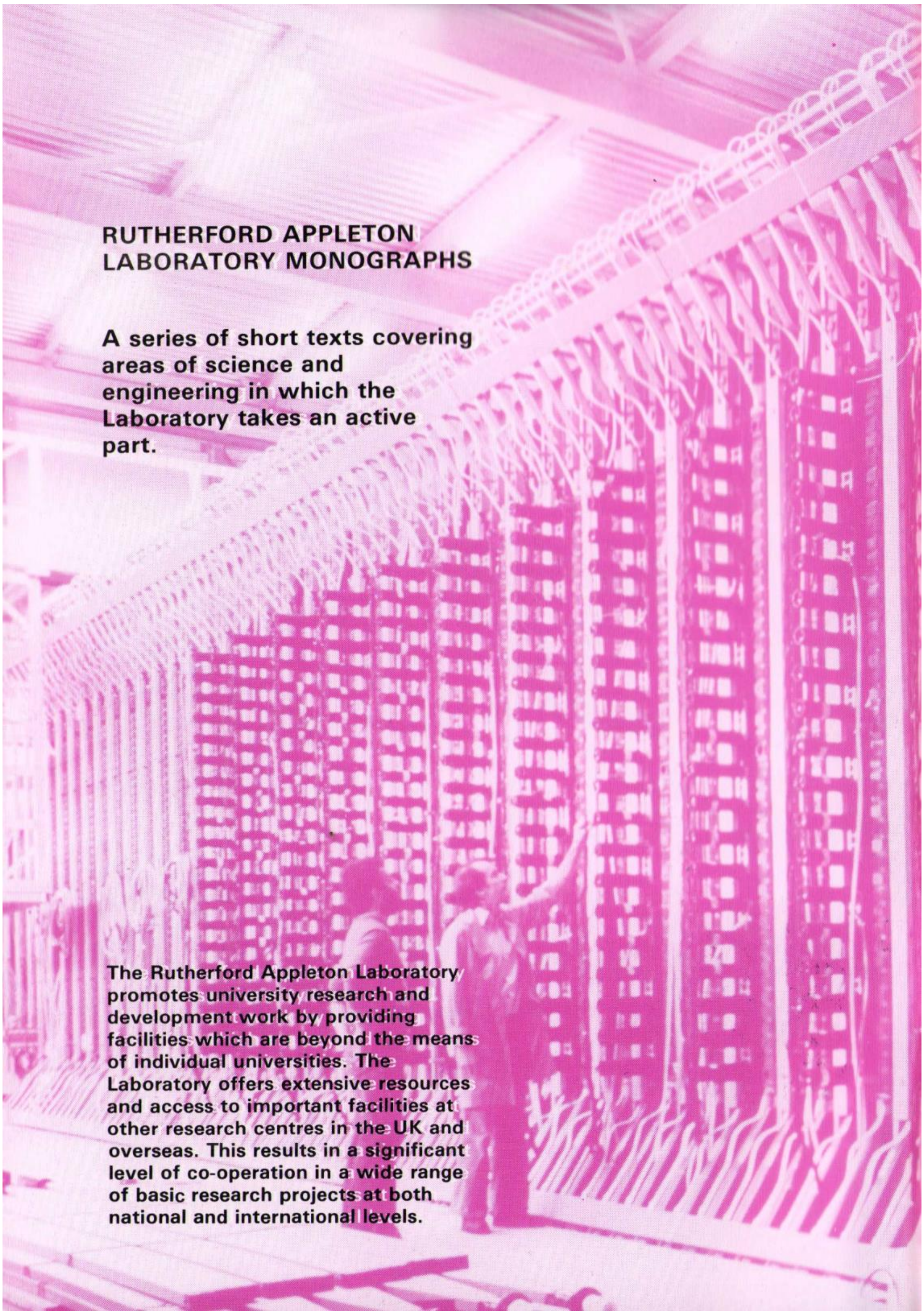
A Rutherford Appleton Laboratory Monograph

Experimental Particle Physics



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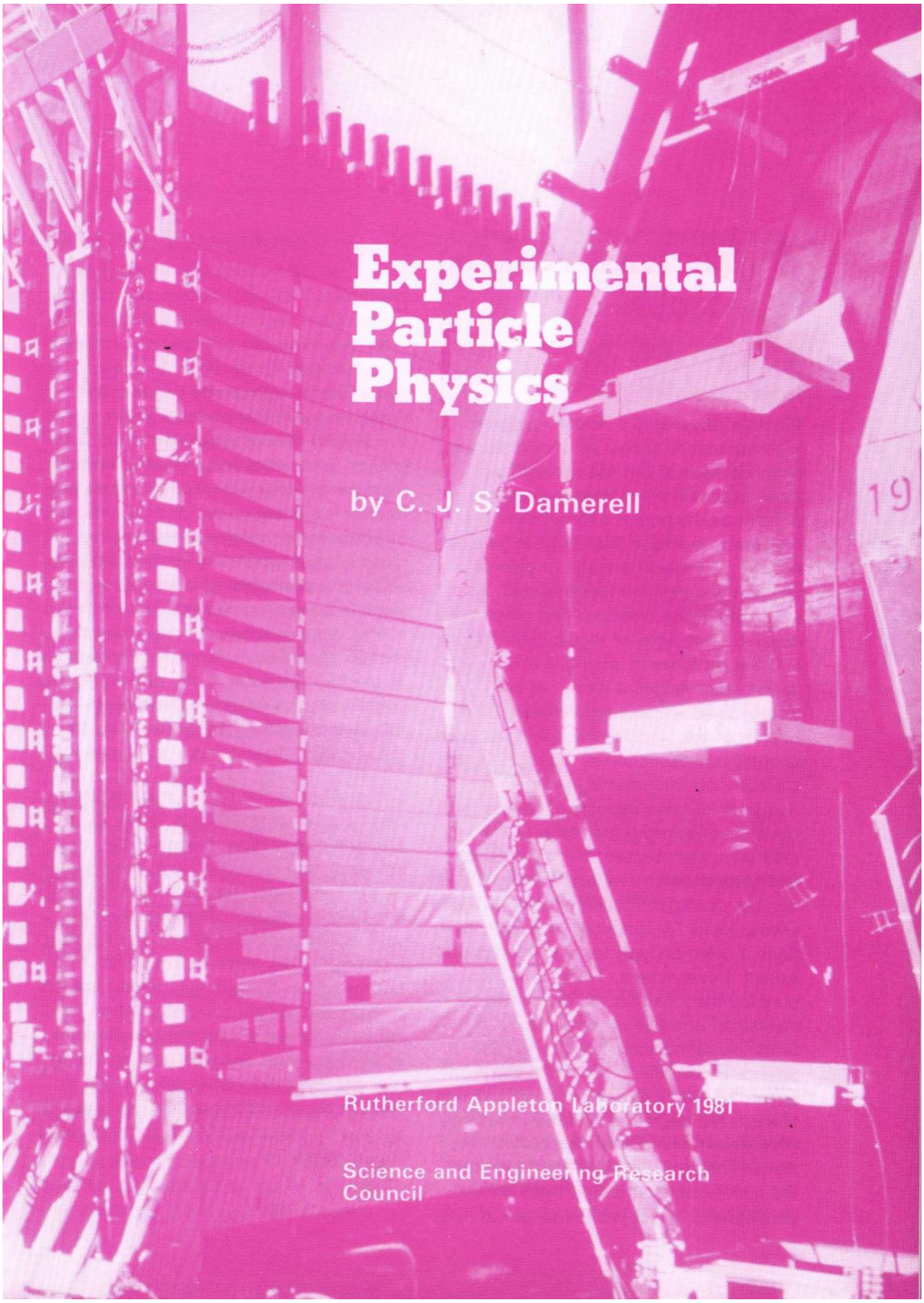

