The Prehistory of the Neutrino

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In this paper I will address the experimental work and results that provided the background for Wolfgang Pauli's "desperate solution:" that a very light, neutral particle, with spin 1/2 was emitted along with the electron in β decay. The story begins with the discovery of radioactivity by Henri Becquerel in 1896 and the subsequent work that showed that there were three types of decay: α and β decay, observed by Ernest Rutherford, and γ decay found by Paul Villard. One question that arose was what was the energy spectrum of the electrons emitted in β decay. William Bragg had shown that the α particles emitted in α decay were monoenergetic. By analogy most physicists in the early 20^{th} century believed that the electrons emitted in β decay were also monoenergetic. There was experimental support for this in the work of Lise Meitner, Otto Hahn, Hans von Baeyer, and Heinrich Schmidt. In 1914 James Chadwick reported a continuous energy spectrum for the electrons emitted in β decay. This was not generally accepted by the physics community. It was not until 1927 that Charles Ellis and William Wooster conclusively demonstrated that the energy spectrum was continuous. This posed a serious problem for the physics community. If β decay was a two-body process, as most physicists believed, then the laws of conservation of energy and momentum required that the electrons be monoenergetic. Pauli's hypothesis that a neutral particle was also emitted solved the problem. In a three-body decay the electron need not have a single definite energy.

In the early 20^{th} century physicists believed that β decay was a two-body process in which a radioactive nucleus emitted an electron and transformed into a different, daughter nucleus. Applying the laws of conservation of energy and momentum to such a process required that the emitted electron, for each radioactive nucleus, have a discrete and unique energy. Over a thirty-year period it was found that the spectrum of emitted electrons was, in fact, continuous. This posed a problem for the conservation laws. In 1930 Pauli proposed his "desperate way out." He suggested that a very light, neutral, spin 1/2 particle, later named the neutrino by Enrico Fermi, was also emitted in β decay. This solved the problem of the conservation laws because in a three-body decay the electron is not required to have a unique energy [a] [b].

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[a]For a more detailed history of this episode see [1], Chapters 1 and 2
[b]As discussed below, the neutrino also solved a problem involving the spin of nuclei.

The story begins with the discovery of radioactivity, the process in which an atomic nucleus emits a particle and is transformed into the nucleus of another element.

1 The Discovery of Radioactivity

In 1896 Henri Becquerel made an almost accidental discovery of radioactivity[2,3,4,5,6]. Becquerel's work was stimulated by the then recent discovery of x-rays by Wilhelm Röntgen in 1895. Becquerel had been working on phosphorescence, the delayed emission of light by a substance after it has been exposed to an external source of light. After Röntgen's announcement, Becquerel began an investigation of whether phosphorescent substances would emit x-rays if they were exposed to intense light. His initial experiments produced no effects, but when he used uranium salts, which he had prepared for phosphorescence experiments fifteen years earlier, he found a striking effect. Becquerel placed a uranium salt, or pure uranium, on a photographic plate that was covered in black paper. When the plate was developed it showed a dark area, indicating that something had exposed the plate (Figure 1).

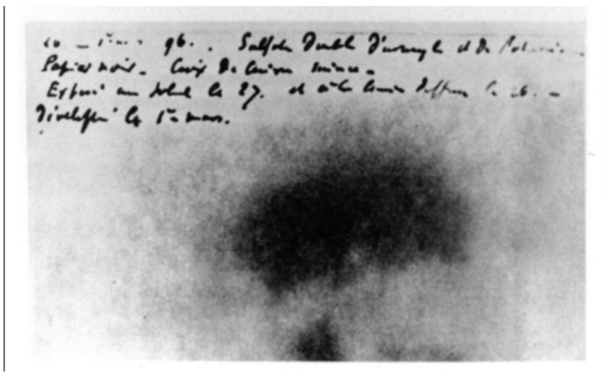

Figure 1 – Becquerel's original photograph. The outline of the radioactive substance is seen.

