of the so-called "valley of stability" (see Figure 4). Stable light nuclei have nearly equal numbers of protons and neutrons, but with increasing numbers of protons the neutrons become more numerous, outnumbering protons 2½ to 1 for the heaviest nuclei. For any given element, only a few stable isotopes are found near the bottom of the valley. Many isotopes away from the valley floor can be produced in the laboratory however. Those far up the valley walls are called exotic and exist only for a very short period of time. They are, nevertheless, particularly interesting since they provide a means of testing our understanding of the nucleus over a wide range of conditions.

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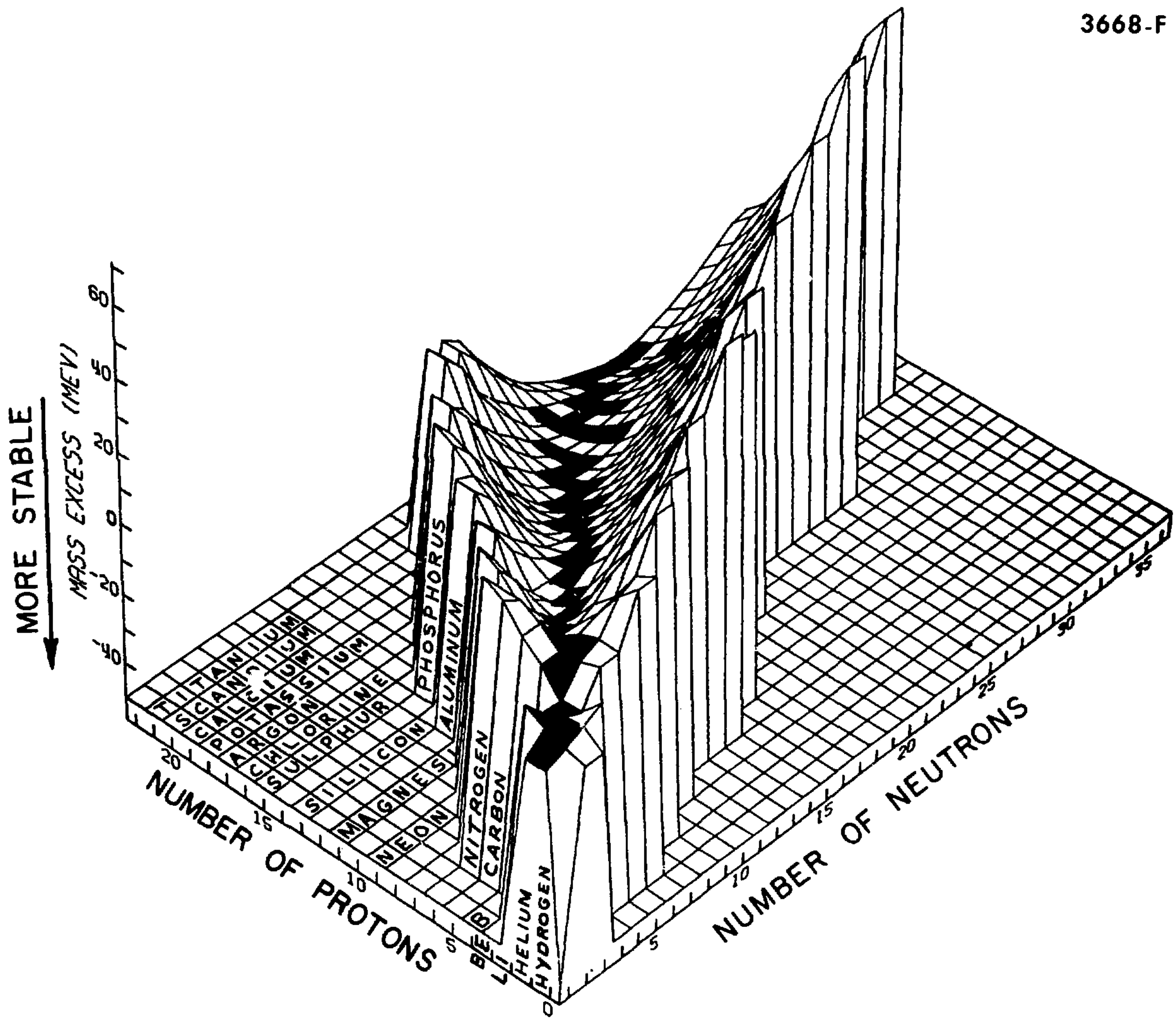

Fig. 4 The "valley of stability". All of the known isotopes of the elements up to titanium are represented by the raised section of the graph, which locates each isotope according to the number of neutrons and protons it contains, and shows, in the vertical direction, relative stability; the figure can readily be extended to heavier elements. Nuclei near the bottom of the valley shown in black are stable. Relative stability is measured as a difference in mass (mass excess) given here in energy units (MeV). Nuclei located on the sides of the valley are, in general, unstable, i.e. radioactive, and decay to the stable nuclei in the valley floor. The surface of the valley is "rough". These local effects and the overall shape of the valley are related to the structure of the nucleus. Many nuclei are still to be discovered but the farther they are from the valley floor the faster they decay and the harder it is to make or study them.