Experimental Particle Physics

by C. J. S. Damerell

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Science and Engineering Research Council

Experimental Particle Physics

Introduction

Particle physics is a field of research with aspirations almost as ancient as the historical record; but the realisation of these aspirations becomes increasingly difficult as the goal is approached. The motivation seems at first sight to be clear enough. We live in a world of diverse physical composition (earth, wood, light, electricity, living creatures and so on). We observe clear signs of regularity in Nature, and the centuries of scientific investigation have yielded a wealth of laws which describe these regularities. The motion of the planets, the drifting of continents, the respiration of plants, the cell structure of living matter, these and hundreds of other aspects of Nature have slowly evolved from the realm of the unknown, the obscure, the mysterious and been shown to be based upon a small number of elegant general principles. Man always looks for simplicity in Nature, and finds it often enough to be encouraged to expect it everywhere. Thus he has long pursued the idea that the apparently diversified universe is composed of a few fundamental building blocks. Particle physics is the 20th century chapter in the history of Man's search for these building blocks. The degree of optimism that they have at last been found has waxed and waned through the centuries. At present the general opinion is that these elusive constituents, if not yet found, are at least perceived through a very thin veil; this optimism may be short-lived. Each succeeding chapter involves the study of smaller (and hence more elusive) objects than the previous one. Today we are performing experiments which cost millions of pounds and which are designed to glean some fragmentary information about tiny **particles** which exist for a small fraction of a millionth of a second before they break up. All the previous periods of optimism, from the Greek view of the four elements to the atomic physics of the early 20th century, have been followed by periods of confusion as the theories have been proven to be wrong.

The most common question asked about particle physics research is **"Why do it?"** The grand aspiration may never be achieved, and even if it were, what would be the justification for the enormous cost and effort involved? There are several valid answers which I think can be given, but these I shall leave for the conclusion. Let me at this stage simply regard particle physics as the field to which Nature has led us in our search for the constituents of matter. I shall describe how we have reached this point, what we are able to learn in our experiments, and why we are excited by the prospects of some answers to our questions.

Historical Background

As early as the 5th century BC, an attempt was made to reduce the infinitely varied physical world to four basic constituents. Empedocles proposed that *fire, air, water* and *earth* constituted the primary building blocks of matter. This theory was disputed a century later by Aristotle, who suggested that the four elementary qualities of *heat, cold, dryness* and *moisture*, in the appropriate mixture, were the constituents of all Earthly things. He required a fifth element to produce the heavenly bodies. His theory formed the basis of alchemy, which persisted until late in the 17th century. The possibility of changing one substance into another (transmutation) by changing the proportions of the elements (e.g. by adding heat) was a matter of keen investigation. Fig. 1 is a drawing dating from 1554 which depicts one of the experiments being conducted by our forerunners in the search for the true elements of matter. These transmutation experiments failed because they were based upon an incorrect theory of the elements. Such experiments were nevertheless vital to the development of the subject.

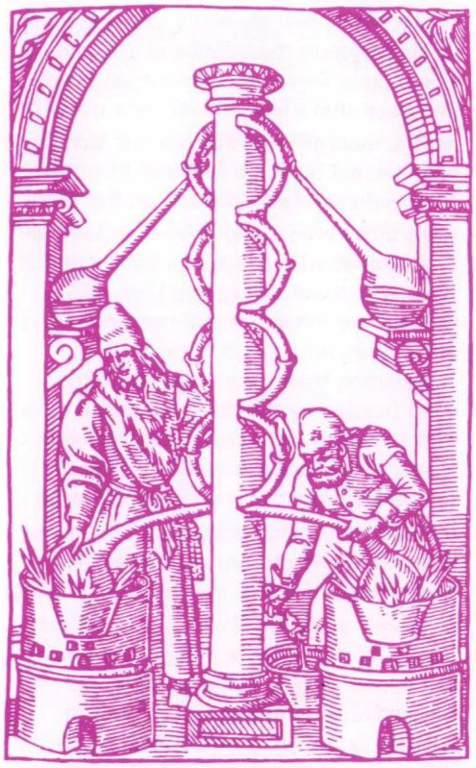


Fig. 1. Drawing of an early experiment in alchemy, dated 1554.

By the 17th century, the alchemical experiments were showing up a rather striking pattern. Many of the substances studied could be broken down into what might be constituents and some of these appeared rather frequently. Others, to the contrary, were extremely resistant to such decomposition processes. These results gave encouragement to the theory that the seemingly infinite variety of matter which we encounter on Earth may be composed of a rather small number of basic irreducible materials called *elements*. The earliest lists of the elements were both incomplete and inaccurate (including numerous substances which later proved to be compound). A further two centuries of active research (a lesson here that one must be patient when it comes to scientific progress) led to the recognition of the ninety-two elements which are still fundamental to the science of chemistry. The atomic theory was developed which proposed that the elements were made of minute indivisible particles called *atoms* which could combine together to form all other substances (compounds). But there were those who could not be content with this picture, who needed to understand in what way these ninety-two kinds of atoms were different from one another. There were others, led more by observation than by speculation, who were puzzled by the discrete wavelengths of light which were emitted by atoms in certain circumstances (see Fig. 2) or by the penetrating "radiations" which were emitted by certain substances. The early decades of the present century led to spectacular advances in the understanding of atomic structure. From ninety-two elements whose atoms might (for all that was known) have consisted of white blocks coming in ninety-two different shapes, or of balls painted in ninety-two different colours, or of ninety-two cheeses of different flavour, the mists cleared and the modern quantum mechanical atom stood before us. This was a dynamical system of extraordinary complexity, considering its unthinkably small size; a miniature solar system which was always made up in much the same way, with heavy particles (*protons*) glued together by electrons to form a tight central nucleus, and a number of lightweight particles (*electrons*) in orbit round the nucleus. But we were really getting into very deep water at this stage, from which we have not yet fully emerged.

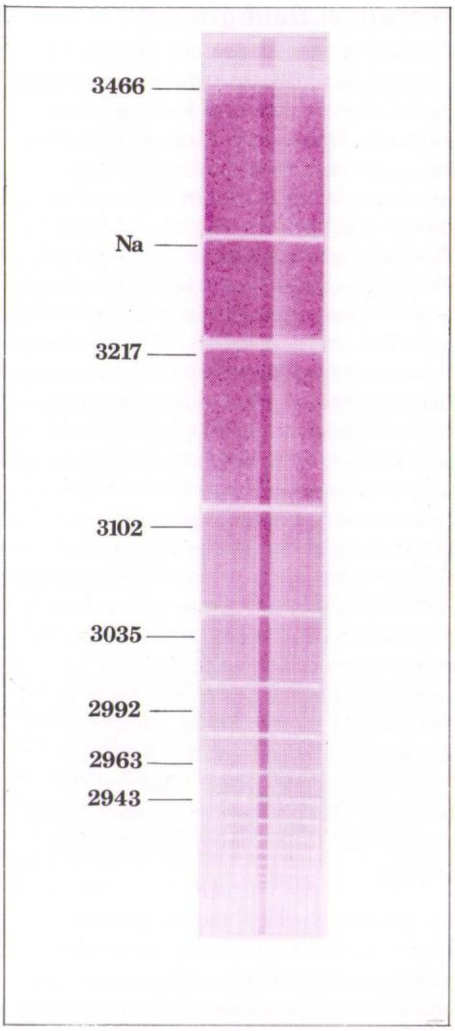


Fig. 2. Spectral lines — light emitted by atoms at certain discrete wavelengths which appears as separate lines when analysed in a spectroscope.

