The Rutherford Memorial Lecture, 1983

Rutherford and beta decay

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Rutherford's concern for the properties of the α-particle did not divert him from the more difficult task of characterizing beta decay. The lecture traces the experimental steps by which some of the main features of this process were established in his laboratories at Montreal, Manchester and Cambridge. It concludes with a brief account of some beta-decay experiments that throw light on the mass of the Z⁰ boson of the weak interaction.

1. Introduction

As Chairman of the Rutherford Memorial Committee of the Royal Society of London from 1964 to 1981 it was my privilege and pleasure to help with arrangements for the delivery of a Rutherford Memorial Lecture in countries of the British Commonwealth. The lectures given in New Zealand of course always had a special significance because of the respect of that country for its most celebrated citizen. But those delivered in Canada seemed to me to have an equal if not greater scientific context because Rutherford's time at McGill University saw the creation of the new science of radioactivity, for which he as a principal author received the Nobel Prize for Chemistry in 1908. It is good to know that the Royal Societies of Canada and of London have recently agreed to sponsor a new scheme of reciprocal visiting lectureships, to be known as the Canadian Rutherford Lectures, since the title will recall an exciting chapter of scientific history. Previous Memorial lecturers here in Canada, beginning with Chadwick thirty years ago, spoke of many aspects of a remarkable achievement and the lectures of Philip Dee in 1965 and of Norman Feather in 1977 especially were mainly concerned with α-particle matters. I do not wish to traverse that ground again, even if thereby I seem to ignore Rutherford's favourite particle, and so I have chosen to speak on the other main particle of classical radioactivity, the electron of β-decay and to attempt to trace our understanding of its behaviour from the early days of 'penetrating radiation' through a number of complexities to the unified theories of the present day. It is a journey in
which many of the first steps were taken by Rutherford and his students in Montreal, Manchester and Cambridge.

Before coming to this topic, however, I should perhaps try to justify my presence here by giving you some account of my personal contact with Rutherford, meagre as that may well seem. The Royal Society Memorial Committee has always been aware that as the years went by the task of finding a lecturer who knew Rutherford and who had something of contemporary interest to say would become increasingly difficult. It has indeed decided more than once to break this link and the time when this must inevitably be done cannot now be many years distant. For this year, however, the traditional practice has continued and that is why to my great pleasure I have been invited to be with you. Let me therefore begin with a brief reference to the development of high voltage equipment in the Cavendish Laboratory, Cambridge, which Rutherford encouraged and in which I was involved.

On the 27th of July 1936, I was a second year graduate student in the Cavendish Laboratory. At lunch time on that day I was alone in Cockcroft and Walton's High Tension Laboratory, which had been handed over by them to Dee, Gilbert and Lewis and their students to continue the programme of artificial transmutation studies that had started in 1932. You have all seen pictures of the Cockcroft-Walton equipment; I was 'outgassing' it, (or 'conditioning' it as we would now say), a process in which the voltage applied to the rectifier column and acceleration tube is gradually raised until a useful level is reached and can be sustained with a proton beam in the tube. Outgassing is a process that, above all, demands patience and I suppose that I must have displayed enough to attract the attention of senior members of the Laboratory. Whatever the reason, the door opened while I was so engaged and Rutherford came in and sat down on one of the tall stools that were regulation furniture in the Cavendish. He at once began to talk about the new high tension equipment that the laboratory was to have and how it could be paid for from the magnificent gift to the laboratory by the automobile manufacturer Sir Herbert Austin, which had been announced on 1 May. The Cockcroft-Walton principle could now be extended into the 1–2 MV range and he wished me to help Oliphant to get the new laboratory working and to take part in the experimental programme with the new facility. Not unnaturally I was delighted with this distinction, and especially that Rutherford had taken the trouble to tell me and to encourage me personally. Of course, that was his way with all his students who were to him just fellow workers, and it got him the results that he expected.

Later that year, after some tough bargaining between the Philips Company of Eindhoven and Oliphant, Rutherford approved the purchase of a cascade generator for 1250 keV at a cost of £4000; I still treasure the sheet of laboratory notepaper on which he had scribbled the word 'satisfactory' in answer to the Philips quotation. The '1 MV set' as it came to be called was installed in a new building and commissioned by Oliphant and later Dee, under both of whom I worked. It was producing a proton beam at energies up to 900 keV by the autumn of 1937 and Rutherford had the pleasure of seeing it in operation shortly before his untimely
death in October of that year. The 1 MV set became the prototype for many University installations throughout the world in the late 1940s, at which time I wrote a brief description of it (Burcham 1947); it survived for 34 years, ending its career in 1971 in South Africa. A year later, as it happened, the Science Research Council of the United Kingdom approved the construction of a large electrostatic generator (Nuclear Structure Facility or N.S.F.) at their Daresbury Laboratory. The N.S.F., although operating on a different principle, is the direct lineal descendant in the United Kingdom of the Cockcroft–Walton apparatus; I am happy to report that it has now embarked upon a programme of work planned by the nuclear structure community that Rutherford founded in the United Kingdom.

2. BETA DECAY

I come now to the beta particle. The classification of the complex radiations from uranium into α-rays and β-rays on the basis of their penetrating power in matter dates from Rutherford’s studies of the ionization of gases in Cambridge in 1898. His results appeared in print early in the following year (Rutherford 1899), by which time he had moved to McGill University and detailed study of both types of radiation took place there over the next few years. Much of the apparatus used is preserved, and reveals even to the most cursory inspection the need for the utmost care and patience in its use if reproducible results were to be obtained. Rutherford certainly had in abundance the skill and perseverance necessary to extract the maximum amount of information from such equipment, which is described fully in his first book (Rutherford 1904a), though in later years there are well known stories of the element of impatience that crept into his process of adaptation to the successful counting of scintillations in darkened rooms.

It was not long before Rutherford formulated some hypotheses about the nature of the alpha and beta radiation. Becquerel had shown in his early experiments that part at least of the uranium radiation was deviable by a magnetic field of (probably) a few hundred gauss† and from joint electric and magnetic deflexion experiments he had ascertained that the specific charge \( e/m \) for this radiation was about 1000 times as great as that known for hydrogen in the electrolysis of water. Rutherford (1902) commented on the apparent identity of these deviable particles with the Thomson electrons, or cathode rays, and in further work (Rutherford & Brooks 1902) he confirmed that the magnetically deviable rays were in fact the more penetrating of the two uranium radiations, namely the β-rays. The experiments also indicated that the β-rays were travelling with nearly the speed of light. The characterization of the α-rays as positively charged particles with a mass of the same order as that of the hydrogen atom took longer, but even at this early date the sensitive electrical method of studying the radiations indicated much stronger ionization of air by these particles than by the β-rays. In Rutherford’s opinion (1903), ‘there seems to be no doubt that the emission of β-rays is a secondary

† 1 gauss = 10⁻⁴ T.
phenomenon and that the $\alpha$-rays play the most important part in the changes occurring in radioactive matter'. Had he reached a different conclusion at this point and concentrated more on the $\beta$-radiation the discovery of the nucleus might have been delayed. But there was no doubt I think in his mind at this point; his diagrams

![Diagram](image_url)

at the time show the $\alpha$-particle as a sphere of finite radius and the electron, either accidentally or prophetically, as a point, a representation with which we would indeed now concur.