Becquerel concluded that, "the phosphorescent substance in question emits radiations which penetrate paper that is opaque to light." Becquerel drew no conclusions concerning the nature of the radiation emitted. Subsequent experiments, by the Curies and others, showed that other substances, including the newly discovered elements, radium and polonium, emitted similar radiation. What that radiation actually was, however, remained a mystery.

2 What Are the Becquerel Rays? The Alphabet: α, β, γ

In 1897 J.J. Thomson demonstrated that cathode rays were negatively charged material particles and measured their mass to charge ratio[7]. He found that ratio to be approximately 1000 times smaller than that of the hydrogen ion, the smallest previous measurement, and concluded that these particles were constituents of atoms[c].

The first step in deciphering the nature of the radiation emitted by uranium was taken by Ernest Rutherford[8]. He reported the results of an experiment on the absorption of that radiation. He placed uranium, or a uranium compound, on a zinc plate. The radiation emitted by the uranium ionized the air and produced an electric current that was detected by an electrometer. The rate of charge deposited was proportional to the ionization produced and to the intensity of the radiation. Rutherford measured the intensity of the radiation as a function of the thickness of aluminum foils placed over the uranium. He found that, at first, each plate reduced the amount of radiation by the same, constant fraction, but that beyond a certain thickness the intensity of the radiation was only slightly reduced by adding additional layers. "It will be observed that for the first three layers of aluminum foil, the intensity of the radiation falls off

[c]For details see [1], pp. 17-21

according to the ordinary absorption law, and that, after the fourth thickness the intensity of the radiation is only slightly diminished by adding another eight layers (p. 115)." Rutherford concluded, "These experiments show that the uranium radiation is complex, and that there are present at least two distinct types of radiation – one that is vary readily absorbed, which will be termed for convenience the α radiation, and the other of a more penetrative character, which will be termed the β radiation (p. 116)." (Figure 2).

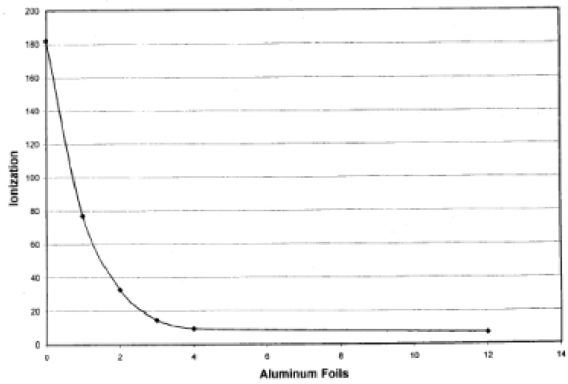

Figure 2 – The ionization produced by the radiation emitted from a uranium source as a function of the number of aluminum foils used as an absorber (Rutherford's 1899 data). The rapid decrease is due to the absorption of α particles. The remaining β rays are only slightly reduced by the addition of each foil.

It was initially believed that the α particles were electrically neutral because they could not be deflected by a magnetic field. Rutherford found, however, that they could be deflected in the same direction as a positive charge when he applied a strong magnetic field. The β rays were negatively charged and the γ rays, a third type of emitted radiation discovered by Paul Villard in 1900, were electrically neutral.

In 1904 William Bragg demonstrated that α particles of equal initial energy or velocity had equal ranges in matter, an important point for later work. In Bragg's own words *In the case when all the rays are initially of uniform velocity, the curve obtained ought to show, when the radium is out of range of the ionization chamber, an effect due entirely to β and γ rays, which should slowly increase as the distance diminishes [or decrease as the distance increases]. When the α rays can just penetrate, there should a somewhat sudden appearance be of the ionization, and for a short distance of the approach, equal to the depth of the chamber, the curve should be a parabola. Afterwards it should become a straight line.*

This is exactly realized [Figure 3]; and so far the hypothesis is verified. But a further effect appears. As the radium is gradually brought nearer to the chamber, the straight line suddenly changes its direction; and indeed there appear to be two or three such changes ... (see ref. [9], p 723). [d]

In a paper a year later, Bragg summarized his results. "Each α particle possesses therefore a definite range in a given medium, the length of which depends on the initial velocity of the particle and the nature of the medium ... All the particles of any one group have the same range and the same initial velocity [10]."

