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Physics in Perspective

William Wilson and the Absorption of Beta Rays

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In the first decade of the 20th century, physicists believed that the β particles emitted in radioactive decay were monoenergetic and that such monoenergetic electrons would be absorbed exponentially in passing through matter. Conversely, they also believed that if electrons followed an exponential absorption law then they were monoenergetic. William Wilson showed conclusively that this view was wrong. After Wilson's work, physicists changed the experimental technique they used to investigate the phenomena. Instead of using absorption to measure the decay energy, they now used magnetic spectroscopy with various detectors as their standard method. Although Wilson's work changed the entire practice of the field and showed that the accepted view on electron absorption was wrong, references to it soon disappeared. Perhaps more surprisingly, after 1912 Wilson himself no longer published work on β particles and disappeared from the physics literature completely. The reasons for this also will be discussed.

Key words: William Wilson; beta decay; electron absorption.

In Hans Christian Anderson's fairy tale, "The Emperor's New Clothes," a child points out that the Emperor is not, in fact, wearing any clothes. William Wilson played a similar role in the early study of the absorption of the β rays (electrons) emitted by radioactive nuclei by demonstrating that the view accepted by the physics community was, in fact, wrong. In the first decade of the 20th century, physicists believed that the β particles emitted in radioactive decay were monoenergetic and that such monoenergetic electrons would be absorbed exponentially in passing through matter. Conversely, they also believed that if electrons followed an exponential absorption law then they were monoenergetic. As discussed below, there was evidence supporting that view. Wilson, however, with some supporting evidence from other experimentalists, showed conclusively that this view was wrong. Within a very short period of time, the physics community accepted his results. He also showed that the previous experimental results, on which the view of exponential absorption had been based were, in fact, correct. They had been misinterpreted.

Following Wilson's work, experimenters no longer believed that the exponential absorption of β rays showed that they were monoenergetic, although they still

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accepted the view that they were monoenergetic.[1]* They also changed the experimental technique they used to investigate the phenomena. Instead of using absorption to measure the decay energy, they used magnetic spectroscopy with various detectors as their method. Although Wilson's work changed the entire practice of the field and had shown that the accepted view on electron absorption was wrong, references to it soon disappeared. Perhaps more surprisingly, after 1912 Wilson himself no longer published work on β particles and disappeared from the physics literature completely. The reasons for this will be discussed below.

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

In 1896 Henri Becquerel discovered that uranium emitted radiation that exposed a photographic plate.[2] The first step in deciphering the nature of this radiation, called Becquerel rays, was taken by Ernest Rutherford in 1899. Rutherford measured the intensity of the radiation as a function of the thickness of aluminum foils placed

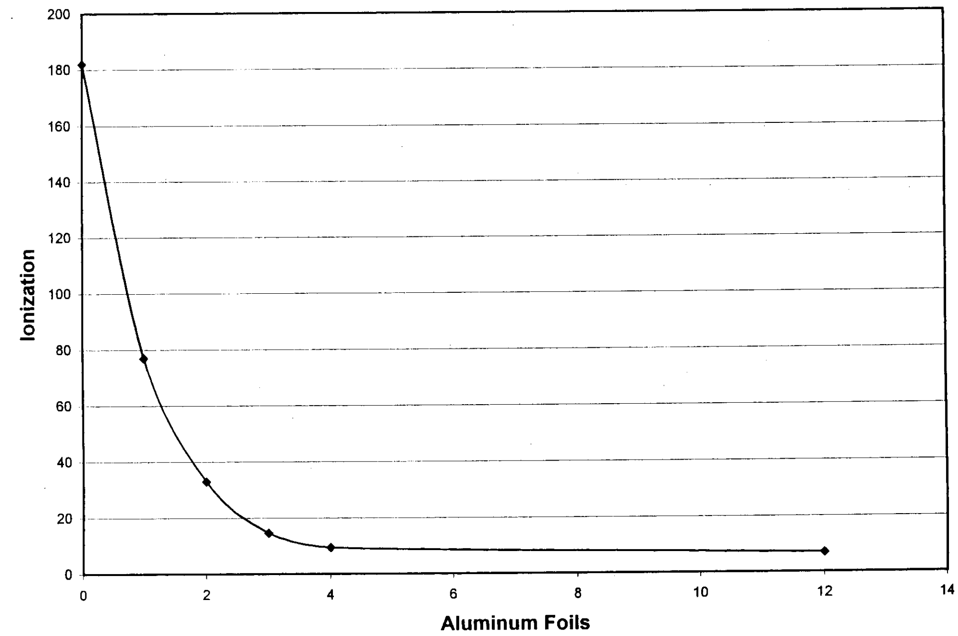

Fig. 1. The ionization produced by the radiation emitted from a uranium source as a function of the number of aluminum foils used as an absorber. The rapid decrease is due to the absorption of α particles. The remaining β rays are only slightly reduced by the addition of each foil. Source: Author's plot of data in Rutherford, "Uranium Radiation" (ref. 3), p. 115.

