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THE PRESENT STATE OF THE PROBLEM OF ACCELERATION OF ATOMIC PARTICLES *

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IN the course of the past few years experimental physics has made extraordinary advances in the problem of artificially obtaining particles with energies of hundreds of Mev. Only a few years ago, such particles could be observed only in cosmic rays, and then with negligible intensity.

The artificial production of beams of protons and electrons with enormous energy made it possible to investigate and discover a variety of phenomena of fundamental importance for nuclear physics and for all of science. A new and very promising field of nuclear physics has come into being—the physics of high-energy particles. The tempo of developments in this new field has been extraordinary. The production of intense beams of mesons shed new light on the nature of nuclear forces and the discovery of the existence of new elementary particles—heavy neutral mesons, antiprotons, and antineutrons. This whole stream of new facts is due to the development of methods for acceleration of charged particles. An independent branch of experimental physics, devoted to accelerators, has developed. This field depends on the latest achievements of radio engineering and is related most directly with an advanced state of the electronic and radio-engineering industry.

The importance of fast particles for the study of the properties of nuclei was first made clear by the celebrated experiments in which Rutherford succeeded in producing the disintegration of nitrogen nuclei by bombarding them with the α particles from the natural decay of RaC.

The rapid development of nuclear physics was accompanied by the production of artificial nuclear "artillery"—machines which can impart high energies to atomic particles, electrons, and protons.

The decisive step in this direction was made with the invention of the cyclotron by Lawrence, who first applied the resonance method to the acceleration of charged particles. As you know, nuclear physics owes many very important achievements to the cyclotron. However it already became apparent at the end of the Thirties that the solution of the problem of nuclear forces required the development of accelerators capable of producing beams of particles with energies far greater than those which could be obtained using the cyclotron. Ever since, physicists have tried to develop accelerators giving particles with greater and greater energies.

Allow me to give a brief explanation of the reasons for this situation.

In 1937 there were discovered in the cosmic rays charged particles with a mass intermediate between the masses of electron and proton. These particles were called mesons. Soon after, the existence of several types of mesons was established. This discovery was essentially the beginning of a new chapter in the development of our concepts of the nature of nuclear forces and the structure of nucleons. Physicists were faced with the problem of developing and inventing accelerators which could produce mesons artificially, and of using the mesons for the investigation of the nature of nuclear forces.

The study of cosmic rays had shown that the collision of high-energy nucleons with atomic nuclei is an efficient method for producing mesons. The mass-energy relation of the theory of relativity shows that, in order to produce a new particle by the collision between a particle "projectile" and a nucleon or nucleus at rest, the accelerated particle must be given an energy at least equal to (and, in fact, even greater than)

$$W = M_0c^2,$$

where M_0 is the rest mass of the particle to be produced in the collision process, and c is the velocity of light.

The rest mass of the meson is several hundred times as great as that of the electron, and corresponds to an energy of approximately 150 Mev. At the time of the discovery of mesons, physicists had no means for artificially producing such particles. This problem could not be solved by using the cyclotron.

You know that the principle of operation of the cyclotron is the use of resonance between the frequency of revolution of the protons moving in the magnetic field of the cyclotron and the frequency of the alternating electric field that accelerates the protons.

Roughly speaking, such a resonance exists only so long as the velocity of the protons moving in the

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cyclotron is sufficiently smaller than the velocity of light. However as the energy rises the velocity of the particles increases and then, in accordance with the theory of relativity, the mass of the proton increases. As a result the matching of the period of revolution of the particles and the frequency of the accelerating electric field becomes poorer and poorer, until finally the cumulative detuning from resonance makes further acceleration impossible.

The maximum energy to which protons can be accelerated in the cyclotron is around 10 Mev and is thus one-twentieth the energy needed for the artificial production of mesons.

All sorts of attempts were made to overcome the difficulties related to the relativistic increase in mass of the accelerated particles. It appeared (and this opinion prevailed for many years) that the relativistic increase in mass is a fundamental difficulty and sets a limit on the possibility of accelerating protons to high energies.