What then of the β rays? As early as 1899 three different experiments, those of Becquerel, of Giesel, and of Meyer and von Schweidler, as well as one performed by Pierre and Marie Curie in 1900, had found that β rays had the same negative charge as that of cathode rays. At approximately the same time, Walter Kaufmann began a series of experiments on β rays emitted from a radium source. In 1902 he concluded that, "for small velocities, the computed value of the mass of the electrons which generate Becquerel rays ... fits within observational errors with the value found in cathode rays (Kaufmann 1902), cited in [11], p. 87)." Other experiments at the

[d] Bragg had also shown a series of α particle emissions.

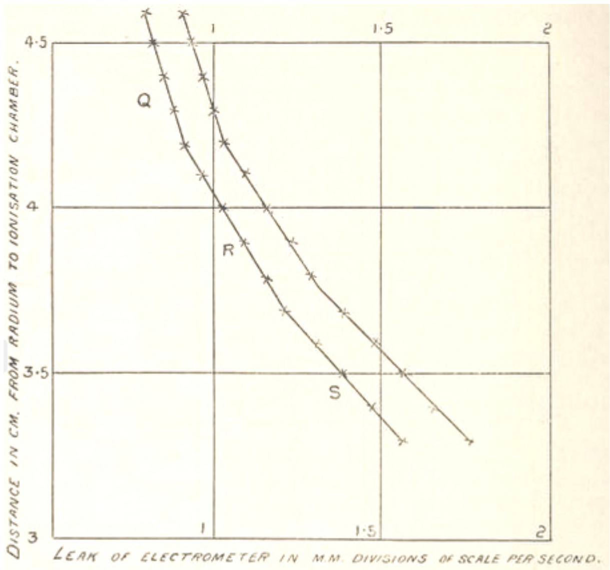

Figure 3 – The ionization produced in the chamber as a function of the distance from the radioactive source R. There are several changes in the slope of the curve indicating the presence of several α particles, each with its own energy. Source: Bragg [9].

time confirmed Kaufmann's result. From that time forward the physics community regarded the β rays as the same particles as cathode rays. They were electrons.

3 The Energy Spectrum in β Decay

Kaufmann's experiments, discussed above, also showed that radium emitted electrons with a wide range of velocities. A similar result was also found by Becquerel in 1900. Despite the evidence provided by both Kaufmann and Becquerel, the physics community did not, at this time, the first decade of the twentieth century, accept that the energy spectrum of electrons emitted in β decay was continuous. There were, at the time, plausible reasons for this decision. Physicists argued that the sources used by both Kaufmann and Becquerel were not pure β-ray sources, but contained several elements, each of which could emit electrons with different energies. In addition, even if the electrons began as monoenergetic each electron might lose different amounts of energy in escaping from the radioactive source. This view was due, in part, to a faulty analogy with α decay. As discussed earlier, each of the α particles emitted in a particular decay has the same, unique energy, as well as a definite range in matter, and physicists at the time thought, by analogy with the α particles, that the β rays would also be emitted with a unique energy.

It was believed, at the time, that monoenergetic electrons would follow an exponential absorption law when they passed through matter. This was a reasonable assumption. If electron absorption was dominated by the scattering of electrons out of the beam, and if the scattering probability per unit length was constant, then this leads to an exponential absorption law. As William Bragg stated, "Nevertheless it is clear that β rays are liable to deflexion through close encounters with the electrons of atoms; and therefore the distance to which any given electron is likely to penetrate before it encounters a serious deflexion is a matter of chance. This, of course, brings in an exponential law (see ref [9], p. 720)."