The transformation theory of radioactivity took shape in the paper 'Radioactive change' (Rutherford & Soddy 1903) and appeared in full in the famous Bakerian lecture to the Royal Society in the following year (Rutherford 1904$b$). It is of course difficult for us now to place ourselves in a position in which the nucleus does not exist, but only the atom, and we can but admire the insight with which Rutherford assembled the facts that were later to be coordinated by the nuclear hypothesis. Basic to his ideas was the conviction that radioactivity was not a consequence of one element changing into another but the actual *accompaniment* or agency of the change. The radioactive rates of change were shown to be described by the familiar geometrical progression, characteristic of a monomolecular chemical reaction, which we now express in the form

$$I_t = I_0 e^{-\lambda t}$$

(1)
where \( I_t, I_0 \) are activities measured at times \( t \) and \( 0 \) and the decay constant \( \lambda \) is one of the most important properties of the decay process. The independence of \( \lambda \) of physical and chemical agencies was recognized but not understood, and a series of changes such as are shown in figure 1 was described completely by the equations for the production and decay of bodies each characterized by a different \( \lambda \)-value, or more conveniently half-life \( (T_\frac{1}{2} = 0.693/\lambda) \). Individual half-lives could often be distinguished by discriminating between \( \alpha \)-decay and \( \beta \)-decay. The radioactive changes were sometimes accompanied by a further penetrating radiation, undeviable by a magnetic field, which resembled the Röntgen rays and was described as \( \gamma \)-radiation; its association with the \( \alpha \)- or \( \beta \)-rays was later to be the subject of much speculation and experiment. There were also changes described by Rutherford as ‘rayless’ which connected one element with another, but later these were found to involve the emission of low-energy \( \beta \)-particles.

The role of the \( \beta \)-particle in helping to establish the atom after \( \alpha \)-emission ‘into an arrangement of fairly stable equilibrium’ was already recognized in 1904 but no explanation of the large energy changes, in comparison with chemical energies, could be advanced. The \( \alpha \)- and \( \beta \)-particles, it was postulated, participated in a violent motion within the atom and succeeded from time to time in escaping, when their velocity reached the externally observed value. The end product of a series of such changes, such as are shown in figure 1, was, according to its estimated mass, an atom of lead (Rutherford 1905). With the assumption that the \( \alpha \)-particle was essentially an atom of the helium gas always to be found in addition to lead in radioactive minerals, the atomic weight of the residual lead from the uranium–radium series was expected to be 205, taking Curie’s atomic weight of 225 for radium as the starting point (we now know that the actual mass numbers are 206 and 226). The powerful chemical methods used in reaching these conclusions were very effectively supported by the sensitive ionization chamber method of detection with its discriminating ability which could sort out the \( \alpha, \beta \) and \( \gamma \) components of the total radiation. To read in Rutherford’s papers from McGill how he and Soddy deployed these techniques in the wonderful early years of the 20th century is to participate in a voyage of joyous discovery to which the award of the Nobel Prize in Chemistry was indeed a fitting tribute.

I will not even outline the events that led to the nuclear hypothesis, and to the understanding of atomic number, following Rutherford’s move to Manchester in 1907. Beta particles were indeed used as probes of the atomic constitution, but for the history of beta decay the importance of the nuclear atom model was that it focused attention on the question of the origin of the radiation, namely whether it emerged from the nucleus or from the electronic structure surrounding it. It seems clear that for a time Rutherford (1912, 1913) was attracted by the idea that whereas \( \alpha \)-emission concerned the nucleus, the \( \beta \)-particles might originate from a reorganization of the atomic electrons, and he at first believed that like the \( \alpha \)-particles, they left the atom with homogeneous velocity. He further elaborated this picture in the light of the magnetic analyser experiments over the period 1910–1912 by von Baeyer,
Hahn and Meitner in Berlin, and by Danysz in Paris, which established a linespectrum for the $\beta$-radiation of mesothorium. Since, according to work by Moseley, each atomic transmutation of substances like RaB and RaC yielded only one

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Main $\beta$- and $\gamma$-decay radiations of RaB, RaC and RaC'. The level energies are shown in MeV and the spin-parity $J^\pi$ is indicated for each level. An example of a long-range $\alpha$-transition is included. Half-lives $T_\frac{1}{2}$ and energy releases $Q$ are shown in the table inset.}
\end{figure}

$\beta$-particle per disintegration, Rutherford reasoned that the line spectrum arose because of a modification of the energy of the particle on its way out of the atom. Such a modification might well give rise to the observed $\gamma$-rays if these proved to be the characteristic X-rays of the atom concerned. Moreover the $\gamma$-rays excited in this way would be homogeneous and could eject electrons from atomic 'rings' which would contribute to the line spectrum of $\beta$-rays at energies depending on the 'ring' (or shell) from which they originated. This concept, as Feather (1963) points out in a commentary on Rutherford's papers of 1912 and 1913, is the only one of his early ideas on the connection between $\beta$- and $\gamma$-rays to have survived (as the process of internal conversion). And indeed Rutherford at that time seems not to have been wholly convinced about the $\beta$-rays, since Hevesy (1938) reports that when in the
early days of the nuclear hypothesis he asked Rutherford whether the β-rays were nuclear in origin he was advised to consult Bohr, who was in Manchester from April to July 1912 as well as later during World War I. Bohr himself had no doubt; β-emission had to be nuclear in order to understand the empirical displacement laws proposed by Fajans and Russell and Soddy in 1913. Rutherford himself soon firmly adhered to the same view since he wrote at the end of 1913 in a comment on a suggestion of Soddy that the nucleus should contain only positive electricity: ‘There appears to me to be no doubt that the α-particle does arise from the nucleus and I have thought for some time that... the β-particle has a similar origin.’ He goes on to support this conclusion by noting the apparent absence of any effect on β-emission of changes of physical and chemical conditions, and the magnitude of the β-particle energy in comparison with that stored in the atomic electron distribution. The electron thus became a nuclear constituent and survived in this role until the discovery of the neutron in 1932. Its uneasy predicament in this environment is fully documented by Gamow (1931).

The connection between the β-rays and the γ-rays was certainly not fully and satisfactorily established in 1912 and following his normal practice Rutherford set out to resolve the problem experimentally. First it was of course necessary to consolidate the available data and his students and colleagues at Manchester were rapidly assigned to this task in accordance with a carefully planned programme. The elements studied were chiefly RaB (226Pb) and RaC (214Bi) and in order to understand the results and conclusions reached I show in figure 2 the main features of the presently accepted decay scheme of the corresponding nuclei. First of all Rutherford & Richardson (1913) examined the γ-radiation from RaB and RaC using absorption in aluminium and lead, with a magnet to remove β-ray effects and an ionization chamber connected to an electroscope to determine the radiation intensity. A glance at figure 2 will make it clear that the complex pattern of radiation following the β-decays could hardly be unravelled by absorption methods but it was established that a soft component behaving like the L X-radiation of a heavy element was present for RaB. With RaC only a much harder radiation was found and by extrapolation of known absorption data this was tentatively identified with K X-radiation. The quoted attenuation coefficient in fact agrees with that now tabulated for the 2.2 MeV line shown in RaC' (figure 2) rather than with that for Bi K-radiation. Not surprisingly, Rutherford sensed the lack of resolution inherent in the absorption method and having in his own laboratory the equipment necessary for determining X-ray wavelength by the crystal reflexion method recently developed by Bragg, he asked Andrade to apply the technique to the radiation from RaB (i.e. the transitions shown between the levels of RaC in figure 2). This was a courageous experiment of high technical quality and it succeeded (Rutherford & Andrade 1914) in demonstrating the presence of radiation of a wavelength apparently equal to that of the L-radiation of lead. Unfortunately an error occurred at this point because, as figure 2 shows, the characteristic radiation (due to internal conversion of γ-radiation) associated with the β-decay of RaB must belong to
bismuth and not to lead. This faulty observation, coming as it did at the beginning of the war years, may have delayed a proper understanding of the connection between the $\beta$- and $\gamma$-radiation for a lengthy period.