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* The history of this episode is more complex. For a time it appeared that the energy spectrum of electrons from β decay was a line spectrum, with groups of electrons each having the same discrete energy. It was established ultimately that the energy spectrum was continuous, leading to Wolfgang Pauli's suggestion of the neutrino.

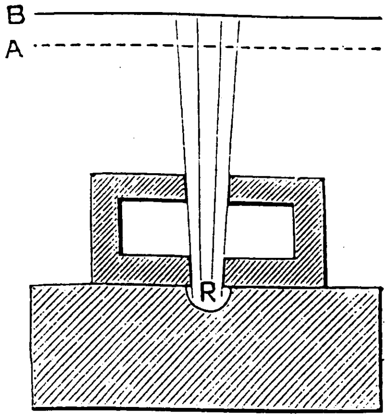

Fig. 2. Bragg's apparatus for measuring the range of α particles. The radiation emitted from R is collimated into a thin beam by the lead stops. The ionization chamber AB can be moved relative to the radioactive source. Source: Bragg, "On the Absorption of Alpha Rays and on the Classification of Alpha Rays from Radium" (ref. 7), p. 722.

over a uranium source. 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 (figure 1). "It will be observed that for the first three layers of aluminum foil, the intensity of the radiation falls off 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."[3] 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 very 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."[4] The first four foils each reduced considerably, and finally eliminated entirely, the α radiation. The remaining β radiation then was reduced only slightly by each of the following foils. It was believed initially 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.[5] 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.[6]*

In 1904 William Bragg argued that α particles of equal initial energy or velocity had equal ranges in matter, an important point for later work. Their range depended both on their initial energy and on the material through which they

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* Subsequent work by Rutherford and others showed that the α particles were helium ions. Rutherford later used the scattering of these high-energy α particles from gold and other foils to argue for the nuclear model of the atom – a very small, heavy, positively charged nucleus surrounded by negatively charged electrons, a miniature solar system. After the discovery of this nuclear, or Rutherford model of the atom, the α particles were considered to be helium nuclei. The γ rays were found to be high-energy electromagnetic radiation.

passed. Bragg assumed that the α particles lost energy only by ionization, by knocking electrons out of the atoms in the material. The ionization was thought to be independent of the velocity of the α particles, so that the ionization produced, or the energy lost by the α particle, in each equal length of its path would be constant. For β particles, Bragg assumed that they lost energy not only by ionization, but also by collisions in which they were deflected and eliminated from the beam.

Bragg's experimental apparatus is shown in figure 2. The radiation emitted from the radium source at R was collimated into a pencil-like beam by the lead stops. The ionization produced in the ionization chamber AB was measured. 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

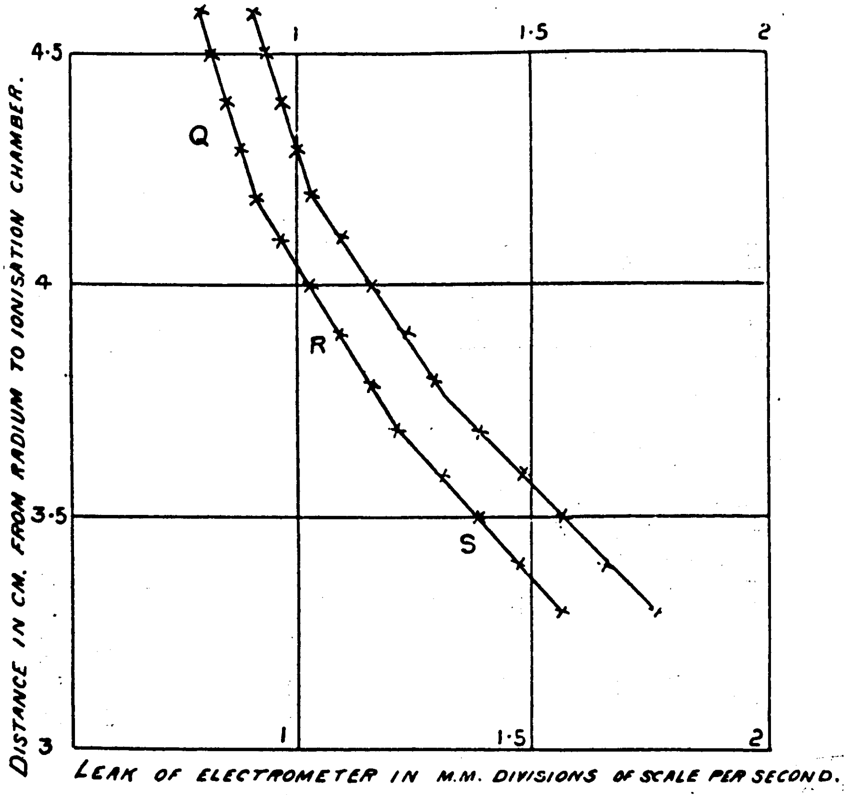

Fig. 3. The ionization produced in the chamber as a function of the distance from the radioactive source R. There are several changes in the slope of the curve, indicating the presence of several α particles, each with its own energy. Source: Bragg and Kleeman, "On the Ionization Curves of Radium" (ref. 7), p. 736.