In 1944 I and (somewhat later) MacMillan succeeded in showing that the relativistic mass increase not only is not a hindrance to the development of efficient methods of acceleration of charged particles but, on the contrary, the relativistic effect makes it possible to accomplish the resonant acceleration of electrons and protons to extremely high energies. The key to this advance was the discovery of the phenomenon of autophasing (phase focusing; Transl. note). Autophasing made possible the development of a whole variety of accelerators, both for the acceleration of electrons as well as for the acceleration of nuclear particles, protons, and deuterons.

I shall not enumerate all the types of accelerators based on the use of autophasing, but shall mention only the main ones.

The first of these is the cyclic electron accelerator called the synchrotron. One of the first machines of this type, with an energy of 30 Mev, was already built in 1947 in the P. N. Lebedev Physics Institute of the Academy of Sciences, U.S.S.R.

At present there are many different synchrotrons operating in various countries, giving beams of electrons with energies up to a few hundred Mev. Synchrotrons already exist giving electron beams with an energy of 1.5 Bev, and synchrotrons for 7 Bev are under construction. As you know, in the Soviet Union for many years the synchrotron of the Physics Institute has operated at 280 Mev and the synchrotron of the Leningrad Physico-Technical Institute at 100 Mev.

Synchrotrons enable us to obtain ultra-hard electromagnetic radiation. The existence of the neutral π meson was established using such machines. High-energy electrons and photons are among the most efficient tools for investigating the structure of nucleons, the fundamental building blocks from which atomic nuclei are made.

The next important type of accelerator is the phasotron (or synchrocyclotron). It is used to accelerate protrons, deuterons, and α particles, and is a very efficient generator of π mesons. There are at present more than ten phasotrons operating throughout the world. The largest of them is the one constructed in the Soviet Union under the direction of Meshcheryakov, D. V. Efremov and A. A. Mints. Almost all we know about the role of π mesons in the problem of nuclear forces has come from the use of powerful beams of mesons generated in phasotrons.

The third type of accelerator is the well known synchrophasotron (proton synchrotron; Transl. note). Machines of this type are the American cosmotron at 3 Bev, the bevatron at 6.3 Bev and, finally, the synchrophasotron constructed in our country, which gives a beam of 10-Bev protons. The 10-Bev synchrophasotron belongs to the Joint Institute for Nuclear Research. Its parameters have been reported many times in the press, and I shall not talk about them. Intensities of approximately 10^9 particles per pulse have been obtained with this accelerator, and physical investigations on rapidly-increasing have already begun. It is to accelerators of this type that we owe the vital knowledge we have concerning the physics of elementary particles. These machines opened the way to the discovery of long-lived neutral mesons, antiprotons, and antineutrons.

All the accelerators enumerated above are of the cyclic type. They are all characterized by the fact that the particles to be accelerated move in a closed trajectory and traverse the same electric field over and over again. There is still another type of resonance accelerator, the linear accelerator, in which the particles to be accelerated move in a straight line. The rapid development of these machines is also linked to the discovery of the phenomenon of autophasing.

I shall try to give a very general picture of the principle of autophasing, without going into details about the special features of the operation of this mechanism in each particular type of accelerator.

Every cyclic accelerator contains two fundamental elements:

1. A magnetic field that guarantees the cyclic character of the motion of the charged particles.

2. An accelerator structure, in which an alternating electric field is excited, and which is in-

tended to communicate energy to the charged particles. The frequency of the electric field can be either constant or variable in time. The magnetic field can also be constant or increase with time. These two elements are enough to cause the appearance of the mechanism of autophasing.

Allow me to use a few very simple formulas to make the operation of the autophasing mechanism clear.

Let us try to give an expression for the time spent by the particles moving in the magnetic field in going through one revolution. This time T will obviously be determined by the ratio of the path length s traversed by the particle during one revolution to the velocity of the particle v; i.e.,

$$T = \frac{s}{v}.$$

For charged particles moving in a magnetic field which is uniform and constant (or almost constant) in time, we know that the trajectory is a circle whose radius R is given by

$$R = \frac{Mvc}{He} = \frac{M_0 vc}{\sqrt{1-\frac{v^2}{c^2}}\,He},$$

where H is the magnetic field strength, $M = M_0/\sqrt{1-v^2/c^2}$ is the total mass of the particle, e its change, and v is its velocity.

