High-energy particle accelerators

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The big machines for the acceleration of charged particles are among the most complex and costly of modern scientific devices, but there is still little general understanding of their principles and applications. This authoritative article describes the main types now in use, with some details of individual machines, and gives examples of the kinds of research for which they are needed. Of particular interest is their use for the artificial production of some of the new particles which have been identified in cosmic rays.

Only forty years ago Rutherford and his collaborators first demonstrated the nuclear model of the atom by studies of the scattering of α-particles, derived from naturally radioactive sources, by the Coulomb field of atomic nuclei. Since those days, the electrical acceleration of charged particles in large machines has contributed much to the rapid development of nuclear physics. In the early 1930's the first accelerators—the high-tension generator of Cockcroft and Walton and the cyclotron of Lawrence—accelerated protons by a few hundred kilovolts. The biggest accelerator today, at Berkeley, California, produces protons of 6×10^9 electron volts, or 6 (U.S.) billion electron volts—hence its name 'Bevatron'. (In Europe it is now the accepted practice to use GeV for 10^9 electron volts, in place of the American BeV.) Two machines are now planned for producing protons with energies of 20–30 GeV. One of these machines is to be built in the newly constituted *Organisation Européenne pour la Recherche Nucléaire* (CERN) at Geneva. The United Kingdom is one of the twelve member states of CERN; the others are Belgium, Denmark, France, the Federal German Republic, Greece, Holland, Italy, Norway, Sweden, Switzerland, and Yugoslavia. The other machine will be built at the Brookhaven National Laboratory in the United States.

The main tasks for both existing and future machines are concerned ultimately with attempts to obtain an understanding of nuclear forces. Typical lines of attack are the study, over a wide range of bombarding energies, of the scattering of protons by protons and of neutrons by protons, and, in the larger of the existing machines, studies of the production of π-mesons and their interaction with other particles. π-mesons, which are observed in positive, negative, and uncharged forms, have masses about 280 times the mass of the electron and are unstable; their mean lives are of the order of 10^{-8} second (positive and negative forms) and 10^{-15} second (uncharged form). They are thought to play a very important part in the forces which hold neutrons and protons together in nuclei. Although the charged varieties of π-mesons were discovered in studies of cosmic rays by C. F. Powell and his collaborators at Bristol, they are produced only very weakly by cosmic rays. They can be obtained in comparative abundance when nuclei are bombarded by intense beams of particles possessing kinetic energy of some hundreds of MeV. At still higher energies other, and more massive, unstable particles, including the V-particles discovered in cosmic rays by P. M. S. Blackett's school in Manchester, are produced artificially. Many examples of these have already been observed, using the 2·8 GeV Cosmotron at the Brookhaven National Laboratory. The significance of these strange particles, which have been discovered in considerable variety in cosmic rays, is still obscure, and it is necessary to learn much more about them. The very large machines will be needed for these studies; it seems reasonable to expect considerably greater yields, and greater variety, of these particles as the available bombarding energy is increased. The 20–30 GeV machines now being planned will also produce enough energy to create pairs of particles of nucleonic mass in collisions between two nucleons, if such processes occur, as it is believed they should, with sufficient spare energy to ensure good yield and high velocity of the artificially produced particles. Studies of the properties of negative protons and of the circumstances in which they may be produced would be of very great theoretical importance.

Low-energy machines are not necessarily made obsolete by the development of bigger ones, and there is much interest in all energy ranges, including the 1 MeV region, first reached long ago. It is always necessary to examine rare processes and to strive for greater precision in experiment,

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and such work requires beams of high intensity. Machines designed to give great energies are, however, usually not the best sources of particles of lower energy, since it is necessary to sacrifice intensity, and often flexibility, in order to obtain high energies at acceptable cost. The gaps in our knowledge of nuclear phenomena are still enormous, and experiments with particles of all obtainable energies are still needed to help to fill them.

Both electrons and heavy particles, usually protons, are used in high-energy experiments. In some types of machines it is electron acceleration that is the more easily or more cheaply obtainable, but the two kinds of particles cannot be accelerated in the same machine. Protons, however, are, in general, more powerful tools in nuclear physics, and accordingly more effort has been put into the making of proton machines than of electron machines. However, there are certain electromagnetic phenomena which can be investigated only with the help of electron beams.

General Features of High-energy Accelerators

All accelerators of high-energy particles use stepwise acceleration by radio-frequency electric fields, with the exception of the betatron; this machine has been used to accelerate electrons up to about 300 MeV by means of the electric field associated with a changing magnetic field. The central problem dominating the design of big machines is that of particle stability; this problem has two aspects. First, the particles repeatedly encounter electric fields, applied across gaps by a radio-frequency source, and it is necessary to ensure that a useful proportion of the particles continue to arrive at the gaps at times in the radio-frequency cycle when further acceleration can occur. Secondly, it is essential to adopt some means of focusing the particles into a beam, so that useful numbers pass through the gaps instead of striking solid parts of the accelerating system. The phase of the particles with respect to the radio-frequency field is influenced by the properties of the particle injection system, unavoidable constructional and similar errors, and amplitude and frequency errors in the radio-frequency field. Unwanted changes in the direction of motion of the particles are caused by injection conditions, constructional errors, and scattering by residual gas in the vacuum chamber. The relative importance of these different factors varies with the type of accelerator, but in all very big machines, where many individual accelerations occur and the total path-length of the particles is long, it is necessary to provide positive 'focusing' of both phase and direction for a proportion of the injected particles large enough to be useful. There will be stable oscillations of the phase, and therefore of particle energy and position, about certain equilibrium or synchronous values. Similarly there will be oscillations of particle position associated with the spatial focusing forces. These oscillations have a great influence on the design and performance of the machines.