> diminishes [or decrease as the distance increases].* When the α rays can just penetrate, there should be a somewhat sudden appearance 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 ... .*
>
> For all this there is a ready explanation. The atom passes through several changes, and it is supposed that at four of these an α atom is expelled. Probably the α particles due to one change are all projected with the same speed.[7]

In a paper a year later, Bragg summarized his results:

> In previous papers ... we have shown that the α particle moves always in a rectilinear course, spending its energy as it traverses atoms of matter, until its velocity becomes so small that it cannot ionize and there is in consequence no further evidence of its motion. 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. Moreover, the α particles of radium which is in radioactive equilibrium can be divided into four groups, each group being produced by one of the four radioactive changes in which α particles are emitted. All the particles of any one group have the same range and the same initial velocity.[8]

Bragg not only had shown that α particles were emitted with the same energy in each particular radioactive decay, but that they also had a constant range in matter.**

The careful reader will note that Bragg's discussion implies that α particles in fact should have a longer range than β particles of the same energy, because α particles lose energy by only one process, ionization, whereas β rays lose energy by both ionization and collisions. Yet Rutherford had shown that the α particles had a much shorter range. The answer is that the β particles are emitted with much higher velocities than that of the α particles and lose less energy by ionization because of their higher velocity. (The β particle, or electron in fact, does not have a well-defined range in matter because it loses energy by ionization, by collisions, and by a third process, the emission of radiation.)

What were the β rays? As early as 1899 three different experiments, those of Becquerel, of Friedrich Giesel, and of Stefan Meyer and Egon von Schweidler, as well as one performed by Pierre and Marie Curie in 1900, had found that β rays

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* As the distance between the source and detector decreases, the solid angle subtended by the detector increases, increasing the ionization, or the number of particles detected.

** Bragg had found, in addition, a radioactive decay series. In radioactive decay, an atom of one element can emit either an α or β ray and transform into an atom of a different element. (The emission of a γ ray leaves the element unchanged.) The daughter atom produced can itself be radioactive. The sequence of decays will continue until a stable atom is produced. Thus, if we start with radium we will end up with lead, after a series of radioactive decays. Bragg, based on the work of Rutherford and Frederick Soddy, had searched for such an effect.

have 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."[9] Other experiments at the 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.[10,11]*

The Exponential Absorption of β Rays

Kaufmann's experiments demonstrated that radium emitted electrons with a wide range of velocities. A similar result also was found by Stefan Meyer and Egon von Schweidler in 1899[12] and by Becquerel in 1900. Becquerel, as had Meyer and von Schweidler, deflected the β rays in a magnetic field. In such a field the electron, a charged particle, will move in a circular orbit whose radius is proportional to its momentum, or velocity. Lower-velocity electrons will experience a larger deflection and a smaller radius of curvature. The orbit of higher velocity electrons will have a larger radius of curvature. Becquerel found that the electrons from radium traveled in orbits with a range of radii. In other words, they were emitted with a wide range of velocities. In addition, Becquerel found that when various absorbers were placed above the photographic plate electrons with lower velocity, or energy, were more readily absorbed than the higher velocity electrons.

Despite the evidence provided by both Kaufmann, by Meyer and von Schweidler, and by Becquerel, the physics community did not accept, at this time (the first decade of the twentieth century), that the energy spectrum of electrons emitted in β decay was continuous.[13] There were plausible reasons for this. Physicists argued that the sources used by both Kaufmann and Becquerel were not pure β-ray