Thus the path traversed by the particle during one revolution will be $s = 2\pi R = 2\pi Mcv/He$. Consequently, we get the time T for one revolution by dividing the path s by the velocity of the particle, i.e.,

$$T = \frac{2\pi M_0 c}{\sqrt{1-\frac{v^2}{c^2}}\,He}.$$

According to relativity theory, $Mc^2 = w$, so we get $\frac{2\pi}{He}\frac{w}{c} = \frac{2\pi}{ec}\frac{w}{H}$.

This formula contains essentially all that we need for understanding the mechanism of autophasing. It shows that in every cyclic accelerator there is a simple relation between the three fundamental quantities: the strength of the magnetic field which controls the motion of the particles, the period of revolution of the particles, and their energy. Consequently our problem is, using the relation between these quantities, to find and establish conditions in which the particle energy can be increased continually by making appropriate changes in one or both of the other parameters. It turns out that the solution of the problem is essentially very simple. We must use the already known resonance method of acceleration. But the amplitude of the potential difference of the electric field which accelerates the particles can no longer be chosen arbitrarily but must satisfy a simple condition.

The most significant feature of this method of acceleration is that, because of the dependence of the particle mass on velocity, any deviation of the time of revolution of the particles from the resonance value causes a change in the energy increment given to the particles by the electric field, so that the period of revolution automatically returns to its resonance value. It turns out that to produce such a mechanism we can vary the magnetic field or the frequency of the electric field slowly, or we can keep them both constant and apply sufficiently large potential differences to the accelerator structure. If for some reason the particle acquires energy too rapidly during acceleration, the resonance between its period of revolution and the frequency of the electric field is spoiled, and the particle begins to pick up less energy in each revolution and is then brought back into resonance. On the other hand, if for some reason the particle energy rises too slowly during the acceleration to maintain resonance, the particle begins to receive greater increments of energy from the electric field, and the necessary additional energy is thus automatically given to it.

Such an automatic maintenance of balance between the period of revolution of the particle and the period of the accelerating field can be achieved in cyclic accelerators of the most varied types. For example, one can keep the magnetic steering field constant in time and decrease the frequency of the accelerating electric field according to an arbitrary law. One can also do the reverse: increase the magnetic field and keep the frequency constant. Finally, one can change both. Phasotrons are accelerators of the first type, in which the magnetic field is constant, synchrotrons are of the second type, with constant frequency, and synchrophasotrons, which I have already mentioned, are instruments of the third type.

In all cases, in order to have autophasing it is sufficient to satisfy a very simple inequality relating the potential difference of the accelerating electric field to the rate of change of the magnetic field or the frequency.

Compared with the cyclotron, autophasing accelerators have made it possible to raise the limiting energy by a factor of 1000, and apparently this figure is not a final limit.

Permit me now to turn to another characteristic feature of the autophasing accelerator, which is very important for the consideration of the prospects of future development of charged-particle accelerators.

The energy increase achieved by using the principle of autophasing is not gotten for nothing. For example, while the ordinary cyclotrons have pole diameters of 1 or 1.5 m and weigh from a few tens to hundreds of tons, the present-day phasotrons already weigh several thousand tons and their pole diameters are 5 to 7 meters. The weights of synchrophasotrons go up into the tens of thousands of tons, while the radius of the electromagnet is tens of meters, and in accelerators under construction even becomes hundreds of meters. This tendency of present day accelerators was cleverly underscored by the famous Italian physicist Fermi, who remarked jokingly in one of his last lectures that if one extrapolates the present ratio of maximum particle energy to accelerator dimensions, then to obtain particles with an energy of 10^{16} ev one would have to build an accelerator with an orbit diameter equal to the diameter of the Earth and with a vacuum chamber encircling the equator.

This is a facetious description. But it undoubtedly describes the main physical features of present accelerators. Furing the past 15 years physicists have worked to get higher and higher energies. Autophasing enabled them to solve this problem. But the consequence of autophasing is that the intensity, i.e., the flux of particles, which we can get from the accelerator always decreases when the particle energy increases. For example, one can obtain a current of around 100 milliamperes from the cyclotron, while the phasotron gives only a microampere. Synchrophasotrons like the bevatron or the accelerator at the Joint Institute give a current of only 10^{-3} microamperes. Lawrence pointed out that, if the situation develops further in this way, we might get in Fermi's fantastic accelerator an intensity of one proton per day.

