Rutherford Laboratory
Technical leaflet

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A BRIEF HISTORY OF ELEMENTARY PARTICLE PHYSICS

The rapid growth of elementary particle physics since about 1900 derives from two separate but complementary approaches. The major theoretical advances have been the development of the special theory of relativity by Einstein (1905) and of the quantum theory by Planck, Einstein, Bohr, Schrödinger and others (1901 onwards). In parallel there have been many crucial experimental developments ranging, for example, from the observation of radioactivity by Becquerel (1896) to the sophisticated experiments carried out with the aid of the large particle accelerators which are a prominent feature of contemporary high energy physics.

The work of Thomson (1897) may be taken as a starting point of this brief history. By using electric and magnetic fields to deflect the cathode rays in a low pressure gas discharge tube he showed that their ratio of charge to mass was about 2000 times as great as the corresponding ratio for the hydrogen ion. Shortly afterwards Townsend measured the charge in the droplets forming on ions in saturated air. He assumed that each droplet contained just one ion and that the charge of the ions was the same as the charge of the cathode rays investigated by Thomson. From a knowledge of the charge and of the ratio of charge to mass, it became clear that matter existed in the form of particles whose mass was about 1/2000 of that of the hydrogen atom. The existence of the electron was thus established and the first step towards understanding the structure of the atom had been made.

The next major experimental advance was made by Geiger and Marsden in 1913. By scattering alpha particles on various materials they were able to confirm the model of the atom put forward by Rutherford in 1911, in which a central positively charged nucleus containing protons (nuclei of hydrogen atoms) was surrounded by a diffuse cloud of negatively charged electrons, the whole atom being electrically neutral.

The early version of the quantum theory due to Bohr (1913) was able to explain many aspects of the behaviour of these extranuclear electrons, in particular how, by a change in its state of motion, the electron was able to emit a quantum of light, in other words, to emit radiation. (That the emission and absorption of light was a discrete rather than a continuous process had already been established by Planck in 1901). In order to explain the mass of, for example, the Carbon atom (atomic weight = 12; atomic number = 6) it was necessary to assume that the nucleus consisted of 12 protons and 6 electrons, giving a net charge of +6 units. However the new development of the quantum theory from 1926 onwards, particularly the discovery by Heisenberg of the uncertainty principle, raised serious objections to this theory, since it did not seem possible for low energy electrons to be confined within a volume as small as that of the nucleus. The evidence of β-decay suggested that any electrons in the nucleus had rather low energies. To overcome this objection Rutherford postulated in 1920 the existence of an electrically neutral particle (the neutron) with a mass equal to that of the proton. In a famous experiment (1932) Chadwick verified the existence of the neutron, thus completing a reasonably consistent picture of the atom. In this new scheme, the carbon atom mentioned above consisted of a nucleus containing 6 protons and 6 neutrons with 6 external electrons. The later refinements of the quantum theory due to Dirac (1930) were able to describe with great accuracy the behaviour of these external electrons. However this same theory, which was a synthesis of the early quantum theory and the special theory of relativity, predicted the existence of an "antiparticle" to the electron. Identical to the electron in all respects except that it had opposite charge and magnetic moment, the "positron" was detected experimentally by Anderson in 1932. Already the simple picture of the electron, proton and neutron as the three fundamental constituents of matter had become inadequate.

Another serious problem still remained to be solved if the Rutherford model of the atom was to be acceptable: why was the nucleus stable? Since it consisted of neutral and positively charge particles, electrostatic repulsion should have caused it to disintegrate. Clearly a stronger attractive short range force served to bind the constituent particles together. Yukawa (1935) was able to suggest a possible explanation. According to the quantum theory, the Coulomb force between two electric charges arose from the exchange of photons (light quanta) between the two charges. The infinite range of the force (the inverse square law) was due to the zero mass of the photon. By analogy, the short range nuclear force could be due to the exchange of a "meson" which Yukawa estimated to be about 200 times as massive as the electron. In 1937 a particle of about this mass (now called the μ-meson) was discovered in cloud chamber studies of cosmic rays.