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* The caveat about small velocities in Kaufmann's claim concerning m/e was important. He had found that radium emits electrons with a wide range of velocities, up to almost the speed of light. He had used those high-speed electrons to investigate the variation of electron mass with velocity. This was an important question at the time. In the early 20th century, several theoretical physicists, including Max Abraham and Alfred Bucherer, had attempted to explain the origin of the mass of the electron and derived an expression for the variation of the electron's mass with its velocity. Hendrick Lorentz and Albert Einstein, using the principle of relativity on which Einstein's special theory of relativity was based, also had calculated such an effect. The three expressions differed. Kaufmann's results seemed to favor the theories of Abraham and Bucherer, and disagreed with that of Lorentz and Einstein. Kaufmann's results, in fact, were so credible that in 1906 Lorentz wrote, in a letter to Henri Poincaré, that, "Unfortunately my hypothesis of the flattening of electrons is in contradiction with Kaufmann's results, and I must abandon it. I am, therefore, at the end of my Latin (ref. 10)." Einstein agreed, but was more sanguine. "With admirable care Mr. Kaufmann has ascertained the relation between A_m and A_e [the variation of electron mass with velocity], for β rays emitted from a radium bromide source … . The theories of the electron's motion of Abraham and Bucherer [agree better with Kaufmann's data] than the relativity theory. In my opinion both theories have a rather small probability … ." Other physicists urged caution and suggested that Kaufmann's analysis of his data might be incorrect and that there might be unknown sources of uncertainty in his experiment. This turned out to be correct. Later experimental work, particularly that of Adolf Bestelmeyer and of Bucherer, not only supported the Einstein-Lorentz theory, but also pointed to difficulties in Kaufmann's experiment. The evidence supported the special theory of relativity.

sources, but contained several elements, each of which could emit electrons with different energies. In addition, even if the electrons were initially 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 also would be emitted with a unique energy. Physicists also knew that electrons did not have a unique range in matter. In discussing the behavior of a beam of electrons in air, William H. Bragg noted that such a beam would become diffuse because of the scattering of the electrons and that the electrons would lose energy owing to ionization.

> If such a jet of electrons be projected into the air, some will go far without serious encounter with the electrons of air molecules; some will be deflected at an early date from their original directions. The general effect will be that of a stream whose borders become ill-defined, which weakens as it goes, and is surrounded by a haze of scattered electrons. At a certain distance from the source all definition is gone, and the force of the stream is spent. There is a second cause of the gradual "absorption" of a stream of β rays. Occasionally an electron in passing through an atom goes so near to one of the electrons of the atom as to tear it from its place, and so to cause ionization. In doing so, it expends some of its energy.[14]

The difference between the behavior of the α and β particles was due to the difference in their interactions with matter. Alpha particles lose energy almost solely by ionization, whereas electrons lose energy by several processes including both ionization and scattering, and by other processes unknown to physicists in the early twentieth century. 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 an exponential absorption law would follow. As William H. 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."[15]

Early experimental work on electron absorption gave support to such an exponential law and therefore to the homogeneous (monoenergetic) nature of β rays, particularly the work in 1906–1907 of Heinrich Schmidt.[16] Schmidt fitted his absorption data 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.* That the logarithm of the ionization, a measure of

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* 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.

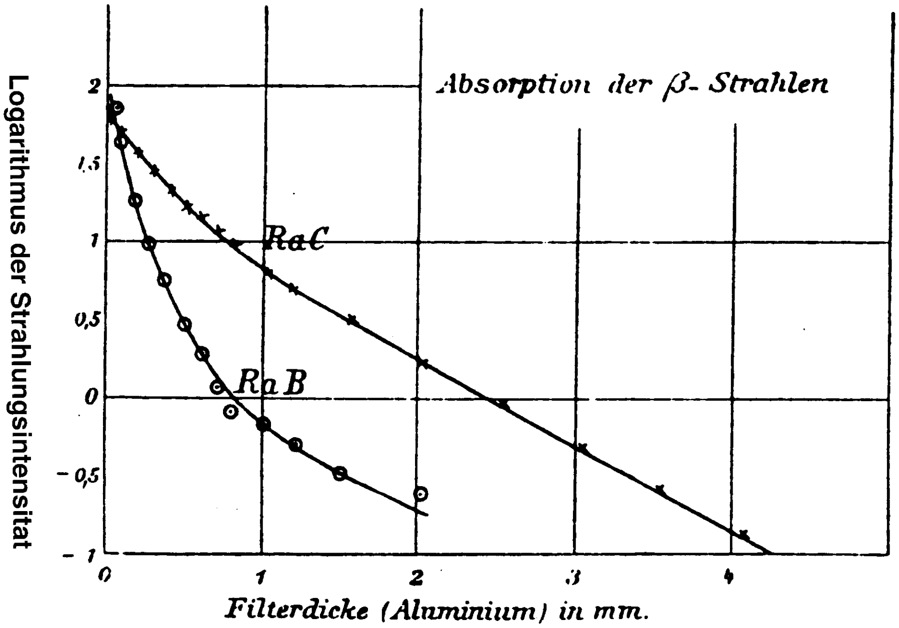

Fig. 4. Schmidt's result on the absorption of β rays. The logarithm of the electron intensity (ionization) is plotted as a function of absorber thickness. Each of the curves is a reasonable fit to two straight lines, indicating to Schmidt both exponential absorption and the presence of two groups of monoenergetic electrons for each substance. Source: Schmidt, "Uber die Absorption der β-Strahlen des Radiums" (ref. 16, 1906), p. 765.

