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The remarkable technological advances in the field of atomic energy since it first attracted public interest a decade ago promise basic changes in many aspects of our social and economic life. But the achievements, however spectacular, have been of the nature of engineering and inventive successes, not scientific discoveries. Nuclear fission and thermo-nuclear fusion, the basic phenomena which have inspired the major efforts of our atomic energy program, were known to physicists before that program was started. Since that time our detailed knowledge of them has been greatly enlarged, but our understanding of the principles has not changed in fifteen years.

The main reason for this state of affairs is that nuclear phenomena and the laws governing the behavior of sub-nuclear particles appear to be considerably more complicated than, for example, electrical phenomena and the laws governing the structure of the atom. Our ability to classify and predict nuclear phenomena is in a more primitive state than was our understanding of electricity at the time of Edison's inventions. The successful harnessing of nuclear energy has by-passed the normal evolution of invention by virtue of great effort and expense in the face of urgent national needs.

Accordingly, it is very much in the national interest that a certain amount of basic research be supported; work, that is, directed not toward a specific technical development, but toward the vaguer goal of improved understanding of what goes on inside the atomic nucleus. We are today living on a capital of the discoveries of the 1930's; future fundamental inventions will more probably be derived from current and future fundamental discoveries.

Historically, the development of nuclear physics involved first a study of nuclei as they exist in nature. The general picture was formed of the atom as consisting of a number of electrons circulating at relatively huge distances about a small, massive, electrically charged object. The properties of matter which are familiar to us arise from the actions of the electrons, either in a single atom or under the influence of adjacent atoms, as in a molecule or crystal. The object at the center, called the nucleus of the atom, appeared to be impervious to any known influence. Electrons can be rearranged or removed from an atom with relative ease, but no amount of heating, hammering, soaking, or chemical action produced the slightest detectable effect on the nucleus. Radioactivity was a truly exceptional phenomenon in that it appeared that the nuclei of certain elements could change into nuclei of different elements by emitting electrically charged fragments.

Now an essential aspect of physical research is the development of techniques for manipulating the objects of study for taking them apart and reconstructing them in a systematic way. The first success in this respect came in 1919 when Rutherford found that the fragment emitted by radium could penetrate the nucleus of a nitrogen atom, be absorbed, and cause a hydrogen nucleus to be emitted, leaving behind the nucleus of an oxygen atom. Subsequently it was found that several elements could respond in a similar manner. In particular, the neutron was discovered and identified as a particle emitted by various nuclei when struck by the fragments emitted by radioactive nuclei, immediately establishing the picture of the nucleus as composed of protons and neutrons.

These events were, of course, not the only significant ones in that earlier period, but they served to point up the value of experiments built around the technique of causing nuclei of simple type to impinge on matter with momentum sufficiently great to penetrate the atoms of a material, overcome the electrical repulsion of the nucleus, get inside it, and upset its constitution. The use of naturally occurring nuclear fragments for this purpose is severely limited as to type and range of velocities available, and the urge was great, in the late '20's and early '30's, to produce nuclei moving at high speed by artificial means.

This need has been met in a number of ways and the devices which do the job constitute a family known as particle accelerators or "atom smashers". Their importance in basic research has grown to the point where many of our large nuclear research establishments are geared to the capabilities of one or more accelerators for which they are responsible. These devices are often impressively large and expensive, so that public contact with basic research is primarily through press notices of the beginning or completion of new machines.

Before considering in detail the functioning of some of these accelerators, a few illustrative numbers might be of interest. The nuclei most commonly used as projectiles are the proton (hydrogen nucleus) and its heavier isotope, the deuteron (composed of one proton and one neutron). To produce appreciable nuclear effects they must be accelerated to speeds in excess of 5,000 miles per second; recent machines bring them almost to the velocity of light (186,000 miles per second), a limit which cannot be exceeded by any material body, according to Einstein's theory of relativity. In hydrogen gas at room temperature the molecules move about at the respectable average speed of about one mile per second, but they are essentially standing still as far as nuclear events are concerned. To induce nuclear reactions at an observable rate might require a million million accelerated protons arriving each second at the piece of material to be bombarded. One in a million of these protons might manage to penetrate a nucleus of the target material and cause a disruption. The particular event of interest to the experimenter -- say the ejection of a neutron in a particular direction with a particular speed-- might happen as rarely as once a second. Because the electric charge of a single proton is so small, a current meter connected to the bombarded material would register less than one millionth of an ampere. Because the proton's mass is so small the multudinous stream striking the target would exert a force on it measured in millionths of a gram. In short, the large scale effects of beams of nuclei from particle accelerators are slight. Only on a sub-atomic scale do nuclear events seem catastropic; only when the events involve the emission of particles which can produce similar events in neighboring nuclei, as in the chain reactions, do the macroscopic effects become important.