The machines fall into two general groups, namely linear accelerators and closed-orbit accelerators. In linear accelerators, many gaps and many radio-frequency power sources (or, in a small machine, a single source of high power) are used to accelerate particles in a straight line. In the closed-orbit accelerators, a magnetic guide-field is used so that the same gap, or series of gaps, may be used repeatedly, with few radio-frequency sources of relatively low power. For protons or other heavy particles the closed-orbit machines (the synchrocyclotron and the proton synchrotron) are well ahead in the race for the highest energies. For electrons the linear accelerator may possibly be the machine of the future, even for the highest energies; at lower energies, from say five MeV to a few hundred MeV, its superiority over existing types of closed-orbit machines appears to be already evident.

The reason for this state of affairs is that there are difficulties inherent in the linear accelerator which are important only when protons are to be accelerated, and that there is a difficulty in the closed-orbit machine which is important only when electrons are to be accelerated. The region of phase-stable acceleration in a linear accelerator is one in which strong directional defocusing occurs. At extreme relativistic velocities, which occur at quite low electron energies, however, the motion caused by the defocusing electric forces virtually disappears, and trouble may be readily avoided after the first few MeV (in practice the first few metres) of acceleration in a linear machine. Moreover, linear accelerators of electrons may be operated at short wavelengths, usually about 10 cm, and the accelerator proper consists of a corrugated waveguide of small diameter. Compact microwave power sources, each giving several megawatts in short pulses, have become available by the development of klystron valves at Stanford University. On the other hand, slow particles, e.g. protons of a few hundred MeV or less, may be accelerated efficiently only by the use of longer wavelengths, of the order of 1 metre, and with conventional systems a large and relatively costly waveguide has to be used. Compact, efficient, high-power sources for these wavelengths have not yet been developed, and this circumstance, together with the focusing difficulty and the great success of closed-orbit machines, explains why the linear accelerator of protons has undergone relatively little development so far.

The difficulty with closed-orbit electron machines, electron synchrotrons, is that energy is radiated by the circulating electrons, and this loss of energy has to be made good by the radio-frequency accelerating system. The effect is very small with the heavier protons, even in the biggest machines now planned, but it becomes serious with electrons at energies of a few GeV. In the linear accelerator radiation loss is completely negligible, even with electrons.

Economic Factors

The larger accelerators are exceedingly costly, and economic considerations play a very large part in determining the types of accelerator which can be used for the highest energies. For example, the Brookhaven Cosmotron, which produces 2·8 GeV protons (to be increased to 3·0 GeV), is reported to have cost $7 000 000, and the 20–30 GeV machine now being designed at Brookhaven is expected to cost $20 000 000. The magnet and its power supplies accounted for one-quarter of the cost of the Cosmotron. The particle energy in a closed-orbit machine is determined by the product of orbit radius and magnetic field strength, but the magnetic field is restricted, by saturation effects in the iron, to 20 000 gauss or less. Consequently particle energy can be increased only by increasing the orbit radius.

The synchrocyclotron has proved to be one of the most reliable and powerful accelerators ever developed, but its use is precluded for the highest energies because the magnet cost rises very rapidly with the energy required. The magnet of a 600 MeV synchrocyclotron to be built by CERN in Geneva will contain 2500 tons of steel and will cost roughly £500 000; it will have a final orbit radius of about 225 cm. The proton synchrotron, on the other hand, accelerates particles in a magnetic field which increases with time in such a way that the orbit radius remains constant. The magnet of this machine has therefore to produce a strong field only in an annular volume, with a consequent saving of steel for a given orbit radius. The Brookhaven Cosmotron is a machine of this type; its magnet contains about 2000 tons of steel for an orbit radius of about 9 metres, so that protons having four or five times the energy of those obtainable from the CERN synchrocyclotron may be accelerated, using rather less steel. However, the proton synchrotron poses many problems, concerned with maintaining particle stability, which are absent from the synchrocyclotron and, moreover, produces, with present techniques, a beam of much smaller intensity. At the highest energies now being aimed at, 20–30 GeV, even the proton synchrotron in its present form would be much too expensive, and attempts are being made to exploit a principle, recently discovered at Brookhaven and independently by N. Christophilos, a Greek scientist, which makes it possible to use a magnet gap of much smaller volume and thus to reduce the weight and cost of the magnet still further.

Some Features of Particular Types of Accelerators

LINEAR ACCELERATORS

We are here concerned only with high-energy accelerators, and only one linear electron accelerator in this category has yet been built. This is at Stanford University, and consists of a sectioned, corrugated waveguide having a total length of 60 metres and operating at a wavelength of 10 cm. Power is supplied by twenty-one special klystrons developed at Stanford, each giving more than 10 megawatts of power in pulses of about a microsecond duration. An energy of about 600 MeV has been attained, and it is hoped to increase this to some extent in the future. Already important results on the scattering of high-energy electrons by atomic nuclei have been obtained with the help of this machine.