Thus, together with the tremendous increase in energy there occurs a marked decrease in the intensity of the flux of accelerated particles. The point is that as the dimensions and weight of the accelerator increase, there is a very rapid rise in the power requirements of the electromagnets of the cyclic accelerators and of the high-frequency generators used to produce the accelerating electric field. Since the rating of the power sources is limited, the result is that the number of pulses of accelerated particles produced by the accelerator in one second decreases catastrophically. In the cyclotron the number of pulses is 10^7 per sec, in the phasotron of the Joint Institute this number is already only 100 per sec, while in the 10-Bev synchrophasotron we get a pulse every 12 seconds.

This situation is very typical, since it is intimately related to the acceleration principle which we are utilizing and which requires that the dimensions and weight of the accelerator must increase in order to raise the energy of the particles.

There are two classes of problems, two tremendous fields of research, which require an even greater increase in the energy of charged particles and, at the same time, a further increase in the intensity of the flux of accelerated particles. One of these fields is in the domain of basic research: the study of the nature of elementary particles.

The recent advances in physics of which I spoke earlier require the continual development of accelerators with higher and higher energies. To produce π mesons we must impart an energy of 150 Mev or more to the particle "projectiles", to observe antiprotons we need about 6 Bev, and to produce pairs of the so-called cascade hyperons we already require about 10 Bev. There can be no doubt that further discoveries will emphasize this tendency and in turn demand still greater energies from accelerators.

At the same time, there is a second and possibly no less important class of problems for the solution of which we need to develop powerful accelerators capable not only of producing very high energies of the order of tens of Bev or possibly even higher, but at the same time a very intense flux of accelerated particles.

I cannot discuss these problems in any detail. I mention only that they are related to the possibility of practical use of accelerators and may encompass the most varied aspects of everyday life.

I should like to try and discuss very briefly, almost sketchily, the outlook for developments in the two directions just mentioned. Let me begin with the question of maximum energy. At present the most energetic particles are gotten from cyclic accelerators. The maximum particle energy which can be obtained in a cyclic accelerator with magnetic field strength H is practically independent of the type of accelerator, and is determined only by the strength of the magnetic field which can be used to maintain the particles in their orbit, and by the radius of the orbit. In all presently known materials, the limiting field strength does not exceed 30,000 oersteds. Therefore, if we want to continue in the direction of increasing particle energies using existing methods, there is only one way available to us—that of simply increasing the dimensions of the accelerator. But here we shall rapidly get to the limit of what is reasonable, and we are already close to the limit. Earlier the physicist did not have to concern himself with problems of an economic nature. But in the design of more and more powerful accelerators, essentially only the technological and economic factors are now decisive. Everyone will understand that if the magnet of an accelerator weighs around 40,000 tons, if we need to erect enormous buildings and foundations for it, if we must build power stations giving a pulsed supply of hundreds of thousands of kilowatts, then unfortunately these problems cannot be avoided by physicists. But purely economic factors alone do not limit us in simply increasing the dimensions of existing accelerators. It can be shown that the engineering difficulties in producing tremendous electromagnets, their weight, the rigidity of the requirements for their magnetic characteristics, etc.—all these factors increase, as the dimensions of the electromagnet increase, roughly as the 2.5 power or cube of the limiting energy.

What is the reason for such a rapid increase in the dimensions of accelerators? It turns out that it is caused by a single physical phenomenon, the satisfying of the conditions for stability of the motion of the particles. In any cyclic accelerator, and especially in an accelerator which makes use of autophasing, the particles go through an enormous number of revolutions during the process of acceleration. For example, in the synchrophasotron of the Joint Institute, during the acceleration time, which lasts 3.3 seconds, the particles go through a few million revolutions and traverse a path of a million kilometers. If, over such a long path, random effects such as collisions with gas molecules, perturbations of the motion due to inhomogeneity of the magnetic field, etc, are not to result in a catastrophic loss of accelerated particles, it is necessary that the motion of the particles be stable. We know that in order to have stable conditions the magnetic field must have a very definite configuration that guarantees cyclic motion of the particles.