Footnote:
Figures 2, 3 and 4 are reproduced with permission from Max Born "Atomic Physics", 8th edition (Blackie, Glasgow, 1969).

The solar-system model worked beautifully and explained many subtle features of the spectroscopy experiments, but necessitated radical changes to the rules of mechanics, which placed these systems beyond the limit of intuitive visualization. Simple pictures of the atom co-existed with the new ideas of the Heisenberg uncertainty principle; the indistinguishability of particles and waves and various mathematically elegant solutions. For example, Fig. 3 shows a semi-classical orbit of an electron precessing around an atomic nucleus and Fig. 4 is a set of electron density distributions calculated for quantum mechanical states of the atom.

As summarized by Max Born *(Atomic Physics)*, the subject was dominated for two decades by a homogeneous picture:

"There are two primitive atoms, the atoms of electricity, the negative electron and the positive proton; they have equal and opposite charges, but (very remarkably) quite different masses. From these all matter is built up, and that in two stages: there is first formed, from protons with some cementing electrons, the very small and compact nucleus; then this is surrounded by a cloud of electrons of relatively loose structure."

Attempts to delve more deeply into the atom (in particular to understand how the particles of the nucleus are glued together) and observations involving high energy collisions of cosmic rays with matter (which might result in the break-up of nuclei) indicated that the appealing picture of ninety-two elements made up of only two basic elementary particles was by no means the full story. On the contrary, experiments revealed a trickle of new particles.

First came the *neutron*, which might be somehow accommodated as a proton and electron glued together. But any optimists who believed that the problem of the

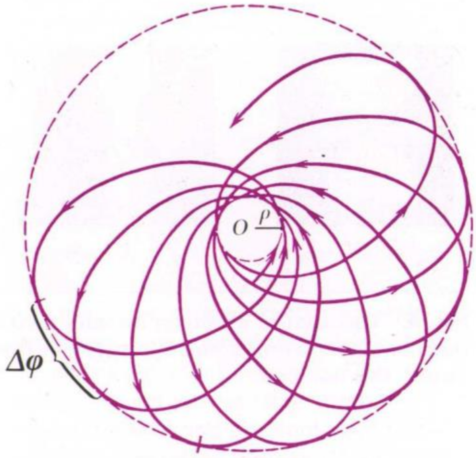


Fig. 3. Semi-classical picture of the orbit of an electron about the atomic nucleus. The precession is due to the relativistic variation of the electron mass with its velocity.

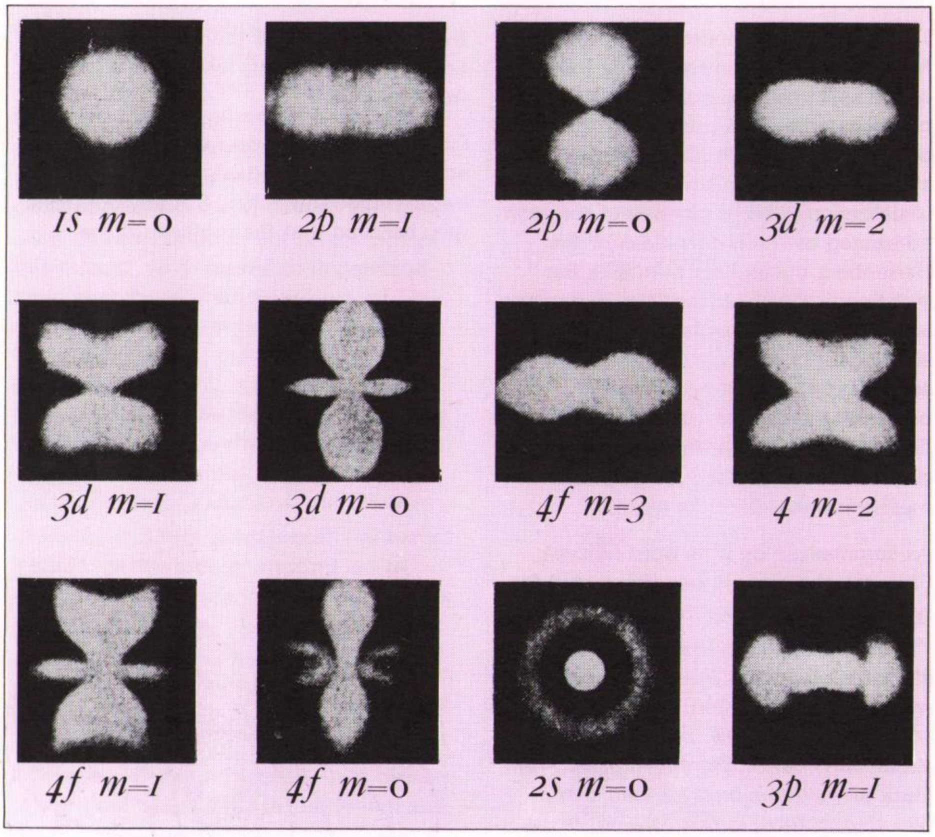


Fig. 4. Calculated electron density distributions corresponding to various *quantum mechanical states* **("orbits" in the classical language) of the electron about the nucleus.**

basic structure of matter was nearly solved (and most physicists of the day were just such optimists), must rapidly have changed their minds as the first *mesons* (particles intermediate in mass between electrons and protons) were discovered. These mesons were theoretically desirable to explain the way in which the particles in the nucleus were glued together, but their number and variety became altogether excessive as the first high energy accelerators began to operate in the 1950s, and the trickle of new particles turned into a flood. The further discovery of *hyperons*, particles heavier than protons, added to the confusion.

By now, the number of sub-nuclear particles exceeded the number of atomic elements, so the simple pattern of many species being built from few constituents had vanished. In such circumstances, the physicist naturally follows the intuitively appealing (and historically rewarding) approach of searching for a set of "even more basic" constituents. This can be done in several ways. The theorist will look at the known array of mesons, hyperons, etc. and try to find some pattern in their masses, electric charges, and other properties which give a hint as to what they are made of. The experimentalist may choose to do experiments which search for new mesons, hyperons, etc. so that the pattern may be made more complete. He may study known ones (most of which live only for a very short time) investigating detailed properties or seeing how they break up ('decay'). He may try to cut corners, avoiding these tedious studies (which are analogous to the careful experiments in atomic spectroscopy of a hundred years ago) and look for the constituents directly. The recent situation in defining the constituents of elementary particles is described in the RAL Monograph by F. E. Close. In this article I will concentrate on how one carries out experiments in this field of research.