The biggest linear accelerator for protons now in operation is a 32 MeV machine constructed some years ago at the University of California, but a 60 MeV machine is nearly complete at the University of Minnesota. At the Atomic Energy Research Establishment, Harwell, and at Metropolitan-Vickers Electrical Company Limited, a design study has been made for a much larger machine, for protons of 600 MeV. The absence of beam-extraction problems means that, compared with a synchrocyclotron accelerating the same proton current, more intense beams of particles can be made available for experiments. This, together with the possibility of subsequent extension to higher energies, makes the high-energy linear accelerator for protons an attractive machine, particularly for work in π-meson physics, if it can be constructed at reasonable cost. Recent improvements in the extracted beam from the synchrocyclotron, referred to later, have, however, diminished its advantages. A proton linear accelerator for 600 MeV would be about 300 metres in length and would require 100–150 megawatts of radio-frequency power during the pulses. In the Harwell design, most of this power would have to be provided at a frequency of 400 Mc/s, and a valve development programme would be an essential part of the project. The pulse duration would be 200 microseconds, and the pulses would occur 50 times per second, so that the mean radio-frequency power required would be 1–1·5 megawatts.

THE SYNCHROCYCLOTRON

Here the particles travel in concentric closed orbits in a steady magnetic field, and are accelerated by a radio-frequency electric field. They start with very small velocity, and therefore with very small orbit radius, and the orbit radius increases as acceleration proceeds. The orbital period increases slightly with increasing energy. Some of this increase is accounted for by the fact that the magnetic field is made to decrease slightly as the radius increases, in order to provide the necessary focusing forces, and the remainder by the relativistic increase of mass of the particles with increasing velocity. The frequency of the accelerating field is reduced slowly, during acceleration, to an extent which compensates for the increasing orbital period, so that some of the particles may remain in step with the accelerating field. It can easily be shown that, over a broad range of operating conditions, phase stability of an appreciable fraction of the injected particles can be achieved in this way. Moreover, the focusing forces produced by a slight radial decrease of the guiding magnetic field are strong enough to ensure that few particles are lost after 'trapping' into the phase-stable orbits has occurred.

This machine has been applied only to heavy particles, such as protons, and not to electrons, because electrons acquire almost the velocity of light at quite low energies, and consequently a very wide range of frequency modulation would have to be used in handling them.

There are six large synchrocyclotrons in the United States, ranging in energy from 140 to 450 MeV; one in Canada (110 MeV); one in Sweden (190 MeV); and two in Great Britain. The new Liverpool synchrocyclotron (figure 3) produces 400 MeV protons, and the Harwell machine, which has been operating since 1949, produces protons of 175 MeV (figure 4). The machine at Berkeley, California, which was the first to operate (1946), is shortly to have its maximum proton energy increased from 340 to 730 MeV. The new 600 MeV machine which is being designed for CERN at Geneva has already been mentioned.

A notable advance in synchrocyclotron technique has recently been achieved in H. W. B. Skinner's laboratory at Liverpool. A new method of beam extraction, originally proposed at Chicago some time ago but developed theoretically and experimentally by K. J. Le Couteur, A. V. Crewe, and others at Liverpool, has been applied to the new 400 MeV synchrocyclotron. Already 3 per cent of the internal beam current has been extracted; this is an improvement, by a factor of at least 1000, over previous methods, and will enormously extend the usefulness of synchrocyclotrons in high-energy research.

THE ELECTRON SYNCHROTRON

Here the guiding magnetic field is increased with time, during acceleration by the radio-frequency field, in such a way that the orbit radius remains constant. If the electrons are injected at an energy of a few MeV, or are accelerated by betatron operation in the early stages, their velocity will be essentially constant thereafter and the frequency of the radio-frequency field may also remain constant. The magnetic field need be applied only over an annular volume, but the magnet yoke has to be laminated in order to avoid eddy-current effects as the field is varied.

In experiments with electron synchrotrons it is customary to use the *Bremsstrahlung*, the continuous spectrum of electromagnetic radiation produced when electrons are absorbed in an internal target. This high-energy electromagnetic radiation provides a powerful experimental tool. Although some success has been achieved in attempts to extract the electron beam, the technical difficulties are considerable.

There are several large electron synchrotrons in the United States, producing about 300–350 MeV, and a 350 MeV machine was recently completed in Glasgow (figure 5). A machine of this type at the California Institute of Technology produces electrons of nearly 1 GeV, and a new 5–6 GeV machine has been proposed as a joint venture by the Massachusetts Institute of Technology and Harvard University.

THE PROTON SYNCHROTRON

This type of machine is of special interest, since with present techniques it gives the highest artificially produced particle energies. As with the electron synchrotron, the magnet is laminated, has an annular gap, and produces a field increasing with time during acceleration. However, the proton velocity increases appreciably as the energy increases, until the velocity of light is approached at energies of several GeV. It is necessary, therefore, to increase the frequency of the radio-frequency field during acceleration in order to maintain constant orbit radius, and the correlation ('tracking') of the frequency variation with the magnetic field variation has to be very accurately carried out. This introduces considerable complication that is not present in the other machines. Moreover, it is not economically possible to recycle the magnetic field very rapidly in a large magnet, and the particles are accelerated in bursts occurring a few times per minute. In contrast, the frequency variation in the synchrocyclotron can be made quite rapidly, and in that machine it is common practice to use about 100 bursts per second. As a result of these various factors the mean intensity of the particle beam of a proton synchrotron is, with present techniques, at the most one-thousandth of that of a synchrocyclotron.

