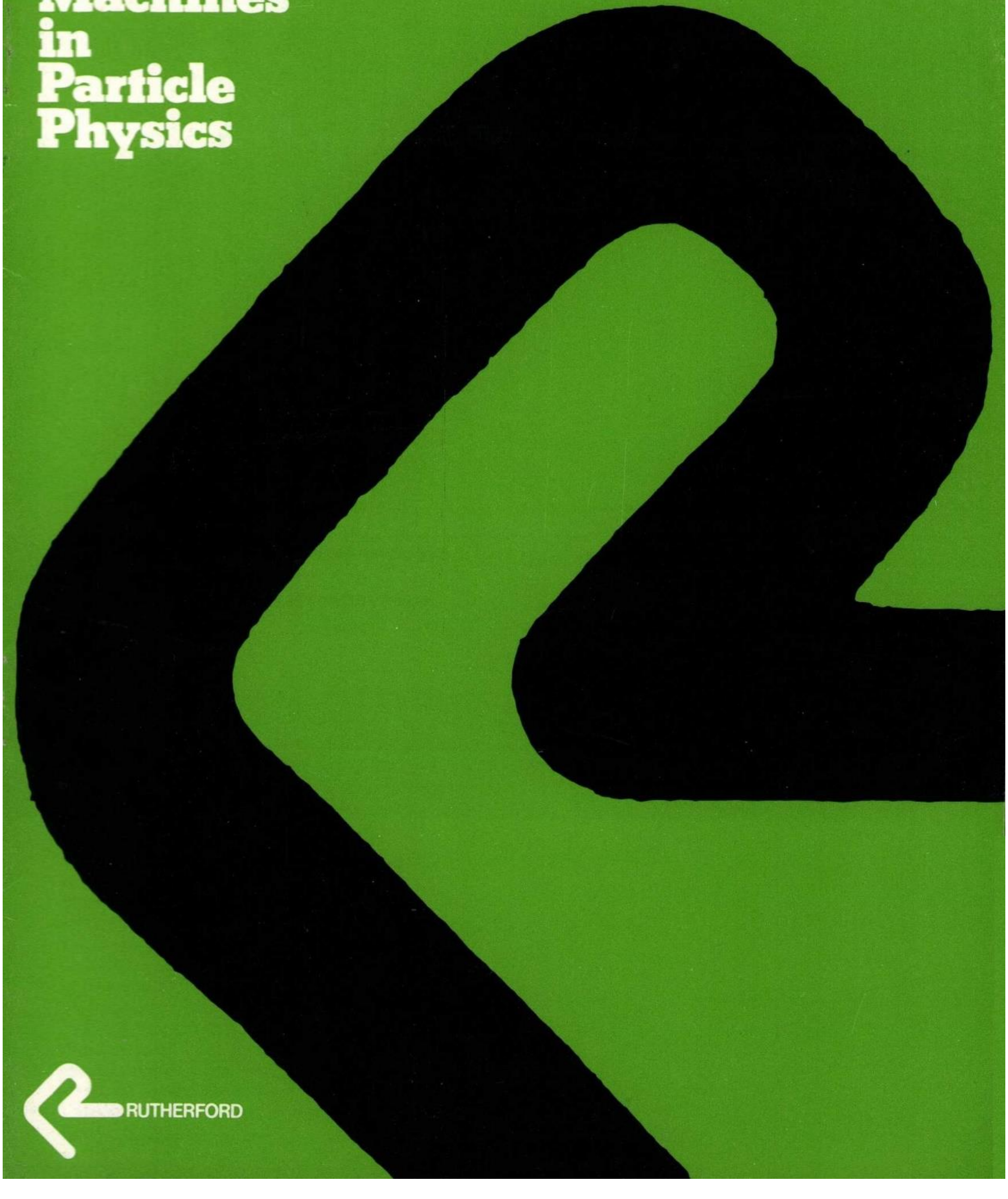
A Rutherford Laboratory Monograph

The Use of High Energy Machines in Particle Physics



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The use of high energy machines in particle physics

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Introduction

Since the turn of the century we have experienced a remarkable advance in our understanding of the nature of the physical world. These advances have occurred in part by the development of new theoretical ideas, in part through new experimental observations and in part by the development of new experimental techniques. All three components play an essential role but the aim of this short text is to describe the advances which have been made through the construction of particle accelerators, and to highlight the key discoveries which have come about as larger and more powerful accelerators have come into operation.