In parallel with the work of Richardson on the $\gamma$-rays, Robinson had been asked to mount an attack on the $\beta$-radiation itself. Using a magnetic spectrometer of the semi-circular focusing type, and improving on the technique of Danysz, he obtained very clear line spectra of the electrons from RaB and RaC (Rutherford & Robinson 1913), confirming immediately the greater energy and greater complexity of the RaC radiation that is obvious from figure 2. The highest energy line for RaC has $B\rho = 9965$ gauss cm and corresponds with an electron energy of 2.53 MeV; it is a faint line and would now be ascribed to the internal conversion of one of the weak high energy transitions in $^{214}$Po which have not been included in figure 2. The totality of lines found in this experiment was first used to test Rutherford’s idea that an initially homogeneous $\beta$-ray energy was being modified to a discrete spectrum by the excitation of characteristic X-rays (of lead for RaB and bismuth for RaC it was then assumed). But within a few months the picture had dramatically changed by the observation of Rutherford et al. (1914) that for RaB the electron lines seen in the spectrometer when a thin lead converter covered the source were approximately identical, in a certain range, with those from the unscreened emitter so that it then seemed that the electron lines were being produced wholly by the $\gamma$-rays. The day after completing the paper describing this work, and in the darkening shadows of the war that was to interrupt it for so long, Rutherford (1914) attempted to sum it all up in a note to the Philosophical Magazine on ‘The connexion between the $\beta$ and $\gamma$ ray spectra’. Unfortunately this hardly advanced understanding of the problem because he still proposed that the primary $\beta$-particle from the nucleus would excite atomic oscillators which in turn produced characteristic radiation which could either escape and be observed as $\gamma$-rays, or interact with the electrons of the parent atom to generate the observed line spectrum of these particles. The primary $\beta$-particles in colliding with the atomic electrons would suffer randomly distributed energy losses, which would explain the continuous type of spectrum that had at about the same time been found by Chadwick in Berlin to be numerically the strongest feature of the $\beta$-decay process. Artificial assumptions were introduced to explain the variations in $\beta/\gamma$ ratio observed both between different elements and also between isotopes of the same element. Altogether we have to judge that the discussion in this paper is ingenious but unconvincing, leaving many questions unanswered and failing to distinguish clearly between $\gamma$-rays and characteristic X-rays. As Feather (1963) remarks, ‘In the upshot, the issue remained unresolved for eight years, until Ellis, in Rutherford’s laboratory in Cambridge, produced compelling evidence for the modern view that the $\gamma$-rays, like the $\alpha$-particles and the $\beta$-particles, originate in the nucleus.’ Rutherford himself seemed throughout the war to have held the view that any true nuclear $\gamma$-radiation would be so penetrating as to be beyond the bounds of detectability. He did, however, point out (1917), as a result of experiments with X-ray tubes, that
the energy of β-ray groups could be used, in terms of quantum relations, to determine the wavelength of penetrating γ-radiation, and later on Ellis did just this. But by the end of the war, Rutherford’s attention was engaged, in conclusion of his Manchester period, with the notable series of experiments that culminated in the disintegration of the nitrogen nucleus.

The Cambridge period 1919–1937 was dominated by artificial transmutation. At the very beginning Rutherford (1920) gave for the second time the Bakerian Lecture of the Royal Society. In it, developing the reasoning that led him mistakenly to suppose that in some transmutations he had produced \(^{3}\)He particles, he speculated that if such a presumed 3-proton, 1-electron body could exist, then so could \(2 - p, 1 - e\) and \(1 - p, 1 - e\). These would be respectively an isotope of hydrogen and a neutral system resembling a hydrogen atom, but much more tightly bound, and therefore of a mass considerably less than that of the hydrogen atom. This clear prediction of the existence of a neutron and the discovery of this particle by Chadwick in 1932 make a story that has often been told and one that was celebrated last year in Cambridge at the Neutron Jubilee Conference. It may be read in the Rutherford Memorial Lecture of my predecessor (and supervisor) Philip Dee (1967) and it is referred to somewhat modestly in Chadwick’s own Rutherford Lecture (Chadwick 1954), in which it is pointed out that Rutherford believed in the neutron because of its probable role in nuclear constitution. I have already referred to the difficulties encountered in accommodating electrons in the nucleus, and the Bakerian Lecture of 1920 notes that although nuclear electrons play the important part of reducing the nuclear charge to the observed atomic number they must be ‘much deformed’. Eleven years later, Gamow (1931) was to make the same point, denying to the nuclear electron its rightful properties of angular momentum, magnetic moment and statistics. The neutron was the answer to all these problems and when in 1935 Chadwick and Goldhaber showed that the neutron had a mass greater than that of the hydrogen atom, the β-decay of the free neutron was seen to be possible while the similar decay of the bound particle when permitted energetically offered an explanation of natural β-radioactivity. Rutherford had in the last year of his life encouraged an attempt in the Cavendish Laboratory to measure the half-life of the neutron (Gilbert et al. 1937); how excited he would have been to hear of Robson’s beautiful experiments here in Canada in 1950–1951 in which the rate of the fundamental process

\[ n \rightarrow p + e^{-} + \bar{\nu}_e \]  

(2)

was determined. And how dearly would he have liked to have written the survey paper (Wilkinson 1982) that 50 years to a day almost after the discovery of the neutron was able to present its decay properties to an amazing accuracy.

I must return more specifically to the history of β-decay and quickly trace it through the Cambridge days. In the last twenty years of his life Rutherford wrote only three papers on β- and γ-ray problems, although he frequently referred to the subject in the many public lectures that he was called upon to give. He saw to it
however that the main questions left unsettled in 1914 were answered by his staff and students, notably Chadwick, Ellis and Wooster. These questions may be summarized as follows:

(i) how are we to understand Chadwick’s observation that the main β-particle emission from a decaying nucleus forms a continuous spectrum;

(ii) what is the real origin of the line spectra of electrons in β-decay;

(iii) what is the generic connection between the β-rays, the γ-rays and the X-rays that seem to be present among the decay radiations;

(iv) what is the origin and the spectrum of the γ-rays?

Rutherford must have insisted on a rapid confirmation of the first point because in 1922 Ellis, who had been attracted to nuclear physics while held with Chadwick in a prisoner-of-war camp at Ruhleben, Germany, collaborated with his fellow internee in a further study of the Ra (B + C) problem (Chadwick & Ellis 1922). Using magnetic analysis and electroscope detection they clearly saw the continuous spectra of both RaB and RaC and the homogeneous lines superimposed on the former (the homogeneous lines of the latter spectrum were seen in later experiments with photographic recording). Chadwick himself did not work again on beta spectra and the responsibility for further understanding under Rutherford’s guidance moved fairly and squarely to Ellis, who advanced the experimental base of the subject continuously until just after Rutherford’s death.