M. L. E. Oliphant, when he was at Birmingham, was the first to propose the machine which later became known as the proton synchrotron. The Birmingham machine (figure 6) has been operating for some time at an energy of 1 GeV. Figure 7 is a photograph of the 2·8–3·0 GeV Cosmotron at Brookhaven. Protons are first accelerated to about 4 MeV in an electrostatic generator, and are then injected into the gap of the large magnet, where they are accelerated further during the course of about 3×10^6 circulations, made in about one second. The distance travelled in this process is about $1{\cdot}6 \times 10^5$ km. The magnet is energized in pulses by a 21 000 kVA alternator carrying a 45-ton flywheel on the driving shaft. In this way the flywheel gives up a fraction of its kinetic energy to the electrical system during the pulse, after which it is accelerated again, in readiness for the next pulse, by a relatively small motor (1750 H.P.). About 75 per cent of the stored energy in the magnet (about 10^7 joules) is returned to the flywheel, with the help of gas-discharge switches in the alternator circuit, during the interval between pulses. The same system, with variations in detail, is used in all existing proton synchrotrons. The 6 GeV Bevatron at Berkeley, California, is even larger (figure 8). The magnet weighs 10 000 tons and the orbit radius is about 18 metres, and in this case the particles are injected from a 10 MeV proton linear accelerator. A new machine for 15 GeV, using an air-cored magnet, is being built in Australia under the direction of Oliphant.

The focusing forces, which are necessary in order to return straying particles to the correct orbits, are associated with stable oscillations of the particles about the correct orbits. As we have seen, it is an important economic consideration in the proton synchrotron to use as small a magnet gap as possible, but the space required by these oscillations, and by perturbations due to unavoidable constructional and timing errors, sets a limit to it. If the frequency of the oscillations could be increased, it is clear that the amplitude resulting from a given angular displacement of a particle would be correspondingly reduced. With the normal (constant gradient) method of focusing in a closed-orbit accelerator, particle stability requires that $1 > n > 0$ where n is a parameter which describes the magnetic field distribution and is defined by

$$n = -(r/B)\, \partial B/\partial r,$$

where B is the magnetic field intensity and r is the orbit radius. For synchrotrons the value of n is commonly about 0·6.

The frequencies of the oscillations associated with the focusing forces (the 'betatron oscillations') are:

$$f_r = (1 - n)^{\frac{1}{2}} f_0 \quad \text{(radial)}$$
$$f_v = n^{\frac{1}{2}} f_0 \quad \text{(axial)}$$

where f_0 is the orbital frequency. There is clearly little scope for changing the frequencies, and an increase in one will involve a decrease in the other.

M. S. Livingston, E. D. Courant, and H. S. Snyder at Brookhaven, and independently Christophilos in Greece, showed in 1952 that a net focusing effect may be achieved in a suitably arranged system which is alternately focusing and defocusing along the path of the moving particles. With n numerically $>> 1$, but with n alternately positive (radially defocusing, axially focusing) and negative (radially focusing, axially defocusing), a synchrotron may be designed with much stronger focusing forces for displacement in both directions, i.e. with higher frequencies of stable oscillations, than those of the conventional synchrotron.

The frequencies of the betatron oscillations are now greater than the orbital frequency, and, as was first pointed out by J. D. Lawson at Harwell, the particle motion in an alternating gradient synchrotron is very sensitive to small misalignments of the individual focusing or defocusing sections of the guiding magnet. In particular, disastrous resonance effects occur if the number of betatron cycles per orbital revolution becomes integral or half integral, resulting in loss of the particles to the walls of the vacuum chamber. The values of n, i.e. the strength of focusing, have therefore been reduced below the 5000–10 000 originally contemplated, in order to leave, as it were, more operating space between the resonances. Even at the values of a few hundred for n at present envisaged at CERN and Brookhaven, for the 20–30 GeV machines, a considerable reduction of magnet aperture is still possible, with a corresponding saving in capital cost. There are many other problems, mostly concerned with the maintenance of particle stability, and both groups have been actively studying these, as well as engineering design, for about two years.

The orbit radii of these machines will be about 100 metres, and the particles will have to be constrained to move through an aperture about 7×12 cm during many thousands of orbits. Very close mechanical, magnetic, and timing tolerances will have to be achieved, but the total weight of steel in the magnet can be kept down to about 4000 tons for an energy of 25 GeV. This is only twice the weight of steel in the Cosmotron, which has a vacuum-chamber aperture of 91×23 cm.

The same method of alternating gradient focusing, but with zero field along one axis, has made it possible to be reasonably confident of success in attempting to focus the beam of a proton linear accelerator without serious loss of particles.