Classes of Experiments

There are several reasons why electrons and protons are familiar in so many spheres of 20th century science and technology, while the other elementary particles tend not to be. Protons and electrons have finite electric charge and are stable. These particles are easier to detect and evaluate than neutral particles. Unstable particles have such short lifetimes that special techniques are required for their detection. The problem for the experimentalist is generally the dual one of producing the particles and then studying them. What he studies tends to be more frequently the *decay products* (i.e. the stable particles produced when the parent particle breaks up) rather than the parent particles themselves. The particles found earliest (apart from the proton, neutron and electron) were the relatively lightweight mesons. The special theory of relativity implies the interchangeability of matter and energy. Thus if one wants to produce heavy elementary particles, one needs to convert a large amount of energy into matter. This is done by inducing collisions between stable particles (e.g. a proton collides with a proton) where the projected particle has a high energy relative to the target particle. This requirement has led to an expanding sequence of particle accelerators which can be used to induce increasingly energetic collisions. These collisions yield increasing amounts of available energy which may materialise in the form of yet more massive particles than any seen before. This may sound contrary to the aim of finding the fundamental constituents, but it is one of the many anomalies of the new mechanics that the building bricks may each be heavier than the finally constructed house!

Heavier particles tend to break up into a large number of final-state products, and higher energy collisions produce more particles. Thus during the last 20 years, we have seen the energy of accelerator-induced proton-proton collisions increase from millions of electron volt energies (i.e. MeV) up to millions of MeV, producing an extraordinary increase in the complexity of the "events" which the physicist has to understand in order to find which particles are being produced. (An "event" means an individual collision process; a typical experiment will involve a detailed analysis of millions of events.) Fig. 5 shows two bubble chamber photographs of typical events at 600 MeV and 200,000 MeV; the contrast in complexity is striking. This situation has had the result that the increasing scale and complexity of accelerators needed to produce higher energy particles has been matched by an increasing scale and complexity of the experiments needed to make an adequate analysis of the collisions between the particles. Fig. 6 shows two accelerators at the CERN Laboratory in Geneva. The first view is of the 600 MeV Synchro-Cyclotron and the second shows part of the 400,000 MeV Super Proton Synchrotron which occupies a tunnel of 7 km diameter. Fig. 7 shows the equipment for typical experiments being run soon after the completion of each of those machines.

There are several fundamentally different classes of experiments in high energy physics:

(a) Fixed Target Experiments
High energy particles (usually protons or electrons) may be extracted from the accelerator and made to collide with a target of some material and the events studied. Alternatively these primary interactions may be used as a source for other kinds of particles (mesons, etc.) and these particles can be made to collide with other targets and the events studied. Another alternative would be to allow the secondary particles to simply travel along and to study how they decay 'in flight'.

Commonly used secondary 'beams' of particles (so named for their similarity with beams of light, though shot from a gun might be a better analogy) are pi mesons, K mesons, photons, neutrinos and hyperons. Apart from *decay* experiments, one may do *formation* experiments, *production* experiments, *elastic* and *inelastic scattering* experiments, and so on (as summarised in Fig.8).

Fig. 5. (a)

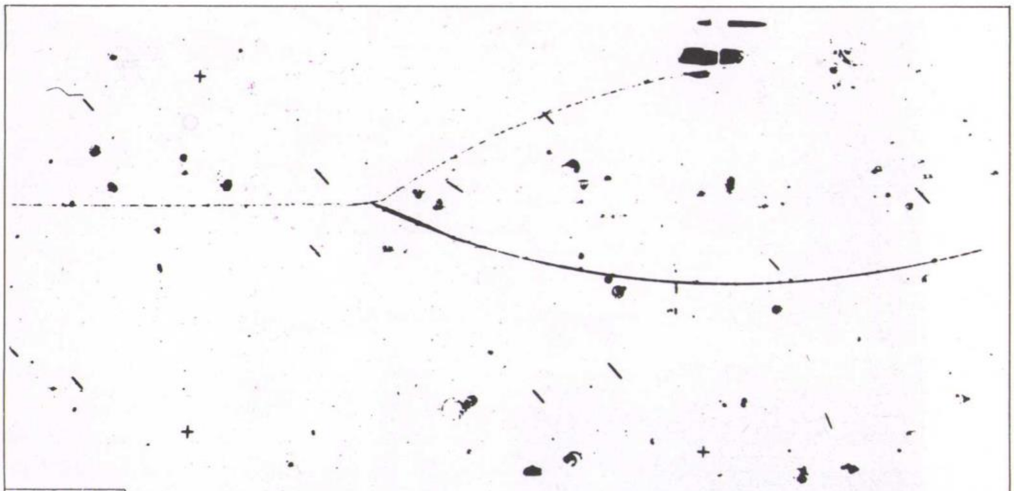


Fig. 5. (b)

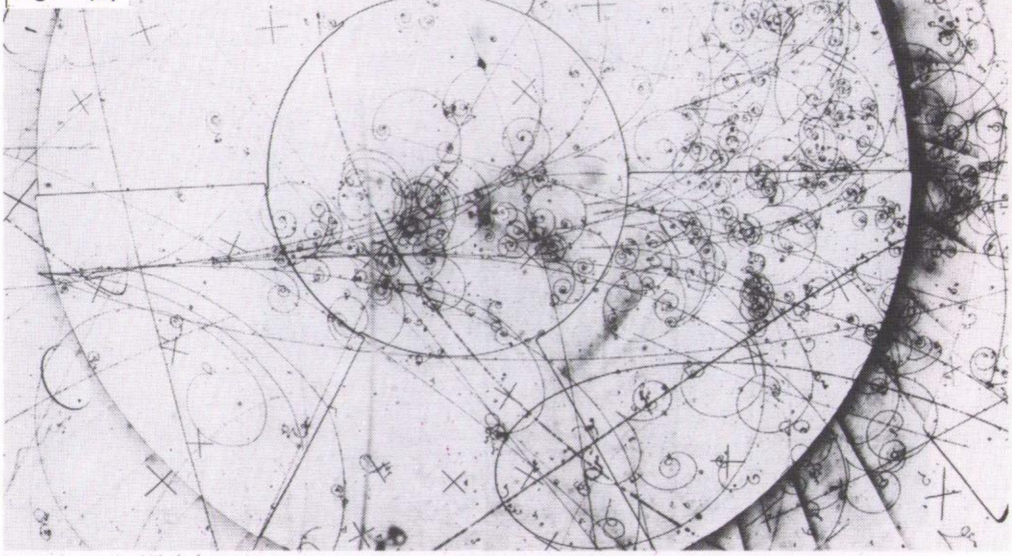


Fig.5.(a) A typical collision at 600 million electron volts (considered to be high energy 20 years ago). (b) A high energy neutrino (200 thousand million electron volts) collides with a nucleus in the Big European Bubble Chamber (BEBC). The large magnetic field bends the trajectories of the charged particles.

