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NUCLEAR PHYSICS : A BENEFICIARY TO SOCIETY

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INTRODUCTION:

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Society supports fundamental research in the expectation of benefits that support national priorities. These benefits take many forms. Satisfying natural human curiosity about the workings of nature is one, and this is the principal motivation for most researchers. Their search for new knowledge often stimulates advances in the limits of technology. It leads to instrumentation and theoretical concepts that address problems of societal concern, and to advances in other areas of science. The concepts and techniques of nuclear physics have had exceptional impact in this regard.

An equally important aspect is the contribution, nuclear physics makes to the education of the technically sophisticated workforce that is essential for the nation's present and future economic well-being. Graduate education in nuclear physics provides broad training, involving experimental and conceptual techniques from a broad range of science and technology. As a result, nuclear physicists contribute in many areas of our society, frequently well beyond their original training in nuclear physics. Nuclear physics laboratories also provide an infrastructure for the hands-on education of younger students, involving undergraduates in research and exposing secondary school teachers and their students to the subatomic world and to scientific research.

The direct applications of nuclear physics have a major overlap with the priorities of the nation: improvements in human health, the environment, the efficiency of industrial processes, energy production, the exploration of space, Bottom of Form and national security. Beyond these direct applications is the general benefit that arises from pressing forward the frontiers of high-technology development.

Some of the most pervasive applications of nuclear physics are in medicine. Medical imaging techniques now widely used, such as positron emission tomography (PET) and nuclear magnetic resonance imaging (MRI), provide information in three dimensions about the structure and biochemical activity of the human interior. Radioactive isotopes produced by accelerators and reactors are routinely used in medical diagnostic procedures, in treatment, and in medical research. Cancer radiation therapy mainly uses electron accelerators and radioactive sources. Treatment with protons, neutrons, and heavier ions is becoming more widespread and shows great promise for improved selectivity and effectiveness.

Many applications to environmental problems take advantage of the exceptional sensitivity of nuclear techniques such as accelerator mass spectroscopy to obtain information not available by other means. One can determine oceanic circulation patterns, the rate of carbon dioxide exchange between the atmosphere and the land and oceans, and the historic climate record. All of these have major implications for an understanding of climatic change. Studies of groundwater resources and their recharge rates, and of the origin of atmospheric pollutants, also provide unique information.

The assortment of industrial applications reflects the great variety of industrial processes. One common theme is the use of nuclear techniques and accelerators to determine the composition and properties of materials, their structural integrity after manufacture, and their wear in use. Another is the development of techniques for the modification of materials through accelerator ion-implantation, as in the doping of microelectronic circuits, or the introduction of defects to increase the current-carrying properties of high-temperature superconductors.

Safety and national security are areas with broad applications of nuclear techniques. Their use in detection of explosives and weapons has occupied increasing attention as a barrier to terrorism. Diagnostic procedures based on nuclear physics techniques will play a major role in noninvasive monitoring of chemical weapons and in controlling the distribution of enriched uranium and plutonium from dismantled nuclear weapons. Such procedures will also be important in the stewardship of the remaining nuclear stockpile. Intense beams from accelerators may in the future serve a joint role in production of the tritium required to maintain the required stockpile of nuclear weapons and in disposal of radioactive wastes. Top of Form Bottom of Form and of some others with a good chance to become important in the future—are given here.

Human Health

Technologies emerging from nuclear research have an important impact on human health and have resulted in a new field, nuclear medicine. In the United States, 1,600 radiation oncology departments operate 2,100 linear accelerators. Nuclear diagnostic medicine generates approximately $10 billion in business annually, radiation therapy using linear electron accelerators about the same, and instrumentation about $3 billion. Over 10 million diagnostic medical procedures and 100 million laboratory tests using radioisotopes are performed annually in the United States. Three areas of particular medical significance are cancer radiation therapy, diagnostic imaging, and trace-isotope analysis.

Radiation Therapy for Cancer

Over a million new patients develop serious forms of cancer every year, and about half of them receive some form of radiation therapy. Traditional radiation treatments use streams of x- rays or nuclear gamma rays. These high-energy photons deposit most of their energy where they enter the body. Thus, for a single exposure, healthy tissue unavoidably receives a higher dose than the cancer. The damage to healthy tissue can be ameliorated by irradiating the tumor from many different directions, all intersecting at the site of the tumor. Teams of radiologists, physicists (many with training in nuclear physics), and computer programmers design three-dimensional treatment plans (conformal therapy) that maximize dose-deposition in the tumor while minimizing the exposure of healthy tissue.

Recent developments by nuclear scientists and radiologists that use protons, neutrons, and heavy ions for radiation therapy promise to reduce the problems inherent in treatment with photons. As new accelerators designed explicitly for cancer treatment come into wider usage over the next decade, it is likely that there will be significant improvements in radiation treatment, resulting in more cures and fewer side effects. These advances will use techniques, knowledge, and accelerators that stem from nuclear physics.

Cancer Therapy with Protons

The use of protons for radiation therapy has the advantages that protons deposit more of their energy where they stop, not where they enter the body, and that their depth of penetration can be precisely controlled so that they stop within the tumor. This allows radiologists to increase the radiation dose to the tumor while reducing the dose to healthy tissues.

Over 20,000 patients have been treated with protons, mostly at accelerators originally built for physics research. Now, physicists are designing accelerators optimized for cancer therapy; one has been in operation since 1990 at Loma Linda Hospital near Los Angeles, and many others are in various stages of planning and construction, both in the United States and overseas.