The theory shows that in all existing accelerators the magnetic forces which assure stability and keep the particles near the equilibrium trajectory are in general very small, so that the amplitudes of oscillation of the particles about the equilibrium trajectory are large. Thus the region of space in which the particles move, and in which the magnetic field configuration must satisfy the stability conditions, must also be made quite large. Increasing the energy of the accelerator and correspondingly increasing the orbit radius makes it necessary to increase the height and width of the region of space in which the particles move. This results in an increase of the weight of the electromagnet proportional to the cube of the orbit radius. In the synchrophasotron of the Joint Institute the width of the "track" in which the particles move is about one-and-a-half meters. If we wanted to increase the maximum particle energy to 30 or 50 Bev, using the same stability conditions, we would have to build an electromagnet weighing close to a million tons, which is obviously already completely unrealistic.

A few years ago a group of American physicists proposed a very ingenious idea for getting around this difficulty. The method developed by these physicists provided a new approach to the stability problem and has been called "strong focusing." It was shown that one can get a marked increase in the magnetic forces, which guarantee stability of the particle motion, by making the magnetic field configuration vary periodically with azimuth.

I cannot spend the time to discuss this question in any detail. I may only say that this new idea makes it possible to reduce the amplitude of oscillation of the particles about their equilibrium orbit by almost an order of magnitude, and thus to reduce correspondingly the weight of the electromagnet and the power required for it. This makes it possible for us to go further in the direction of obtaining still higher energies.

At present accelerators based on the principle of strong focusing are being designed and constructed all over the world. In the Soviet Union, under the direction of V. V. Vladimirskii, E. G. Komar, and Mints, with Efremov assisting, a 50-Bev strong-focusing accelerator is under design. The weight of the proposed accelerator will be about 30,000 tons. But the gap will be only 10 cm wide and 6 cm high, even though the orbit radius will be approximately 250 meters. Accelerators of a similar type, designed for 30 Bev, are being constructed at a rapid pace in Switzerland and America. In these accelerators, as in the usual synchrophasotrons, the acceleration is accomplished by using the autophasing principle. We may anticipate that the strong focusing method will enable us to go several times higher in energy than the figures already achieved at present.

I should say, however, that the advance made by using strong focusing is purchased at a very high price. I am thinking of the extremely difficult problem of eliminating resonant blowup of the particle oscillations. The theory shows that in such systems the requirements on the precision of all parts of the accelerator are raised by a tremendous amount.

To give a qualitative indication of the difficulties with which one has to cope, I mention that for a 50-Bev strong-focusing synchrophasotron, having a ring magnet radius of approximately 250 meters, the settling of the foundation on which the magnet is to be placed must be uniform (strictly speaking, the 30'th harmonic must be kept uniform) to 0.1 mm, even though the total weight of the electromagnet is some tens of thousands of tons and the perimeter of the electromagnet is about 1.5 kilometers. Extremely rigid requirements must also be imposed on the constancy of the magnetic field configuration and on the precision of all sorts of other parts of this gigantic accelerator. As you see, even though these problems are apparently technically solvable, their solution is still an extremely difficult job.

For just these reasons, the strong-focusing method cannot enable us to make a marked advance upward in the energy scale. Despite all the ingenuity of this method, its use enables us only to raise the maximum particle energy but little. The problem of getting a large increase in intensity of particle beams and of moving on to ultrarelativistic particles with energies in the hundreds and thousands of Bev, which is important from many points of view, cannot be solved by the methods I have been describing. We must look for some completely new direction if we want to plan for a rapid advance.

I shall now turn to the last part of my talk, which will necessarily contain a relatively large element of speculation, and which concerns the prospects for accelerator development.

I shall first talk about an idea in which the two questions, the question of getting large currents and the question of getting high energy particles, are linked together in a surprising way.

Let us put this simple question to the experimental physicist: "What do you want to do with a high energy particle?" The experimenter gives the trivial answer that he uses the accelerated particle as a projectile which interacts with a particle at rest in a target, and observes scattered particles, meson production, antinucleons, etc.

But why should the target be at rest? There appears to be a possibility of observing processes at ultrahigh energies if the target (which until now was always at rest) itself moves with high velocity opposite to the beam of particles which we use as projectiles.