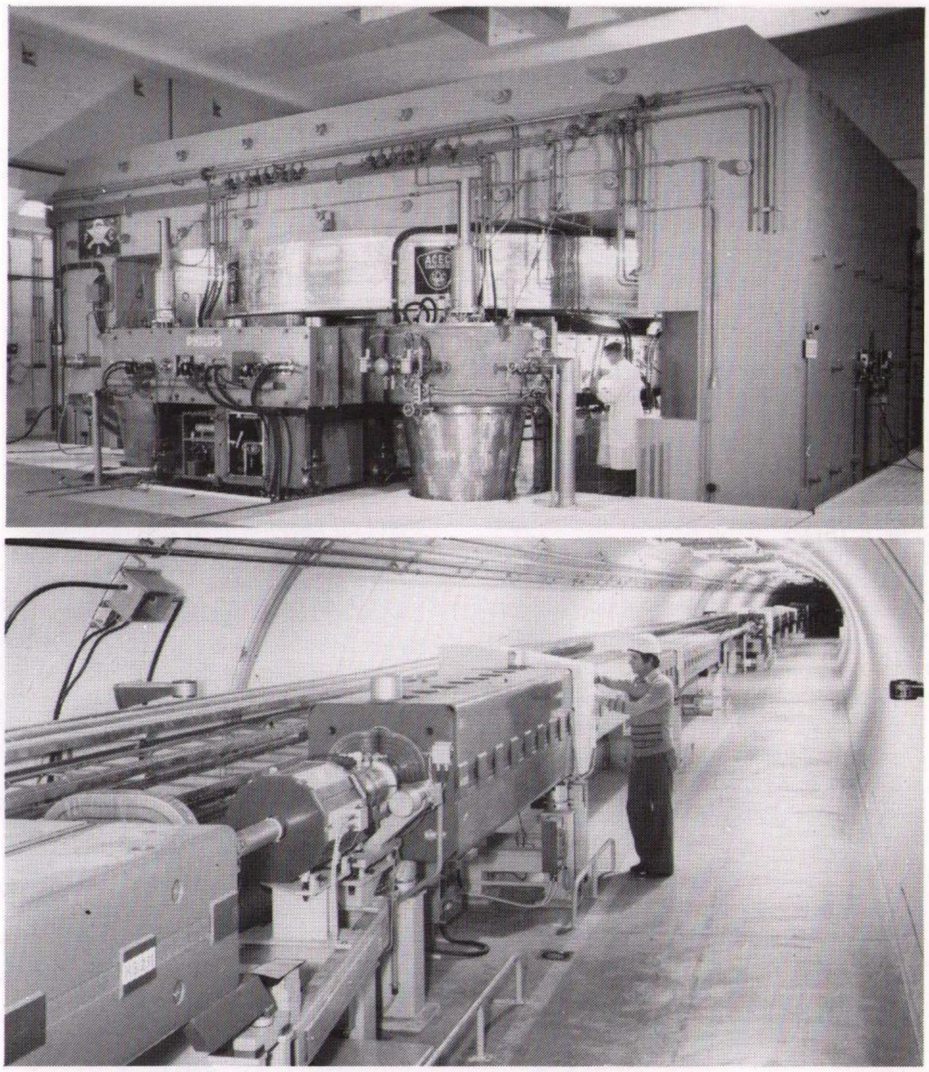
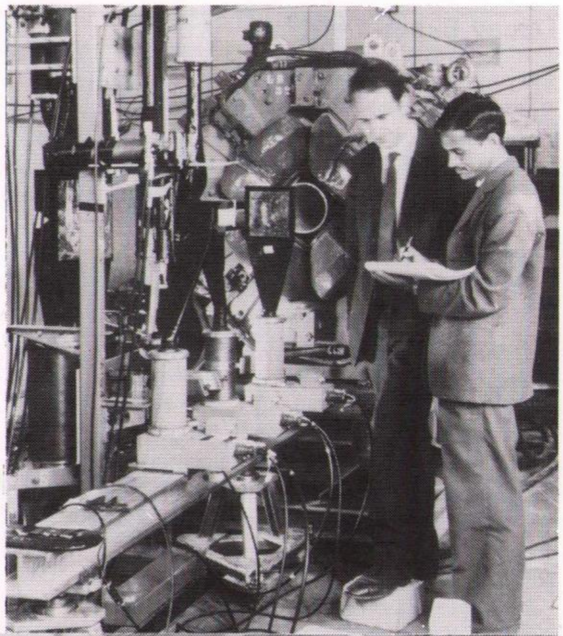
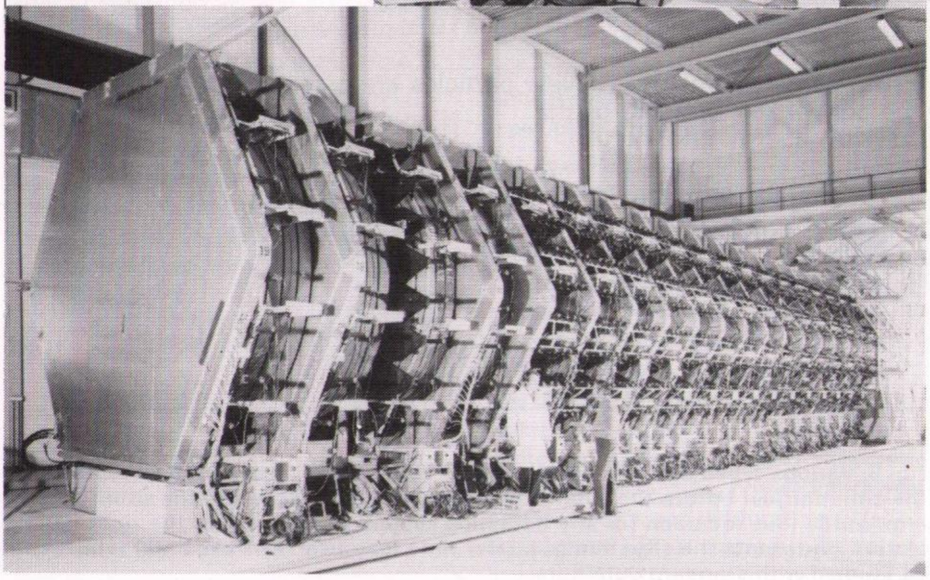


Fig. 6 (a) The upper picture shows the 600 million electron volt Synchro-Cyclotron at the CERN Laboratory in Geneva (CERN photo 1.555).
(b) Below, shows part of the Super Proton Synchrotron in its underground tunnel at CERN. (CERN photo 110.04.76).

Fig. 7. (a) Layout for a typical particle physics experiment in 1963. Note the extreme simplicity and the small scale of the equipment.



(b) An experiment at the CERN Super Proton Synchrotron in 1977. The scale and complexity have increased by an enormous amount. (CERN photo 212.02.77).