Some Typical Experiments with High-energy Accelerators

PROTON POLARIZATION

The discovery, at the University of Rochester in 1953, of polarization effects in the scattering of high-energy protons by nuclei, exemplified the element of the unexpected in scientific research. It had long been thought that polarization should occur in the scattering of nucleons by other single nucleons, as a result of non-central components of the nucleon-nucleon forces, and attempts were being made to obtain experimental evidence. Polarization may be detected in a 'double scattering' experiment, in which particles, scattered in a particular direction with respect to the primary beam, are passed through a second scattering device. If polarization effects are present, the beam emerging from this second device at a fixed angle with respect to the first-scattered beam will have a different intensity when scattered to the left as compared with the right. In a polarization experiment on proton-proton scattering, the bombarding particles would be protons, and ideally both scatterers would consist only of hydrogen. The use of hydrogen is inconvenient, however, and at Rochester the practice was adopted of using hydrocarbons, a subsequent experiment with pure carbon enabling the effect due to hydrogen to be distinguished. Polarization in proton-proton scattering was detected, but a considerably stronger polarization was discovered in the pure carbon. All elements which have been tried exhibit similar effects. The phenomenon has been found to be associated with the nucleus as a whole, and not with the individual nucleons, and the strongest polarization appears to occur in elastic collisions, i.e. those in which nuclear excitation or disintegration does not take place.

There has been great activity in this field during the past year, and results have been obtained at Rochester, Chicago, and Berkeley in the United States, and at Harwell in Britain. Figure 1 is a diagram of the experimental arrangement used at Harwell. Protons of maximum energy 160 MeV are allowed to strike a target T_1 in the vacuum chamber of the Harwell synchrocyclotron; those scattered through an angle of about 20°, and possessing an energy of 135 MeV, escape from the magnet through a magnetic shielding channel C. These first-scattered particles pass, in an evacuated tube, through a concrete shielding wall S and are collimated by slits. A second scattering takes place in the target T_2, and the second-scattered particles are detected in a system of counters D arranged as a 'telescope' and set at an angle θ with respect to the first-scattered beam. The primary beam, and the first- and second-scattered beams, are all arranged to be in the same plane. The detecting counters D may be rotated through 180°, about the first-scattered beam as an axis, into the position shown in dotted lines in figure 1. If there is polarization, the number of particles counted in these two positions, for a standard bombardment in each case, will be different. Elaborate checks are made, of course, to ensure that any effect observed is not attributable to errors in the alignment of the apparatus. The quantity determined is the 'asymmetry,' defined as

$$\varepsilon = \frac{N_1 - N_2}{N_1 + N_2}$$

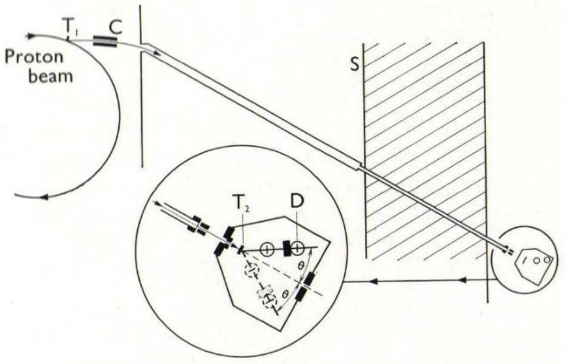

FIGURE 1 – *Plan of an experiment on the polarization of high-energy protons, using the Harwell synchrocyclotron.*

where N_1 is the number of particles scattered in the same direction as the first scattering (same azimuthal angle) and N_2 is the number of particles scattered in the opposite direction (azimuthal angle different by 180°).

The polarization at a particular angle can easily be calculated from the observed asymmetry, provided that one and the same process is known to be involved in each scattering and the two scattering angles are the same. Much of the experimental programme on this phenomenon has to be devoted to attempts to separate the different scattering processes which occur when high-energy protons strike a target. However, if a finite value of ε is obtained, then polarization is clearly taking place, and figure 2 shows the observed values of ε as a function of second-scattering angle in experiments at Harwell.

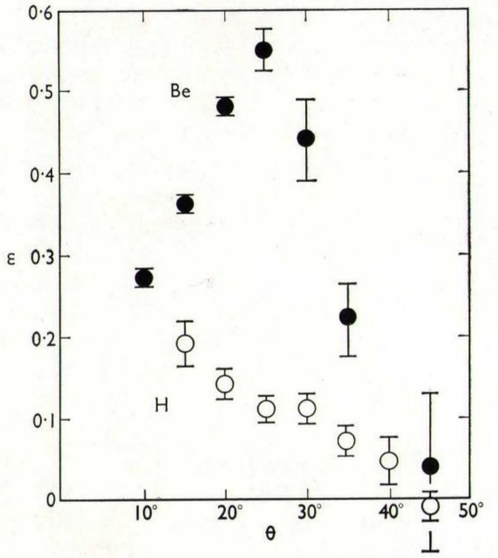

FIGURE 2 – *Variation of observed asymmetry* ε *with second scattering angle* θ, *in Harwell experiments on the polarization of high-energy protons.*

OBSERVATION OF INDIVIDUAL PARTICLES

It is always necessary to use, in addition to counter techniques, methods of detection which display the tracks of individual particles for visual examination. These methods are very laborious when statistics comparable with those obtainable with counters are required, but are indispensable in the initial interpretation of many phenomena, particularly when 'new' particles are involved. Tracks may be made visible in cloud chambers and similar instruments, and in special photographic emulsions.