Leaving the continuous spectrum as an established fact with no obvious interpretation, Ellis turned his attention and his apparatus to the line spectra. Using a source of Ra (B + C) he observed the lines already seen by Rutherford et al. (1914) and he examined the lines excited by the photoelectric effect of the γ-radiation in lead and gold radiators. From these electron spectra, with the use of X-ray data, he showed how photon energies beyond the reach of the crystal diffraction method could be measured as predicted by Rutherford in 1917. Unfortunately his first experiments did not clearly identify the residual atoms from which the line spectra arose and he accepted for a time the identification based on the work of Rutherford & Andrade according to which most of the lines from RaB originated in the RaB atom itself (although one line certainly seemed to agree better with an origin in RaC). A major advance at this point, made possible by the increased precision of measurement, was the association of the γ-rays that produced the line spectra with nuclear energy levels, rather than with the atomic levels so long favoured by Rutherford and the energy level scheme for RaB proposed by Ellis & Skinner (1924) is in fact nearly that now accepted for RaC. It was natural at the time for it to be thought that the nuclear levels were occupied by electrons as for the Bohr atomic levels and there was the tentative suggestion that after producing a series of γ-rays the cascading electron might ultimately reach a special level from which it was ejected as the primary β-ray, with a continuous energy distribution. It was soon pointed out by Kuhn, however, that the observed homogeneity of the γ-radiation was inconsistent with electronic transitions because of the width due to radiation damping so that on the picture of a particle cascade, either α-particles or protons
ought to be involved. At the same time Meitner suggested that the emission of the primary β-particle should come first, before that of the γ-radiation.

It seems that up until 1924 only the last of the four questions about the β- and γ-rays that I have listed had been answered, and there was still confusion about the time-ordering of the β- and γ-radiation. It was a situation with which Ellis became increasingly uneasy, and with the improving precision of magnetic spectroscopy (with absolute calibration) and of X-ray data he must have been embarrassingly aware of the difficulty of fitting the results of Rutherford & Andrade to anything but a highly artificial model. In a crucial experiment (Ellis & Wooster 1925) the β-ray lines from Ra (B + C) were compared directly and accurately with photo-electrons from platinum excited by γ-radiation from the same source and the results showed at last without any doubt that the RaB lines originated in the element of atomic number 83. At the same time, partly no doubt because Ellis’s uneasiness, Rutherford & Wooster (1925) repeated the Rutherford–Andrade experiment and found that there had indeed been something wrong eleven years before: the L X-ray lines associated with RaB (\(^{212}_{82}\)Pb) in fact belonged to RaC (\(^{214}_{83}\)Bi). These results removed the last obstacle to the development of a consistent picture of the connection between β-decay, γ-emission, the β-ray line spectra and the accompanying X-radiation. This picture of course is the familiar one shown in figure 2: the γ-radiation follows the emission of the primary disintegration electron and takes place between quantized energy levels of the daughter nucleus. As an alternative to γ-ray emission the excitation energy might be transferred to an electron of the daughter atom, forming the line spectrum of internal conversion electrons super-imposed upon the continuum of disintegration particles and giving rise to subsequent X-radiation which could itself be internally converted within the atom. For the crucial conclusion on the time-order of the radiations, Ellis generously gave the credit to Meitner; one must assume that the whole matter had been very carefully discussed with Rutherford.

Of the four main questions, only the first and most difficult now remained to be answered. If the disintegration β-particles linked together two definite nuclear states of well-defined binding energy, as certainly seemed to be true in the case of α-particle decay, how could a continuous energy distribution, with an upper limit, arise? If there were secondary atomic processes causing a broadening of initially homogeneous radiation why did they not operate for the internal conversion electrons? Fortunately a direct experimental test of secondary interaction broadening could be made by determining the average energy released per disintegration using a calorimetric method. In a classic experiment Ellis & Wooster (1927) compared the heat output from an RaE (\(^{210}_{83}\)Bi) source with that of its β-decay daughter product RaF (\(^{210}_{83}\)Po) for which the heat generation could be calculated from the energy of the decay α-particles. It was a triumph of the technique of observation of small effects and the result was incontestable; the mean energy delivered to the calorimeter by all radiations absorbable in 1.2 mm of lead was 0.34 ± 0.03 MeV per disintegration compared with 0.39 MeV calculated from an average over the beta spectrum.
A small amount of radiation was found outside the lead but not enough to affect the striking conclusion that the apparent energy change in the $\beta$-decay of RaE is continuously distributed up to a certain limit (1.16 MeV). Ellis and Wooster speculated briefly on a somewhat artificial nuclear model proposed by Rutherford to explain both 'quantized' $\alpha$-particle emission and 'unquantized' $\beta$-emission but they did not relish it and their work remains a crucial step in the development of $\beta$-decay theory. It provided the experimental motivation for Pauli, when a few years later he began to speak of the possibility of a light neutral particle accompanying the electron in $\beta$-decay, an inspired hypothesis which has done for the weak interaction the same sort of service that Rutherford's idea of the neutron achieved for nuclear structure. And just as Pauli's idea was emerging, Ellis & Mott (1933) further supported it by confirming that in $\beta$-decay the upper limit of the spectrum must be used in calculating energy changes, as illustrated in figure 3 for members of the thorium series.

In all this work Ellis is scrupulous in thanking Rutherford for his support and encouragement and there can be little doubt that Rutherford kept closely in touch with progress, even if he did not participate in $\beta$-decay work as much as he continued to do with $\alpha$-decay and later with artificial transmutation. In 1931, however, he drew many of the threads together in a paper (Rutherford & Ellis 1931) on 'The origin of the $\gamma$-rays', in which the quantitative aspects of the decay of RaC (figure 4a) are explored. The figure shows one of several transitions in which $\beta$-decay excites levels in the daughter nucleus (RaC') from which both $\gamma$-radiation and $\beta$-delayed...
long-range $\alpha$-particles are emitted; there is convincing agreement between the energy of the $\gamma$-rays, previously studied by Ellis and Aston, and the $\alpha$-particles. Five years later I was to have the privilege, under Dee's guidance and with Rutherford's knowledge, of studying $\beta$-delayed $\alpha$-emission in a light element produced in the Cockcroft–Walton accelerating equipment (Lewis et al. 1937), as shown in figure 4. (a) Beta-delayed (long-range) $\alpha$-particles from RaC'; a similar transition is shown in figure 2. The $\alpha$-emission competes poorly with $\gamma$-decay of the excited level. The group shown is only part of the total spectrum. (b) Beta-delayed protons from $^{25}$Al. The $\gamma$-decay competes poorly with the particle emission. The groups shown are only part of the total spectrum. (c) Beta-delayed $\alpha$-particles from $^8$Be; no competing $\gamma$-rays have been observed. In each diagram level excitations in MeV and spin-parity values $J^\pi$ are given.

in figure 4c, although in this case the Coulomb barrier is so low that rapid $\alpha$-emission is dominant and there are no competing $\gamma$-rays or conversion electrons. Much later the emission of $\beta$-delayed protons was discovered in Canada (Barton et al. 1963); it is another process of the same type (figure 4b) and would certainly greatly have pleased Rutherford. In the RaC–C' decay the $\gamma$-radiation predominates over the delayed particles and from the observed branching ratio and penetrability calculations it was possible to estimate an entirely reasonable value of about $10^{-14}$ s for the $\gamma$-ray lifetime and to conclude that this radiation probably arose from $\alpha$-particle transitions between the levels of the RaC' nucleus. In the same paper of Rutherford & Ellis the intensities of the internal conversion lines in the $\beta$-spectrum of RaC are discussed and attention is drawn to the notable case of the total internal conversion of the 1.416 MeV transition.