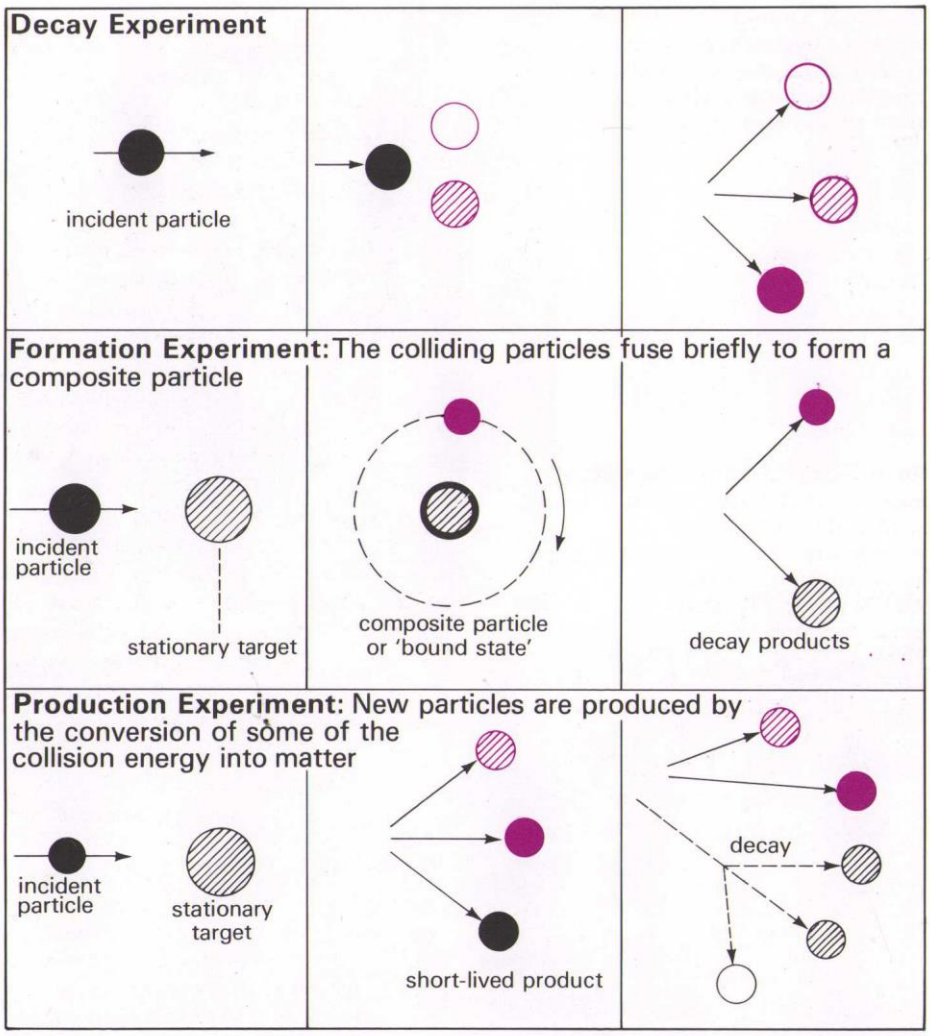


Fig. 8. Various types of experiment. In each case, the left hand picture represents the situation just before the event, the centre picture represents the situation just afterwards (but too soon for any detection system to reveal) and the right hand picture represents the situation at a later time (say after 10^{-9} seconds) which can be studied with standard detectors.

(b) Colliding Beam Experiments

Some accelerators produce collisions between beams of particles moving in *opposite* directions in the machine. In this way one can study head-on collisions of electrons, protons and their anti-particles (positron-electron collisions, antiproton-proton collisions, electron-proton collisions etc.). Again one can do formation experiments (such as when an electron and positron fuse together to form 'charmed' mesons) or production experiments (where the energies obtained are far in excess of fixed target experiments).

In all such experiments, the new particles produced tend to decay so rapidly that they cannot in any way be detected directly. We can only hope to find the pieces (stable, lighter particles) which result from their decay, and then work backwards to infer their own transitory existence. The general aim is therefore to concentrate enormous densities of available energy in a very brief period of time (in the collisions themselves) and then to hope that some interesting particles will be created from this energy, only to decay to well-known final state particles which may be detected, as will now be described.

Particle Detectors

Particles involved in high energy collisions typically travel with velocities close to the speed of light. Nevertheless, like a jet plane producing a vapour trail in a clear sky, particles leave in their wake a fine trail (of ionized matter) by which their trajectories may be determined. In addition, the paths of charged particles may be curved by the application of a magnetic field (usually from giant electromagnets), the degree of curvature being a precise measure of their momentum. In cases where the particle velocity exceeds the speed of light in the medium being traversed (e.g. air), the particles generate a cone of light called "Cerenkov radiation", much as the supersonic Concorde generates a shock wave or "sonic boom". These general effects have led to a variety of detectors which are used to determine precise details of the particles produced in the extremely brief collision processes. Some of the types of particle detectors commonly used in experiments are now described.

The Bubble Chamber

In the bubble chamber (Fig. 9a) a volume of liquid is kept at a temperature just below its boiling point. If the pressure is lowered immediately after the passage of the particle, the trail of ionization produced causes the liquid to start to boil preferentially along the particle tracks. The bubble trails may be seen by illuminating the chamber and recording them photographically. An accurate measurement of the film yields precise information on the incident and produced particles. Examples of bubble chamber pictures are given in Fig. 5.

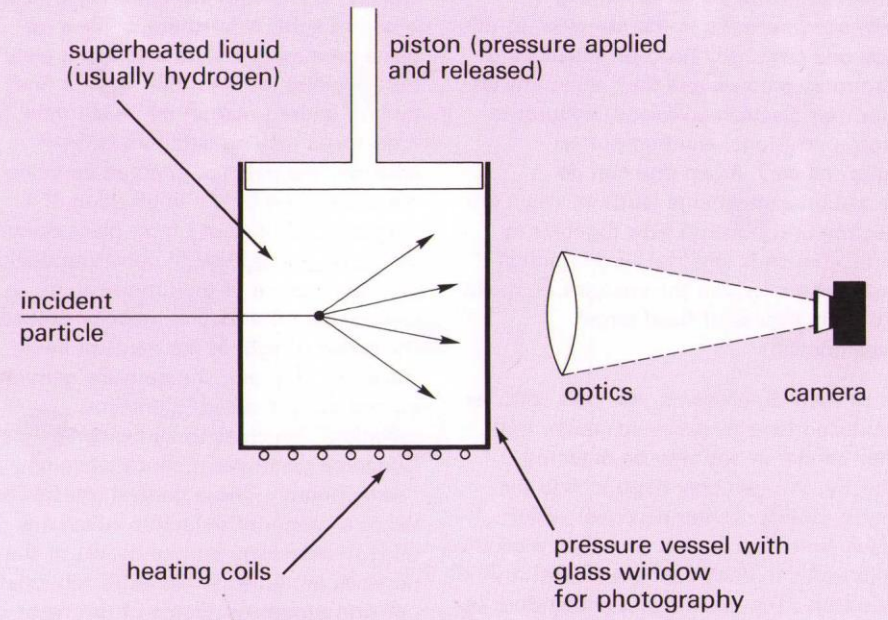


Fig. 9. (a) Bubble Chamber

The Scintillation Counter

In the scintillation counter (Fig. 9b), the ionization produces a flash of light in the material. This was one of the earliest detection methods (using zinc sulphide screens) but has been advanced by the development of large area, low cost, scintillating plastic materials. The light energy is converted into electrical energy using a device called a photomultiplier. This produces an electrical signal which is used to detect and count the particles, or to provide accurate timing information.

The Multiwire Chamber

Another type of detector, based on the trail of ionization produced by the charged particle (using a gaseous medium), is the multiwire proportional chamber (Fig. 9c). Electrons released in the gas between the plates drift in the electric field towards the wires. The arrival of the electrons produces an electrical pulse on the nearest wire. Each wire acts as an independent detector and therefore high positional accuracy can be achieved even for several particles traversing the chamber simultaneously. The multiwire chamber can record millions of particles per second.