Early experimental work on electron absorption in the first decade of the twentieth century gave support to such a law and therefore to the homogeneous (monoenergetic) nature of β rays, particularly the work of Heinrich Schmidt [12,13]. Schmidt claimed to be able to fit the electron absorption curves for electrons emitted from different radioactive substances with either a single exponential or with a superposition of a few exponentials. Figure 4 shows the absorption curve that Schmidt obtained for electrons from radium B and from radium C, respectively [e]. The fact that the logarithm of the ionization, a measure of the electron intensity, decreases linearly with the thickness of the absorber indicates an exponential absorption law. Each curve actually consists of two straight lines, showing the superposition of two exponentials. Schmidt interpreted this result as demonstrating that two groups of β rays were emitted in each of these decays, each with its own unique energy and absorption rate [f]. There was, in fact, a circularity in the argument. If the β-rays were monoenergetic then they would give rise to an exponential absorption law. If they followed an exponential absorption law than they were monoenergetic.

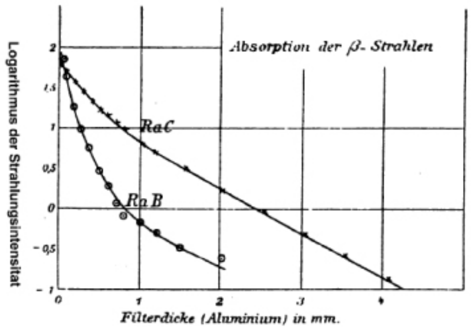

Figure 4 – Schmidt's result on the absorption of β rays. The logarithm of the electron intensity (ionization) as a function of the absorber is a straight line, indicating an exponential absorption law. RaC is ^{214}Bi and RaB ^{214}Pb. Source: [12].

It was this association of homogenous electrons with an exponential absorption law, that informed early work on the energy spectrum in β decay. This was the situation when Lise Meitner, Otto Hahn, and Otto von Baeyer began their work on the related problems of the absorption of electrons in matter and of the energy spectrum of electrons emitted in β decay in 1907 [14,15,16,17,18,19,20,21].

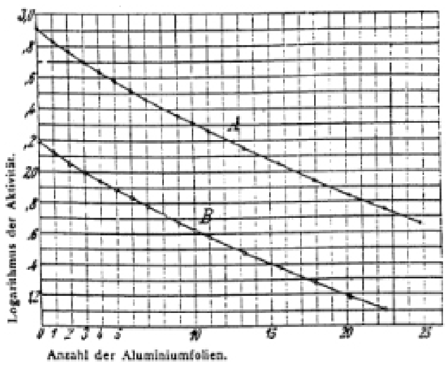

Figure 5 – The exponential absorption curve obtained by Hahn and Meitner for mesothorium. Source: [20].

They first examined the absorption of electrons emitted in the β decay of several complex substances, uranium + uranium X (^{234}Th), radiolead + radium E, radium E alone, and radium. They found that the absorption of these electrons did, in fact, follow an exponential law, confirming the results obtained by Schmidt (Figure 5).

The evidential situation changed dramatically with the work of William Wilson [22]. Wilson was investigating what was, in retrospect, a glaring omission in the existing experimental

[e] The decay products of various elements were sometimes named with a letter or with a numerical suffix, and were later shown to be isotopes of other elements. Thus, radium B was an isotope of lead, ^{214}Pb; radium C was bismuth, ^{214}Bi; and radium E was ^{210}Bi.

[f] Other substances might emit several groups of electrons.

program, the actual investigation of the velocity dependence of electron absorption. He noted that his "present work was undertaken with a view to establishing, if possible, the connection between the absorption and velocity of β rays. *So far no actual experiments have been performed on this subject ...*" (ref[22] p. 612, emphasis added). Wilson was right.

Wilson used momentum selected electrons from the β decay of radium bromide or radon to actually investigate the energy dependence of the absorption of β rays. His results are shown in Figure 6 and clearly demonstrate that the absorption is linear not exponential. He also performed a calculation that showed that if the electrons were inhomogeneous, lost energy in passing through matter, and that lower energy electrons were preferentially absorbed, that the absorption would be exponential (Figure 7). Wilson had provided an explanation for conflicting results with Schmidt, and with Meitner Hahn, and von Baeyer. The other experimental results were not incorrect, they had been misinterpreted.

