Cavendish Laboratory photograph (1930)

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NUCLEAR PHYSICS TODAY AND IN RUTHERFORD'S DAY*

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[Plates 2 to 6]

I HAVE entitled this lecture 'Nuclear physics today and in Rutherford's day' but it must be made clear at the outset that what I am taking as nuclear physics today is high energy particle physics rather than the study of nuclear structure and what I am defining as Rutherford's day is the period 1929-1937 during which I had direct personal contact with him. This autumnal period of his career was a golden one. It marked the end of an era while at the same time containing already the seeds of change which led to the remarkable expansion of the subject in the postwar epoch.

The period begins only three years after the discovery of the equations of wave mechanics which brought to an end perhaps the darkest age of confusion to beset the development of physical science, a time when one kind of experiment seemed to prove positively that light was a wave motion and another that it was with equal certainty a stream of particles. The new mechanics and its influence on atomic physics was still in its early stage but its appearance initiated, on a sound exploitable basis, the first phase in the development of the study of atomic structure. It became possible to investigate and interpret in detail the electron distributions in atoms, their relations to atomic and molecular properties and thence to the properties of matter in bulk.

The Cavendish Laboratory in 1929 was, however, already concentrating attention on the exploration of the atomic nucleus, research designed to carry the study of the structure of matter to a second phase. This was Rutherford's prime interest.

THE CAVENDISH LABORATORY AND NUCLEAR PHYSICS IN THE 1930S

By the time I had become a university student in Melbourne the Cavendish Laboratory and its distinguished leader occupied a unique position in the scientific world. Any young man aspiring to a career in research in physical science naturally regarded the chance to work in the Cavendish as the greatest opportunity which he could possibly hope for. The fact that Rutherford was himself

* An expanded and updated version of the Rutherford Memorial Lecture delivered at Christchurch, New Zealand in October 1967.
a New Zealander was an additional attraction to those of us who were born and brought up in the Empire as it then was.

Although I had attended lectures given by Rutherford during his tour in Australasia in 1927 my first personal contact with him was on my arrival in England in September 1929. It so happened that he had just returned from a meeting of the British Association in South Africa. Realizing that I had also just concluded a long journey by luxury liner (first-class free passages were made available for a number of scholars proceeding 'home' and in those days they were first class indeed), he began the conversation by discussing with me the merits of different forms of deck sport, quoits, bullboard, deck tennis and all. It was well calculated to put me at ease and it was some time before we began to discuss research.

As it was only three years since quantum mechanics had been discovered an aura of mystery was still associated with it. Rutherford referred to the rather esoteric branches of mathematics which seemed to be required to exploit the new mechanics, saying with a chuckle that even his son-in-law, R. H. Fowler, the mathematical physicist, was finding group theory unfamiliar, to say the least. The importance of symmetry relations, expressed in group theoretical terms, was already apparent and we shall see that it remains important in the most advanced present-day applications to particle physics.

At the time the study of the atomic nucleus was still in its infancy. The only particles known were the electron, proton and photon but the new mechanics made it difficult to see how these would be adequate to build up atomic nuclei—the uncertainty principle made it impossible to confine electrons within such small regions of space. On the positive side Gamow (1928) had just shown how α-radioactivity could be interpreted in terms of wave mechanics. This was of great interest to Rutherford who regarded α-particles as almost his own personal property.

The total number of research workers in the laboratory was about forty, small enough for everyone to have a good idea of what everybody else was doing and to be interested in it (see plate 2).

**Experimental techniques**

In 1929 the main experimental method for studying nuclei, as now, consisted in bombarding them by high-speed projectiles and observing the consequences of any collisions which took place. However, only one type of projectile was available, the α-particles produced from natural radioactive substances, while the targets were effectively at rest.
Even at this stage detectors were sufficiently sophisticated to be classified under the headings of time- or space-resolving according as they gave information primarily about the time at which a high-speed particle was detected or about its path in space.

The Geiger counter in one or other form was the principal component of any time-resolving detector and the application of new techniques of valve electronics to expand the potentialities of these counters was just beginning. By 1929 scintillation counting, which involved the often rather subjective visual observation of flashes on a screen but which nevertheless had played a major role in earlier work, was no longer employed.

Thus, quoting from a paper by Chadwick, Constable & Pollard (1931) on artificial disintegration by $\alpha$-particles, 'The scintillation method, though simple and powerful, has certain disadvantages which cannot be avoided. The strain of counting the scintillations is such that the observers must be carefully controlled and they can be allowed to count only for very limited periods, amounting on the average to about 6 hours per week . . . For this and other reasons it is desirable to use an electrical method of detecting the protons arising from artificial disintegration. . . . For the experiments described here we have adopted the method of amplification by valves . . .'