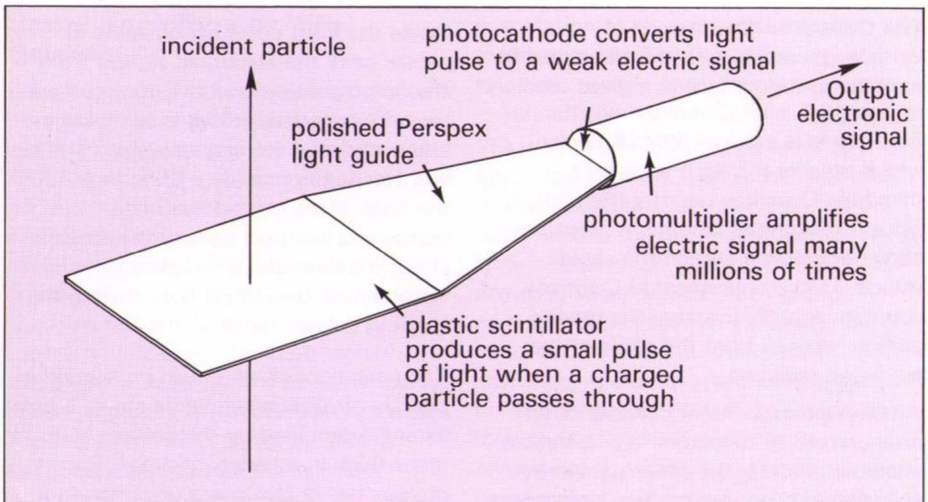


Fig. 9. (b) Scintillation Counter

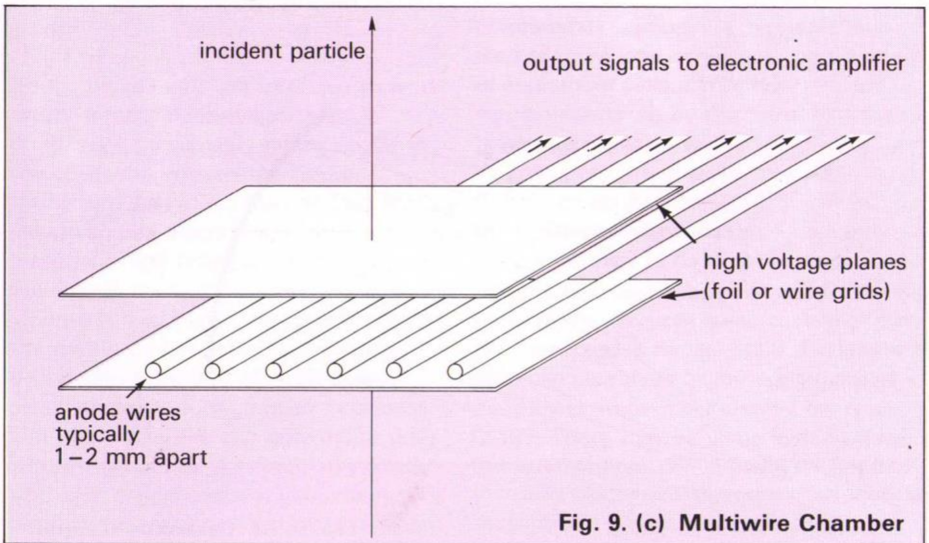


Fig. 9. (c) Multiwire Chamber

The Cerenkov Counter

Particles travelling with velocities greater than the speed of light in a given medium (e.g. a gas), emit Cerenkov radiation in the form of a cone of light. A device which detects this light is called a threshold Cerenkov counter (Fig. 9d), since it recognises whether a particle is above or below a certain threshold velocity. More sophisticated Cerenkov counters actually measure the precise particle velocity from the angle of the produced radiation.

A complete experiment consists of an arrangement of detectors, e.g. a bubble chamber in a magnet accompanied by scintillation counters, multiwire chambers, Cerenkov counters and other devices not described here. The scale of typical experiments is shown in Fig. 7b and inside the front cover. Thousands of cables carry the electronic signals from the detectors to a counting room where they are encoded, stored in computers and transferred to magnetic tape. The on-line computers provide a "first look" at the data. More powerful off-line computers are used to read the tapes, check the data and attempt to 'reconstruct' the events (i.e. analyse the event in detail).

The limitations of what can be learned in particle physics experiments are to a great extent determined by the present state of technology in a variety of areas. Particle physics has in fact played an important part in pushing forward the technology of cryogenics, magnet design, fast electronics and readout systems.

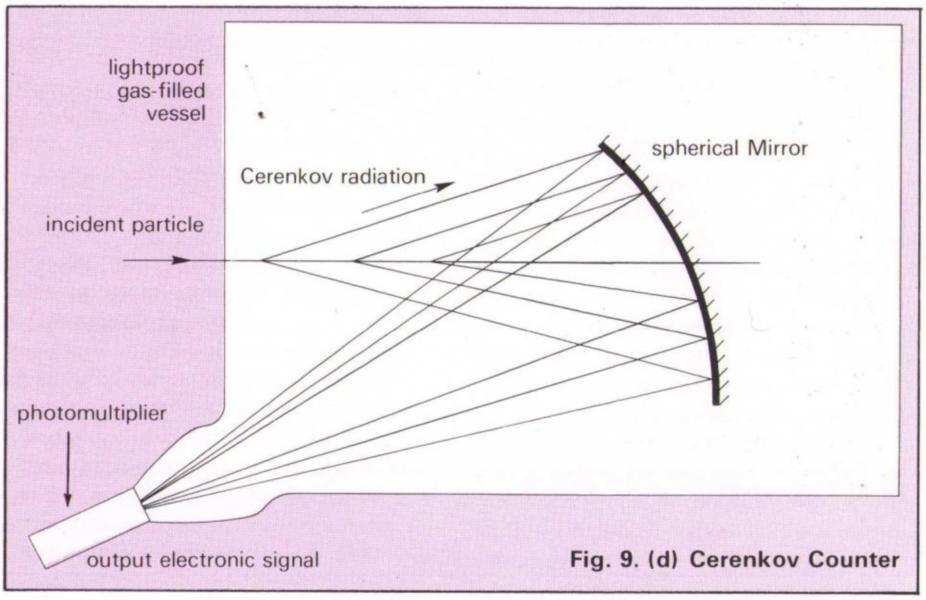


Fig. 9. (d) Cerenkov Counter

Some Sociology of 'Big Science'

Groups doing particle physics experiments have, over the last 20 years, expanded in size from a few people per group to about 100! Physicists are not all instinctively sociable in their attitude towards research, and working in large groups can cause problems. Large experiments costing some millions of pounds are in any case not put together by the scientists. They are of a scale which demands the involvement of many highly skilled engineers and technicians as well. The management of these projects is further complicated by the fact that equipment for one experiment may be built up in several engineering workshops and laboratories in different countries. Scheduling of the accelerator time (which is very expensive) imposes tight time-scales on getting the experiments to work properly.

Young people who are attracted to work on solving the mysteries of particle physics are presumably rather similar to the ones who entered the field in Rutherford's day. Yet they end up doing a job which has a good deal more managerial and financial content than was the case in his era. Strangely enough, Big Science is successful, and this is because the driving motive remains absolutely unchanged from that of small-scale experimental science. It is an inconvenient fact of life that one can only get to grips with the problems of particle physics if one uses large expensive equipment. The dedicated physicist accepts this fact and gets on with the job, using his imagination to keep the equipment modest, in order to obtain the results as easily, quickly and cheaply as possible.