Let us see what happens if the projectile and target move opposite to one another with equal relativistic velocities. It is easy to show that if two protons having energies of say 10 Bev move opposite to one another and collide, the whole interaction process will proceed as if one of the protons was at rest while the other moved with an energy of approximately 20 Bev. Thus if we make two beams of high energy particles move opposite to one another and observe the processes which occur in the collision, we will be able to investigate phenomena which would occur if we had at our disposal an accelerator giving particles with an ultra-high energy equal to twice that of the individual particles in the colliding beams.

Such a method for setting up processes which could be produced only by particles with superhigh energies seems to me to be very promising. But it is not so easy to realize in practice. This is because the cross section for the collision of, say, two protons is a minute quantity. To observe such collisions it would thus be necessary, as a computation shows, to have in each of the colliding beams an enormous current, of the order of 50 to 100 amp. It is doubtful whether one can get such currents from existing autophasing accelerators. The maximum pulsed currents which can be attained at present are 0.1-0.01 amps. Let me make it clear that I am now speaking of instantaneous currents and not of the average current which I talked about earlier.

To make possible the practical realization of the colliding-beam method, we must raise the instantaneous currents by a factor of 500 to 1000. There are all sorts of ingenious ideas for doing this. In 1953, V. A. Petukhov, M. S. Rabinovich, and A. A. Kolomenskii in the Soviet Union, and somewhat later Kerst, Simon, et al. in the U. S. A., proposed new magnetic systems with a magnetic field which is constant in time and which would make possible a considerable increase in the current of accelerated particles.

There are suggestions for using existing accelerators for current storage. It is proposed to build magnetic storage systems, in which particle beams from present-day accelerators can be stored for a long time, after which by some means one brings about a collision between the beams accumulated in two storage vessels. We are of course a long way off from realizing these rather crude proposals; I mention them only to point out the somewhat unexpected connection between the two problems of obtaining high currents and of getting ultrahigh energies.

The principles of operation of all the accelerators which I have discussed up to now are essentially related to the problem of the motion of an isolated particle in given magnetic and electric fields. The rapid development of accelerators was made possible by the setting up of a rigorous theory which enabled accurate calculation of particle motions. The basic theory was formulated by the Soviet theoretical physicists M. S. Rabinovich and A. A. Kolomenskii, and also by some physicists in other countries.

The new ideas which I am now going to discuss briefly belong to the realm of phenomena in which one must take account of the collective interaction of particles. For this reason a lot of the material is still qualitative. I am thinking of the relativistically stabilized beam proposed by A. M. Budker, the coherent method of acceleration proposed by me, and Ya. I. Feinberg's idea of plasma waveguides.

Although all three ideas are completely different, they have a common feature. All contemplate the use of a plasma for producing intense beams of high-energy particles.

For lack of time, in the preceding discussion I touched only on questions relating to the present state and prospects of development of the cyclic method of acceleration. In the course of the past ten years, under the influence of the stormy progress in radio technology and the use of the principle of autophasing, linear accelerators have also begun to develop rapidly. Despite the fact that they have all sorts of advantages for high energy work, linear accelerators are still not as efficient as cyclic accelerators. One of the main reasons for this is that in ordinary resonators and waveguides it is not possible to produce and make sufficiently efficient use of very high electric field strengths. Also, in these accelerators it is difficult to achieve simultaneously the conditions for phase and spatial focusing of particles. In 1956 Ya. I. Feinberg pointed out the possibility of simultaneously overcoming both these difficulties by using a plasma, at rest or in motion, placed in a longitudinal magnetic field. Such a plasma acts like a waveguide, and has all sorts of surprizing properties. Waves having a wavelength much greater than the transverse dimensions of the guide can propagate through such a plasma waveguide. The possibility arises of producing extremely high field intensities in just that small region of space in which the accelerated particles move. The difficulty in combining phase and radial stability of the accelerated particles disappears.

All these points promise to open new prospects for linear accelerators.

I shall now turn to the question of stabilized beams.

I mentioned earlier that in a cyclic accelerator the maximum energy that can be given to the particle is determined only by the magnetic field strength at the orbit.