Historical

The first particle accelerator to be built and used in the laboratory for research was probably Roentgen's X-ray tube, for in this instrument electrons were accelerated by a potential of some thousands of volts. When the electrons were slowed down in a target, quanta of electromagnetic radiation were emitted and a new tool became available to scientists.

In 1911 Lord Rutherford in Manchester used high energy alpha particles emitted by radioactive nuclei, a naturally occuring accelerator, to bombard a thin gold foil. To Rutherford's amazement the results of the experiment could only be understood if it were assumed that the atom of gold contained a nucleus 10,000 times smaller than that of the atom itself. A little later in 1919 Rutherford succeeded in producing artificial transmutations of normally stable light elements by bombarding them with α particles from radioactive nuclei.

Early Accelerators

Although Rutherford made tremendous advances using very simple apparatus and naturally occuring radioactive substances he realised the importance of having available in the Laboratory a controllable source of high energy particles. This objective was achieved in 1932 and Cockcroft and Walton disintegrated lithium nuclei with protons which had been accelerated by a voltage of 500 KV. A photograph of this machine is shown in Figure 1. The accelerating tube for this machine was made of glass cylinders mounted one on top of the other with metal plates in between acting as electrodes to distribute the voltage along the length of the tube. The glass cylinders came from the petrol pumps which were used in those days and they were stuck to the metal electrodes with plasticine to a allow the accelerating tube to be evacuated–a far cry from modern technology. It soon became clear that the way to higher particle energies was unlikely to be by developing higher voltage generators and longer accelerator tubes.

At the time that Cockcroft and Walton were building their accelerator in Cambridge, Ernest Lawrence in the USA was developing a method of accelerating particles which was based upon an idea first proposed by Wideroe in 1928. Lawrence's accelerator, the cyclotron, consisted of a large electromagnet with circular pole tips between which protons could rotate in a spiral orbit in a vacuum.