Most isotopes are thus "unstable" and eventually "decay" spontaneously to more stable nuclei in one of several ways. Common ways are by emission of a helium nucleus (alpha decay) or an electron (beta decay). Some heavy nuclei may spontaneously divide into roughly equal fragments (fission). In ^{235}U, spontaneous fission is very slow compared to alpha decay; on average one ^{235}U nucleus in two would fission spontaneously in about 10^{18} (a million million million) years, whereas alpha decay is about a billion times faster. However, ^{235}U can be stimulated to fission almost immediately by bombardment with slow neutrons in a nuclear reactor. The fission fragments fly apart with great speed. When they enter surrounding materials they produce heat as they slow down. This heat from many fissions occurring at once is used to raise steam in a CANDU power reactor.

Nuclei are also capable of storing energy. While possessing this extra energy they are said to be in an "excited state". Excited states can be created as a result of any of the decay modes above, or by bombardment with a radiation beam. They often involve the nucleus in rotation, vibration or more complicated motions of the constituent nucleons. After a time that is characteristic of each excited state, usually a very short time, the energy is again released, commonly in the form of gamma radiation (gamma decay). The study of the various decay modes (alpha, beta, gamma, fission) reveals to the researcher the nature of the nucleus and the forces that bind its components together.

So far, only the nuclear and electromagnetic forces have been mentioned, but decay measurements reveal the existence of another - the weak force. It is this force that is responsible for beta decay. The simplest manifestation of its effect is the decay of a free neutron (i.e. one outside a nucleus), which changes into a proton, an electron and a neutral particle called an anti-neutrino. When this occurs in a nucleus, the electron and anti-neutrino escape so that the net effect is that one of the constituent neutrons has been changed into a proton, and the nucleus into a more nearly stable nucleus of the neighbouring element.

2.3 Major CRNL Achievements in Nuclear Physics

Since the beginning of the Canadian nuclear program in the 1940's, nuclear physics at CRNL has been noted for major discoveries relating to the structure of nuclei, for the precision of its measurements, and for the development of sophisticated apparatus and theoretical techniques. In the early years most of the research made use of the neutron beams of the nuclear reactors, but later the emphasis switched to the various accelerator beams.

Some of the earliest experiments, using neutron beams from the NRX reactor, were directed toward understanding the fission process. In 1948, the energies of both fragments were measured simultaneously and the distributions of fragment masses and of fragment energies were obtained. In 1950, some of the first measurements on tripartite fission (fission into three instead of two fragments) were carried out. In 1952, the angular distribution of emitted neutrons was measured, and in 1954, the number of neutrons emitted as a function of fragment mass was determined. These studies helped establish CRNL as an authoritative laboratory in the world on the process of fission.

The first high-resolution measurements of high-energy neutron capture gamma rays (the gamma rays emitted when a nucleus captures a neutron) were made at the NRX reactor in 1948; in a wide-ranging exploration of these gamma rays, almost all elements from hydrogen to uranium were studied in the next few years. These measurements were augmented subsequently by precise high-resolution measurements of lower-energy neutron capture gamma rays.

Using a neutron beam from the NRX reactor a CRNL scientist in 1951, concurrently with a Russian group, provided the first reliable measurement of the half-life of the free neutron.

A very precise instrument, called the $\pi\sqrt{2}$ beta spectrometer, was designed and constructed in the late 1950's for the measurements of electrons and gamma rays emitted by excited nuclei. Among its many uses was the provision of accurate gamma-ray energies that could be used as standards. Another use was in pioneering research done into the mechanism of beta decay. The $\pi\sqrt{2}$ spectrometer was the most advanced of a series of spectrometers used at CRNL and was copied by several laboratories around the world.

An accurate measurement of the muon lifetime was made in 1951 with the aid of a cosmic ray counter arrangement. (Muons are particles with similar properties to electrons but with a mass 207 times heavier. Even today the reason for their existence in nature is a mystery.) The laboratory made a large contribution to cosmic ray monitoring between 1950 and 1973, being responsible, among other things, for perfecting techniques for cosmic ray meson and neutron counting. The apparatus for cosmic ray monitoring was transferred to the National Research Council of Canada in 1973 and is still in use today.

CRNL scientists have pioneered the development of techniques for measuring very short lifetimes of excited nuclei. For lifetimes longer than 10^{-10} s (0.0000000001 second) direct timing between the formation and decay of a nuclear state is possible by fast electronic circuits. For the range from 10^{-10} s down to 10^{-15} s the Doppler shift effect (the shift in energy of a gamma ray when it is emitted by a moving nucleus) can be used to measure lifetimes with good accuracy. Experiments were begun at CRNL in the 1970's to push the accessible time even lower to 10^{-16}s. Two methods were developed: one makes use of the so-called "crystal blocking effect", while the other compares an unknown nuclear lifetime with a known atomic one, in effect making use of a miniature atomic clock.

The ion beams of the vertical Van de Graaff were used by CRNL scientists to discover, in 1955, that nucleons in certain light nuclei moved in unison in rotational and vibrational motions previously observed to occur only in much heavier nuclei. With the aid of carbon beams from the EN Tandem, CRNL scientists were able to show, in 1959, that two nuclei could remain in contact for a long time without actually coalescing. The "nuclear molecule" formed by this dumb-bell shaped combination has continued to this day to attract further study by researchers both at CRNL and abroad.

