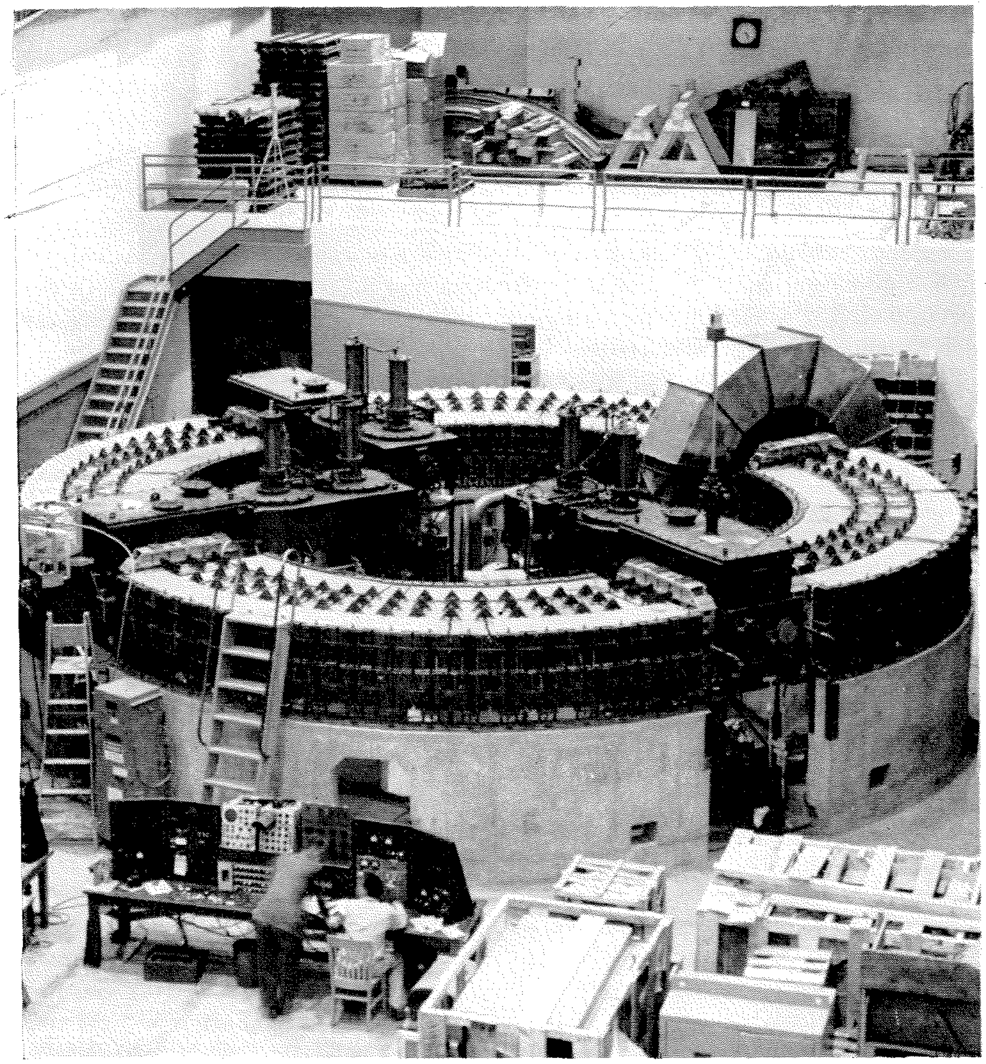

The synchrotron now under construction at Caltech is expected to produce between 500,000,000 and 1,000,000,000 volts

By MATTHEW SANDS

RESEARCH WITH LARGE ACCELERATORS

A NUMBER OF LABORATORIES have recently constructed, or are in the process of constructing, large machines for research in physics. The cost of these accelerators may run from several hundred thousand dollars to several million dollars; and their design and construction may consume several hundred thousand man-hours of work by skilled scientific personnel. I should like to try to give some idea here as to the motivations behind these expenditures of money and effort.

From the beginning of physics, physicists have taken upon themselves the problem of trying to understand and explain the motions of objects about them. Galileo and Newton, the first natural scientists who were interested in the subjects which we now call physics, tried to find regular rules of behavior for motions of objects. It was Newton who first hit upon the idea that one could more easily understand the motions of various objects if one divided the problem into two parts. He ascribed to every object rules of behavior which he conceived would govern its motion. These rules of behavior we now call the *laws of motion.* But the motion of an object is, in general, influenced by the presence of neighboring objects. These influences he described in terms of the *laws of force* between objects. Then, by combining the laws of force between objects with the laws of motion of the individual objects, it was possible to describe in a precise way the motion of an object under various possible circumstances.