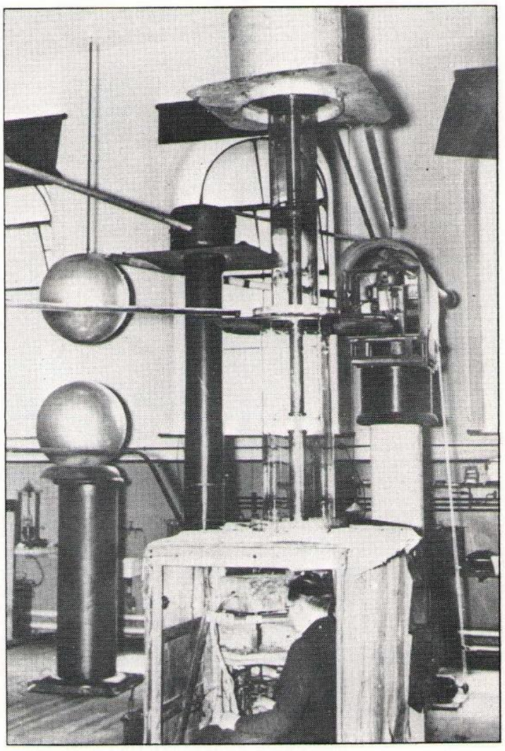

Fig. 1
Cockcroft and Walton's original particle accelerator

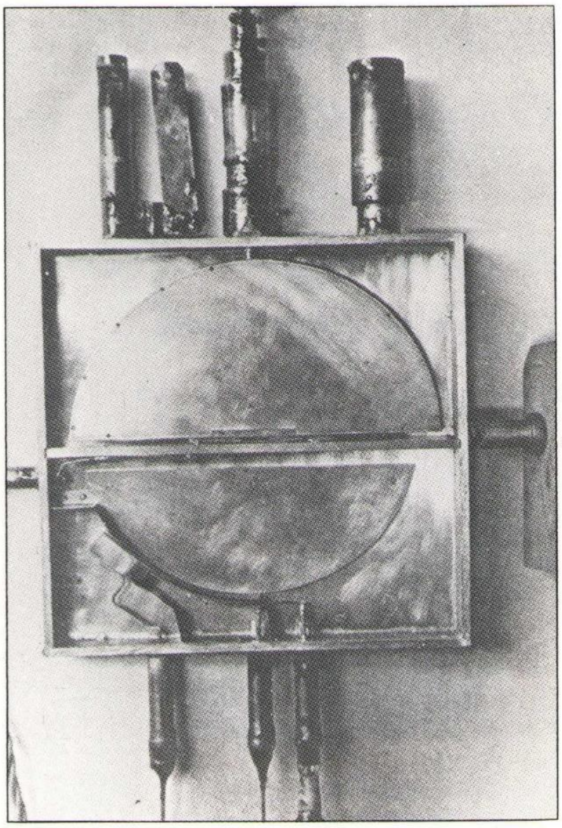

Fig. 2 The vacuum chamber of the first cyclotron

On each revolution the particles were accelerated by a high frequency electric field. The magnetic field constrained the particles, while the electric field provided the acceleration. High energies were achieved by the repeated and phased application of the electric field and not by the single application of a high voltage. The advantages are obvious.

The first cyclotron accelerated protons to an energy of 1.2 MeV and disintegrations in lithium and other targets were obtained by Lawrence, Livingston and White in September 1932. Figure 2 shows the vacuum chamber of the 1.2 MeV cyclotron and Figure 3, which is a picture of this cyclotron, amply demonstrates that by 1932 the technology in the USA had not advanced any further than in the United Kingdom. Nevertheless, Lawrence, Cockcroft and Walton all were awarded Nobel prizes for their work.

The early post-war period

The discovery by Rutherford of the tiny size of the nucleus raised the question as to what holds it together, for the electrical forces tending to push it apart must be 10^8 times stronger than anything experienced in chemistry or atomic physics because the distances are 10^4 times smaller. The only conclusion one can draw is that there is a specifically nuclear force between the particles which is short range and very much stronger than the electromagnetic force.

It was the Japanese physicist Yukawa who in 1934 attributed the nuclear force to the existence of a new particle, the π meson, which in being exchanged between nucleons bound them together. The range over which the force exerts its effect is inversely proportional to its mass and by equating this to the known range of nuclear forces Yukawa was able to predict that its mass was about 300 electron masses. An important qualitive prediction of Yukawa's theory was that if two nucleons collide with sufficient energy a π meson could materialise. This prediction was partially confirmed by Powell and his co-workers at Bristol in 1947 through the study of photographic emulsions exposed to cosmic radiation.

The full confirmation of the theory was established when π mesons were artificially produced in the USA shortly afterwards. The machine which was used for this was built by Lawrence. It had a huge magnet with 184 inch diameter pole tips, and finally accelerated protons up to an energy of 720 MeV. This very high energy only became possible through the discovery of the principle of phase stability which was announced almost simultaneously in 1945 by E E McMillan at Berkeley and V V Veksler in Moscow.

Fig. 3 Lawrence's 1.2 MeV cyclotron

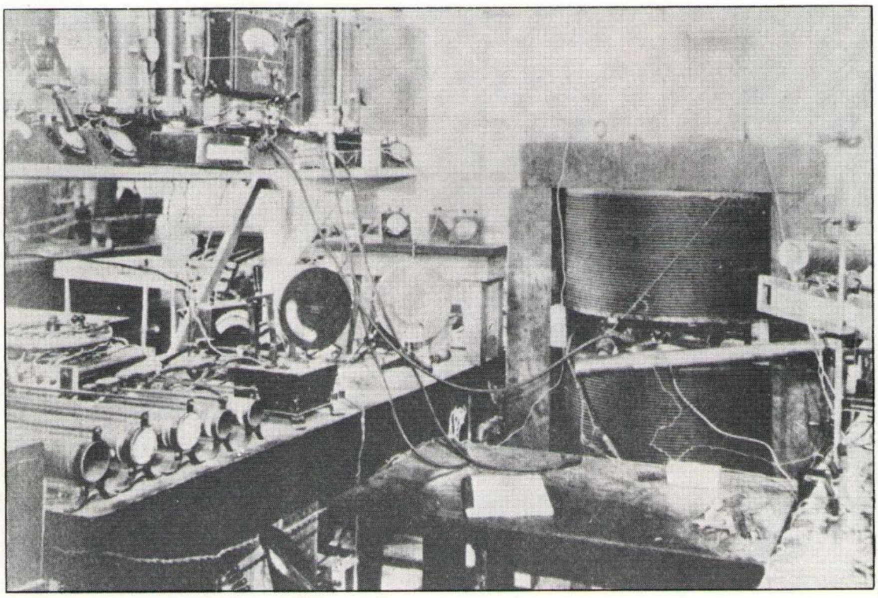

Fig. 4 Berkeley scientists inside the frame of the 184-inch magnet for their synchrocyclotron