Two recent developments in the cloud chamber technique have greatly increased its effectiveness for use with accelerators. The original cloud chamber of C. T. R. Wilson produces supersaturation of a vapour-gas mixture by a controlled adiabatic expansion, and the tracks of ionizing particles are indicated by the formation of droplets on the ions. The tracks are photographed, usually by a stereoscopic camera so that the particle trajectories may be reproduced in three dimensions. Momentum measurements may be made if a magnetic field is applied during the passage of the particles through the chamber, and tracks may be observed resulting from nuclear collisions in the gas or vapour or in plates of solid material introduced into the chamber. Although this technique has been greatly developed, mainly by cosmic ray physicists, it is not very economical of the running-time of large accelerators, because the time required between expansions is greater than the normal interval between accelerator pulses. In the diffusion cloud chamber, first proposed by A. Langsdorf and developed in recent years mainly at Brookhaven, a gas may be continuously supersaturated with vapour by means of a thermal gradient on the walls of the containing vessel. This technique has been made to work very well with hydrogen, at about 20 atmospheres pressure, in vessels a few metres wide; a chamber of this kind is capable of receiving beam pulses at the full rate of about 10 per minute from a machine such as the Cosmotron. Hydrogen is, of course, a particularly important substance in studies of elementary nucleonic processes, and it is always important, when studying rare events, to be able to observe a particle traversing a great mass of material, so that the high pressure and large size of the chamber are important features. Figure 9