This somewhat arbitrary division which Newton made between the laws of motion and the laws of forces between objects has turned out to be a convenient one, and has set a pattern which physicists have followed until today. For some time after Newton proposed his fundamental principles, it was possible to explain a large number of phenomena — from motions of the planets to the motions of every-day objects around us.

This fine state of affairs was only disturbed when electrical and magnetic phenomena were discovered, and it became evident that the law of gravitation, which Newton had proposed to explain the interactions between objects, did not obtain between objects which were electrified or magnetized.

For some years, physicists examined in detail the nature of the influences which magnetic and electrical objects held over each other, and these researches culminated in the work of Maxwell. In his summary of these new phenomena Maxwell found that it was only necessary to set down new rules of forces between electrified and magnetized objects, and that these new laws of forces, combined with the old laws of motion of Newton, were adequate to give a precise description of occurrences in this new field of observation.

By the beginning of this century, however, it became evident that there was some hidden inconsistency between Maxwell's laws of force and Newton's laws of motion, and that one or the other was a little in error. This conflict was finally resolved by Einstein when he proposed his theory of relativity.

The theory of relativity

The theory of relativity was based upon the idea that Maxwell's laws of forces for electrified objects are correct, but that Newton's laws of motion are only approximately correct for most observations. By introducing new laws of motion, somewhat different from Newton's original laws, it was possible to describe all the then known physical phenomena in terms of these new laws of motion, and the fundamental laws of force which had been prescribed by Newton and by Maxwell.

Further researches in physics, however, disclosed new phenomena which could not be explained in terms of the old laws of force and the laws of motion. These were atomic phenomena.

When it became possible to study in detail the motions of atoms, the manner in which the various parts of an atom hold together, and the way many atoms hold together to make large scale things such as chairs and tables, it was realized that it would be necessary to make certain modifications in the laws of motion or in the laws of force when dealing with infinitesimal objects. After some puzzling over this matter it finally evolved that one could understand the motions of atoms and the way that atoms held together in a solid object only by making another modification in the laws of motion.

It was Schroedinger with his theory of *quantum mechanics* who finally brought to a precise mathematical expression all of the known relationships between small objects such as atoms, electrons, etc. Thus, by introducing at this time a new law of motion, but maintaining the old laws of forces—gravitational, electrical, and magnetic—it was possible to explain all that was known about the motions of objects of all sizes.

This state of affairs, however, was still only provisional. Just as Newtonian mechanics was found to be only an approximation that needed modification as one made measurements under situations not ordinarily encountered in everyday life, so the new mechanics that Schroedinger had invented was not sufficient to explain all possible phenomena.

During the last 10 or 15 years the final mathematical theories of electrical effects were developed by Dirac, Pauli, and finally by Feynman and Schwinger; so now we have theories capable of giving a complete description of all the electrical, magnetic, and atomic effects so far observed.

There is, however, another realm in physics, in which observations have been made for some fifty years now, for which these laws of motion and laws of force do not seem to apply. This is the realm of nuclear mechanics, which is concerned with the study of the motions of the parts of the core of the atom, namely, the nucleus. Some progress has been made in trying to explain the motions of the parts of the nucleus, and the interactions of forces between various components of the nucleus of an atom. But at the present time occurrences in these fields are still not clearly understood.

We have no knowledge of the mathematical relationships which explain in any precise way what goes on inside this nucleus—or what the rules are which govern the behavior of the various parts. Of course this does not prevent our making practical use of nuclear energy, as in the atomic bomb or in work with radioactive materials. But we have here some tantalizingly mysterious behaviors, and physicists today are expending a great deal of effort in trying to formulate them precisely.

The study of the nucleus had its beginning with Rutherford when he first observed the effects of the radioactivity of certain natural minerals. Some time later other workers managed to make, in the laboratory, artificially radioactive materials. Still more recently, the scope of these researches has widened so that now the transmutations of elements, and the fission of the nuclei of atoms, are practical uses of nuclear energy.

The need for larger machines

Development of the methods of nuclear research has entailed the development of special techniques and tools, the latter often involving machines of some size and complexity for the production of nuclear projectiles of large energy. To illustrate the need for still more powerful machines, let me draw an analogy with the experimental methods employed in another field.

Suppose we had a large structural I-beam whose properties we wished to examine in detail. There are a number of ways that we could go about this. One way, though perhaps not the best, would be to pound on the I-beam with a tack hammer. By observing the sounds which came out and the minute vibrations which ensued, we could certainly draw some conclusions as to the nature of the particular I-beam.