Fig. 5 The Dubna synchrocyclotron


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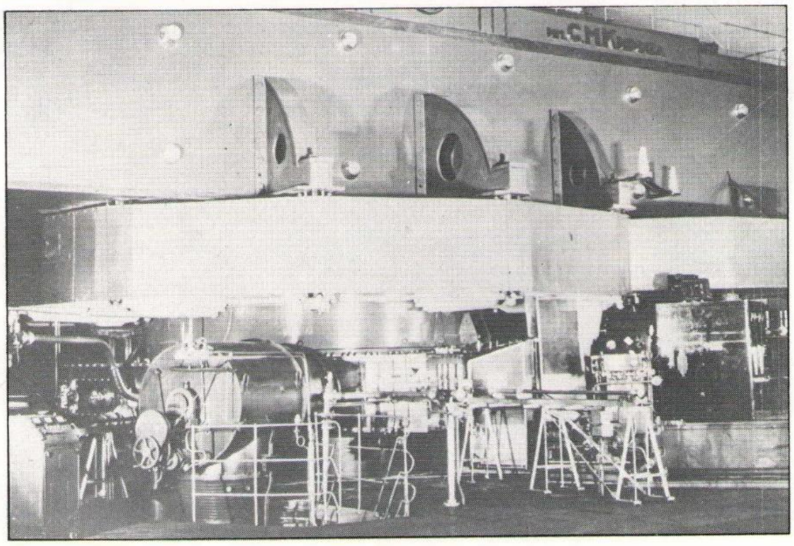
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The machine was christened a synchrocylotron. It differed from the conventional cyclotron in that the frequency of the alternating electric field was made to vary over a small frequency band to allow for the relativistic increase in the effective mass of protons. The sheer size of these machines can be appreciated by Figure 4 where we see the Berkeley scientists photographed within the frame of the 184 inch magnet. This is a historic photograph containing many great scientists. Lawrence is seated in the middle of the first row and other Nobel Laureates there are McMillan and Alvarez. R R Wilson who has built America's largest accelerator at the Fermi National Accelerator Laboratory near Chicago is third from the right in the back row. Figure 5 is a photograph of a similar machine built at the Dubna Laboratory near Moscow.

The discovery of the π meson was in itself a tremendously important step in confirming Yukawa's theory. The availability of controllable beams of π mesons has also led to many other important developments.

Synchrotrons

The limitations to the energy which can be obtained with synchrocyclotrons is an economic one rather than one of principle, but fortunately new ideas for accelerators were still forthcoming. The synchrocyclotron had a constant magnetic field. At low energies the protons had a small radius of curvature and as the energy increased so did the radius of curvature — hence the need for a solid magnet. In the synchrotron we use a ring shaped magnet with the protons constrained at a fixed radius. Both the magnet and electric fields are varied synchronously. By eliminating the solid magnet much larger diameter machines and hence much higher energies are possible. The proton synchrotron which is in operation at the CERN Laboratory in Geneva has a diameter of 2.2 kilometers. Imagine the cost of a solid magnet of this size.

Actually the first proposal for a proton accelerator using a ring magnet was made in 1943 by Oliphant but because of wartime security the proposal was not published. Following the work on phase stability by McMillan and Veksler a definitive theoretical analysis of orbit stability and a detailed design was made and published by the group under Professor Oliphant, then at Birmingham University. A 1 GeV proton synchrotron was built in Birmingham but unfortunately it came into operation in 1953 one year after the Americans had built a 3 GeV proton synchrotron at the Brookhaven National Laboratory.

Once again the advance into a new energy region revealed new phenomena. Using a π meson beam and a hydrogen target two new particles, the K meson and the Λ

hyperon were produced. The strange fact, as foreshadowed by some earlier cosmic ray results by Rochester and Butler, was that these particles were always produced in pairs. The explanation put forward independently by Gellman and by Nakano and Nishijima is that there must exist a new property of matter hitherto totally unknown which they christened Strangeness.

The particles were produced in pairs because one of the new particles had a value of $S = +1$ and the other a value of $S = -1$, i.e. total strangeness of zero. The sum of the strangeness of the π-and proton is also equal to zero.