It was first pointed out by A. M. Budker that, by using a relativistic plasma, one can establish a magnetic field approximately two orders of magnitude greater than can be gotten with any ferromagnet, i.e., one can obtain a field of order 10^6 oersteds. Budker's idea is based on the utilization of the relativistic properties of a stream of charged particles. He showed that if one produces a sufficiently high current in a cyclic accelerator by using relativistic electrons and compensates the repulsion of the electrons by means of positive ions, intense electromagnetic radiation will appear in the plasma. The appearance of radiation causes the diameter of the plasma tube to contract markedly, and a tremendous magnetic field develops inside the plasma and on its surface. One can make use of this magnetic field by placing particles inside the tube of plasma and then accelerating them by any standard method, such as autophasing. This idea is very beautiful, but its realization requires that many difficulties be overcome. Still, if it could be done we could count on getting particles with an energy of approximately 10^{11} ev.

In the method which I just described, the problem of producing very high magnetic fields is solved, while the acceleration of the particles is accomplished by the old method. A few years ago I pointed out the possibility of establishing a new principle of acceleration of atomic particles. It was called the coherent method. There appear to be all sorts of ways of realizing coherent acceleration. This principle can be used both for the acceleration of charged particles and for the acceleration of quasineutral aggregates. Allow me to give a very brief discussion of a few examples of this new mechanism.

Imagine that we have a small cluster of charges containing n positive ions. Suppose further that we send toward this cluster a stream of electrons which move with velocity v past the cluster. It is easy to show that then each particle in the cluster will experience an accelerating force, which is the greater the number of charges in the cluster. Thus the effective accelerating field can, at least in principle, be made very large, even reaching values of millions of electron volts per centimeter. A qualitative estimate shows that the efficiency of this mechanism is close to unity. Naturally this is a very attractive idea. But it must be said that there are great difficulties in the way of its realization, mainly related to the problem of obtaining high currents of relativistic electrons.

The next variant of coherent acceleration, which is of interest for many reasons, is the acceleration of quasi-neutral clusters. Imagine a quasineutral cluster, consisting of electrons and positive ions or of electrons and positrons. We direct toward this cluster an electromagnetic wave whose wavelength is somewhat greater than the dimensions of the cluster. The electromagnetic wave will induce polarization oscillations of the electrons in the cluster. Part of the momentum of the electromagnetic wave will be scattered by these oscillations, as a result of which the whole cluster will pick up momentum and will begin to move in the direction of propagation of the wave. Obviously, this variant of coherent acceleration is essentially a special case (of course, under quite different conditions) of the phenomenon of light pressure discovered by P. N. Lebedev.

The most important advantage of this method is that in accelerating neutral globs of plasma one can accelerate more particles than in any other acceleration method. In principle, the coherent method gives one the hope of accelerating particles to energies of 10^{12} ev and even higher. It seems to us that the only way of obtaining such tremendous energies is by using impact acceleration, in which a cluster (or a current ring) of relativistic electrons collides with another cluster or current ring containing ions. It can be shown that if the mass of the relativistic cluster of electrons is much greater than the mass of the ion cluster, the ions will be given an enormous ultra-relativistic energy in the collision.

There are also other variants of coherent acceleration, but I shall not mention them here.

I was of course able to give only a very quick survey of these three methods, which are related to the use of plasmas and are still complete novelties for the physics of accelerators.

Recently the important role of plasma processes in nature has become clearer. A few years ago the possibility was pointed out of producing electromagnetic radiation by means of the Cerenkov effect. It was also pointed out that charged particles may be accelerated through the motion of streams of plasma in the magnetic fields of stars. Many attempts were made to relate the mechanism of cosmic-ray production to these processes. In these processes, stochastic or probability mechanisms of acceleration may play an essential role. We know that in the plasma of a gas discharge there occur very often fast particles whose energy is far greater than the potential difference applied to the plasma. One can show that the motion of clusters of plasma in the inhomogeneous magnetic fields of cosmic space must be accompanied by the production of relativistic electrons. So you see that in astrophysics the problem of the acceleration of charged particles is related most intimately to the peculiarities of plasma.

The struggle to attain those enormous energies in the millions of electron volts, which by some mechanism unknown to us are generated in cosmic space, the use of these artificial projectiles for the study of the nature of elementary particles—these are the most interesting problems confronting physicists and engineers working in this enchanting branch of science.

Translated by M. Hamermesh