The observation of particle tracks was carried out by means of the Wilson cloud chamber about which Rutherford, in his Norman Lockyer lecture to the British Association in 1936 (Rutherford 1936a), said: 'I cannot imagine anyone with the most vivid scientific imagination who could have predicted the possibility of an instrument with such unique powers and potentialities. '

The vintage year—1932/3

While experiments using these instruments were being carried out work was going on to improve the techniques. It all led up to the famous 'vintage year' of 1932/3.

This began with the discovery of the neutron by Chadwick (1932) as a product of collisions between $\alpha$-particles and beryllium nuclei. He used electrical methods of detection in which the new electronic techniques played an important role. A little later, observations of tracks in a Wilson cloud chamber due to particles projected in impact with neutrons were reported (Feather 1932). This discovery represented a major step forward in the expansion of the second phase of the study of the inner structure of matter as it overcame the difficulty of requiring electrons to be structural units within nuclei. We shall say more about this later.
Only a little after Cockroft & Walton (1933) succeeded in producing nuclear transformations for the first time using artificially accelerated protons as projectiles. Even though the protons were accelerated by direct application of a high voltage this opened out great new possibilities by expanding the variety and energy of projectiles. At first it seemed that almost any nucleus could be transformed by bombardment with the protons provided by Cockroft & Walton. However, with the elimination of secondary effects such as contributions from the disintegration of boron in the Pyrex glass envelopes of the vacuum equipment, the observed rates of transformation were found to be compatible with those estimated from quantum mechanics.

As if this were not enough for one year, Blackett & Occhialini (1933) announced results obtained through their development of a new technique, that of combining space- and time-resolving detectors in a counter-controlled Wilson chamber. They produced decisive evidence of the existence of positrons, confirming the results announced earlier by Anderson (1933) using a conventional cloud chamber.

The existence of positrons had been predicted theoretically as a consequence of Dirac’s relativistic theory of the electron. Dirac himself, in 1930, had hoped that the positively charged particles concerned might be protons but Oppenheimer a little later had shown that they must possess the same mass as an electron. At first they were regarded as too fantastic to be real but the particles observed by Anderson and by Blackett & Occhialini were found to have the predicted properties as far as creation and annihilation are concerned.

Eddington and the Constants of Nature

The remarkable success of the Dirac relativistic theory, even before the discovery of the positron, encouraged the belief that the time was now ripe for application of purely theoretical concepts to derive the values of the fundamental constant of Nature. Already in 1929 Eddington had produced arguments, based on the transformation properties of Dirac’s equation, that the fine structure constant $\alpha = \frac{2\pi e^2}{\hbar c}$ should have the value $1/136$. This he corrected, in a later note, to $1/137$. Whether or not this was soundly based it stimulated measurements of the constant with greatly increased precision and it was possible at least to obtain some notion of the argument used by Eddington in deriving his results. In 1931, however, he went further to obtain a theoretical value for the ratio $m/M$ of the mass of the electron, $m$, to that, $M$, of the proton. I can well remember his presentation at a meeting of the Cambridge Philosop-
ical Society (Eddington 1931) to a very distinguished audience not any of whom were able to follow the argument after the first few minutes. As a counter to excessive extension of the belief that theory alone was good enough Beck, Bethe & Riezler in 1931 published a letter in Die Naturwissenschaften which purported to show that the absolute zero of temperature should be \(-\frac{2}{\alpha - 1}\). Although viewed, I believe, somewhat askance by Sommerfeld this conveyed a valuable warning about giving undue weight to numerical coincidence. It is only fair to Eddington to say that his first work on the value of \(\alpha\) was remarkably penetrating and interesting. In view of recent developments in nuclear physics he could hardly have succeeded (see, however, Wyler 1969, 1971). Apart from this, theoretical physics enjoyed, through the discovery of the positron, a position of high prestige, a position which, in the field of particle physics, it could hardly be said to enjoy at the present time.

Yukawa’s hypothesis—the meson

In 1935, moreover, it received a further fillip from the work of Yukawa (1935). With the discovery of the neutron three bricks were available out of which to construct all the atoms of matter, provided the appropriate cements are available. For binding electrons to nuclei, the cement is available in the form of photons, particles which transmit the electrical forces between charged particles. There still remained the question of what cement binds protons and neutrons together in atomic nuclei. Yukawa suggested that this takes the form of a ‘heavy photon’. If the mass of this particle is of order 200 times that of an electron the range of the attraction between neutron and proton would be such as to confine atomic nuclei to about the dimensions observed. Yukawa proposed also that his heavy photons might possess positive or negative electric charges. Particles of about the predicted mass were soon after observed in cosmic rays (Anderson 1937; Street & Stevenson 1937).