The way in which the large team of physicists organise themselves and their workshops to put together a big experiment reflects the historical background. A large collaboration generally consists of about 10 small groups, each group coming from a separate institution (a national laboratory or a university). In the past many groups worked independently on their own accelerators, but nowadays they need to work together as the complexity and size of the experiments has increased. To form a successful collaboration, the groups should know one another's strengths and weaknesses, and agree informally on a suitable allocation of the work. General decisions (such as choosing options in the physics programme) are taken in joint meetings of the collaborations, while detailed planning of equipment production, data analysis, etc. is undertaken by the member groups, often at their home institution. In this way, a large central laboratory such as CERN can act as a focus for the work of the collaboration, whose members may work separately in different parts of Europe. This organisation of collaborations benefits the physicist working in the field, his colleagues in related fields and students who can also share in the excitement of the subject without necessarily being at CERN. There may be some inefficiencies in this arrangement which could be avoided in a fully centralised laboratory but these are negligible in comparison with the advantages which have been mentioned.

Conclusions and the Future

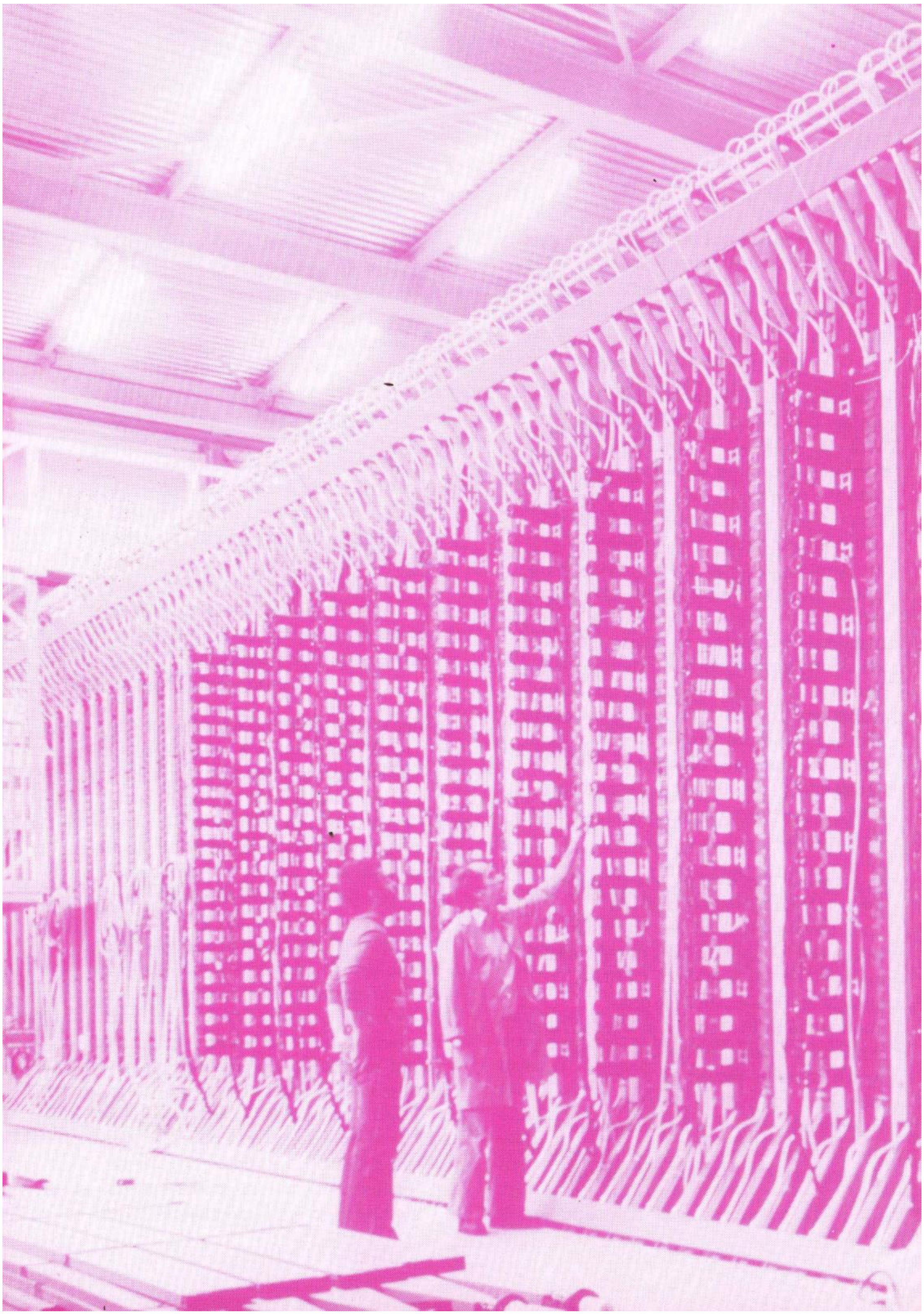
During the past 20 years we have seen particle physics move from a basis of many modest accelerators in university physics departments to a small number of well-equipped national or international centres. The overall expenditure of money and effort has expanded enormously. The community of talented physicists working in the subject is highly productive, dynamic and enthusiastic. But the subject has become Big Science, with costs per head which are high, and costs per experiment which run into millions of pounds. Can this be justified? This is a question which has always to be considered by those inside and outside the field, including the taxpayer who funds the laboratories.

If one looks for a justification in terms of the search for absolute truth, final answers etc., I think one would be in great difficulty. History teaches us that one may from time-to-time unravel a new layer in the scale of physics over which we have some sort of understanding, but new mysteries await us if we explore further. We might build an accelerator with the diameter of the Earth and still not see the full picture. To the physicist, this position is not discouraging. He is familiar with the time and effort which has been needed to reach the present state of our knowledge, and of the transitory states of completeness which have apparently been achieved in the past. The present generation of particle physicists will be well content to solve a few of the most immediate puzzles without concern for useless speculations about the long-term future and absolute answers. Given that the present problems of sub-nuclear physics may well represent an infinitesimal fragment of the undiscovered world which lies beyond, it seems difficult to justify spending hundreds of millions of pounds on clearing up these areas. Nevertheless, I am confident that this work can indeed be justified. The emphasis in each branch of physics (mechanics, electricity, radioactivity, etc.) has moved from being a curiosity, through a phase of increasingly intense study, then into the calm waters of the known and understood and finally to a period of technological applications. This process may take hundreds of years, but is very significant for Mankind. None of the currently understood areas of physics could be deleted from our knowledge without profound difficulty for our industrialised societies.

The most popular current theory of the sub-structure of the elementary particles is that they consist of particles (the so-called "quarks") whose electric charge is smaller than that of the electron ($\frac{1}{3}$ or $\frac{2}{3}$ of this charge). If such particles are ever produced, and are stable, the consequences will be immense. Materials with new physical and electrical properties might be produced by appropriately doping known substances with such particles. The implications might be as profound as the exploitation of semiconductors in electronics. Countries without access to such 'doping' facilities might become technical backwaters. The investment in large accelerators, seen in these terms, is a cheap insurance policy.

The actual value of particle physics to society may be quite different from the above speculation, it may even arise principally from the accelerators rather than the physics. A very active field of fusion research at present is concerned with the application of high energy accelerators to target compression. Here again, the possible economic advantages outweigh the present investment by an overwhelming factor. For these reasons I am confident that particle physics will continue to flourish. Accelerators, experiments and collaborations will grow bigger and become more international. At some stage we shall have one or two "world accelerators" which will represent the ultimate limit of co-operation in our field of research.

In achieving these goals, the physicists, the scientific managers and the governments involved will learn lessons which will be applicable in other areas of international co-operation. CERN is already an organisation of great importance in the history of Europe, and it gives us several indications of the role which could be played by a world laboratory for particle physics. Scientifically and in many broader areas, the future decades hold great promise for developments in this field of research.



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