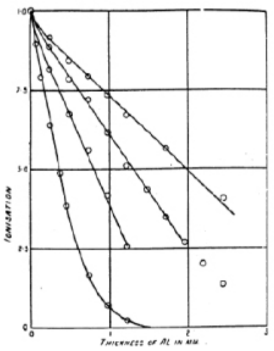

Figure 6 – The ionization, not its logarithm, as a function of absorber. It is a straight line, indicating a linear, not an exponential, absorption law. Source: [22].

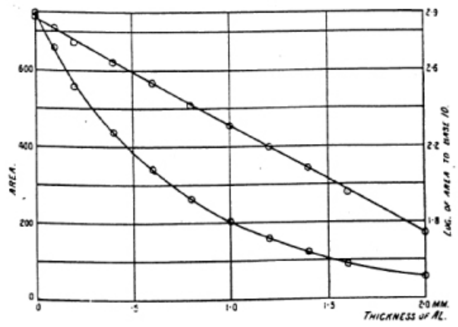

Figure 7 – Wilson's calculated absorption curve assuming an inhomogeneous energy spectrum for the emitted β rays. Source: [22].

Wilson wasn't satisfied with only a calculation to show that other experimenters had misinterpreted their results on electron absorption. In subsequent experimental work he showed experimentally that an inhomogeneous beam of electrons was absorbed exponentially [23]. He began with a monoenergetic beam of electrons and showed once again that it did not obey the exponential absorption law. He then modified that beam and made it heterogeneous by allowing it to pass through a thin sheet of platinum before striking an aluminum absorber. This resulted in an observed exponential absorption curve (Figure 8), similar to the one he had previously calculated.

Meitner, Hahn, and von Baeyer improved their experimental apparatus (Figure 9) and began to examine the energy spectrum in β decay. Electrons emitted from the radioactive source S were bent in a magnetic field, passed through a small slot F, and then struck a photographic plate P. Electrons of the same energy would follow the same path and produce a single line on the photographic plate. The results showed a line spectrum and seemed to support the view that there was one monoenergetic electron for each radioactive element. The best photograph obtained with a thorium source showed two strong lines, corresponding, the experimenters believed, to the β rays from the two radioactive substances present (Figure 10).

Subsequent work and further improvements in the experimental apparatuses showed numerous lines and cast serious doubt on the one element-one line hypothesis of Meitner and collaborators.

James Chadwick, who had worked with Rutherford in Manchester, had gone on to work with Hans Geiger in Berlin. In a letter to Rutherford he hinted at the solution. "We [Geiger and Chadwick] wanted to count the β-particles in the various spectrum lines of RaB + C and then to do the scattering of the strongest swift groups. I get photographs very quickly easily, but with the counter I can't even find the ghost of a line. There is probably a silly mistake somewhere

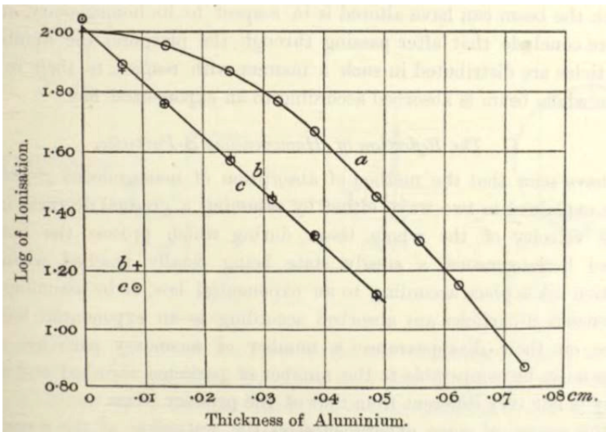

Figure 8 – Wilson's experimental graph showing the exponential absorption of a beam of inhomogeneous electrons. Curves b and c show the absorption of homogeneous electrons after they have passed through a platinum sheet rendering them inhomogeneous. Curve a shows the absorption of the homogenous electrons. The logarithm of the ionization is plotted. The exponential absorption is clearly shown for b and c. Source: [23].