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 unique energy and absorption rate.* "We have seen that the β-rays from radium are absorbed according to a pure exponential law within certain filter thicknesses. Should this not be taken to mean that there exists a certain group [of rays] with a constant absorption coefficient among the totality of β-radiations? Indeed, could we not go one step further and interpret the total action of β-rays in terms of a few β-ray groups [each] with a constant absorption coefficient?"[17] 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, then they were monoenergetic. As Ernest Rutherford remarked, "Since Lenard had shown that cathode rays ... are absorbed according to an exponential law, it was natural at first to assume that the exponential law was an indication that the β rays were *homogeneous*, *i.e.* consisted of β particles

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* Other substances might emit several groups of electrons.

projected with the same speed. On this view, the β particles emitted from uranium which gave a nearly exponential law of absorption, were supposed to be homogeneous. On the other hand, the β rays from radium which did not give an exponential law of absorption were known from other evidence to be heterogeneous."[18]

This association of homogenous electrons with an exponential absorption law informed early work on the energy spectrum in β decay. This was the situation in 1907 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.[19] 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, in fact, did follow an exponential law, confirming the results obtained by Schmidt (figure 5). They formulated the simple and attractive hypothesis that each pure element emitted a single group of monoenergetic β rays. With the complex sources they used, consisting of several elements, the absorption curves consisted of several superposed exponentials. The only exception seemed to be mesothorium-2. As Otto Hahn later remarked, "but we felt so certain about the uniformity of beta rays from uniform elements that we explained the noncompliance of mesothorium-2 by a still not understood complexity in the nature of mesothorium-2."[20]

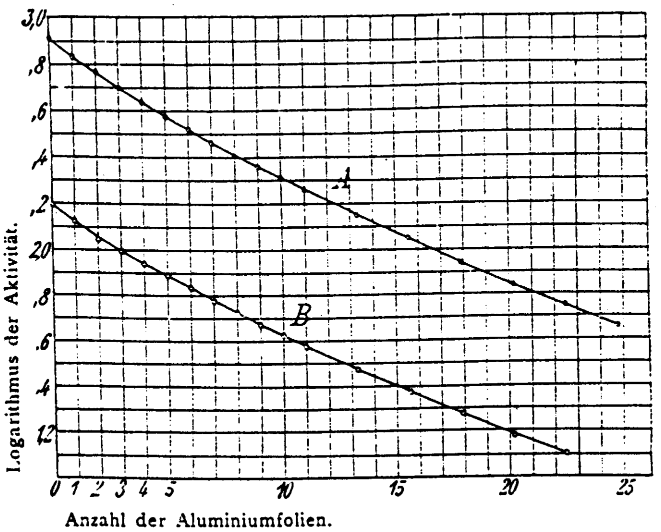

Fig. 5. The β-ray absorption curve obtained by Hahn and Meitner for mesothorium. The curves are a reasonable fit to straight lines. Source: Hahn and Meitner, "Uber die Absorption der β-Strahlen einiger Radioelemente" (ref. 19, 1908), p. 323.

Fig. 6. William Wilson (1887–1948). Courtesy of Professor Robin Marshall, Department of Physics and Astronomy, University of Manchester.

The Experiments of William Wilson

The evidential situation changed dramatically with the work of William Wilson (figure 6). Wilson investigated what was, in retrospect, a glaring omission in the existing experimental program, the actual investigation of the velocity dependence of electron absorption.[21] 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* … ."[22] Wilson was right. Although Schmidt's experiments had provided some information on the subject, there had been no real investigation of the issue. Wilson commented that, "It has generally been assumed that a beam of homogeneous rays is absorbed according to an exponential law, and the fact that this law holds for the rays from uranium X, actinium, and radium E has been taken as a criterion of their homogeneity."[23] Wilson questioned that assumption. "The assumption is open to many objections, for the exponential law may be due to rays of different types being mixed in certain proportions. If the distribution of the rays and their velocity do not change in passing through matter, and if the absorption of the particles is proportional to the number present, we should expect an exponential law of absorption [as previous experimenters had assumed], *but if their speed diminishes*, the absorption should be greater the greater the thickness of matter traversed.''[24]

Wilson's paper is a splendid example of how experimental work should be done and reported. Wilson included not only detailed arguments for the credibility of his result, but also gave careful consideration of backgrounds that might mask or mimic the effect he wished to measure and how he dealt with them. He also included an explanation of why his results differed from those obtained previously by other experimenters.

Wilson used radium as the source of his electrons. As he noted, Kaufmann had shown that radium emitted electrons with a wide range of velocities. Wilson thus selected electrons within a narrow band of velocities, an almost monoenergetic beam, and investigated their absorption. He stated his remarkable conclusion at the beginning of his paper: ''Without entering at present into further details, it can be stated that the ionisation [the electron intensity] did not vary exponentially with the thickness of matter traversed. But, except for a small portion at the end of the curve, followed approximately a linear law.''[25] This result contradicted those of Schmidt and of Meitner, Hahn, and von Baeyer.