Systematic experiments have been performed over many years to determine the precise energies, decay lifetimes and other properties of excited states of nuclei. These studies have proven invaluable in testing models of nuclear structure.

During the past 10 years, by concentrating studies on certain key isotopes that exhibit a particular form of beta decay, CRNL has contributed importantly to testing certain fundamental theories that describe the weak force responsible for beta decay.

2.4 Some Current Areas of Research

A unique isotope separator called "ISOL" has been installed in the MP Tandem facility (Figure 5). It isolates nuclei of a selected isotope generated by the radiation beam of the MP Tandem thereby facilitating the studies of the isotope's properties. Studies of these nuclei - often far from the bottom of the valley of stability (Figure 4) - provide sensitive tests of current nuclear theories.

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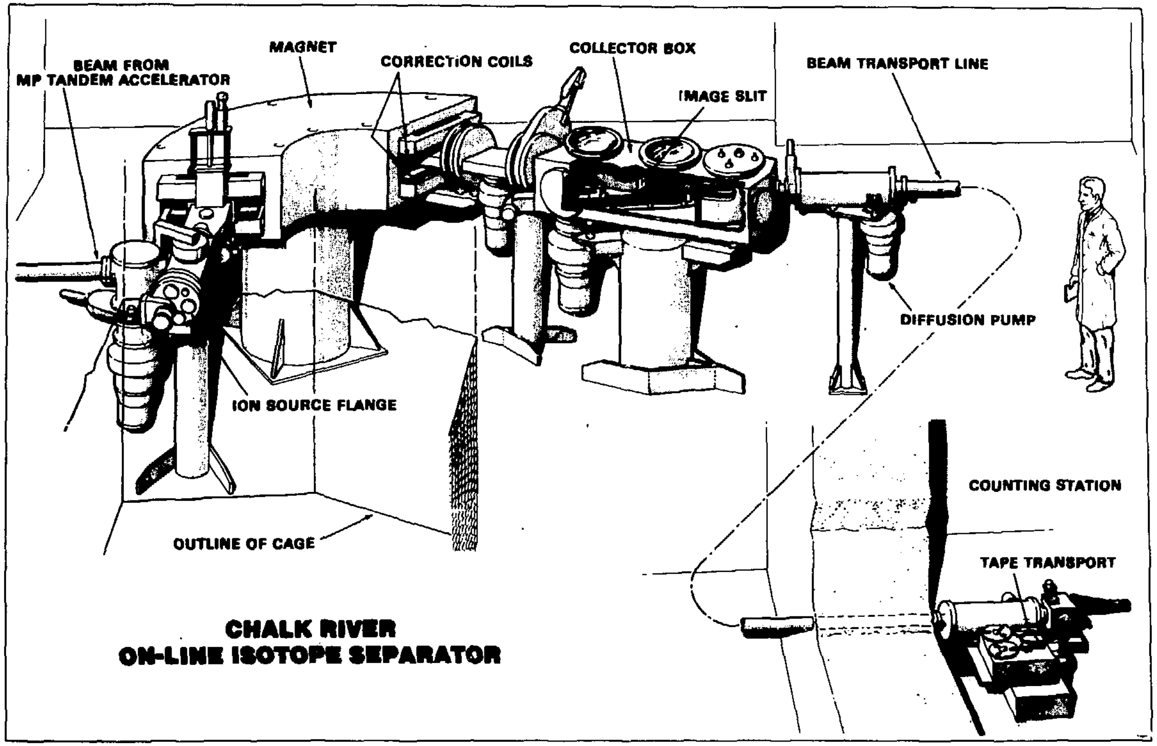

Fig. 5 This instrument, called ISOL, is used to separate one selected isotope from the many that are produced simultaneously when a target is bombarded by projectiles from the Tandem accelerator. The selection is made "on-line", i.e. while the bombardment is in progress, and a beam of the isotope of interest is sent to a counting station where studies of its nuclear properties can be conducted. Since these studies are made concurrent with the isotope's production, it is possible to work with very short-lived species, some existing for less than a second.

Separation is made by forming an ionized beam of all isotopes produced during the bombardment, accelerating the beam, and passing it between the poles of a curved magnet. The magnet acts on the ion beam as a prism acts on a beam of light. A slit placed after the magnet can be arranged to pass isotopes of a particular mass while all others are stopped. The selected beam of isotopes then is conducted through an evacuated tube to a shielded counting area for study.

A new line of research has been initiated in which collisions between the heavy ion beam of the MP Tandem and a heavy nucleus produce nuclei that rotate very rapidly. The aim is to test theories predicting how nuclei deform, distort and decay under high rotations (see Figure 6).

The ion beam of the MP Tandem has been used to measure the minute quantities of ^{14}C in very small samples in order to establish the age of, for example, archeological artefacts, old earthquakes or ground water; the latter information is of use in the selection of a site for the ultimate disposal of waste fuels from a nuclear reactor.

Recently developed theories on the fundamental origin of the weak and electromagnetic forces have suggested properties of gamma rays emitted in the decay of excited states of some nuclei that would be different from those predicted by the older standard theory. Very precise measurements of these gamma rays are under way to test these new theories.