The only practical means of applying accelerating forces to nuclei which have so far been suggested exploit the fact that the nuclei carry an electric charge. Acceleration of electrons by strong electric fields is today a commonplace. In a radio tube electrons boiled off the hot cathode are drawn to the positively charged plate, picking up speed as they go. When the plate of a high power transmitter tube gets hot, it is because the accelerated electronsstrike it, dissipating their kinetic energy as heat. The spot which runs across the screen of a television set to form the picture is caused by a narrow pencil of electrons which has been gathered together at the rear end of the tube and accelerated to a speed sufficient to disturb the molecules of the screen material. The molecules respond by emitting light, just as a nucleus, properly struck, responds by emitting particles, or occasionally X-rays of very short wave-length. And just as the light can be analyzed to give us information about the structure of the molecule, so can the radiation from the nucleus be analyzed; indeed, there are very few other ways of learning about nuclei.

Appreciable nuclear effects can be produced with an installation not much more complicated than a television tube. An electrical discharge similar to that in a neon sign tubing to strip the atomic electrons away, an evacuated, electrically insulated, pipe in which acceleration can take place, X-ray transformers in the range of 100,000 volts to maintain an electric field, and a supply of heavy hydrogen can provide a laboratory with a generous source of neutrons, for deuterons give up their neutrons very easily when they strike stationary deuterons. For intensive research, there are better neutron sources, but many a student has had his first taste of nuclear physics through such a device.

To obtain higher voltages requires more complicated equipment. The first nuclear transmutations by artificially accelerated nuclei were caused by protons accelerated through a potential difference of 500,000 volts. The voltage was achieved by an electronic circuit designed to multiply voltages. A simultaneous (1930-32) development which ultimately led further was the Van de Graaff generator, in which charge is deposited on a high voltage electrode, not by wires and vacuum tubes, but mechanically, by spraying it on a conveyor belt at the ground end and removing it at the high voltage end. Both devices were limited at first by sparks from the high voltage terminal to the walls of the surrounding building-- a dirigible hangar was the most suitable enclosure. Presently it was realized that sparking could be prevented by increasing the air pressure in the region surrounding the accelerator, with the result that today compact and reliable Van de Graaff machines that generate as much as six million volts are available commercially.

Since the voltages which can practically be maintained are so sharply limited, the production of more energetic nuclear projectiles requires a less direct approach. Instead of giving the particles one big push, an [illegible] device must provide means for giving them a large number of [illegible] boosts in kinetic energy. With few exceptions, the big accelerators of [illegible] follow this approach. Acceleration is provided by a succession of suitably timed impulses, and in the interests of saving space and avoiding complexity the particles are usually guided around in closed paths so that the same accelerating electrodes can be used over and over again.

The machine based on the principle of repeated accelerations which first produced nuclear disintegrations was the cyclotron. It has been known for some time that a magnetic field, which can push sideways a wire carrying electric current, as in an electric motor, has a similar effect on a stream of charged particles moving through space. In particular, a field uniform in magnitude over an extended area will cause such a stream to travel in a circle whose radius is proportional to the speed of the particles. Thus the time required for them to go around is the same regardless of their speed, so that an alternating electric voltage applied across a diameter of the circle will increase the kinetic energy of the particles each time around, provided that its period matches the orbital period of the particles. In practice, the alternating voltage is applied between two halves of a pillbox structure cut along a diameter and placed between the poles of a large electromagnet. The protons or deuterons are generated in an arc at the center of the pillbox, circulate inside it while they are being accelerated, and are finally pulled out electrically through a slit in the outer edge of the electrodes when they reach the maximum speed and radius.

In a cyclotron of modest proportions, that is, one which might be constructed and maintained by a university or a private research group, protons and deuterons can be brought to speeds [illegible] could [illegible] achieved with [illegible] voltage of the order of 10 million volts. [illegible] range of [illegible] cyclotrons [illegible] can be increased [illegible] rapidly [illegible] the [illegible] following [illegible] many machines of this category were built, primarily in this country [illegible] Europe and Japan.

The cyclotron also is subject to a practical limitation in particle energy. It depends for continuing acceleration on a precise match between orbital period and the period of the applied voltage, a condition which cannot be strictly maintained. It is an unfortunate consequence of the theory of relativity that as the speed of a particle increases its mass also increases, and the orbital period does depend on particle mass. It also depends on the magnitude of the magnetic field, but other factors exclude the possibility of making compensatory changes in the magnetic field as the radius of the orbits increases. A way to forestall particle and applied voltage falling out of synchronism is to use as high an applied voltage as possible so that the particles have to go around as few times as possible. In this direction, a cyclotron at Oak Ridge producing protons of kinetic energies corresponding to 25 million volts is probably close to the ultimate.