There was no suspicion at the time that these particles were not those endowed with the properties suggested by Yukawa. It seemed indeed that the way was set fair for a description of the properties of all matter in terms of electrons, protons, neutrons, photons and Yukawa’s heavy photons (charged or uncharged), the latter after a brief period of designation as yukons having finally been dubbed mesons. Once the interactions of mesons with neutrons and protons were clarified—and it was hoped this could be done by analogy with the equations of electrodynamics—then the second phase in the interpretation of the structure of matter could be thoroughly exploited without much fear that quantum mechanics would be invalid.
The mystery of $\beta$-radioactivity—the neutrino?

This was more or less the theoretical position at the time shortly after Rutherford’s death. Even then phenomena were known which pointed to the possibility that the full picture was rather more complex. In particular, $\beta$-radioactivity continued to present the puzzling appearance of a breakdown of the conservation of energy. In most $\beta$-transformations energy seemed to be lost although many experiments had been carried out to detect it. Pauli in 1932 had suggested that the missing energy was carried away by a second particle, possessing no charge and very weak interaction only with the other particles involved. In fact it would be so difficult to observe that Pauli, without feeling he was risking anything, had promised a case of champagne to anyone who was able to detect the neutrino as this then hypothetical particle was called. There was no place for the neutrino in the simple world picture referred to earlier.

The dawn of new techniques

The late 1930s, including the last few years of Rutherford’s life, marked the beginning of an era in the development of new techniques for experimental research in nuclear physics. In 1934 Lawrence & Livingston invented the cyclotron which showed how limitations imposed by the difficulty of maintaining high voltages for direct acceleration of particles could be circumvented by the use of indirect methods. This was the first in the long line of accelerators leading up to the present time.

The counter-controlled chamber developed by Blackett & Occhialini (1933) was the precursor of many elaborate devices for particle detection and identification.

Along with such developments as the cyclotron began the extension of vacuum techniques to metal chambers. Hitherto it was considered that such vacua were only attainable within glass vessels.

It is interesting to recall that in the middle 1930s one of the most admired pieces of equipment in the Cavendish Laboratory was the magnet designed by Cockcroft to provide a field of 10 kG for the accurate determination of the velocities of long-range $\alpha$-particles. Plate 3a is a reproduction of a photograph of this magnet from a paper by Rutherford, Wynn-Williams, Lewis & Bowden (1932).

Application of nuclear energy?

Until the discovery of nuclear fission, which did not occur until nearly eighteen months after Rutherford’s death, little thought was given to any pos-
sibility of the application of nuclear energy to the large scale production of power. In his Watt Lecture to the Greenock Philosophical Society in 1936 Rutherford (1936b) expressed the following view on this subject:

While the overall efficiency of the process varies with increase of energy of the bombarding particles, there seems to be little hope of gaining useful energy from the atoms by such methods. On the other hand, the recent discovery of the neutron and the proof of its extraordinary efficiency in producing transformations at very low velocities opens up new possibilities, if only a method could be found of producing slow neutrons in quantity with very little energy. At the moment, however, the natural radioactive bodies are the only known sources for gaining energy from atomic nuclei, but this is on far too small a scale to be useful for technical purposes.

In this passage attention is drawn to the remarkable nature of collisions between slow neutrons and nuclei. This subject speedily became a matter of intensive experimental study and Bohr in 1936 had provided the basis for the theoretical interpretation of the results in terms of the concept of the resonant formation of collision complexes. Some puzzling features of the observed results of neutron impact on uranium nuclei were known but not understood so that Rutherford himself was never aware of the existence of nuclear fission as such.

SUMMARY OF THE POSITION AT THE END OF THE PERIOD

Summarizing the position towards the end of the 1930s it can be described as one of optimism that we were very close to a detailed interpretation of the structure of matter in terms of three structure particles (the electron, proton and neutron) and four ‘cement’ particles (the photon and the neutral, positive and negatively charged mesons). A new era in the development of elaborate techniques for production and detection of fast particles was just beginning but there was no feeling that large scale applications were just around the corner.

THE SITUATION TODAY

Now we turn suddenly to compare and contrast the situation today, thirty-four years later. What do we find?