Perhaps a more significant experiment would consist of placing large weights on the beam and observing the deflection of the beam under various weights. Still another way to get some information would be to subject the beam to the forces which can be delivered by a very large hydraulic press. If these forces were large enough, it would be possible to bend the beam to its breaking point. The measure of the force required to break the I-beam would certainly be one of its important characteristics and would provide us with a number which would be used in the design of structures employing such beams.

In working with atoms and the nuclei of atoms we can, by certain experiments, joggle these nuclei gently (an action corresponding to tapping the I-beam with a tack hammer) and, by observing the small motions of the nuclei under these gentle influences, learn something about the nature of the nuclei. Still another way is to exert somewhat more pressure on the nucleus and to observe the changes that take place in it under these stronger pressures. Finally, as in the destructive test of the I-beam, we can perform destructive tests on the nucleus, and find out what forces are necessary to break it into smaller parts. By measuring the forces required to do this, we can obtain valuable information as to the fundamental constitution of the nucleus.

Just as measurements on I-beams are made in terms of some scale of forces—say, the weight of the hammer that is used to hit the beam, or the force in pounds that the hydraulic press would exert upon the beam in breaking it—so do we need a scale or measure of the disturbance that we make on the nucleus.

Nuclear measurements

When we speak of the forces that we impress on a structure, it is convenient to talk in terms of pounds. In the study of the nucleus we find it convenient to speak in terms of the electrical potential necessary to apply the forces to the nucleus, and the unit of electrical potential that we use is the same one used in everyday life—the volt.

It is possible to do research on the nucleus with potentials of a few volts—in a manner analogous to attacking a structural member with a tack hammer—or, in a somewhat more vigorous manner, with forces of a million volts or so. However, it has become apparent that to perform destructive tests on a nucleus, and to find out what its inner workings really are, it is necessary to use forces corresponding to 100,000,000 volts and more. It is to achieve these forces that large nuclear research machines are now being made.

It is universally understood that an atom is a minute object. The nucleus of the atom is 100,000 times smaller still. The small size and obscureness of the nucleus prohibit us from applying to it, in a direct way, any strenuous electrical or mechanical force. We can, however, stress the nucleus by striking it with minute projectiles which are traveling at high speed. The electric forces which I spoke of before are, then, applied only in an indirect way, by imparting large striking power to a projectile.

To obtain these projectiles of large striking power one begins with an atom, or a fragment of an atom such as an electron, that is electrically charged. This charged fragment is subjected to the electrical force of a battery or of a high voltage generator. The electrical forces (governed by the well-known laws mentioned earlier) accelerate our charged fragment to a high speed. The striking power which such a projectile has depends on the magnitude of the electric potential used. Its value is, therefore, used as a measure of a projectile's striking power. In other words, when an electrically charged fragment is accelerated by an electric potential of 1,000,000 volts, it acquires a striking power measured by this 1,000,000 volts.

Projectiles of such striking power are obtained with large electrostatic machines such as those in Caltech's Kellogg Laboratory, where, by the use of refined techniques, it is possible to study the nucleus carefully and to come to rather important conclusions about the structure of any particular nucleus, even with the rather gentle effects of 1,000,000 volt projectiles.

The means of accelerating projectiles by subjecting them simply to the electrostatic potentials of a few million volts is not practical if one wishes projectiles to strike with power greater than about 10,000,000 volts. So, new principles and methods have been devised and are employed in the cyclotrons and synchrotrons and other large nuclear accelerating machines now being constructed for work in high energy physics.

In these machines the projectiles are accelerated in a way that is somewhat analogous to the way in which an automobile engine begins at a slow speed and is accelerated to high speed. In the automobile engine a single firing of a cylinder does not immediately cause the engine to rotate at high velocity; but the cumulative effect of a large number of firings of one cylinder after the other is sufficient to give the engine a high velocity. Similarly, in a cyclotron or a synchrotron, a rather small electrical voltage—say 1,000 volts—is applied for 1,000,000 times to the same projectile, and the combined effect then provides the projectile with 1,000,000,000 volts of striking power.

But one might ask, if it takes no more than 1,000 volts, why is it necessary to have large machines? Certainly it does not take a larger machine to make 1,000 volts than it does to make 1,000,000 volts.