The two different versions of Wilson's experimental apparatus are shown in figure 7. In the apparatus on the left a radium bromide source was placed at C. The collimated β rays from the decay of radium were bent in a circular path by a magnetic field perpendicular to the plane of the paper, passed first through slits MM and F, then passed through an absorber, and were detected by the ionization produced in electroscope E. The radius of the circular path is proportional to the velocity of the electrons, so that by selecting only electrons with certain path radii, Wilson was selecting electrons within a certain velocity (or energy) range, whose width was approximately 10%. Varying the strength of the magnetic field changed the velocity of the selected electrons so that the absorption of the electrons as a function of velocity could be measured. Wilson found that most of the electrons emitted were absorbed before leaving the radium bromide source, so in later experiments he substituted a thin-walled glass bulb containing radium emanation (radon), a radioactive gas emitted by radium, for the original radium bromide source to increase the signal.

There were important sources of background, however, that limited the accuracy of the measurement. Wilson devoted considerable care and effort to both reducing this background and, in cases where it could not be eliminated, to measuring the size of the background signal so that it could be subtracted from the total signal to obtain a correct measurement. A major source of such background were the γ rays that also were emitted by the radioactive source, which produced ionization in the electroscope that mimicked the ionization produced by the decay electrons. This background effect was typically about 60% of the entire ionization produced, and for large absorber thicknesses, when the number of decay electrons remaining was greatly reduced, accounted for almost all of the ionization produced. If the background could not be eliminated, or greatly reduced, then the experiment would be impossible. Wilson replaced the radium bromide source with one consisting of radium emanation (radon) and reduced the γ-ray background to no more than 20% of the total signal. He also measured the ionization produced by the γ rays by

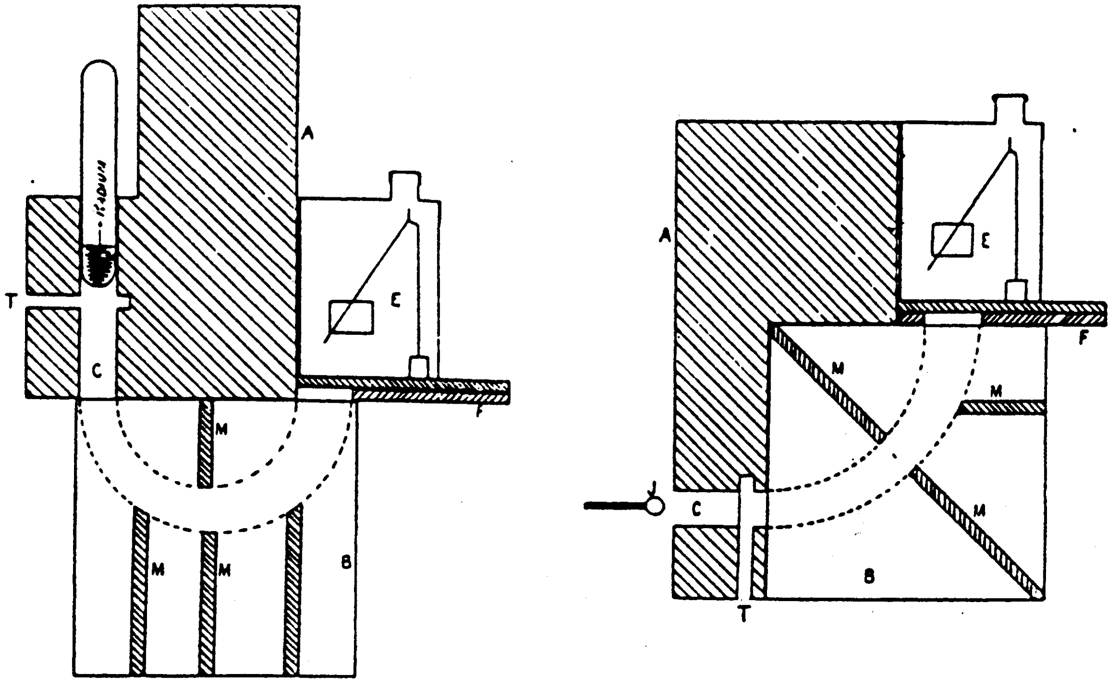

Fig. 7. W. Wilson's experimental apparatuses for measuring the absorption of β rays. Electrons from the radioactive sources pass through slit C, are bent by a magnetic field perpendicular to the plane of the paper, and pass through the slits in plates MM and F. This defines a range of radii of curvature and thus, a range in momentum or velocity. Varying amounts of absorber were placed above slit F and the β rays were detected by the electroscope. Source: Wilson, "On the Absorption of Homogeneous β-Rays by Matter, and on the Variation of the Absorption of the Rays with Velocity" (ref. 21), p. 613.

inserting a lead plate at slot T. The plate was thick enough to eliminate all of the decay electrons, but left the γ-ray background essentially unchanged. The remaining ionization measured by the electroscope then was entirely due to the γ-ray background, which was measured and subtracted from the total signal for each setting. Background from electrons scattering from other parts of the apparatus was greatly reduced by the lead screens (M and MM in figure 7).