Two years later a larger proton synchrotron, the 5.7 GeV Bevatron at Berkeley, came into operation and in the following year Chamberlain and his co-workers produced and identified the antiproton — thus confirming the theoretical ideas on antimatter proposed by Dirac as far back as 1928. Owen Chamberlain and Emilio Segre were awarded the Nobel Prize for this discovery. The discovery of the anti-neutron followed one year later. Once again we had an increase in energy which resulted in discoveries of profound importance. Figure 6 shows a general view of the Berkeley Bevatron and Figure 7 is a similar picture of the 7 GeV proton synchrotron "Nimrod" at the Rutherford Laboratory. The Bevatron magnet weighs about 10,000 tons so once again there were economic factors limiting the way to higher energies.

Alternating-Gradient Synchrotrons

The route to higher energies was opened up by an idea put forward in 1952 by Courant, Livingston and Snyder. This new principle for focusing the proton beam within the accelerator greatly reduced the amplitudes of oscillation of the particles about their circular orbit and so reduced the cross-section of the magnet, its cost and power consumption. It is important to record that the principle of alternating gradient focusing proposed by Courant and his co-workers in 1952 was developed independently 2 years earlier by N C Christofilos, a Greek electrical engineer working in Athens.

The first proton synchrotron to be completed using this new focusing principle was the 28 GeV machine at CERN in Geneva which operated in 1959, closely followed by the completion of the 33 GeV machine at Brookhaven National Laboratory in the USA. Figure 8 shows a view of the CERN 28 GeV proton synchrotron and illustrates quite dramatically when compared with the Bevatron the size reduction made possible by the new focusing principle. The CERN machine uses 120 tons of steel per GeV against 1500 tons per GeV for the Bevatron and 3500/GeV for a similar Russian accelerator.

The advances made in particle physics since these two machines came into operation are tremendous. If I have to make a choice my personal vote would place in importance the experiments done first at Brookhaven and shortly afterwards at CERN which established the existence of the neutrino and the fact that there were indeed two kinds of neutrino — one associated with the electron and one associated with the muon.

Another discovery made on the 33 GeV Brookhaven synchrotron of profound

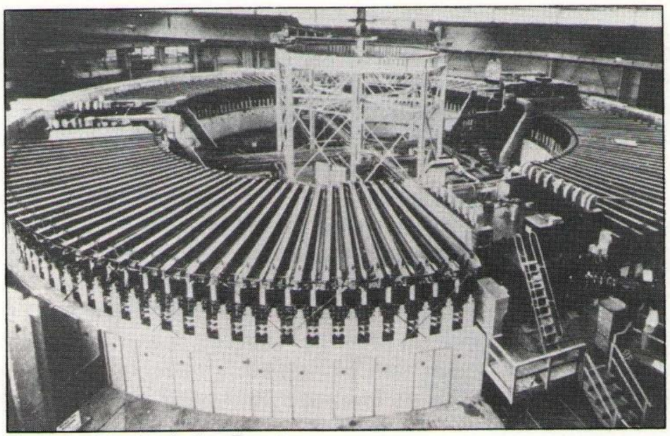

Fig. 6 The Berkeley Bevatron

Fig. 7 Nimrod at the Rutherford Laboratory

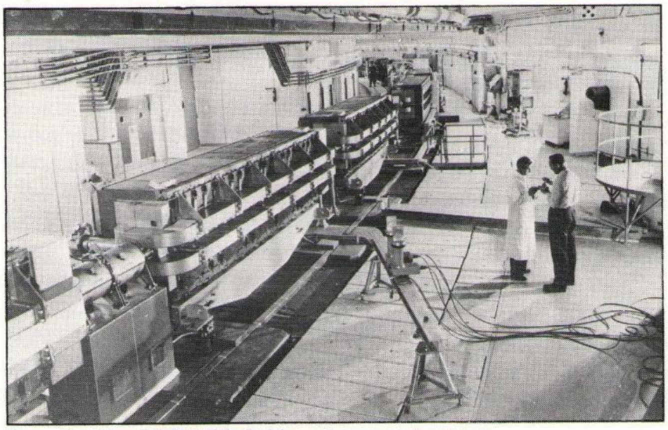

Fig. 8 The CERN 28 GeV proton synchrotron

significance was the identification of the so-called Ω^- (Omega minus) particle. The importance rests on the fact that such a particle had been predicted by the theory of Unitary Symmetry first suggested by Ohnuki in 1960 and developed by Gellman and by Ne'eman. This theory greatly clarifies our understanding of the strong interaction and the relationship between the many so-called elementary particles which have been observed. It predicts too that there should exist a new set of particles called 'Quarks' which are fractionally charged, may be very massive but which have not yet been observed.