The next substantial increase in accelerator size, putting us in reach of an entirely new class of nuclear phenomena, came at the end of the war. It was pointed out that synchronism could be maintained by varying the period of the applied voltage or the strength of the magnetic field, not spatially but in time. The profundity of this suggestion lay in the demonstration that, subject to certain easily attainable conditions on the parameters of the machine, the system can be made self-regulating--that is, the particles will automatically try to stay in step with the applied voltage, much as a synchronous clock motor is forced to turn at a rate proportional to the frequency of the applied voltage. This innovation, which lends itself to several variations, has increased the practical range of particle energies by a factor of 1000, and thereby opened whole new sub-fields in the study of nuclear physics.

The first machines to accelerate protons according to the new scheme were called synchro- or frequency-modulated-cyclotrons. They are large versions of the cyclotron, with one exception. As the particles pick up speed and spiral outward the frequency of alternation of the applied voltage is changed to correspond to the changing orbital period of the particles. According to the synchrotron principle, the continuous readjustment of frequency can be made without concern about keeping up with the particles; instead the particles adjust their energy and radius of curvature to keep up with the imposed frequency changes. The applied frequency is changed by a mechanical control at a relatively leisurely rate. A packet of particles runs around in circles of ever increasing radius until the applied frequency reaches a value appropriate to the extreme radius of the magnet, whereupon those energetic particles are extracted or intercepted by a target; the applied frequency is then readjusted to pick up a new packet at the source of supply at the center.

The synchro-cyclotron also brings us into a new organizational category. Its size, entailing an inevitable increase in the complexity of research programs and auxiliary services, necessitates separate buildings, facilities, and a full-time staff of specialists in many categories. Its cost requires the financial assistance of the government. It is at this point that basic research essential to the future of nuclear physics becomes a subject of public concern and responsibility.

Existing synchro-cyclotrons cover a range of kinetic energies from 100 to 450 million "electron volts"-- a unit of energy referring to the equivalent d.c. voltage. They could be made substantially larger, butthe electromagnet and accelerating electrodes become increasingly expensive and unwieldy. The next upward step in particle energy was made in the proton synchrotron, a machine which continues with the same principle of acceleration, but with a great change in superficial appearance. The magnetic field is set up, not over a large circular area as before, but in a narrow ring of large diameter. The particles are kept at constant radius all the while they are being accelerated, by increasing the strength of the magnetic field at just the right rate. The alternating voltage is applied at one point along the circumference, its frequency changing as the particle's speed changes. To maintain the proper relations between magnetic field and applied frequency so that the particles will stay near the narrowly proscribed circle is indeed a complication, but only through the saving in magnet size thus made possible have we been enabled to go to higher particle energies.

There are three such machines in operation and each has its own name; the proton synchrotron in Birmingham, England, the Cosmotron at Brookhaven, and the Bevatron in Berkeley. They all accelerate protons, of kinetic energies 1.3, 2.8, and 6.2 billion electron volts, respectively. These machines have been in operation only a short time, so that it would be presumptuous to judge their historical significance; suffice it to say that the phenomena appearing in the higher energy ranges are so new and perplexing that even now the Brookhaven laboratory is undertaking construction of a still larger accelerator.

This new device again uses the same principle of acceleration and the same general layout as the proton synchrotron but with a significant change in detail. To steer a beam millions of times around a ring of small cross-section requires some means for keeping the particles from straying into the walls of the evacuated acceleration chamber. This is done in general by having the magnetic field strength vary in a particular way across the chamber to form a sort of electrical trough in which the protons tend to pull toward the center of the chamber. The Brookhaven group has developed a field configuration which promises a much tighter control on the transverse motion of the ions; the accelerating chamber and the surrounding magnet can be made much smaller in cross-sectional area, with almost proportional saving in cost. The alternating gradient synchrotron, as it is called, should produce protons five times as energetic as the Bevatron for about twice the cost.

This completes a description of the main line of development of nuclear particle accelerators. Another approach must be mentioned which is gaining increased attention in recent years. This type is called the linear accelerator, a machine which uses no magnetic field; instead, the particles are sent down the axis of a succession of concentric metal cylinders, where an alternating voltage is applied between successive cylinders. In passing from one to the next, the particles are accelerated. The lengths of the cylinders progressively increase in just such a way that the particles arrive at the next interface at the right time to be accelerated again. This procedure can be carried on indefinitely, and has the distinct advantage over the circular machines that the accelerated beam comes out the end in a straight, concentrated pencil of sharply defined kinetic energy. A linear accelerator in Berkeley, producing protons at 32 Mev, is the only one which has been used extensively. The University of Minnesota is now building one for 50 Mev, and the British Atomic Energy Establishment is planning one for 600 Mev.