Wilson's results are shown in figure 8. The upper graph shows the ionization (*not its logarithm*) for various velocities as a function of absorber thickness. It is clearly linear, and not exponential. This is made clear in the lower graph in which the logarithm of the ionization is plotted against absorber thickness. As we have seen earlier in the results obtained by Schmidt, if the law of absorption were exponential then this graph would be a straight line. It isn't.

Wilson recognized that his result, which disagreed with all of those obtained previously, needed to be argued for carefully.* He did so. "Experiments were then performed to determine whether the effect observed is really a property of the rays or due to the experimental conditions."[26] Wilson identified three possible influences that might affect the absorption curves and give an incorrect result: (1) the lack of saturation in the ionization current, (2) the shape and size of the electroscope opening, and (3) the proximity of the magnetic field to the electroscope, which might cause irregularities in its operation. Wilson compared the time it took for the gold leaf of the electroscope to travel very different parts of the scale for various values of the ionization. If the ionization was saturated, then the ratio of the times should be constant when the ionization level was varied, and it was. This was further checked by measuring the absorption curves obtained with two sources of very different strengths. They were identical, further indicating that saturation was not a problem.

Wilson also checked that his electroscope gave the same absorption curve for actinium as that obtained in previous measurements. This is an example of calibration, in which the experimenter checks that his apparatus can reproduce previously obtained results. If it does, then we legitimately have confidence in its measurements.** Wilson further checked for possible magnetic-field effects by measuring that same absorption curve with the magnetic field both on and off. No difference was observed, indicating that the magnetic field did not affect the operation of the electroscope, or his result.

Wilson's results were internally consistent. He obtained the same result with both versions of his experimental apparatus, even though the magnetic field required to deflect the electrons into the electroscope was far larger in the first than in the second. This is an example of independent confirmation. If two different experiments give the same result, then we legitimately have more confidence in that result than if we merely repeated one measurement twice with the same apparatus.***

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* Frederick Soddy, one of the leading scientists in the field, later referred to Wilson's work as "revolutionary."

** If our new optical spectrometer correctly reproduces the known Balmer series of light emitted by hydrogen, then we trust other measurements made with it.

*** If we want to know the correct time, then it is better if we compare watches than if we look at one watch twice.

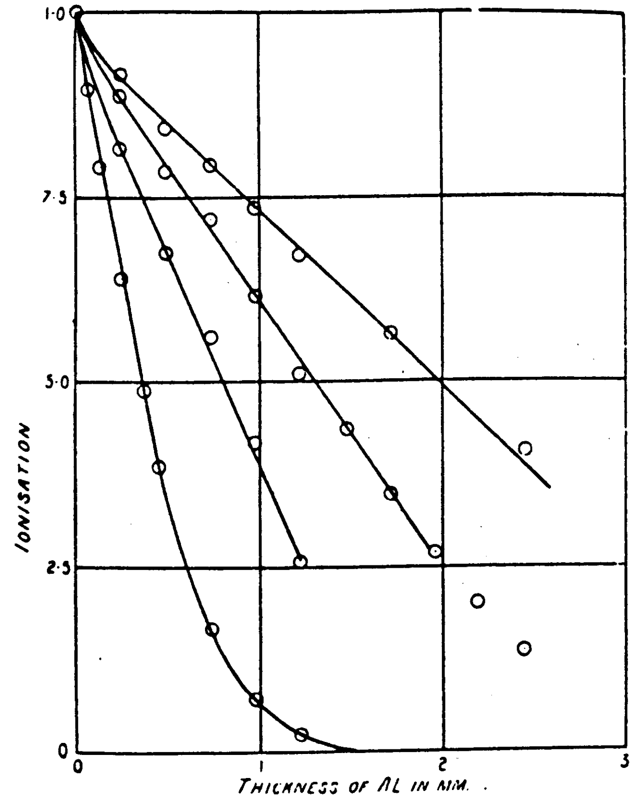

FIG. 3.