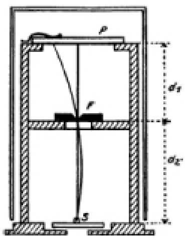

Figure 9 – The experimental apparatus used by Meitner, Hahn, and von Baeyer. The β rays emitted by the source S are bent by a magnetic field, pass through a slit at F and strike the photographic plate P. Source: [24].

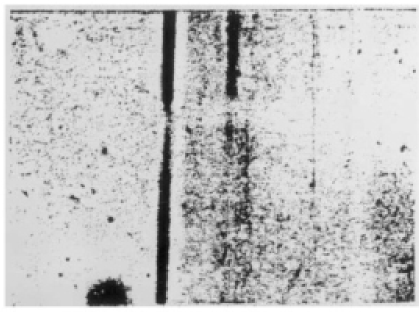

Figure 10 – The first line spectrum for β decay published by Meitner, Hahn, and von Baeyer. The two observed lines were thought to be produced by the two radioactive elements present in the source. Source: [20].

(J. Chadwick, letter to Rutherford, 14 June 1914, Cambridge University Library)." Using both Geiger's newly-invented counters and an ionization chamber they could not reproduce the line spectra found both by others and by themselves using photographic methods. Chadwick's results are shown in Figure 11 [25]. He had found four lines, identical to some found in previous spectral measurements, superposed on a larger continuous energy spectrum.

Despite the apparent decisiveness of Chadwick's experiment, not everyone within the physics community accepted the observed continuous energy spectrum as that of the primary decay electrons. In part, this was due to the fact that no other experimenter had replicated Chadwick's result, with either a radium source, the source that Chadwick had used, or with another radioactive element and, in part, because there was no theoretical explanation of the continuous spectrum. In 1922, Lise Meitner argued against the continuous spectrum on both experimental and theoretical grounds [26,27]. She noted the complex nature of the β-decay spectrum which, in her view, contained many lines, some of which were made diffuse by the fact that the electron emitted lost energy in scattering from atomic electrons. She argued that Chadwick's experimental apparatus did not have sufficient energy resolution to resolve these lines and that this accounted for his observed continuous spectrum. She also noted that Chadwick's result had not, as yet, been replicated.

Later that year, Chadwick and Ellis repeated Chadwick's original experiment and obtained the same result [28]. Meitner further argued that a quantized system such as an atomic nucleus

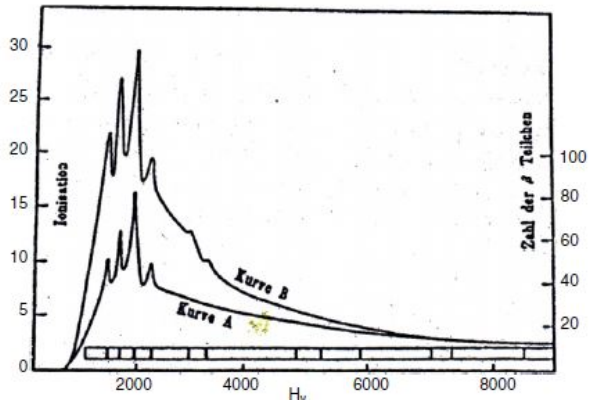

Figure 11 – Chadwick's results for the number of β rays as a function of energy. A few discrete lines are seen above a continuous energy spectrum. Source: [25].

was unlikely to emit such a continuous spectrum. She also suggested mechanisms for the energy loss by the initially monoenergetic electrons including: 1) Compton scattering, the production of recoil electrons of varying energy by the scattering of γ rays emitted by the nucleus from atomic electrons, 2) the emission of continuous γ rays by the electron as it passes through the intense electric fields of the atom after it is emitted by the nucleus, and 3) the scattering of the primary electrons from the planetary electrons of the atom.

Ellis and Wooster [29] presented both evidence and argument against these possibilities and rejected all three. Compton scattering was rejected because it would have resulted in an incorrect energy spectrum for radium B and also could not explain the spectrum of radium E, which did not emit any γ rays. The absence of γ rays in the decay of radium E also argued against the continuous emission of γ rays as an explanation of the continuous spectrum. The third explanation, electron scattering, was rejected because it would result in the emission of several electrons in the β decay of a single nucleus and experiment had already shown that only a single electron was emitted in each decay.