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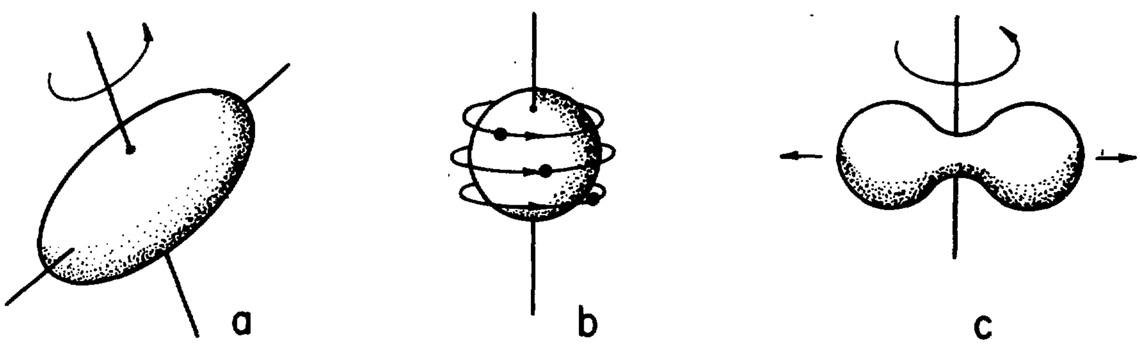

Fig. 6 Nuclei with High Spin. Some nuclei, even when not spinning rapidly, are ellipsoidal-shaped as in (a); when induced to spin rapidly the nucleus can be pulled into an even more elongated blob-like shape. In some cases nuclei given a high spin invest rotary motion in a few nucleons that rotate in aligned orbits as depicted in (b). At very high spin some nuclei may deform to the point of fissioning as in (c).

At the NRU reactor, studies of neutron capture reactions are continuing with emphasis on reactions that have a low probability of occurring, including some in which a proton or a heavier particle is emitted. The experimental facility is exceptional in providing an environment for measurements in which extraneous (background) radiation has been reduced to very low levels.

The gamma monochromator facility at NRU (see Section 2.2) is being used to study fission stimulated by the absorption of a gamma ray.

2.5 Radioisotope Standardization

Technological and commercial requirements have made worldwide standardization of radioisotopes and intercomparison of standards between laboratories increasingly necessary. In Canada standards are set and maintained by the National Research Council in cooperation with the International Bureau of Weights and Measures. CRNL maintains its own in-house Radioisotope Standardization Laboratory that supplies standards to users at CRNL and other AECL sites. Through international intercomparison activities, this laboratory has gained a worldwide reputation for accuracy.

2.6 Prospects for the Future in Nuclear Physics

The laboratory is at present engaged in adding a superconducting cyclotron to boost the energy of the ions emerging from the MP Tandem. The facility will increase the energy of all heavy ions from lithium to uranium by a variable factor around 10, but high enough so that nuclear reactions will be possible with any projectile element on any target element. At present the number of combinations of projectile and target is severely limited, thus the new facility will give much greater scope to nuclear studies.

The cyclotron is being built in CRNL as an accelerator project (cf. AECL-7074). The "superconducting" nature of the cyclotron is a CRNL innovation which is being emulated abroad. The buildings of the MP Tandem laboratory are in the process of being expanded to receive the new cyclotron. It is expected that the first beam will be accelerated in the cyclotron in 1983.

CRNL is also on the lookout for ways of extending its neutron research capability in both nuclear physics and condensed matter studies (next section). Some possibilities for stronger neutron sources than from the NRU reactor may present themselves in the development of powerful accelerators or fusion sources which are under study in the Advanced Systems Research program (AECL-7074).

3. CONDENSED MATTER PHYSICS

The condensed matter physics research at CRNL divides naturally into three parts: thermal neutron scattering studies (Sections 3.1 to 3.3), positron annihilation studies (Section 3.4) and development of detectors for use in both nuclear physics and condensed matter physics research (Section 3.5).

3.1 Basic Principles

The use of beams of thermal neutrons to study both the arrangement and the motions of the atoms in condensed matter (i.e. solids and liquids) was pioneered at CRNL in the late 1950's. The motion of the neutrons through matter is affected in two basic ways: by their interaction with nuclei of the atoms through the strong interaction and, because the neutron has a magnetic moment, through the electromagnetic interaction. By studying the changes in the motion of the neutrons through a material the researcher can deduce the properties of the material.

Neutron scattering is an extremely powerful tool, and it is now employed in several other laboratories around the world. The most versatile and widely used apparatus for exploiting this neutron probe, the triple-axis crystal spectrometer, was originally developed at Chalk River: four of these devices are now mounted at various beam holes at the NRU reactor, and a fifth at NRX. The major components of the N5 spectrometer at NRU are illustrated schematically in Figure 7. To understand how these spectrometers are used, and what they can tell us about solids and liquids, we must begin by discussing some of the basic properties of atoms and molecules in condensed matter.