The acceleration of electrons is also of interest in nuclear physics. Electrons are not part of the nuclear structure and are incapable of feeling the enormous nonelectrical forces which protons and neutrons exert on each other. However, they can exert electrical forces and are able thereby to disrupt nuclei, either in close passage or by generating X-rays which subsequently strike nuclei. They can be accelerated by direct voltages, or by specially designed linear and synchrotron type machines. An important device, unique to electron acceleration, is the betatron, in which the accelerating voltage is provided by a changing magnetic flux - - the electron beam constitutes a one-turn secondary winding of an over-sized transformer. The accelerated electrons vary in energy from a million to a billion electron volts depending on accelerator type and application. The upper limit has been reached at the California Institute of Technology using a machine of the proton synchrotron design.

The particle accelerators are primary tools for basic research in nuclear physics, making it possible to stimulate sub-nuclear events in the laboratory in a controlled and systematic way. The apparatus for detecting and analyzing the nuclear processes is less conspicuous but equally complicated and specialized. It has proved most effective to concentrate equipment in a few localities, though participation is intended to be on a broad basis. The European group, CERN, offers a case in point; the major countries of Western Europe are sharing the responsibilities and benefits of a single laboratory beyond the means of any one country. In the United States the facilities of the national laboratories are open to qualified scientists for extended periods. Brookhaven was, in fact, created by the co-operative efforts of several eastern universities, with the encouragement and support of the government.

There is another aspect of publicly supported basic research which serves a more immediate need than exploration of future paths. In a young field with great potentialities, discovery, change in basic concepts, invention, and development are intimately inter-related. To train a young person for intelligent participation in our atomic energy program requires more than a course of lectures which can be rendered obsolete in a few months' time. He must live and work in the field for some years, observing and learning to judge the changing picture. The apprenticeship is served best in pursuit of basic problems, for in this way he gains the broadest possible background and participates himself in determining new directions. Students entering the field almost inevitably have to rely on government support at some time during their training, for the research work is complex and costly; in return, our national program in all its technical branches draws its new life from this source.

A study of nuclear particles, their properties and modes of interaction is not the only type of basic research in which the atomic energy program is involved. Radioactive materials are easy to produce and find use in many fields. When a nuclear particle enters a nucleus the resulting conglomeration is usually highly unstable and in a time far too short to measure one or more particles are ejected. The residual structure is quite often a nucleus which does not occur naturally and is less stable than another containing the same total number of particles. After a time it changes spontaneously into the more stable form, materializing electrons to carry off the excess electric charge and some of the excess energy, the remainder appearing in the form of x-rays. All elements can be made radioactive, and the ejected electrons and x-rays can be detected by simple means-- a Geiger counter, for example.

In many research problems requiring a detailed tracing of a substance through a succession of processes, suitable radioactive atoms can be sent along as tags. They can be located at any stage because a certain fraction of them convert themselves each second, revealing their presence. The cleaning ability of soap can be tested with radioactive dirt; a plant's method of taking chemicals from the soil can be followed in detail; an element can be traced through a series of chemical reactions. Applications of this sort are many and ingenious and a number of long-standing technical mysteries have been easily solved. Radioactive materials are manufactured routinely at Oak Ridge for use by responsible research groups.

Specific projects within our basic research program are usually initiated by the individual investigator with the approval of his institution. The proposals are examined in Washington with the voluntary assistance of three or four scientists of recognized judgment in the particular subject. If accepted, the closest AEC field office arranges a contract to share the expense with the institution, which usually contributes some salaries and facilities. The projects are extremely varied in purpose. Experiments with high energy particles, in which a nucleus is pretty thoroughly shattered, do much to expand our over-all picture of sub-nuclear phenomena but rarely lead to immediate technological advances. Experiments involving particles with energies of a few million electron volts, in which the struck nucleus remains almost intact, are usually aimed at a more detailed study of nuclear structure, and often lead directly to changes in reactor design and weapons research. Other projects serve to develop measuring techniques and to study the properties of materials under extreme conditions of heat, pressure, and radiation density; still others attempt to correlate results, put the facts in order, and formulate the unknown laws of nature.

Such is the framework within which the science of nuclear physics has been progressing in this country since the end of the war. It is a delicate task for a government agency to make it function effectively, for the inquiries it sponsors must often lead into blind alleys and the physicists whom it supports are as sensitive to criticism and regulation as the traditional prima donna. Enough time has passed to observe that a working system has been well established; the advances we have made in understanding the nucleus are a tribute to the good will and flexibility of purpose of the people participating in the program.