This major paper was Rutherford's last publication to deal extensively with the $\beta$-rays and there is no evidence that he felt inclined to pursue the interpretation of
the main experimental facts that he and his staff had laboured to establish. For the benefit of future workers he presented most of those facts in a monumental book (Rutherford et al. 1930) which summarized three decades of pioneer work. For himself, the quest for the insubstantial neutrino must have held considerably less attraction than his experiments with accelerated deuterons. Chadwick had long since left the field† and Ellis himself, while continuing general observations on β-decay including work with artificially induced activities, which showed β-decay to be a property of unbalanced nuclei throughout the periodic table, made no further major contributions to the subject. Fittingly perhaps, in the year of Rutherford's death, he opened a Royal Society discussion (Ellis 1937) with a clear statement of the position that had been reached with the neutrino hypothesis and with the Fermi theory of the decay process based on the neutron–proton nuclear model. In it he referred to the dependence of beta-decay probability on spin change, which was to explain the existence of distinct families of beta-emitters, first pointed out by Sargent (1933) in Canada. The quantitative successes of the Fermi model were largely to follow; they have been impressive but even more striking have been the new discoveries, not anticipated by Rutherford or Ellis or even Fermi that have been made in the general area of weak interactions. A few experimental aspects of the remarkable story that was about to unfold at the time of Rutherford's death, although in the event it was delayed by war, will form the final part of my lecture.

Although Rutherford often referred to the neutrino hypothesis in the mid-1930s (cf. Rutherford 1935) it is possible that his major satisfaction in this concept was that it restored the validity of a unique energy change $Q_\beta$ between the atoms concerned in the β-decay process. This atomic mass change, apart from a small recoil correction, determines the maximum kinetic energy $T_0$ in the β-particle spectrum when allowance is made for any remaining nuclear excitation energy and the necessary adjustment of $2m_e c^2$ is made in the case of positron emitters. The energy $T_0$ is an important experimental quantity in β-ray studies and I would like to tell you how it has been measured for some interesting light nuclei.

First the neutron: in this case $T_0$ has been measured directly but the most accurate value comes from the independently determined mass difference between the neutron and the hydrogen atom. From figures given by Wilkinson (1982) we find for the process (2) $T_0 = 781.566 \pm 0.017$ keV.

Neutron decay is not complicated by nuclear structure effects and proceeds at a rate which places it in the class of superallowed transitions. In terms of the isobaric spin formalism the decay takes place within the $T = \frac{1}{2}$ multiplet ($\Delta T = 0$) and with the ordinary spins also equal in the initial and final state ($J_i = J_f = \frac{1}{2}^+$ in this case). Similar decays take place between odd-mass mirror nuclei such as $^{13}_7\text{N}$ and $^{19}_8\text{O}$. Another group of superallowed decays is found within the $T = 1$ multiplet, for $J_i = J_f = 0^+$, in light nuclei of even mass number $4n + 2$; a well-known example is

† He did in fact search for the neutrino in 1934, using an ionization chamber (Chadwick & Lea 1934).
the decay of $^{14}$O shown in figure 5. The superallowed positron decay proceeds to an excited state of $^{14}$N:

$$^{14}$O $\rightarrow ^{14}$N* + e$^+$ + ν_e ( + $Q_\beta$); (3a)

and a 2.31 MeV de-excitation γ-ray follows:

$$^{14}$N* $\rightarrow ^{14}$N + γ (+ $Q_\gamma$). (3b)

Several other similar decays, though usually to ground states, are known, but generally only the mass of the stable participating nucleus has been determined accurately by an independent method. It might therefore be thought that the energy release in the β-decay should be determined from the positron spectrum by using a magnetic spectrometer. This was done for $^{14}$O (Fricke 1965) and it was found that

$$T_0 = 1821 \pm 7 \text{ keV}.$$ 

An improvement on this accuracy of 0.4% has been made in later work with other decays, but a more powerful alternative method is to measure the energy change in one of the nuclear reactions by which the unstable nucleus is produced. For $^{14}$O suitable reactions are:

$$^{14}$N + p $\rightarrow ^{14}$O + n ( + $Q_{pn}$), (4a)

$$^{14}$N + $^3$He $\rightarrow ^{14}$O + $^3$H ( + $Q_{He,\beta}$). (4b)

In each of these processes the $Q$-value may be directly related to $Q_\beta$ (or $T_0$) for the $^{14}$O $\rightarrow ^{14}$N* decay; for reaction 4(a) for instance we have (neglecting recoil correction),

$$T_0 = -Q_{pn} - (M_n - M_{He}) c^2 - 2m_e c^2 - Q_\gamma$$

$$= -Q_{pn} - (782.34) - (1022.01) - Q_\gamma \text{ keV}, (5)$$

by using accepted mass values. In work in which I took part some years ago at
A.E.R.E. Harwell (Freeman et al. 1968; see also Clark, G. J. et al. 1973) the quantity $Q_{pn}$ was found by observing the threshold proton energy at which production of $^{14}$O from $^{14}$N began. This was found to be $6355.6 \pm 1.6$ keV and converting to $Q_{pn}$ and using the best available value for $Q_y$, gave from relation (5)

$$T_0 = 1810.2 \pm 1.5$$ keV,

in which the error arose in part from the accuracy with which the energy of a calibration $\alpha$-particle group from ThC was known. The accuracy is considerably better than that of the spectrometer measurement, but it is important to improve it as far as possible, because $T_0$ appears to its fifth power in formulae of the Fermi theory. In more recent years this improvement has indeed been achieved, first at Munich by use of an accelerator calibrated by a precision time-of-flight method (Vonachli et al. 1977, with reaction 4(b)) and second at Auckland by use of a highly precise momentum comparison involving heavy ions of the same magnetic rigidity as the bombarding particles (White et al. 1981, reaction 4(a)). White's work would certainly have pleased Rutherford, not only because it was done in New Zealand, but also because he himself had been interested in the momentum of heavy (recoil) atoms. These experiments give, again with $Q_y$,

$$T_0 = 1807.9 \pm 0.8$$ keV and  
$$T_0 = 1808.25 \pm 0.1$$ keV,

respectively, and have now reached a level of accuracy at which corrections for recoil and atomic excitation effects should be considered. Of course these measurements are not direct determinations of the end-point of the $\beta$-spectrum and they do not help to resolve the question of the existence of a finite mass for the neutrino. That possibility has become of considerable interest following a recent careful analysis of the shape of the $\beta$-spectrum in the superallowed decay of tritium

$$^3H \rightarrow ^3He + e^- + \bar{\nu}_e. \tag{6}$$

This reaction was studied many years ago by Curran, Angus and Cockcroft in the laboratory of Philip Dee at Glasgow and one may trace a direct link with Rutherford in their work. Certainly their results, obtained with a proportional counter, would have appealed to him and for a long time they provided an upper limit for the electron anti-neutrino mass. Now that upper limit has in one experiment become a specific value of about 36 eV and confirmation is being actively sought. Rutherford knew of course from work in the Cavendish Laboratory (Ellis 1934) that the mass of the anti-neutrino was then experimentally consistent with zero.

I will pass over the discovery of non-conservation of parity in $\beta$-decay and its attribution to the helicity of the neutrino, since of these matters there was no hint in Rutherford's time although as is well known the longitudinal polarization of $\beta$-particles might have been established with the techniques available in the 1930s. It is interesting, though not particularly helpful, to note that one of Rutherford's earliest experiments with radioactive radiations was to disprove Becquerel's assertion that these radiations could be refracted and polarized. He found no such
effect and indeed had he done so the state of knowledge at the beginning of this century could have provided no interpretation. So leaving this area of the subject, let me come to the basic probability of $\beta$-decay, that is, the coupling constant that determines the lifetime of $\beta$-emitters when all calculable energy and structure-dependent factors have been taken into account. This can be deduced from observations of the decay energy and lifetime for an $0^+ \rightarrow 0^+$ superallowed transition and it is desirable that the two contributing factors shall be known to comparable and high accuracy.