Cancer Therapy with Neutrons and Heavy Ions

Research is continuing with other forms of radiation therapy that use neutrons and heavy ions. Neutrons produce a high linear energy transfer (LET); i.e., the density of broken chemical bonds in the cell is high. High-LET radiation overcomes a cancer cell's resistance to radiation damage more effectively than low-LET photon, electron, or proton radiation. Thus neutrons appear to be more biologically effective in killing cancers than are many other forms of radiation, especially in oxygen-poor cells. After three decades of clinical experience, it appears that some 10 to 15 percent of patients referred to radiotherapy would benefit from neutron therapy for cancers such as salivary gland tumors, some head and neck tumors, advanced tumors of the prostate, and melanomas.

A recent example of an optimized neutron facility is the superconducting neutron-therapy cyclotron designed and constructed by the National Superconducting Cyclotron Laboratory at Michigan State University. This cyclotron is in operation at Detroit's Harper Hospital, where neutron therapy is part of new cancer treatment protocols that have already shown highly promising results for tumors otherwise difficult to treat.

Beams of heavy ions, such as carbon or neon, with energies of 400-800 MeV per nucleon, are nearly ideal dose delivery vehicles for radiation therapy. They produce high LETs, which may offer the advantage of selectively destroying cancer cells (as compared to normal cells), and a sharply defined dose profile.

Diagnostic Imaging

Diagnostic imaging technology started a century ago when Roentgen, the discoverer of x rays, immediately applied the penetrating power of these high-energy photons to make images of the interior of the human body, thereby revolutionizing diagnostic medicine. New imaging techniques have continued to have revolutionary impacts by providing improved, more sophisticated ways to see inside the body without surgery. Fundamental discoveries in physics have Bottom of Form given us x rays, computerized axial tomography (CAT), nuclear magnetic resonance imaging (MRI), single photon emission computerized tomography (SPECT), and positron emission tomography (PET). Some of these—CAT scans, MRI, and, increasingly, SPECT—are now standard diagnostic tools of comparable importance with basic x rays, and the needed instruments are provided by commercial manufacturers. The practitioners of advanced PET techniques are often nuclear physicists, who continue to develop more powerful instruments and techniques, and work with physicians to apply the techniques in the medical environment.

SPECT and PET Imaging

The SPECT imaging technique uses drugs containing small amounts of short-lived radioactive isotopes, mainly single photon emitters. The emitted photons are viewed by large detector arrays, which are moved around the patient to obtain a complete picture of the drug's concentration in the body. If the drug accumulates only in particular sites, such as cancer metastases, the images show the location of these metastases.

In contrast, the PET imaging technique uses drugs containing small amounts of short-lived radioactive isotopes that emit positrons. When a positron encounters an electron in the patient's body, the two particles annihilate and emit a pair of photons, which move in opposite directions and strike radiation detectors arranged in a circle around the patient. The line connecting the two detectors that were struck passes through the point where the annihilation took place; by using information from all detectors, one can pinpoint the location of the nuclear decay. Since the annihilation takes place near the drug molecule that contained the positron-emitting nuclide, PET devices can image metabolic activity within the human brain for neurological and psychiatric evaluations, or the whole body for detecting cancer, or the metabolism in the heart and other organs. One can study the body in near-equilibrium by administering the positron-emitting nuclides slowly with time, or study the body's dynamic response by administering the positron-emitting nuclides over a short time interval and then observing their spread through the body with time. Physicists are currently developing ultra-fast PETs that could one day be used for online dose verification in cancer radiation therapy, allowing much more accurate dose administration than is now possible.

Nuclear Magnetic Resonance Imaging

An important activity that helped unlock the mystery of nuclear structure was systematic study of nuclear magnetism. In its simplest manifestation, the nucleus behaves like a tiny bar magnet. Developing precision methods for measuring the strength of the nuclear dipole magnet was an early goal of nuclear physics.

Trace-Isotope Analysis

Radioactive nuclear isotopes produced by accelerators or nuclear reactors are used in many areas of biological and biomedical research. These isotopes have chemical properties essentially identical to their stable counterparts, but they decay and emit characteristic radiation that is readily detected. By inserting such radioisotopes as ^{14}C and tritium, it is possible to turn molecules into tiny transmitters without perturbing their natural biochemical properties. The signals from these transmitters (their unique radioactive decays) provide information on how molecules move through the body, what types of cells contain receptors, and what kinds of compounds bind to these receptors. Radioisotopes help researchers to develop diagnostic procedures and to help create new pharmaceutical treatments for diseases, including cancer, AIDS, and Alzheimer's disease. They are also used directly to treat disease. Radioactive tracers are indispensable tools for the new forensic technique of DNA fingerprinting, as well as for the Human Genome Project, which seeks to unravel the human genetic code.

Accelerator Mass Spectrometry

Accelerator mass spectrometry (AMS) was developed by nuclear scientists building on the experimental technology of nuclear physics. It is used in a number of areas of research, medical research among them. The technique uses nuclear physics accelerators to make possible new uses of isotopes in the health sciences, for applications where the common techniques are inadequate. In AMS, atoms from a minute sample are ionized and accelerated to a sufficiently high energy that one can detect and identify individual atoms, using nuclear techniques. One thereby measures the concentration of a given tracer without having to wait for its decay. When the time available for observation in the laboratory is much shorter than the half-life of the isotope, AMS has a much higher sensitivity for long-lived isotopes than does decay counting. Only very small quantities of tracer material are required, greatly reducing exposure to radioactivity.

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