Having eliminated all of the plausible alternative explanations of the phenomenon, Ellis and Wooster concluded, "We are left with the conclusion that the disintegration electron is actually emitted from the nucleus with a varying velocity. We are not able to advance any hypothesis to account for this but we think it important to examine what this fact implies (p. 860)." They also noted that there was, in fact, a direct test of whether the primary electrons lost energy as they escaped from either the atom or from the entire source. "This is to find the heating effect of the β-rays from radium E. If the energy of every disintegration is the same then the heating effect should be between 0.8 and 1.0×10^6 volts per atom and the problem of the continuous spectrum becomes the problem of finding the missing energy. It is at least equally likely that the heating effect will be nearer 0.3×10^6 volts per atom, that is, will be just the mean kinetic energy of the disintegration electrons (p. 860)." They wrote that they were engaged in performing this experiment, but suggested that it would be some time before they had definitive results [g].

In 1927 Ellis and Wooster presented the definitive experimental result they had promised earlier [30]. It firmly established that the energy spectrum of electrons emitted in β decay was continuous. They did this by measuring the average energy of disintegration of electrons in the β decay of radium E, by measuring the heating effect produced by those electrons. If the energy spectrum really was continuous then the average energy obtained from the heating effect measurement would equal the average energy obtained by other methods, including ionization. If the energy spectrum was monoenergetic and the observed spectrum due to unknown energy

[g] One possible explanation, and one rejected by Ellis and Wooster was the possibility that energy was not conserved exactly in each β decay, but only conserved statistically in a number of such decays. They "*[thought] it best to disregard it entirely at present*" (p. 858, emphasis added).

losses, then the average heating energy measured should be at least as large as the maximum energy measured in the continuous spectrum. For radium E the average and maximum energies were 390,000 eV and 1,050,000 eV, respectively. Although Ellis and Wooster remarked that the measurement was quite difficult, they believed that they could easily measure such a large difference (Figure 12).

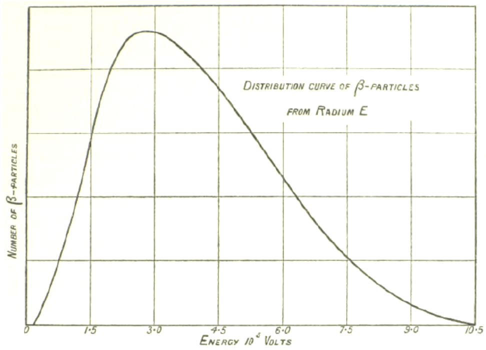

Figure 12 – The energy spectrum for electrons from Radium E. Radium E does not emit any γ rays. Source: Ellis and Wooster [30].

A serious difficulty of the experiment was that the decay of radium E produces polonium, which is also radioactive, emitting an α particle. Thus, the energy deposited in the calorimeter was the sum of the energies from the β decay of radium E plus that of the α-particle decay of polonium. Although this was clearly a serious background effect it also provided an important element of their calculation of the final result. The measured lifetimes of radium E and polonium were 5.1 days and 139 days, respectively. From those quantities and the measured energy of each α-particle decay, the average energy of each radium E decay could be calculated from the total heating effect.

The ratio of the amount of heat generated by the decay of Radium E to the amount of heat generated by the decay of polonium at time t is given by

$$e^{-\lambda Et}(\lambda E - \lambda P)/[X\lambda P[e^{-\lambda Pt} - e^{-\lambda Et}]] \tag{1}$$

where X is the ratio of the energy of a polonium decay to the average energy of a Radium E decay. From the known lifetimes of Radium E and polonium and the data shown in Figure 13, X could be calculated. Using the known energy of the α particle in the polonium decay, 5.3 MeV, (recall that the α particles all have the same energy), the average energy of Radium E could be calculated.