Experiments with beams of neutrinos will be a major component in the research which will be done on the two new 400 GeV proton synchrotrons, namely the one at the Fermi National Accelerator Laboratory in the USA and the one at CERN. A discovery on one machine becomes the tool for investigation with the next generation of accelerators.

To give you some idea of the size of the present generation of accelerators in Figure 9 a plan of 400 GeV synchrotron at CERN has been superimposed on a map of central London.

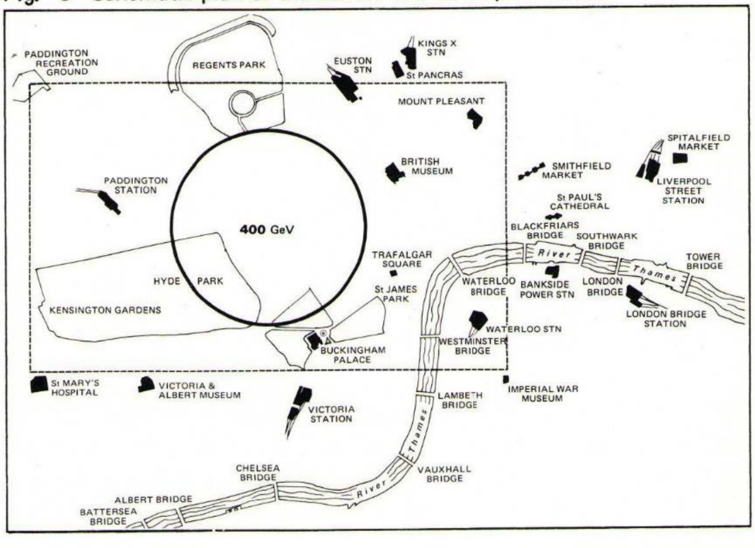

Fig. 9 Schematic plan of the CERN 400 GeV synchrotron

Intersecting Storage Rings

The energy parameter which is of importance in high energy collisions is the centre of mass energy. Unfortunately with a fixed target machine such as those we have been discussing so far, much of the primary energy is wasted in giving kinetic energy to the target fragments. For example the 28 GeV proton machine has an effective centre of mass energy of only about 7 GeV and this increases only as the square root of the energy so that the available centre of mass energy on the 400 GeV accelerator is only about 27 GeV.

From an energy point of view the more efficient way is to collide two beams of protons of equal energy head on. The centre of mass energy is then the sum of the energies of the two beams. So now instead of a centre of mass energy of 7 GeV when a 28 GeV strikes a stationary target, two 28 GeV protons colliding head on yield a centre of mass energy of 56 GeV. To achieve this with a stationary target accelerator, it would need to be designed for a proton energy of almost 1500 GeV.

The one and only proton storage ring built in the world is the 28 + 28 GeV machine at CERN. Figure 10 illustrates one of the intersecting regions on the CERN ISR. This machine is a marvel of technological achievement. A current of about 20 amperes of protons is circulated in a vacuum and stored for many hours — even days — at a time. The magnets have therefore to be built with great precision and it is essential to be able to operate at a vacuum pressure of 10^{-10} to 10^{-12} torr.

Electron-positron storage rings have been built in several places. The two largest are at the Stanford Linear Accelerator Laboratory in the USA (4.5 + 4.5 GeV) and at the DESY Laboratory in Germany (5.0 + 5.0 GeV). The big advantage in colliding an electron with its anti-particle is that we produce a single pure quantum state — a state of pure energy and of extremely high energy density. A most important discovery was made very soon after the Stanford machine came into operation. It was found that at a centre of mass energy of 3.105 GeV, the cross section for the reaction $e^+e^- \rightarrow$ hadrons or e^+e^- suddenly increased by about 100 fold compared with the cross section outside the resonance. Futhermore the width of the resonance was less then 1.3 MeV which is equivalent to an abnormally long life-time for this resonant state. The observation can be likened to the discovery of a new sun as one scans the sky or to the discovery of pulsars. Figure 11 shows the experimental results. The interpretation of this phenomenon, we believe, is that a new state of matter has been observed. As new results have accumulated it appears probable that we have identified a new quantum number — charm — which, in fact, had been suggested by Glashow and others some years ago. There is some evidence that a heavy electron may have been discovered too.