First, a brief remark on the large-scale generation of power from nuclear energy, a possibility hardly considered in 1937. Apart from the knowledge of the fission processes produced in $^{235}$U and $^{238}$U nuclei by neutrons of various energies, and of the properties of various nuclei in relation to neutron impact,
the main contributions to the practical achievements have come from advanced engineering techniques which do not involve nuclear physics. I shall say nothing further about these applications.

The study of the structure of nuclei in terms of neutrons and protons as structural units has developed to a remarkable extent—phase II in the investigation of the inner structure of matter is well developed even though the interaction between neutrons and protons which binds them together in nuclei is now known to be very much more complex than was expected from the apparent success of Yukawa’s prediction of the nature of the ‘cement’ particles involved.

As stated at the beginning we shall not discuss the present position in nuclear structure research but rather go on to describe how much progress has been made in the third phase, the study of the properties and structure of the basic particles themselves. In 1937 it seemed that we need only consider seven particles in all, three structural and four of ‘cement’ type, apart from the anti-structure particles and possibly the elusive neutrino. During the thirty odd years since then the situation has become much more complicated, with unexpected discoveries of particles which seemed to play no essential role and it is only recently that some light is beginning to penetrate into an otherwise deep obscurity. All of this could not have arisen in what is a relatively short period without an extraordinarily rapid development of experimental techniques and it is appropriate to refer first to these before comparing and contrasting the theoretical position with that which prevailed before the introduction of wave mechanics.

Basically the principles involved in the experiments remains the same—detection and analysis of the products of bombardment of target nuclei by high-speed particles. However, the available energies of the bombarding heavy particles has increased to about 500000 times that of the protons in the experiments of Cockroft & Walton and over 100000 times that of natural α-particles. The available detectors are vastly bigger and more elaborate and are much more discriminating. Even the detection of neutrinos is becoming commonplace.

**The modern experimental tools**

*Accelerators*

The proton synchrotron which has been in operation at CERN in Geneva since 1959 accelerates protons up to energies of 28 GeV ($3 \times 10^{10}$ eV). This involves a magnet ring of 0.2 km diameter (see plate 3b) some times larger than the α-particle analysing magnet shown in plate 3a. A very much larger machine,
(a) The magnet (B) designed by Cockcroft which was used by Rutherford in 1932 for the accurate measurement of the velocities of long range \( \alpha \)-particles (reproduced from *Proc. R. Soc. Lond. A* 139, 617, 1932)

(b) Aerial view of the site at CERN showing the scale of the 28 GeV magnet ring on the right and the location of the storage rings for the ISR system towards the left. The area in the background will be occupied by the 400 GeV accelerator. (Courtesy of CERN)
(a) The cryostat of the 3.7 m hydrogen bubble chamber being swung into position at CERN in November 1970. (Courtesy of CERN)

(b) The Gargamelle bubble chamber body in an advanced stage of its preparation at CERN in September 1970. (Courtesy of CERN)
accelerating protons up to more than ten times these energies (400 GeV) and hence using a magnet ring ten times bigger, has just come into operation at Batavia in Wisconsin, U.S.A., while at CERN a machine of comparable magnitude is now under construction.

At Stanford University in California a linear accelerator two miles long (known as SLAC) provides a current of 80 mA of electrons of 20 GeV energy.

**Colliding beams**

Although the scale of these accelerators compared with anything available during Rutherford’s life is remarkable enough, an even more remarkable facility now available is that of working with moving targets. It is a consequence of the special relativity theory—accelerator engineers are the only engineers who must take explicit account of relativistic effects. From the theory, the fraction of particles of light which is accelerated to an energy $E$ considerably greater than their rest mass energy $Mc^2$, the fraction of the beam energy which is available for producing transformations is approximately $(2Mc^2/E)^{1/4}$. There is thus a law of

![Figure 1. Interactions between the crossing beams of the ISR at CERN observed in an experiment being carried out by CERN in collaboration with groups from the Universities of Aachen, Harvard, Genoa and Turin. The points in the diamond-shaped interaction region give the locations of interactions determined from computer analysis of data obtained using spark chambers located on the downstream arm of each beam. The points shown on the upstream arms, which arise from interactions with residual gas, give the horizontal distribution of protons in each beam. (Courtesy of CERN)](http://rsnr.royalsocietypublishing.org/Downloaded from)
diminishing returns in providing machines which accelerate to greater and greater energies. A 300 GeV machine is, from this point of view, only $\sqrt{10}$ times as effective as one of 30 GeV although it costs about ten times as much.