Every material, at sufficiently high temperature and low pressure, exists as a gas, a disordered state in which the atoms or molecules are fast moving, widely separated on average, and interact only through occasional collisions. As the material is cooled, the atoms slow down and eventually condense, usually passing through one or more liquid and then solid phases, before reaching a final low temperature solid structure, in which in most cases the position of the atoms is highly ordered. In the various condensed phases, the atoms are in close proximity and

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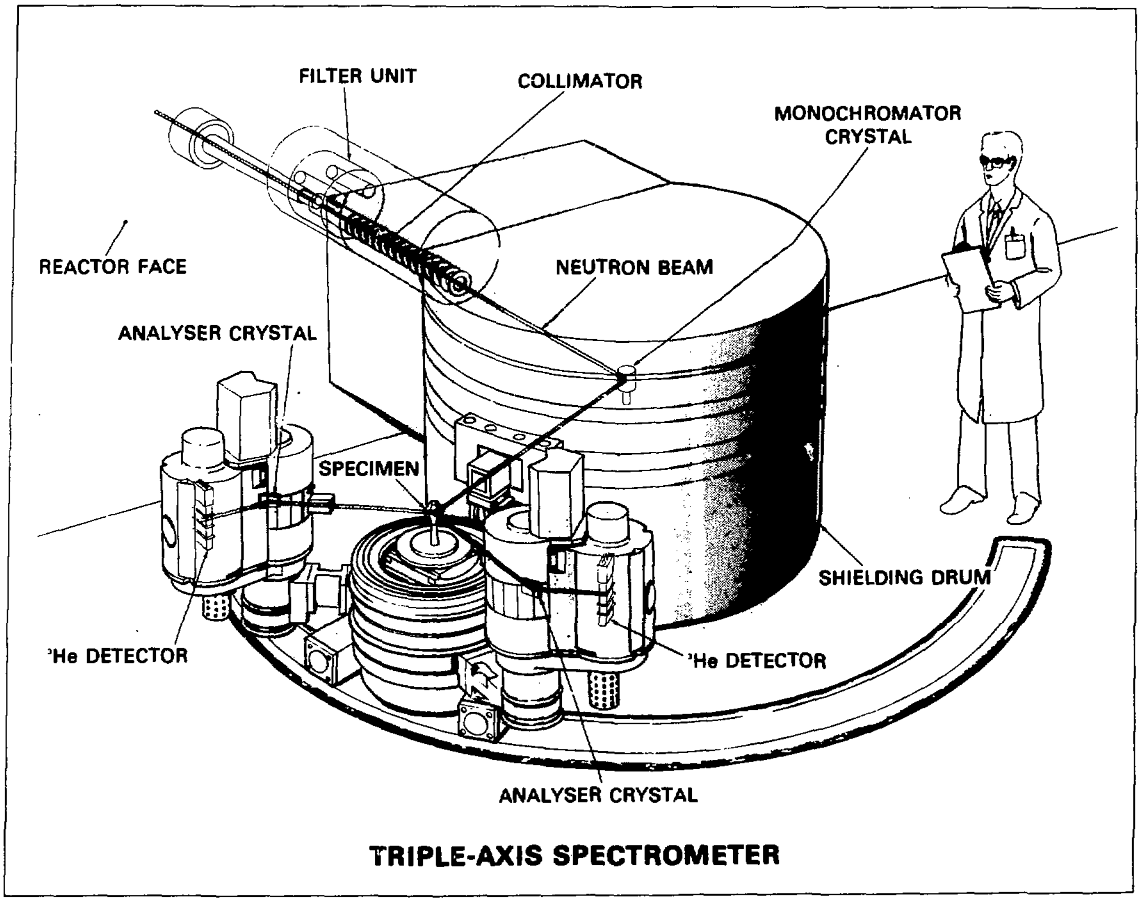

Fig. 7 Triple-Axis Crystal Spectrometer. The neutron beam emerging from the reactor has a broad band of neutron energies. Neutrons of any desired energy may be selected by so-called "Bragg reflection" from the monochromator crystal (first axis). After being scattered by the specimen (second axis), neutrons are again Bragg-reflected by the analyser crystal (third axis) into the ^{3}He gas detector. The neutron energies before and after scattering by the specimen are determined directly from the Bragg reflection angles.

forces which govern both the way in which the atoms are arranged in space and also the way in which they move. Some of the most fascinating areas of condensed matter research are concerned with studying the various phase transitions through which a material may pass on its journey from high temperature disorder to low temperature order.

Condensed matter physicists often describe the behaviour of solids and liquids in terms of various kinds of excitations: for example, the vibrations of atoms in a crystalline solid are described mathematically as a series of waves travelling back and forth in all directions in the crystal. The actual atomic motion is given by adding together all these waves in much the same way that different sets of ripples on a pond add together to produce the actual movement of water at each point on the pond surface. The atomic vibration waves called "phonon modes" are specified by their wavelengths and frequencies, just like ordinary sound waves. However, a typical sound wave has a frequency about 200 Hz (1 hertz = 1 cycle/second), whereas most phonon mode frequencies are in the enormously higher range 10^{11} to 10^{13} Hz, and their wavelengths are extremely short, of the order of interatomic distances, about 10^{-10} metres (see Figure 1).

In order to study these atomic vibrations, the physicist shines a beam of neutrons onto the crystal and observes how these neutrons are scattered by the atomic nuclei. (The neutrons are also scattered by the electrons which surround the nuclei, but this electronic scattering, except in the case of magnetic materials described below, is generally very much weaker than the nuclear scattering.)