When large scale research was resumed after the war, it was discovered by Conversi and others (1947) that the μ-meson did not interact at all strongly with atomic nuclei. Since the Yukawa meson was supposed to be responsible for the very strong nuclear forces it became clear that the wrong meson had been discovered. Later in 1947 Lattes and others discovered events in which particles (π mesons) *did* interact strongly enough in photographic emulsions to cause nuclear disintegrations. Eventually the picture became clear: the heavier π meson was the Yukawa meson, and it could decay into the weakly interacting and rather lighter μ meson. The μ meson itself was unstable, and decayed into an electron. In modern notation:

$$\begin{array}{l} \pi \rightarrow \mu + \nu \\ \qquad \hookrightarrow e + \nu + \nu \end{array}$$

The rate at which the $\pi \rightarrow \mu \rightarrow e$ decay chain took place indicated that the forces causing the decay were comparable in strength to those causing the β-decay of radioactive nuclei. This exemplifies the very important distinction between the strong interactions (such as that between the π meson and protons or neutrons) and the weak interaction responsible for β decay and the slow decay of the π and μ mesons. Another interesting point is that neutrinos (ν) are emitted in these meson decays, just as they are in the β decay of nuclei. In fact the existence of the neutrino was postulated by Pauli in 1931, but direct evidence for this notion was not obtained until 1953 by Reines and Cowan. The neutrino has zero electric charge and mass, and interacts with other particles only through the weak force.

In 1947 the problem of the π meson was solved, but in the same year the first evidence for the so called "strange" particles was obtained by Rochester and Butler in a cloud chamber experiment. In the following years some of these particles were identified as heavy mesons (heavier than the π meson but lighter than the proton), and some as hyperons (heavier than the proton). The "strange" property of these particles was that they were readily produced, indicating a strong interaction between them and other particles such as the proton. However their decay rates were comparable with the slow decay of the π and μ mesons, indicating a weak interaction with other particles.

This difficulty led to the introduction of the concept of strangeness by Gell-Mann and Nishijima. To each particle was assigned an "additive quantum number" called strangeness which was supposed to be conserved in the strong production process but not in the weak decay process. For example, the K^+ meson has strangeness +1 and the Σ^- hyperon has strangeness -1. A system consisting of a K^+ and a Σ^- has a total strangeness = 0 (the total strangeness is obtained by simple addition; this is what is meant by the phrase "additive quantum number"). These two particles can therefore readily be produced in the process:

$$\pi^- + p \rightarrow K^+ + \Sigma^-,$$

since both the π^- meson and the proton have strangeness = 0. After production, the Σ^- can only decay through the process $\Sigma^- \rightarrow \pi^- + n$. This process does not conserve strangeness since the system $\pi^- + n$ has strangeness = 0. The decay is caused by a weak interaction and is therefore slow (on the nuclear time scale).

Another important property of the weak interactions was discovered in 1957, immediately following the suggestion of Lee and Yang that, in these processes, parity may not be conserved. Parity is a quantum number which describes the behaviour of a physical system under reflections. Before 1957 one of the most firmly held beliefs was that parity was conserved in all physical processes. Thus the π meson should decay into a system ($\mu + \nu$) which has the same spatial reflection properties as itself. An even (odd) parity system decays into an even (odd) parity system. One says that the interaction conserves parity. If this process could be observed in a mirror world the same "even ⟶ even" process would be observed. If on the other hand, parity were not conserved, then one would have for example an even parity system decaying to an odd parity system, which would not look the same in the mirror world. The non-conservation of parity is now known to be a feature of nearly all processes caused by the weak interaction; in the strong and electromagnetic interactions parity appears to be rigorously conserved.

Since the advent of the large particle accelerators in the 1950s, many other new particles have been produced, both strange and non-strange. Many of the antiparticles whose existence was suggested by the Dirac equation have also been discovered. The total number of known particles is at present about 100. A physical theory which requires so many basic building blocks is not particularly attractive, and it is quite likely that what we have been pleased to call elementary particles are built up of even more fundmental entities. One recent theory, the SU(3) scheme of Gell-Mann and Ne'eman has not only had considerable success in arranging many of the particles having similar properties into groups and in predicting the existence of the well known Ω^- particle, but also leads naturally to the notion of "quarks". According to the theory there are three different kinds of quarks, out of which all particles are built up. Searches for these particles have been made which have so far been unsuccessful. However there are several good reasons why it may be difficult to detect them, so the theory is by no means disproved.

The present state of elementary particle physics may be compared with that of inorganic chemistry during the latter part of the 19th century. At that time a large number of elements were known, and Mendeleef had succeeded in classifying them in his famous periodic table. Not until the nature of the electronic structure of the atom had been understood in the 1920s was it possible to explain the structure of the periodic table. Today we may be about to discover the corresponding principle which will rationalise our present knowledge of elementary particles.