This difficulty is avoided if the particles in two accelerated beams are allowed to collide. If the collision is head-on all the energy is available. Two beams of 28 GeV energy colliding in this way render possible the study of collisions which would require beams of 1700 GeV energy if the target nuclei were stationary. There is of course a great loss in collision frequency so that the colliding beams must be very intense. Nevertheless, two such intersecting beam systems are in operation—for example, one involving two electron beams or one electron and one positron beam, each of 750 MeV energy, known as Adone, at Frascati and the first involving two proton beams of 28 GeV energy, at CERN. The experimental technique required for success with these machines is most demanding. In the equipment at CERN the pressure in the ring through which the particles circulate must be less than $10^{-9}$ Torr (cf. p. 30 in which reference is made to the first apparatus using metal high vacuum chambers). For effective study of the collisions involved the currents in the colliding beams must be as high as 10A produced by storage of particles from a number of accelerating pulses. Figure 1 shows a computer analysis of the location of the interactions between particles in the two beams at CERN during an actual experiment.

**Detectors**

Turning now to detectors we find equally remarkable developments. Although there has been a convergent evolution between what are essentially track chambers, with high space—but poor time—resolution, and counters, with high time—but poor space—resolution, it is still appropriate to describe the present position in terms of these two initial categories.

Evolution from the original Wilson cloud chamber has led to the present-day bubble chamber. After a glorious period the cloud chamber is now obsolete. During the postwar period the most important discoveries relating to new particles and their properties were made by using either cloud chambers with elaborate counter control systems or a further technique, developed during and just after the war, that of the nuclear sensitive photographic emulsion. In all these cases the bombarding particles were either primary or secondary components of cosmic radiation. Soon after accelerators with energy around 1 GeV became available the new bubble chamber became available and the nuclear emulsion is now obsolescent.

Bubble chambers operate in effectively the inverse way to cloud chambers,
depending as they do on the production of bubbles in a liquid, superheated above boiling point, along the track of a fast particle. Because the working substance is a liquid and not a gas the stopping power of a bubble chamber of comparable size is much greater and hence much more suitable for effective study of the entire tracks of very energetic particles. The sensitive times of bubble chambers may be pulsed in rhythm with the pulses of particles from an accelerator and the chambers may be enclosed in magnetic fields to assist in particle identification. As the energies of accelerators increase so also must the dimensions of the bubble chambers used for detection. Superconducting magnets are now being introduced to produce the large fields required over large volumes.

Two types of working liquid are used. Hydrogen is so important because of the fundamental interest in interactions with protons, that the cryogenic and other problems associated with hydrogen bubble chambers have been successfully overcome. The latest chamber of this type under construction at CERN, with superconducting magnets, is 3.7 m in diameter. Plate 4a shows the cryostat being swung into position. The poles of the magnet used with this chamber are 6 m in diameter.

The second type employs a heavy liquid so as to be able to observe and identify fast secondary products effectively, including particularly photons. As an example of the latest development in this direction we have the Gargamelle chamber at CERN which is nearly 5 m long and has a working volume of 12 m$^3$. It is illustrated in plate 4b.

Another development which attempts to combine some of the advantages of both types of chamber is to introduce a bag of liquid hydrogen inside a chamber containing a mixture of hydrogen and neon.

The rate at which track photographs are obtained by means of bubble chambers is very high indeed, of the order 25,000 per day, so that automatic methods of analysis must be used. These are also very elaborate and their sophistication must match that of the chambers.

Evolution from the system of coincidence counters which developed in the study of cosmic rays, has led to the other major detecting device used in conjunction with very high energy accelerators. This is the spark chamber. It depends on the replacement of the mechanically operated cloud chamber used to show up the track of a particle in a counter-controlled system by an electrical method which eliminates most of the delay in operating a mechanical system. Operation in coincidence of two counters triggers off a high voltage generator so that a pulse of voltage is applied between a series of condenser plates in a chamber containing a gas such as a neon-argon mixture at atmospheric pressure. These pulses produce breakdown in the form of sparks along the particle track.
which are photographed synchronously. The sensitive time of these spark chambers may be as low as 1μs or less so that, even though a bubble chamber gives a somewhat better space resolution, the spark chamber may be used in an intense beam of particles without confusion. Their comparative simplicity makes it possible to build very large chambers without too great expense. Recent developments, involving so-called wire chambers, make it possible to operate with on-line computers which process the data as they are obtained.

Many other auxiliary detectors are used today including automated versions of the scintillation method referred to on p. 27.

The present family of particles

Instead of the small family of seven which it was expected, with some confidence just before the war, would be complete, we now have to deal with an apparently much greater number. These are conveniently divided into two categories the hadrons and the leptons. The latter include not only the electron and two kinds of neutrino (now well established from observation) but also the muon of mass 207 times that of the electron. These are the lightest particles; they are similar as far as their symmetry properties are concerned and there is no evidence that they possess any structure. The most unexpected member of this subgroup is the muon which seems to behave in almost every way like an electron except that it has a greater mass.