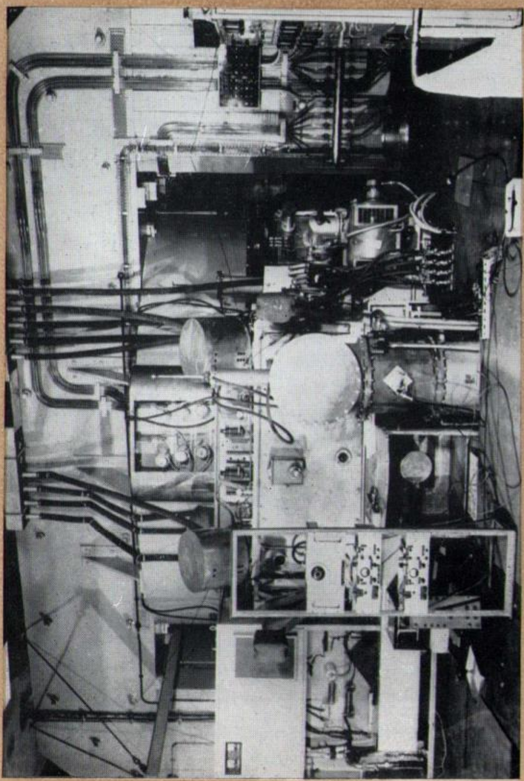

FIGURE 3 – *The 156-inch Liverpool synchrocyclotron.*

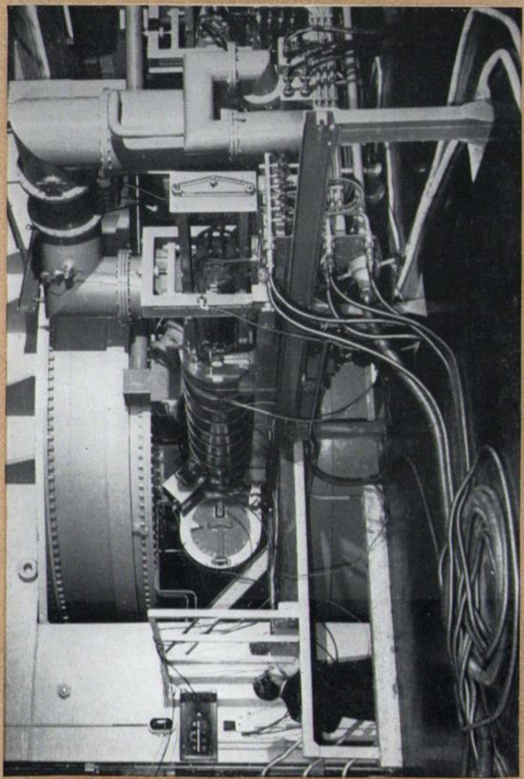

FIGURE 4 – *The 110-inch Harwell synchrocyclotron.*

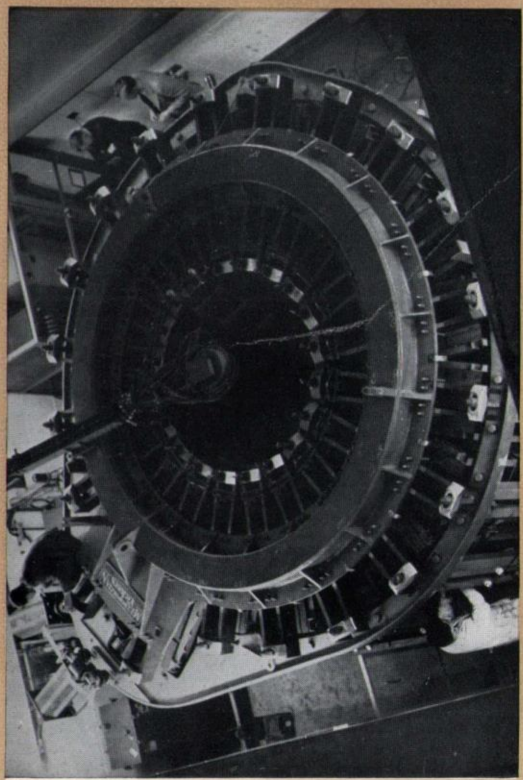

FIGURE 5 – *The Glasgow electron synchrotron.*

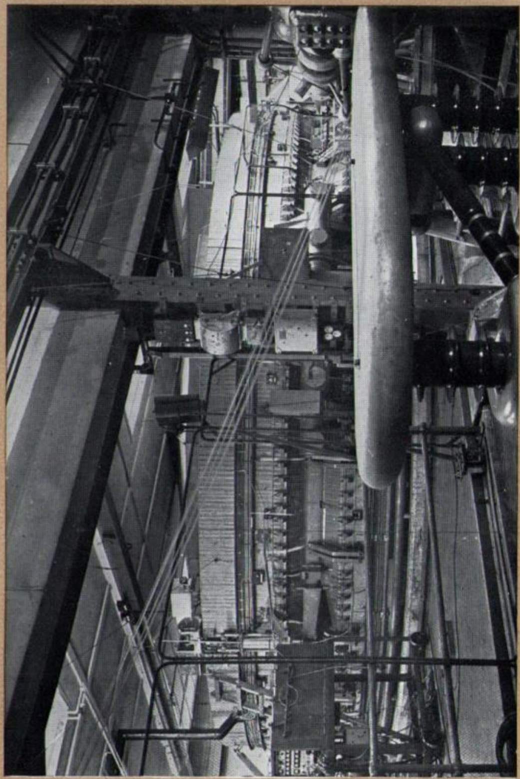

FIGURE 6 – *The Birmingham proton synchrotron.*

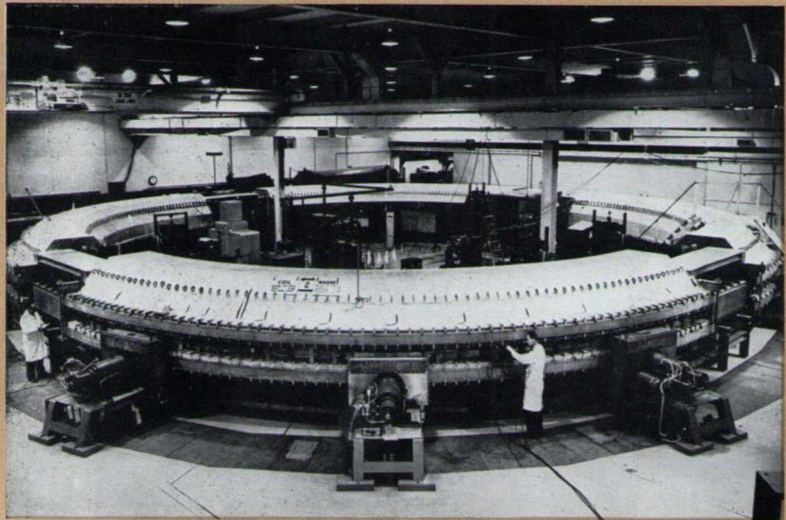

FIGURE 7 – *The Brookhaven proton synchrotron (Cosmotron).*

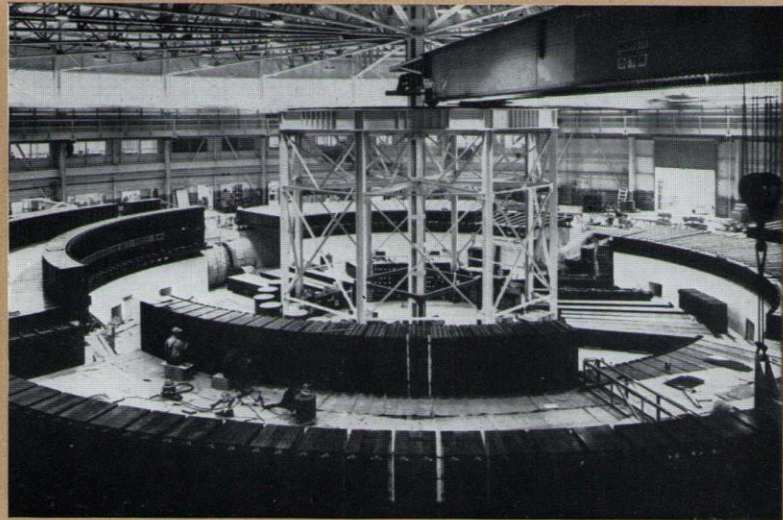

FIGURE 8 – *The Berkeley proton synchrotron (Bevatron), shown under construction.*

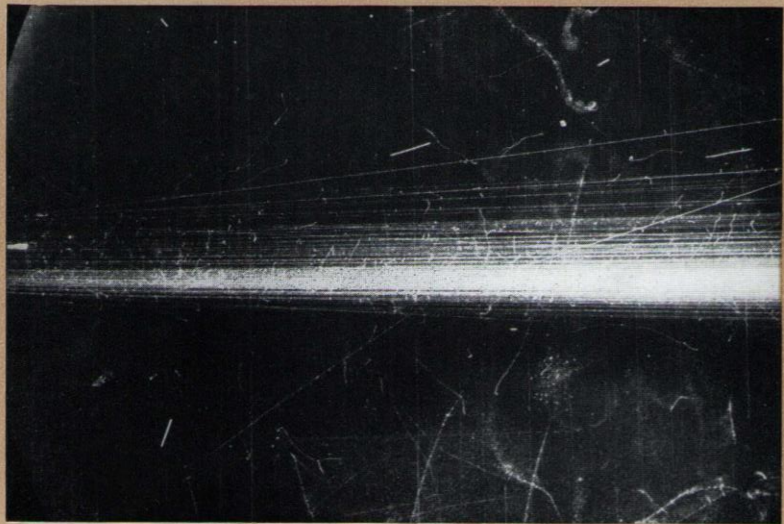

FIGURE 9 – *Tracks in a diffusion cloud chamber irradiated by* 150 *MeV protons from the Harwell synchrocyclotron.*