The difficulty with the idea of repeatedly applying small 'kicks' to achieve a large striking power is that even those projectiles with a small striking power travel with tremendous velocities—in fact at speeds near the speed of light. After the first few kicks, the object will have traveled such a great distance that it is not conveniently available again for the next several thousand kicks that one would like to give it. This is why a large electro-magnet is employed. The function of the magnet is not to impart any of the striking force of the projectile, but merely to act as a guiding arrangement, causing the projectile, by virtue of its electric charge, to rotate in a circle. Then, each time that the projectile passes by on the periphery of this circle, one can kick it with a small electrical force; and the cumulative effect of millions of such kicks is then sufficient to impart a striking force of several billions of volts to the projectiles.

So it is this magnet, and its source of power, which contribute much to the size, complexity, and cost of these large machines. For example, the Caltech synchrotron, which is suitable for 1,000,000,000 volt projectiles, requires a specially designed steel magnet weighing 150 tons and special electrical power equipment capable of delivering 10,000,000 watts.

In addition to the magnet, the other important requirements of the accelerator are the "kicking mechanism"; a large vacuum chamber in which acceleration of the projectiles is accomplished; and other special equipment for operation, control, and protection of the machine and its operating personnel.

Accelerators under construction

The first of these machines were completed in 1947 and 1948. There are now about ten of them, capable of producing projectiles with striking power of from 300,000,000 to 500,000,000 volts. Three machines, still larger, are now nearing completion: the synchrotron at Caltech, which is expected to produce between 500,000,000 and 1,000,000,000 volts; a similar machine at the Brookhaven National Laboratory in New York which will operate between 1,000,000,000 and 3,000,000,000 volts; and a still larger synchrotron at the University of California at Berkeley which is expected to make available projectiles of up to 6,000,000,000 volts. The magnet for this latter machine will require about 10,000 tons of steel.

All these machines are in the United States. It is unfortunate that our European confreres have not been able to procure such machines for their researches. This is due, of course, to the fact that the cost of the machines—both in dollars and manpower—is prohibitive for many of the small countries of Europe. However, the future looks somewhat brighter. Under the leadership of UNESCO, the physicists of Europe are now banded together and are making plans for one large machine to be shared jointly by a number of the European countries. This machine will probably be something like the largest U. S. machine, now under construction in the radiation laboratory of the University of California.

When the large machines have been constructed and go into operation, the essential work has only just begun. Now, with projectiles of enormous striking power, we can proceed to examine the inner workings of the nucleus. Although the aim of the succeeding work may sound somewhat romantic, the methods used are in fact rather simple. We place a piece of ordinary material—aluminum for example—in the stream of projectiles, and place somewhat specialized and rather delicate instruments next to this piece of material and observe—through the instruments—the fragments, or the ricocheting projectiles which come out of the material.

By suitably specialized techniques and instruments it is then possible to single out those particular occurrences which can be traced back to nuclear encounters between the nuclear materials and the original projectile. Of course, what the nature of these fragments will be is still to a great extent unknown, since machines suitable for this work have just begun to function. But we do know that some pieces of the nucleus will come out; and it is already known that new types of material are created in the process of destroying any particular nucleus. These new types of materials, which have received some attention in the newspapers already, are called mesons and are known to be closely related to objects which have been observed in the cosmic ray for some years.

From the observations of these new materials will certainly come new laws and new understanding concerning the fundamental characteristics of the nucleus.

Will this new understanding of the nucleus have any meaning for the average citizen?

Pure research of any kind is a form of calculated risk which a society takes with certain of its resources, gambling that the deeper understanding that will be achieved by these fundamental researches will provide, at some future time, material reward for the particular society. It is never possible to predict in any accurate way what may be the final outcome of research in any particular field. But our civilization has benefited for several centuries now from the discoveries of people who were investigating the world around them only for the fundamental reason of trying to understand the processes which occurred. So it is with nuclear physics, with high energy physics.

What's ahead?

It is, of course, well known that nuclear physics of one sort has turned out to be of some practical, and even some military significance. We should not, from this, be led into thinking, however, that there is any guarantee that research in nuclear physics at high energies will reveal still newer and more startling sources of energy for operating the machines of the world. Indeed, all indications now are that the phenomena observed with these high energy machines are all inefficient ones. They simply absorb a lot of energy and do not give rise to new energy. And there seems to be very little likelihood that research in high energy physics with machines will lead to discoveries of ways of making new and more potent weapons such as the "cosmic bombs" so popular with science-fiction writers.

On the contrary, it is most likely that research in high energy physics will yield primarily a more complete and fundamental understanding of the nucleus, so that the processes which go on in the already discovered forms of nuclear energy can be more properly controlled and utilized. Once this has occurred, perhaps other uses for the very distinctive properties of the nucleus will be found and used to benefit mankind.