The hadrons in turn may be divided into two sub-categories the baryons (including neutrons and protons and the hyperons with greater masses) and the mesons with masses less than that of a proton.

Although the hyperons possess masses greater than that of a nucleon in many ways they possess generally similar properties. Thus they interact strongly with each other with forces comparable with those between nucleons, and they possess the same symmetry properties.

Mesons on the other hand have different symmetry properties. The least massive members of the family can be identified as the Yukawa mesons, the neutral one possessing a mass 264 times and the charged ones 273 times that of an electron. All interact with baryons in the manner characteristic of cement particles.

The hadrons exhibit a weak interaction with electrons and neutrinos which renders all of them, with the exception of the proton, unstable towards electron-neutrino emission. However, other interactions may lead to instability resulting in emission of photons or mesons. The muon also is unstable through the weak interaction and transforms in a time of order 10^{-8}s into an electron and two
neutrinos. In this case the situation is made more complicated by the discovery that there are two kinds of neutrino, one of which is associated with electrons the other with muons.

In this description I have not explicitly referred to the important fact that the nucleons, hyperons and leptons all possess anti-particles.

The full family is very large and it is apparent that very few of the members can be regarded as truly fundamental particles. Remembering that almost all members of the two hadron families are unstable it is more sensible to regard them as excited states of the originally assumed basic particles. It is as if, when observing the excited states of atoms, we had considered each such state as a new atomic species.

One spectral series, that of the baryons, is based on the proton as ground state. The excited states have varying lifetimes depending on their decay processes. If de-excitation through operation of the strong interaction with mesons is possible the lifetime will be very short, of order $10^{-22}$s. These correspond to the so-called resonance particles which have been observed and studied exhaustively in recent years. If for one reason or another this emission is forbidden, states will be much longer lived and are analogous to the metastable states of atoms. These include the hyperons first discovered ($\Lambda^0$, $\Sigma^{\pm}$, $\Xi^0$ and $\Xi^-$) which have lifetimes of order $10^{-16}$s. An intermediate case is the $\Sigma^0$ hyperon which, through the possibility of decay into $\Lambda^0$ through photon emission has a lifetime of around $10^{-16}$s. The extreme case in this series is the neutron which is unstable through the weak interaction and has a lifetime of around $10^{10}$ before transforming to a proton with accompanying emission of an electron and neutrino.

The ground state of the meson series is the $\pi$-meson or pion—ignoring for present purposes the small difference between the masses of the neutral and charged varieties. Unlike the proton the meson ground state is not absolutely stable. The charged pions transform through the weak interaction into muons and muon neutrinos with a mean life of $2.5 \times 10^{-8}$s while the neutral pion, which may transform to two gamma rays, is considerably more ephemeral, the mean life being only $1.8 \times 10^{-16}$s.

**Order in the excited states of the basic particles**

Since we are in a similar position with respect to the third phase of the exploration of the structure of matter, to that in which the first phase found itself after the observation of atomic spectra, we may well ask whether any order corresponding to the spectral series and the selection rules is yet discernible in the spectra of hadrons.
The answer is undoubtedly yes. A number of important conservation rules have been established. Thus the so-called baryon and lepton numbers are conserved in any transformation. These numbers are defined as to the number of baryons (or leptons) minus the number of antibaryons (or antileptons). This appears to be a strict conservation rule.

A second rule which must be obeyed if the reaction is to proceed at a fast rate, in a time of $10^{-20}$s or less, involves the introduction of a new quantum number known as the strangeness. Appropriately enough this is zero for the 'expected' particles such as the nucleons and the pions. On the other hand it is taken as $-1$ for $\Lambda^0$, $\Sigma^0$ and $\Sigma^\pm$ and for the $K^-$ meson, $+1$ for the $K^+$ meson, $-2$ for $\Xi^0$ and $\Xi^-$. For a transformation to be fast in the sense mentioned above the total strangeness must not change. If it changes by $\pm 1$ the reaction time is increased to $10^{-10}$s or more.

There is also a tendency for the states to occur in groups of 1, 2, 3 or more (e.g. the two nucleons, the three pions, the single $\Lambda$-hyperon, the three $\Sigma$ hyperons and the two $\Xi$ hyperons), the different members of which differ in the charge they possess. If the multiplicity is written as $2I+1$, $I$ is known as the isotopic spin quantum number. It also plays a role in determining the symmetry properties of the system.