Accurate determination of $\beta$-decay lifetimes is not a trivial problem (Becker et al. 1978) particularly in the case of accelerator-produced activities. With these, small amounts of contamination activity may make true background estimates difficult and it now seems that the highest accuracy will demand the use of mass-separated samples (Hardy 1980; see also Koslowsky et al. 1983). In most existing work, however, it has been necessary to estimate and to correct for background effects having first chosen experimental conditions to minimize production and detection of the unwanted radiations. At the level of accuracy now desirable in $\beta$-decay measurements, lifetimes must be evaluated using the maximum-likelihood method or procedures equivalent to it and a convenient prescription developed by Robinson (a New Zealander, Rutherford would have observed) has been used in work at Harwell (Robinson 1970). In this procedure the data points, consisting of activity $Y_i$ as a function of time of observation $t_i$ are fitted first to a single exponential plus constant background $b$:

$$Y_i = a \exp(-\lambda t_i) + b. \quad (7)$$

The weighting for each point is not the data point itself ($\sigma_i^2 = Y_i$) but a value obtained from the fit for that point and the calculation is iterated using for weights in the $n$th iteration the data points computed in the $(n-1)$th. The presence of contaminant activities in the data is sought by comparing the lifetimes computed for periods beginning at different times after the conclusion of the target irradiation; if these lifetimes are the same, distortion due to contaminant lifetimes of the order of that under study has been eliminated. It is also necessary, in a preliminary stage of the analysis, to correct the raw data points for pile-up and dead-time effects. These may be studied by observing the variation of indicated lifetime with initial counting rate and if they have not been eliminated in the observations used for analysis appropriate small corrections may be made. Adjustments of about 0.1% may arise in this way. Finally, if it is still felt that intruder activities may be present a two-exponential analysis rather than that given by (7) may be used.

The decay of $^{14}\text{O}$ is especially favourable for accurate lifetime determination because the $^{14}\text{N}^*$ gamma radiation indicated in (3) provides a clear and unambiguous signal for detection and spectroscopic analysis can reveal pile-up effects. In the experiments in which I took part at Harwell (Clark et al. 1973) a value

$$T_\frac{1}{2}(^{14}\text{O}) = 70.588 \pm 0.028 \text{ s}$$

on December 19, 2017
was obtained. The quoted error is statistical, but it was derived from many independent data sets and it was hoped that major systematic effects had thereby been eliminated. Unfortunately the history of lifetime measurements in general does not inspire confidence in such statements and small shifts in the 'best' value for this lifetime are still to be anticipated. For $^{14}$O, the decay includes small contributions from transitions to levels other than that of spin $0^+$ and if correction is made for these

$$T_{1/2}^{(14}O, \ 0^+\rightarrow 0^+) = 71.066 \pm 0.030 \text{ s}.$$  

In the most recent papers on this topic an accuracy approaching 1 part in 3500 is quoted and this is comparable with that in contemporary measurements of the $\beta$-endpoint, raised to the fifth power, as it occurs in Fermi's theory.

What then can be done with data of this sort of accuracy? To answer this let us return briefly to the 1950s when it was already realized that three sorts of weak interaction process, namely $\beta$-decay, muon-decay and muon-capture proceeded at about the same basic rate, i.e. that they were governed by some type of universal interaction. It was also thought unlikely that this universality would result in identical values for the corresponding coupling constants because muon decay involves no strongly interacting particles but the other processes do and would surely be affected by their presence. The situation changed dramatically in 1958, soon after the discovery of parity non-conservation, when Feynman and Gell-Mann discussed $\beta$-decay in terms of the interaction of two currents each containing a vector (V) and axial vector (A) part, and coupled together, following the original idea of Yukawa, by a charged intermediate vector boson $W$ of mass $M_W$. The leptonic current is equally of V and A type and is responsible for the maximal parity-violating effects observed in $\beta$-decay while the hadronic or nuclear current has unequal V and A components because of the influence of the strong interaction. By comparing the hadronic current with the more familiar electromagnetic current Feynman and Gell-Mann showed that the vector part of the current would not be affected by the strong interaction, though the axial current might be, and they formalized this into the conserved vector current hypothesis (C.V.C.). It follows that the coupling constants for a pure vector decay process $G^V_\mu$ and for the muon decay $G^\mu$ should be the same apart from small electromagnetic corrections. These are the propositions that may now be sharply tested by the availability of accurate data; I will take them in order.

C.V.C. predicts that $\beta$-decay processes due to the vector hadronic current are not affected by the strong interaction. The $0^+\rightarrow 0^+ \Delta T = 0$ superallowed decays within the $T = 1$ isospin multiplet are just such processes and we may now compare at least 8 cases to an accuracy of better than 0.1 %. The decays are those of $^{14}$O, $^{26}$Al, $^{34}$Cl, $^{36}$K, $^{42}$Sc, $^{46}$V, $^{50}$Mn and $^{54}$Co and for each transition we assume in the first place that the observables are related to the coupling constant by the comparative half-life formula:

$$fT_{1/2} = \left(2\pi^3 \ln 2 / G^V_\mu |V|^2 \right) \left(\hbar^2 / m_e^5 c^4 \right),$$

(8)
where \( f \) is the phase space factor involving an integration over the positron spectrum and \( |M|^2 \) is a squared matrix element expected to have the value 2 for decays between states of pure isospin \( T = 1 \). In fact, because of mixing by charge-dependent forces, the initial and final states are not pure and \( |M|^2 \) should be replaced by \( 2(1 - \delta_c) \), where \( \delta_c \) is a model-dependent correction about which there has been lengthy discussion; it is generally less than 0.8\%. When this correction is introduced and a calculable electromagnetic correction is included to multiply \( f \) there is a good agreement between the resulting comparative half-lives (table 2) and it seems likely that continual improvement of the data, for which Hardy and his collaborators at Chalk River and White’s group at Auckland are now largely responsible, will further reinforce this verification of the C.V.C. hypothesis. I will not refer to other confirmation of this fertile principle; suffice it to say that little doubt now remains of its essential truth, and its origin in a deeper theory is now becoming apparent.

I turn now to the coupling constants, namely \( G^V_\beta \), which is explicitly shown in (8) and \( G_\mu \) which is obtained also in a first approximation from the expression for the mean life of the muon

\[
\tau_\mu = \frac{192\pi^3\hbar^7}{G^2_\mu m_\mu^5 c^4}.
\]  

(9)

At the time of Feynman and Gell-Mann’s paper, the accuracy of available data on the \( ^{14}\text{O} \) and muon decays was sufficient to show that the muon lifetime could be calculated from \( \beta \)-decay with the assumption

\[
G^V_\beta = G_\mu
\]  

(10)

to within 2\% which was a remarkable confirmation of the (V–A) theory. Recall here that we are considering only the vector coupling constant and that the assertion of (10) is that this constant is not renormalized by strong interaction effects. To some extent of course this confirmation is insecure because expressions (8) and (9) have not been corrected for radiative effects analogous to bremsstrahlung and indeed including this phenomenon though mainly residing in virtual processes. Most of these effects arise because of the production of free charge by the decay process within a Coulomb field and their calculation is complicated, so that it has proceeded at several levels of sophistication.