We can think of the neutron beam as if it were a wave being "reflected" from sheets or planes of atomic nuclei in much the same way as a beam of light is reflected from the surface of a lake. The vibrations of the atoms distort the neutron reflections just like the ripples on the lake disturb the images of reflected light. By measuring these reflections and their distortions, we may deduce the pattern of atomic movements in the crystalline solid, that is to say, we may determine the wavelengths and frequencies of the "phonon modes". The unique properties of slow neutron beams happen to be perfectly suited to the measurements of these very high frequencies and very short wavelengths.

Another type of basic excitation, which is invoked to describe fundamental properties of magnetic materials, is the so-called "spin wave". In a magnetic material, like iron, the atoms behave just like tiny magnets: each atomic magnet tries to make its neighbours line up with it, to produce a ferromagnetic arrangement (all magnets parallel). Because the neutron itself is magnetic, it can be reflected by the rows of iron atoms: from the pattern of neutron reflections, we can deduce the actual ferromagnetic structure. If one magnet is disturbed, it makes its neighbours vibrate in a pattern known as a "spin wave" or "magnon mode", as illustrated in Figure 8. The energy required to set up this magnetic disturbance (that is, to "create a magnon mode") is taken from the neutron beam on its way through the iron crystal. By measuring the energy changes of the neutrons as they are scattered from the array of atomic magnets, we can determine the magnon mode energies, or, equivalently, the spin wave frequencies.

The frequencies of both the phonon modes (vibrations of atoms) and the magnon modes (vibrations of magnetic moments) depend on the strength of the forces between the atoms. These "interatomic forces" can therefore be calculated from our measurements of the phonon and magnon frequencies. A knowledge of these forces is essential for understanding the physics of materials under various conditions of stress and temperature, materials containing defects, alloys, crystalline and amorphous materials, indeed all the diverse states of condensed matter which make up the world around us.

The purpose of a neutron spectrometer, such as the triple-axis crystal spectrometer shown in Figure 7, is to measure the energy and direction (i.e. momentum) of a neutron beam both before and after it is scattered by the specimen under investigation.

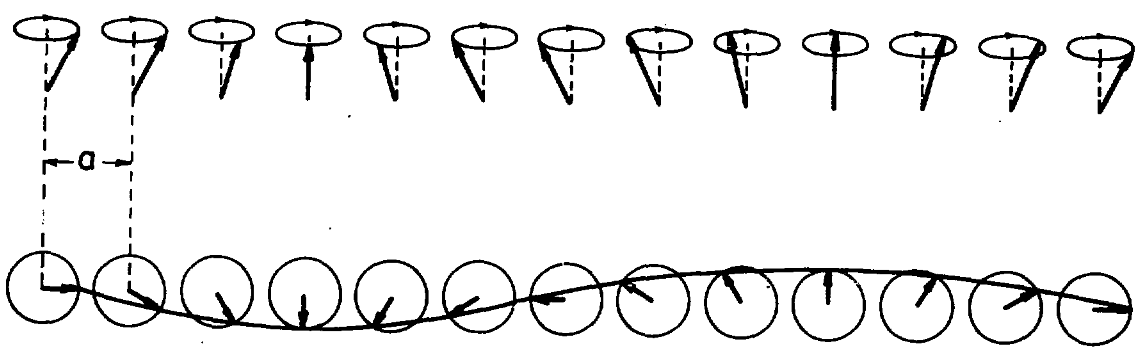

Fig. 8 Illustration of a Spin Wave, or Magnon Mode (side view above and top view below). Each atomic magnet, represented by an arrow, is precessing about its mean (vertical) orientation. In this example of a spin wave disturbance, the precession angle changes by 2π radians, i.e. 1 full wavelength, after 12 interatomic distances, a.

3.2 Major CRNL Achievements in Condensed Matter Physics

Neutron scattering research at Chalk River has produced many significant "firsts", of which perhaps the most important of all involved the measurement of phonon modes in alkali halides, which led directly to the establishment of the famous "shell model" of interionic forces, and to the "soft mode" theory of phase transitions. The phonon modes are basically controlled by interactions between atomic electrons: special electronic effects can sometimes produce fascinating "anomalies" in the phonon spectra. Examples of such anomalies observed and interpreted at CRNL include the Kohn effect in lead, electron band structure effects in transition metal alloys, and phonon-plasmon coupling in the semiconductor lead telluride (the plasmon is yet another basic excitation, in this case of the conduction electrons in the semiconductor).

Several important discoveries concerning the structure and excitations of superfluid helium, made during the course of painstaking and comprehensive experiments, have culminated in the recent determination of the fraction of helium atoms in the mysterious "zero momentum" state. The first complete measurement was made at CRNL of intermolecular vibration and libration modes in a molecular crystal, hexamethylene tetramine, from which the intermolecular forces were derived.

The magnetic moment of the neutron has been widely exploited at CRNL to study the spin wave modes (see Figure 8) of many types of magnetic material, such as compounds containing iron, cobalt, manganese, rare earth metals and uranium. Major advances in this area include the observation of the spin-wave-phonon interaction, of multibranch spin waves, of impurity modes in magnetic insulators containing defects, and the development of a theory of new kinds of spin wave excitations, the so-called "excited state and central modes".