From analysis of the observed particle spectra in terms of these additional numbers certain symmetry relations of comparative simplicity have been derived particularly by Gell-Mann and Ne'eman. Encouraging evidence that these relations have real significance is that Gell-Mann used them to predict the existence of certain then unknown states, including particularly a hyperon of strangeness $-3$, charge $-e$ and lifetime of order $10^{-10}$s, dubbed $\Omega^-$. An intensive hunt for this particle led to its positive detection in a hydrogen bubble chamber photograph taken at Brookhaven in 1964. It is of interest to note that thirty-three names are associated in the publication which announced the discovery (Barnes et al. 1964), almost as many as the total complement of the Cavendish Laboratory in the 1930s. Only in this year, February 1971, has observation of the antiparticle $\bar{\Omega}$ also been announced.

**Quarks**

The symmetry scheme which we have just referred to suggests further that the hadrons may be built up from three more basic particles—one pair with isotopic spin $I = \frac{1}{2}$, zero strangeness and charges $\frac{2}{3}e$, $-\frac{1}{3}e$ respectively and a third with $I = 0$, strangeness $-1$ and charge $-\frac{1}{3}e$. Referring to these as $a$, $b$ and $c$ respectively, a proton would be made up of $2a + b$, a neutron of $2b + a$, a $\Lambda^0$
hyperon of \( a + b + c \) and so on. The mesons would be obtained as combinations of one of the three particles with one of the corresponding three antiparticles, the positive pion being \( \bar{a} + \bar{b} \), the positive K-muon \( a + \bar{c} \) and so on.

We have here a return to the possibility of reducing the basic entities to a very few, a goal which it had been assumed was already reached in the late 1930s. It is of interest that this has been achieved by the use of symmetry relations, the importance of which even in the early days of quantum mechanics had led to Rutherford's remarks referred to on page 26. However, there is still no definite evidence of the existence of the basic three, which have nevertheless already received a generic name, the 'quarks'. The origin of this far from euphonious term appears to be from the passage in *Finnegan's Wake* by James Joyce which reads:

Three quarks for Muster Mark

\[
\ldots
\]

\[
\ldots
\]

You're the rummest old rooster ever flopped out of a Noah's ark.

**Direct investigation of the inner structure of nucleons**

The existence of the hadron spectra is evidence of inner structure within the proton and pion. A further fertile source of information about this structure for nucleons comes from the use of energetic electrons as probes. The scattering of such electrons by nucleons can be compared with that of electrons of a few tens of eV energy by atoms. Figure 2 shows the energy-loss spectrum of electrons

![Figure 2. Observed energy-loss spectrum of electrons of 10 GeV incident energy scattered through an angle of 6° in collisions with protons](http://rsnr.royalsocietypublishing.org/)
accelerated to 10 GeV energy in the SLAC Linac, which have been scattered through an angle of 6° by protons (Bloom et al. 1969).

The spectrum can be analysed into a continuous background on which are superimposed peaks corresponding to discrete energy losses. These can be identified with the excitation of states of the baryon spectrum referred to above. The strength of the background at the highest energy losses observed is very striking. This feature may be related to observations of the differential cross sections for elastic scattering and for inelastic scattering with fixed large energy loss, examples of which are shown in figure 3 (Breidenbach et al. 1969). It will

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**Figure 3.** Observed differential cross sections $\sigma$ for scattering of electrons by protons as functions of $q^2$ where $q$ is the momentum transfer

$\sigma_m$ is the cross sections for elastic scattering by a point nucleus

Elastic scattering: 

Inelastic scattering: • --- , with energy loss 2 GeV;

×,----- , with energy loss 3 GeV;

▲,----- , with energy loss 3.5 GeV.
A neutrino interaction observed with the Gargamelle bubble chamber filled with CF$_3$Br. The event occurs near the bottom of the picture and leads to the three tracks, the left being that of a proton, the right a negative muon and the centre a $\pi$-meson which result from the interaction of a neutrino with a nucleus in the heavy liquid.
(a) Spectrometer in the neighbourhood of the interaction region between the intersecting beams at the CERN ISR to determine the momentum and angular distributions of the different types of 'stable' particles (lifetimes $\gg 10^{-8}$s) produced through the interactions.

(b) Muon detector equipment in the neighbourhood of the interaction region between the intersecting beams at the CERN ISR to determine the momentum distribution of the muons resulting from decay of the mesons produced in the interactions.
be seen that the probability of large energy loss remains high for large momentum transfer in the collisions, in sharp contrast to the elastic scattering. A possible interpretation of these phenomena is that the electrons suffer high momentum and energy loss in scattering by relatively small regions of the nucleons which have already received the name ‘partons’. Although much more remains to be done before the validity of this concept of a presumably fluctuating granular structure within nucleons, it nevertheless may mark a new stage in the study of the inner makeup of the basic particles.