Let us go back to 1961, the year of the Rutherford Jubilee International Conference at Manchester, celebrating the discovery of the nucleus. In the session on the beta-interaction, William Fowler (Caltech) presented numerical data on the \( G^V_\beta, G_\mu \) comparison and some of the figures from a subsequent publication (Bardin et al. 1962) are reproduced in table 1. They show the effect of a number of important corrections including those for radiative processes as calculated by Kinoshita and Sirlin for a contact interaction. Unfortunately divergencies exist in these calculations unless cut-offs are imposed. It is interesting to note that the radiative corrections, which at this point may be thought of as altering the half-life for the decay, operate in different directions for the positron decay and for the muon, and
when applied, increase the difference between $G^V_\beta$ and $G_\mu$. Increasing precision of the experimental data over the next year or two firmly established the difference and it began to seem that the strict universality of the (V−A) theory had been breached. In 1963, however, a major new factor entered the comparison with the

Table 1. $G^V_\beta$, $G_\mu$ comparison in 1962 (Bardin et al. 1962)

<table>
<thead>
<tr>
<th>quantity</th>
<th>uncorrected, with error</th>
<th>corrected (a)</th>
<th>corrected (b)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$fT_\beta^{(14O)}$</td>
<td>3066 ± 10</td>
<td>3074</td>
<td>3126</td>
<td>s</td>
</tr>
<tr>
<td>$G^V_\beta$</td>
<td>1.4164 ± 0.0022</td>
<td>1.4145</td>
<td>1.4025</td>
<td>$10^{-49} \times$ erg cm$^3$</td>
</tr>
<tr>
<td>$\tau_\mu$</td>
<td>2.210 ± 0.003</td>
<td>2.210</td>
<td>2.201</td>
<td>$\mu$s</td>
</tr>
<tr>
<td>$G_\mu$</td>
<td>1.4282 ± 0.0011</td>
<td>1.4282</td>
<td>1.4312</td>
<td>$10^{-49} \times$ erg cm$^3$</td>
</tr>
<tr>
<td>$(G_\mu - G^V_\beta)/G_\mu$</td>
<td>0.8 ± 0.2</td>
<td>1.0</td>
<td>2.0</td>
<td>$(%)$</td>
</tr>
</tbody>
</table>

(a) For $fT_\beta^{(14O)} + 0.265\%$ correction for nuclear size, electron screening, K-capture, second-forbidden matrix elements; for $\tau_\mu$, no correction. No charge-dependent correction to the nuclear matrix element is included.

(b) For $fT_\beta^{(14O)} + 1.7\%$ radiative correction and for $\tau_\mu$ − 0.42\% in addition to corrections (a). 1 erg = $10^{-7}$ J.

proposal by Cabibbo that a new term should be included in the hadronic current to account for the strangeness-changing weak decays of the baryons and mesons. The hadronic current then contained two parts which were taken to be proportional to $\cos \theta_C$ (strangeness-conserving) and $\sin \theta_C$ (strangeness non-conserving) respectively where the ‘Cabibbo’ angle $\theta_C$ is to be determined experimentally. The reduction of the amplitude of the current describing $\beta$-decay means that (10) must be replaced by

$$G^V_\beta = G_\mu \cos \theta_C \quad (11)$$

and with $\theta_C \approx \arcsin 0.23$ as now indicated by strange particle decays $G^V_\beta \approx 0.973 G_\mu$ which is close to the value 0.982 $G_\mu$ required by the figures in table 1. Although this early result suggested strongly that universality must be expressed in the manner prescribed by the Cabibbo theory, difficulties soon began to appear as more data, both on the superallowed decays and on the Cabibbo angle itself, became available. One of these for instance was the fact that the $^{14}$O and $^{26}$Al$^{m}$ values did not agree, and although that discrepancy has now been removed by work at Chalk River, it did emphasize the desirability of a reconsideration of the whole comparison of $G^V_\beta$ with $G_\mu$. This took place over the decade 1968–1978 approximately, a period that embraced a further major advance in general understanding, namely the development of the electroweak theory of Weinberg and Salam in which the electromagnetic and weak interactions are brought together and appear to be distinct only at low values of momentum transfer. In the electroweak theory the conservation of vector current arises naturally, and ceases to be a hypothesis. The relevance of the new theory to the $G^V_\beta$, $G_\mu$ comparison, as we shall see, is also highly significant.

In 1970, Blin-Stoyle & Freeman published a reformulation of the standard theory of superallowed transitions which has been adopted by all subsequent workers. Essentially, following Sirlin, they express that part of the Coulomb interaction
effect in $\beta$-decay which is not contained in the phase-space factor or the nuclear matrix element in the form

$$\delta_R = \delta'_R + \Delta_R,$$

where $\delta_R$ is what has conventionally been described as the total radiative correction, $\delta'_R$ is the model-independent but energy-dependent (and calculable) outer correction and $\Delta_R$ is the model-dependent but energy-independent inner term. Expression (8) may then be written in the form

$$fT_4(1 + \delta_R^2) = \frac{2\pi^3 \ln 2}{G^{\forall}_\beta(1 + \Delta_R)} \frac{\hbar^7}{|M|^2 m_e c^4}$$

or, writing $G^{\forall}_\beta(1 + \Delta_R) = G^{\forall}_0$ and inserting the value $2(1 - \delta_c)$ for $|M|^2$

$$fT_4(1 + \delta_R^2) = \frac{\pi^3 \ln 2 \hbar}{G^{\forall}_0 (1 - \delta_c)} \frac{h^7}{m_e c^4} = \frac{K}{G^{\forall}_0 (1 - \delta_c)},$$

where $K = 6.1531 \pm 0.0002 \times 10^{-55} \text{erg}^2 \text{cm}^6 \text{s}$. †

Similarly for the muon we now write instead of (9)

$$\tau_\mu(1 - \delta'_\mu) = \frac{192\pi^3 \hbar}{G^{\forall}_\mu m^5_e c^4} (1 - 8m^2_e/m^2_\mu),$$

where

$$G^{\forall}_\mu = G^{\forall}_0 (1 + \Delta_\mu).$$

For both processes we note that the formalism explicitly allows the outer radiative correction to modify the decay rate, which is observable, and the inner correction to renormalize the coupling constant, which is not observed but inferred. This has proved a useful separation of effects because the confrontation of $G'_V$ with $G_0$ via the Cabibbo angle now leads directly to the model-dependent quantity $G'_V(1 - \delta'_c)$. It may be useful to mention at this point that although the calculation of the phase space factor $f$ for $\beta$-decay by integration of the statistical terms, (with Coulomb correction) over the energy spectrum is a non-trivial undertaking at the level of precision now required, reliable tables of the vital Fermi function used in this procedure now exist. Different methods have been used to introduce corrections for atomic screening and for finite nuclear size, which entails consideration of second forbidden matrix elements, but the methods (Blin-Stoyle and Nair, Behrens, Jänecke and Bühring, Wilkinson and Macefield, Hardy and Towner) agree to within about 0.15%.

The correction $\delta'_c$ to the nuclear matrix element term due to the perturbation of isospin symmetry by Coulomb forces is model-dependent and ranges up to about 0.8%, but again there is fair agreement between different calculations. One other factor for $\beta$-decay, which has not been shown explicitly so far, has to be calculated because of experimental difficulty in observation; it is the competition of electron capture with positron emission and may be allowed for by a small adjustment to the observed half-life, amounting usually to less than 0.1%.