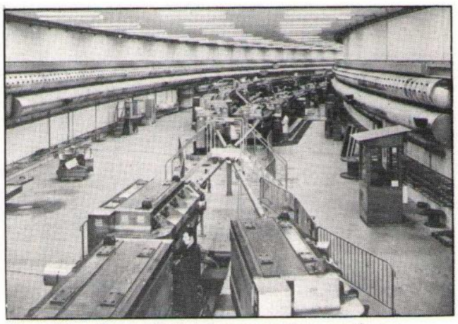

Fig. 10 One of the intersecting regions at the CERN Intersecting Storage Rings

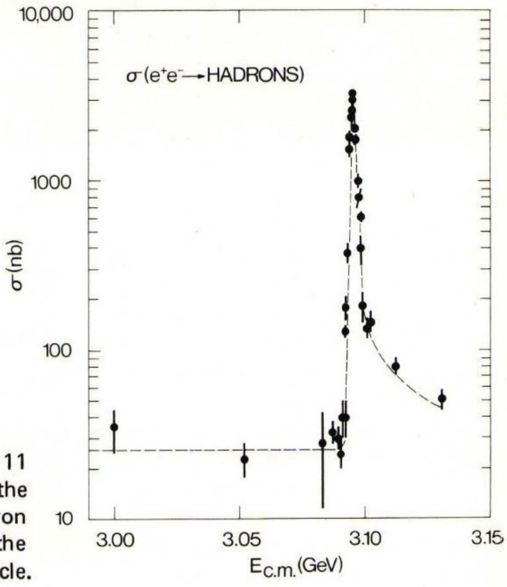

Fig. 11
Experimental results from the Stanford electron-positron storage rings, showing the existence of the J/psi particle.

The Future

Particularly as a result of the discoveries on the electron-positron colliding beam machines over the past 2-3 years, particle physics is today in a state of tremendous excitement and optimism. Great progress has been made both experimentally and theoretically. As new energy regions have been made available to us through the construction of larger and more powerful accelerators so, without exception, have important and frequently quite unpredictable discoveries been made. But in spite of these great advances our understanding of the nature of the strong and weak nuclear forces has in no way reached the fundamental level to which our knowledge of electromagnetism and gravitation extends. We can, however, formulate many questions that will need to be answered by work on the next generation of accelerators.

For example:

- a All known strongly interacting particles can be classified using the quark model — a result which may have as large an impact on physics as the classification of the elements in the periodic table had upon chemistry. And yet the quark has not yet been observed experimentally. Is it a real entity or just a mathematical abstraction? Is it really fractionally charged?

- b A sub-structure to the nucleon is directly indicated by inelastic scattering of electrons and neutrinos. What is the nature of this substructure? We are beginning to get convincing evidence of a new quantum number, charm, so are there other new states of matter and new quantum numbers and if so at what energy will they appear?

- c Neutrino experiments have demonstrated that neutral currents contribute to the Weak interaction. This provides support for Weinberg — Salam types of gauge theory of the Weak interaction and may lead to a means of unifying the Strong and Weak interactions. Such a unification could be as important to physics as was the unification of electric and magnetic phenomena through Maxwell's equations. But if the weak interaction has non-zero range we should observe a new particle, the intermediate vector boson, with a mass of about 100 GeV. It remains to be discovered. There may indeed be a whole series of intermediate bosons, as well as heavy electrons and new kinds of neutrino awaiting discovery.

In the near future there are available to experimental particle physicists the 400 GeV proton synchrotrons in Europe and the USA. There are two 15 + 15 GeV electron-positron storage rings now under construction which should be in operation by 1979 or 1980. The one is at the Stanford Linear Accelerator Laboratory in the USA and the other at DESY in Hamburg in Germany. Beyond this there are various options, none of which has as yet been funded:

- a an electron-positron storage ring with a centre of mass energy of 100 to 200 GeV,

- b a proton proton storage ring up to 400 + 400 GeV, or even to 1000 + 1000 GeV if a machine called POPAE is built in the USA,

- c an electron-proton storage ring in which 20 GeV electrons collide with 400 GeV protons,

and finally

- d a 10-TeV conventional proton-synchrotron with a fixed target.

Any major step in the future will almost certainly require a collaboration on a world scale simply on the grounds of cost. It could be argued that a collaboration on a world scale between physicists would be a good thing for political reasons. Whether this is so or not, all the evidence leads me to believe that it will be of outstanding significance scientifically.

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