Neutrinos

The first direct observation of neutrinos was made as long ago as 1953 (Reines & Cowan 1953) but since that time the experimental study of the ‘unobservable’ particles has become a new branch of physics. High energy accelerators are relatively very effective sources of neutrinos and new methods of detection are so sensitive and so discriminating that observations of neutrino-induced events may be made with astonishing rapidity.

In a typical arrangement very energetic protons from an accelerator impinge on a long thin target to produce in particular $\pi^-$ and $K$-mesons which emerge in all directions. As many as possible of these are captured and concentrated in a beam by a magnetic horn consisting of an aluminium cone through which a current of around 340 A is passed. The concentrated beam, during passage along a tunnel for 70 m, partly decays to produce neutrinos which travel in the same direction. The mixed muon-neutrino beam then enters a steel block 22 m thick which stops all but the neutrinos which then issue into a heavy liquid chamber such as Gargamelle (see p. 35). Experiments on these lines are being carried out by an extensive collaboration of physicists from CERN and from a number of European University laboratories. The performance of this system is such that on the average a neutrino-induced event will appear in every twenty pictures taken—a fantastically fast rate when one remembers Pauli’s offer of 1932. Plate 5 shows a photograph of a typical neutrino event and its interpretation.

The Charged leptons

As remarked earlier the charged leptons exhibit no anomalous behaviour apart from their interaction with neutrinos and apart from the mere existence of the muon. The electrodynamical behaviour of electrons and muons can be predicted to extraordinary accuracy and there is no evidence at all of any structure. However, an effort is being made, using the intersecting beams at CERN
to determine whether muons produced by the interactions there arise in any other way than through muon pair production or from decay of mesons.

Plates 6a and 6b show the experimental equipment just coming into operation in a joint project involving CERN, the Rutherford Laboratory and a number of European University laboratories. Plate 6a shows a spectrometer, operated by the full consortium for the observation of the momenta and angular distributions of the different types of 'stable' particles (lifetimes $\gg 10^{-20}$s) produced in the interaction region of the ISR while plate 6b shows a muon detector operated jointly by the British members of the consortium. This determines the momentum distribution of the muons produced from meson decay with the principal aim of detecting any anomalous features as compared with the distribution expected from the observed momentum distribution of the present particles. The large scale required in the equipment is obvious.

**What would Rutherford have thought of all this?**

Already in the Norman Lockyer lecture which he delivered in 1936 Rutherford said: ‘On account of these great improvements in technique and methods, progress in our knowledge has been so accelerated in the past few years that it is not easy for the investigator to keep in close touch with the rapidity of growth of our knowledge’. The rate of growth since 1936 and particularly in the post-war years has been much faster still.

It can be imagined that Rutherford, while perhaps being surprised by the rapidity with which the discovery of fission led to the large-scale release of nuclear energy, would certainly have regarded the vital role played by neutrons as to be expected (see p. 31).

Rutherford had a proprietary interest in atomic nuclei. After all he first suggested and established their existence. There is no doubt at all that he would have been very interested and involved in post-war developments of the study of nuclear structure.

As regards the large scale research which has shown how far we were in the 1930s from studying the ultimate structure of matter, Rutherford might well have deplored the large scale and complexity of the instrumentation and the teamwork required in present-day high energy physics. He would, however, have recognized its inevitability as he had already done in encouraging work on the use of high voltages in the late 1930s. The remarkable and unexpected results which have come out at such a bewildering rate from the use of these continually advancing techniques would have fascinated him. He would have been particularly encouraged in the belief that Nature is not so complex after
all, by the chinks which have appeared in the curtain surrounding the third
phase in the study of the structure of matter.

At this stage we must not be over optimistic. We are perhaps in a situation
like that at the beginning of the century in the development of the first phase,
the elucidation of the outer structure of atoms. Up to the present, regularities
have been discerned but we have encountered no contradictions such as those
which led to the introduction of Planck’s quantum of action, Bohr’s atom
model and eventually to quantum mechanics. Meanwhile it would surely be a
source of great satisfaction to Rutherford that, although the pursuit of the ulti-
mate structural entities of matter has proved more complex and vastly more
demanding of financial resources and otherwise, this most fundamental branch
of science to which in its first and second phases he contributed so much, has
continued to develop vigorously. With present plans it will continue to do so
for many years yet.

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