† 1 erg = $10^{-7}$ J.
There have been several reviews of recent data for the superallowed transitions in terms of the formalism just outlined. A typical set of data is shown in table 2 which gives the quantities

$$f^{R}T_{\frac{1}{2}} = (1 + \delta_{R}^{(s)})fT_{\frac{1}{2}}$$

and

$$\mathcal{F}T_{\frac{1}{2}} = (1 - \delta_{e})f^{R}T_{\frac{1}{2}},$$

**Table 2. Superallowed Fermi $\beta$-decay, comparative half-lives, 1982**

<table>
<thead>
<tr>
<th>Unstable nucleus</th>
<th>$f^{R}T_{\frac{1}{2}}/s (a)$</th>
<th>$\delta_{e} (%) (b)$</th>
<th>$\mathcal{F}T_{\frac{1}{2}}/s (c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}\text{O}$</td>
<td>$3086.5 \pm 2.7$ (d)</td>
<td>0.15</td>
<td>3081.9 \pm 2.7</td>
</tr>
<tr>
<td>$^{26}\text{Al}^{m}$</td>
<td>$3086.3 \pm 2.1$</td>
<td>0.20</td>
<td>3080.1 \pm 2.1</td>
</tr>
<tr>
<td>$^{34}\text{Cl}$</td>
<td>$3100.1 \pm 2.2$</td>
<td>0.42</td>
<td>3087.1 \pm 2.2</td>
</tr>
<tr>
<td>$^{38}\text{K}^{m}$</td>
<td>$3092.0 \pm 3.0$</td>
<td>0.37</td>
<td>3080.6 \pm 3.0</td>
</tr>
<tr>
<td>$^{42}\text{Se}$</td>
<td>$3098.4 \pm 3.0$</td>
<td>0.37</td>
<td>3080.7 \pm 3.0</td>
</tr>
<tr>
<td>$^{46}\text{V}$</td>
<td>$3103.0 \pm 2.0$</td>
<td>0.48</td>
<td>3088.1 \pm 2.0</td>
</tr>
<tr>
<td>$^{50}\text{Mn}$</td>
<td>$3097.4 \pm 2.3$</td>
<td>0.53</td>
<td>3081.0 \pm 2.3</td>
</tr>
<tr>
<td>$^{54}\text{Co}$</td>
<td>$3108.5 \pm 2.6$</td>
<td>0.59</td>
<td>3090.2 \pm 2.6</td>
</tr>
</tbody>
</table>

Unweighted mean $3083.7 \pm 2.6$

(a) Behrens & Bühring (1982).
(b) Raman et al. (1975).
(c) Omitting errors in $\delta_{e}$.
(d) A recent value, obtained from the work of White et al. (1981), is $3084.4 \pm 1.1$ s.

where the former figures are due to Wilkinson (quoted by Behrens & Bühring 1982) and the latter are derived by using the $\delta_{e}$ values given by Raman et al. (1975).

As stated earlier, the vector current conservation is well verified for the nuclear $\beta$-decays.

The figures in table 2, when averaged, and allowing for errors in $\delta_{e}$, lead to a vector coupling constant

$$G'_{V} = G'_{\mu} (1 + \frac{1}{2}A_{R}) = 1.4126 \pm 0.0005 \times 10^{-49} \text{erg cm}^{3},$$

while the highly accurate muon data (Particle Data Group 1982) give

$$G'_{\mu} = G_{\mu} (1 + \frac{1}{2}A_{\mu}) = 1.43582 \pm 0.00004 \times 10^{-49} \text{erg cm}^{3},$$

so that $(G'_{\mu} - G'_{V})/G'_{\mu} = 1.62 \pm 0.03 \%$ as indicated more crudely by the data of 1962 (table 1). The Cabibbo angle determined by hyperon decays is $\theta_{C} = 0.231 \pm 0.003 \text{ rad}$ and using relation (11) with (18) and (19)

$$A_{R} - A_{\mu} = 2.14 \pm 0.22 \%.$$  

This difference between the inner radiative corrections, which was essentially obtained in 1970 by Blin-Stoyle & Freeman, is as far as the decay experiments can take us, and perhaps as far as Rutherford would have wished to go. The next step, to relate the result in (20) to models of nucleon structure or to theories of the weak
interaction itself, was beset in 1970 by difficulties relating to divergencies in the intermediate charged boson theory. Sirlin however (1974, 1975), has shown that for a range of quark models of the nucleon and of gauge theories of the interaction, these difficulties may be circumvented. For the particular case of the Weinberg-Salam electroweak theory he obtains an expression for $\Delta R - \Delta \mu$ in terms of $\bar{Q}$ the mean charge of the fundamental quark doublet in the nucleon and the mass of a neutral intermediate boson $Z^0$, which is analogous to the photon in the electromagnetic interaction. It is tempting therefore to push the data further to learn something about either $\bar{Q}$ or $M_Z$ on the basis of an assumption about the other. Wilkinson (1975), following the former line, concluded that the indicated quark charges were consistent with the familiar fractional values while Towner & Hardy (1975) showed that $M_Z > 100\text{ GeV}/c^2$, which is not in serious disagreement with the current independent estimate $M_Z \approx 94\text{ GeV}/c^2$. Rutherford would surely have been delighted to learn of this fascinating connection between $\beta$-decay and particle physics, and he might have conceded that his theoretical friends had established something of a lead. He certainly realized, if we may judge from his comments on Faraday at a commemoration in 1931, that ‘the various forces of nature were interrelated and dependent on one another’.

As far as the title of my lecture is concerned, I think that this is the point at which to stop, but it is by no means the end of the story. Very recently data from the 540 GeV(CM)$\bar{p}p$ experiments at the CERN S.P.S. used as an accelerator-storage-ring-collider have established the existence of the W-boson (CERN 1983; see also, Arnison et al. 1983; Banner et al. 1983), and very shortly evidence for the $Z$-boson may follow. And even then we are not at the end because unification within natural order must envisage two further major steps. The first is to link the strong interaction with the weak and the electromagnetic by placing the quarks and the leptons within the same overall symmetry scheme. We then have to allow a quark-lepton coupling which will cause instability of the proton and neutron and therefore of particles that they comprise. Already in his 1906 book Rutherford had considered the stability of ordinary matter against $\alpha$-particle decay: ‘if the expulsion of $\alpha$-particles is taken as evidence of atomic disintegration, a simple calculation shows that the life of ordinary matter is of the order of at least one thousand times that of uranium, i.e. not less than $10^{12}$ years’. Now we know of course that the lifetime of the proton must be vastly longer but the new grand unified theory indeed predicts that it (and Rutherford’s $\alpha$-particle!) is unstable with a lifetime of above $10^{30}$ years. For such a value the mass of the coupling particle analogous to the $Z^0$ and $W^\pm$ must be about $10^{15}\text{ GeV}/c^2$.

The final major step would be to include gravitation in the unified scheme but quantum gravity is still not understood. It is believed that gravitational interactions will only become ‘strong’ at energies of the order of the Planck mass $(hc/G)^{1/2}$, where $G$ is the gravitational constant, and this is $10^{19}\text{ GeV}/c^2$. So there is some way yet to go, and the journey will probably have to be taken with the astronomers. The final goal is a long, long way from our starting point in nuclear
β-decay, but it is one that Rutherford would have encouraged his successors to seek, confident in his belief that in the end Nature will reveal a fundamental simplicity in her answers to questions that are posed by simple (even if increasingly costly) experiments.

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