The final result obtained by Ellis and Wooster is shown in Figure 13. The two curves show the total heating effect as a function of time as well as that due to polonium decay. The difference between them was the energy released by the decay of radium E. The average heating energy found was $344,000 \pm 40,000$ eV, in good agreement with the average value of $390,000 \pm 60,000$ eV obtained by the ionization measurement, and in marked disagreement with the value of more than one million volts expected for the monoenergetic energy hypothesis.

Ellis and Wooster concluded that, "We may safely generalise this result obtained for radium E to all β-ray bodies, and the long controversy about the origin of the continuous spectrum of β-rays appears to be settled (p. 121)." Meitner and Orthmann [31] (1930) repeated the heating effect experiment with an improved apparatus and obtained an average energy per β particle of $337,000 \pm 20,000$ eV, in excellent agreement with that measured by Ellis and Wooster. Meitner wrote to Ellis, "We have verified your results completely. It seems to me now that there can be absolutely no doubt that you were completely correct in assuming that beta radiations are primarily inhomogeneous. But I do not understand this result at all (L. Meitner, letter to Ellis)."

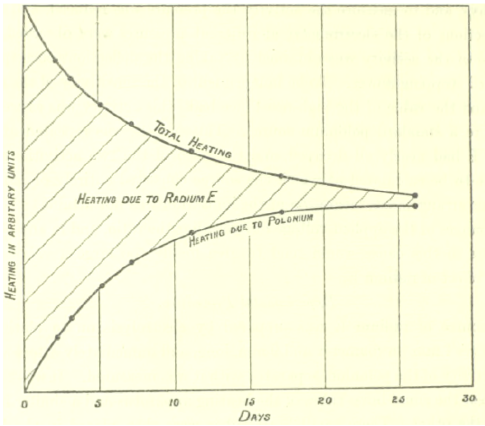

Figure 13 – The experimental result of Ellis and Wooster (1927). The decreasing total energy and the increasing energy due to the decay of polonium are shown.

4 Proposed Solutions

There were two proposed solutions to the problems posed by the continuous energy spectrum in β decay. The first was to give up the conservation of energy. That had been discussed earlier by several prominent physicists including Einstein and Bohr. Experimental work in the 1920s and 1930s argued convincingly against this view. (See ref [1], Chapter 2).

The second solution was offered by Wolfgang Pauli in 1930. He suggested that the atomic nucleus contained, in addition to protons and electrons, a light, electrically neutral, spin 1/2 particles, which he named neutrons [h].

Dear Radioactive ladies and gentleman,
I have come upon a desperate way out regarding the wrong statistics of the N-14 and Li-6 nuclei, as well as to the continuous β-spectrum, in order to save the "alternation law" of statistics and the energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin 1/2 *and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass.–The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant. (W. Pauli, letter to physicists at Tubingen, 14 December 1930, cited in ref* [11]*, p. 315).*

It was also believed, at the time, that the nucleus contained only protons and electrons. Thus the nitrogen nucleus would contain 14 protons and 7 electrons and have half-integral spin. The measured spin of the nitrogen nucleus was one. If the neutrino had spin 1/2 and was a constituent of the nucleus then the problems of nuclear statistics and spin were also solved. The nitrogen nucleus would contain fourteen protons, seven electrons, and seven neutrinos. The spins could then add up to one, and the nucleus would obey Bose statistics.

Pauli's neutrino did not, however, solve all of the problems of nuclear structure. The electron was still a constituent of the nucleus and that required a large, but still unobserved nuclear magnetic moment. There was also the question of nuclear stability. How did the nucleus remain stable when the repulsive force between the protons was larger than the attractive force between the electrons and protons? In addition, if the electron were confined within the very small nucleus the Heisenberg uncertainty principle required that it have such a large energy that it would escape from the nucleus. Chadwick's discovery of the neutron in 1932 and further work solved these problems.

[h] This led to some confusion with the heavier neutral particle found in 1932 by James Chadwick. Enrico Fermi resolved the difficulty later when he named Pauli's particles "neutrinos" or little neutral ones.

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