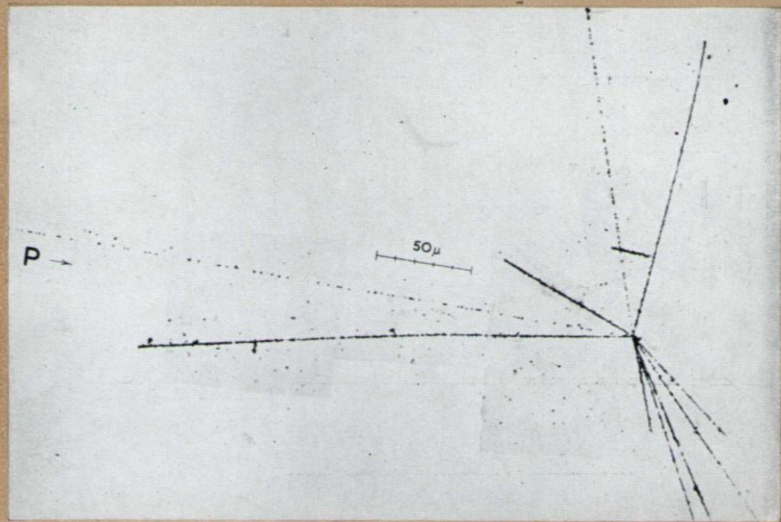

FIGURE 10 – *Nuclear disintegration caused by a* 1 *GeV proton. Tracks produced in a nuclear emulsion exposed to the beam of the Birmingham proton synchrotron.*

is a photograph of tracks made in a diffusion cloud chamber by 150 MeV protons from the Harwell synchrocyclotron.

The second development in this field is a very recent one. Physicists at Brookhaven, Chicago, and Berkeley have developed the 'bubble chamber' technique, in which bubbles of vapour form along the track of an ionizing particle in a superheated liquid. The superheated condition is achieved by making a carefully controlled and timed reduction of pressure. Considerable success has been achieved with liquid pentane, and some success with liquid hydrogen. So far, the biggest chambers are only a few centimetres across, but the great density of the medium is an enormous advantage in work with high-energy particles.

The nuclear emulsion technique has the advantage of employing a medium of very high density, but the bulk of the material consists of silver and bromine, together with carbon, hydrogen, and oxygen, so that this method is less flexible. The modern development of the technique was pioneered by Powell's group at Bristol, for application both to cosmic ray research and to work with accelerators.

Figure 10 shows a 'star' observed in a nuclear emulsion exposed to the beam of the Birmingham proton synchrotron. A nucleus in the material of the emulsion has been highly excited by the impact of the energetic primary particle (a 1 GeV proton), and the energy of excitation was sufficient to disrupt the nucleus into several fragments, which moved away with considerable velocity. The nine charged fragments left tracks visible under the microscope after development of the emulsion. Uncharged particles leave no record in the emulsion, but some would undoubtedly be produced in a disintegration of this magnitude.

The Cosmotron group at Brookhaven has been able to demonstrate the artificial production of some of the new particles identified in cosmic rays, using both cloud chamber and emulsion techniques. They have observed many cases of Λ^0 and θ^0 particles in the diffusion cloud chamber, and some of their photographs show the decay products of one of each of these particles, presumably produced in the same event. Λ^0 particles have a mass somewhat greater than that of the proton, are uncharged, and decay into a proton and a negative π-meson. θ^0 particles have a mass about 1000 times the electron mass, are also uncharged, and decay into a positive and a negative π-meson. The double events were observed when the hydrogen-filled diffusion chamber was exposed to a 1·5 GeV negative π-meson beam emerging from a target bombarded by protons in the Cosmotron. The following reaction is presumed to have occurred:

$$\begin{array}{ccccc} \pi^- + p \rightarrow & \Lambda^0 & + & \theta^0 \\ & \downarrow & & \downarrow \\ & p + \pi^- & & \pi^+ + \pi^- \end{array}$$

The four decay-product particles are identifiable from studies of the photographs.

There is a large class of 'heavy mesons' discovered in cosmic ray research and known collectively as K-mesons. The θ^0 particle is an uncharged member of this family, but there are believed to be several charged varieties with masses about 1000 times the electron mass. Several kinds of charged K-mesons have already been observed in studies of nuclear emulsions exposed to the beam of the Cosmotron.

The situation with regard to these newly discovered particles is very complex, but it is certain that knowledge of their properties and the conditions under which they may be produced will rapidly expand as work proceeds on the large accelerators. All the unstable particles so far known have been discovered in studies of cosmic rays, with the exception of the π^0 meson (which was very nearly discovered by Powell's group!), but the more intense beams produced by accelerators have proved to be essential in studying the production and properties of mesons and their interaction with other particles. In this sense cosmic ray research and accelerator research have been truly complementary.

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