3.3 Current Programs in Neutron Scattering

The increasingly vigorous growth, worldwide, of the application of neutron scattering methods to many different areas of condensed matter research - physics, chemistry, biology, metallurgy - indicates that the field is approaching a fully mature and very active stage. The current CRNL program includes ever more complex investigations into areas mentioned in Section 3.2, particularly as regards liquid helium, molecular solids, and magnetic materials. A most fascinating aspect of this last category is concerned with certain uranium compounds in which the uranium ion appears to be fluctuating between divalent and trivalent states. Another exciting research area concerns the rotational motions of molecules in so-called "plastic" crystals, which are in a sense intermediate between the solid and liquid states. In addition, the techniques of small angle neutron scattering and applications to biologically important molecular materials such as DNA bases are currently being studied at CRNL.

3.4 Positron Annihilation Studies

Positrons are positively-charged particles of anti-matter, identical, except for charge, to the negatively-charged electrons of normal matter. They are emitted with high energy during the β-decay (see Section 2.2) of certain unstable nuclei, such as ^{64}Cu, which can be produced by irradiation of ordinary copper in a nuclear reactor. They stop rapidly in matter (by means of many collisions with the atoms) and remain there until they annihilate with an electron. The combined masses of the two particles, positron and electron, are then converted into energy in the form of two gamma rays which leave the site of the annihilation at the same time and in almost opposite (back-to-back) directions. The small angular difference from a complete back-to-back emission is proportional to the velocity of the electron in the material before it annihilated. The gamma-ray count rate tells us how many electrons in the material have a given velocity. Knowledge of the electron velocities provides one of the few means of testing theories of the electronic structure of metals and alloys.

The apparatus used for these experiments is illustrated in Figure 9. More recently, however, it has been used to make

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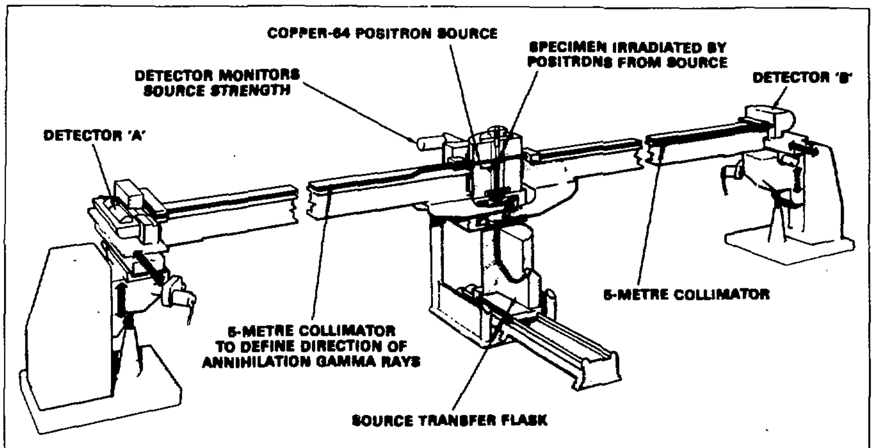

POSITRON ANNIHILATION APPARATUS

Fig. 9 Positron Annihilation Spectrometer: Positrons from a ^{64}Cu source (produced by neutron irradiation of copper in the NRU reactor) strike the nearby specimen at the centre of the apparatus. Two gamma rays are emitted simultaneously in almost opposite directions when a positron annihilates with an electron in the specimen. Small departures from the 180° emission angle are measured very precisely by means of the long collimators leading to sodium iodide detectors at either end of the spectrometer.

positron studies of various kinds of defects in metals and alloys, such as vacancies, voids and grain boundaries. Such studies are possible because the positively-charged positrons, being strongly repelled by the positively-charged nuclei, tend to migrate towards any empty spaces in the sample material, where eventual annihilation with electrons takes place. For example, the energy required to form a lattice vacancy, a quantity of considerable metallurgical importance, has been determined at CRNL for a number of metals and alloys.

3.5 Development of Radiation Detectors

Accurate and reliable measurements of nuclear radiations are essential for very many activities at CRNL, including monitoring reactor performance or employee exposure, studying corrosion processes or fundamental properties of solids, analysing trace contaminants or nuclear structure, producing medical isotopes or radioactive standards.

Three CRNL achievements in radiation detector development deserve special mention. The first was a novel design of a rugged, halogen-quenched Geiger-Mueller counter that operates reliably for years in fields up to 50 roentgens per hour*. Very large detectors filled with boron trifluoride gas (15 cm in diameter and 180 cm long) were successfully developed and produced in quantity as cosmic-ray neutron monitors for the International Quiet Sun Year. Later these detectors (which are still providing international markets for Canadian industry) became important in the U.S. manned space program by providing advance warning of increases in the radiation fields surrounding the earth.

A CRNL achievement responsible for major advances in all fields of nuclear science was the development of large lithium-drifted germanium detectors for high-resolution gamma-ray spectrometry. This was recognized by the American Nuclear Society in 1967 when it made its first Radiation Industry Award to the Chalk River scientists who carried out the work.

Other developments include helium-3-filled detectors (see Figure 7) for neutron scattering experiments, low-background detectors for environmental monitoring and an automated ionization-chamber system for use in the preparation of radioactivity standards for the International Reference System of the International Bureau of Weights and Measures. A continuing effort is directed towards the provision of special designs of high-purity germanium gamma-ray spectrometer systems for monitoring fission products.

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* The roentgen is a special unit employed to express exposure to X- or γ-radiations. 1 roentgen = 2.58×10^{-4} C/kg of air at 273.15 K and 101 325 Pa.

4. THEORETICAL PHYSICS

4.1 Models and Concepts

The goal of theoretical physics is to describe the physical properties of nature through mathematical models. In practice the goal is achieved by comparing the observations from experiment with the predictions from the models. A lack of agreement signifies the need for a modification of the models which, in turn, leads to a greater understanding of the laws of nature. A successful model will lead to correct predictions of the results of all the different types of experiments that can be performed. A theorist strives for models in the various areas of physics (condensed matter, nuclear, elementary particles) that are mutually compatible. The models thus constructed are often used in practical applications, for example in AECL, for the predictions and understanding of the internal behaviour of a nuclear reactor; in the construction of particle accelerators; and in the fabrication of solid state devices.

4.2 Some Past and Present Research Activities

Much work continues to be done at CRNL on setting up and solving the so-called "transport equations", from which the number of neutrons existing in various parts of a nuclear fission reactor can be determined. These equations have to take into account the changes of speed and direction of the neutrons when colliding with atoms present not only in the uranium fuel, but in all the materials that make up the reactor - including the cooling fluid. The absorption of the neutrons in the structural materials is an essential part of the calculations.

As discussed in Section 3.1, the changes in speed and direction of slow neutrons when allowed to interact with liquids or solids can be used to determine the properties of these materials. Much work has been done in developing and improving techniques and models through which such information reveals the properties of the target specimen. Recent collaborations between CRNL theorists and experimentalists have advanced our understanding of the liquid states of helium and neon. A description has been given, from fundamental principles, of the effects of pressure on the density- and spin-density-excitations of normal liquid ^{3}He. The theory of neutron optics (reflection, refraction and diffraction) has been extended and the nature of the rotational motion of molecules in crystals illuminated. A study has been made of the ways in which impurities in a crystal cluster together.

A comprehensive theory has been developed to describe the slowing down of ions in liquids and solids. This theory has been used to analyze the results from nuclear physics experiments (for example, to determine the lifetimes of nuclear states); to determine how ions can be implanted in a material to make a "solid state" device such as a transistor; and to determine how ions penetrate into the structural components of fission and fusion reactors where they can cause various deleterious effects.

Various models for the structure of the atomic nucleus have been proposed which, on the surface, give different views of the nucleus. In one model, the nucleons move in orbits or spherical shells; radiation can be emitted or absorbed by the nucleons jumping from one orbit to another. Another model has the nucleus as a whole in a collective state shaped like a cigar or perhaps a pancake which rotates or vibrates: radiation can be emitted or absorbed by a change in frequency of the rotation or vibration. CRNL theorists have demonstrated how the collective states can arise from the interaction among nucleons and how such models are consistent with the "spherical shell" model (the latter not to be confused with the different model with a similar name in condensed matter physics of Section 3.2).

The recently discovered relationship between the weak and electromagnetic interactions (by scientists in the USA and Europe) has given us a new perspective on the beta-decay process (see Section 2.2) and how this is connected to the decays among the other "elementary" particles (similar to the nucleons) which are created in high energy physics experiments. CRNL theorists are examining the ramifications of this new theory for the understanding of the properties of nuclei and the decay of the elementary particles.

Through a detailed study of both beta and gamma decays of some states of light nuclei it has been found that the basic nuclear model, in which only neutrons and protons are taken into account (see Section 2.2) is inadequate. An understanding of the experimental results has been given by extending the basic model to include explicitly the effect of other particles (e.g. the pion) within the nucleus.

Studies of the properties of the roughly 100 "elementary" particles (like the nucleons) now known have suggested that these are made up of more fundamental objects called quarks. In analogy with the understanding of the electromagnetic-weak forces a new fundamental origin for the strong interaction has been proposed in the USA based on the interaction among the quarks. CRNL theorists are involved in some pioneering studies of these new ideas, for example, in trying to calculate, from such a fundamental strong force, the effective force between two nucleons and the effective force in a many-body system (i.e. understanding the binding of nucleons in nuclei). They are also interested in determining the effects of quark interactions on the decays of elementary particles.

In addition to the main lines of research mentioned above, theoreticians are often called upon to advise on problems and methods associated with the nuclear industry. Such studies have involved, for example, design of precise magnetic spectrometers, methods of isotope separation, hydriding in nuclear fuel rods, and the theory of both laser and magnetic confinement fusion systems.

5. CONCLUSION

Underlying research in Physics at CRNL strives to strengthen the interplay between the purely academic pursuit of knowledge for knowledge's sake and the initial introduction of such knowledge into practical applications. In order to be effective in fulfilling this function the scientists involved must be dedicated to scientific enquiry and at the same time enjoy the deep satisfaction of seeing new ideas put to practical use. Not all scientists are, or need be, blessed with both attributes in full degree; together they form a strong team that can usually supply information, advice, or technical assistance anywhere in their subject area. They are sustained at peak performance by a well-equipped laboratory designed to be as efficient as possible in supporting forefront research across a broad field.

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