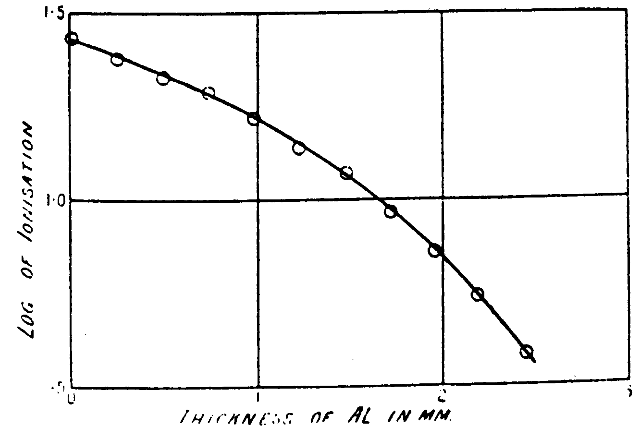

Fig. 8. Wilson's β-ray absorption curves. In the upper curve (Fig. 3) the ionization produced (or electron intensity), not its logarithm, is plotted as a function of absorber thickness for different velocities. The curves are quite reasonable fits to straight lines, except perhaps near their ends, indicating a linear, rather than an exponential, absorption law. The lower curve shows the logarithm of the intensity as a function of absorber thickness. It is not a straight line as would be expected for exponential absorption. Source: Wilson, "On the Absorption of Homogeneous β-Rays by Matter, and on the Variation of the Absorption of the Rays with Velocity" (ref. 21), p. 616.

Wilson's results were credible. He had either reduced the background effects or measured them so that they could be subtracted. He had also shown that none of the effects that might have made his results incorrect or inaccurate were present. He also had calibrated his apparatus and obtained independent confirmation of his result using two different experimental apparatuses. He had eliminated plausible alternative explanations of his result, and was left with the conclusion that it was correct.[27]* This is an example of what we might call the Sherlock Holmes strategy. As Holmes remarked to Watson in *The Sign of Four*, "How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth."[28]

How could capable physicists like Wilson, Schmidt, and the trio consisting of Hahn, Meitner, and von Baeyer reach such different conclusions about electron absorption? Wilson had shown that the absorption of monoenergetic electrons was approximately linear, whereas the others had found that electron absorption followed an exponential law. The simple explanation, available in retrospect, is that Wilson actually had measured the absorption of monoenergetic electrons with various different velocities, whereas the others had assumed that they were measuring the absorption of monoenergetic electrons when, in fact, they were measuring the absorption of electrons with a continuous energy spectrum. What makes Wilson's paper so fascinating is that he provided an explanation, at the time, for these conflicting results. The other experimental results were not incorrect, they had been misinterpreted.

Wilson devoted a section of his paper to an "Explanation of the Exponential Law found by various Observers for the Absorption of Rays from Radio-Active Substances." He began by stating that, "Before entering into a discussion as to the meaning of the absorption curves obtained, it is preferable to try to explain why various observers have found that the rays from uranium X, radium E, and actinium are absorbed according to an exponential law with the thickness of matter traversed. The fact that homogeneous rays are not absorbed according to an exponential law suggests that *the rays from these substances are heterogeneous*."[29]

Wilson then provided an explanation. He began with some data from Schmidt's work that showed the ionization produced as a function of the velocity of the emitted rays. Schmidt had found a range of such velocities, but had not interpreted that result as indicating that the primary electrons were heterogeneous. He, and others, believed that they were emitted with a unique energy, but that they then lost energy by some unknown process. Wilson showed that the ionization curve produced varied with the amount of matter through which the electrons had passed (figure 9).** The figure shows the electron intensity as a function of momentum. Curves *a*, *b*, and *c* were obtained with thicknesses of aluminum of 0, 0.489, and 1.219 mm, respectively. Not only was the total ionization reduced, but the lower-velocity electrons were completely absorbed when the absorber thickness was in-

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* For a more detailed discussion of the epistemology of experiment see Franklin and Howson (ref. 24).

** Wilson's curve was obtained with a radium source, whereas Schmidt had used uranium. Wilson also showed similar results for uranium.

creased. He calculated this effect for various absorber thicknesses and found that the total ionization produced by such heterogeneous electrons as a function of that thickness indeed did follow an exponential law (figure 10). He concluded that, "It is thus clear that the exponential curve for the absorption of rays is not, as has been widely assumed, a test of their homogeneity, but that in order that the exponential law of absorption should hold, we require a mixture of rays of different types."[30]

There was, however, existing evidence that disagreed with Wilson's result that the velocity of electrons diminished as they passed through matter. Schmidt had used the apparatus shown in figure 11 to investigate the constancy of the β-particle velocity.[31] The β rays from a radium E source at A were bent by a magnetic field perpendicular to the plane of the paper so that they passed through a semicircular canal ABC and then passed into an ionization chamber. Schmidt adjusted the field strength to a value H_0, which resulted in the maximum ionization, or the maximum number of β rays. He then placed aluminum foils between the radioactive source and the canal entrance. The β rays passed through the absorber. Once again he adjusted the field strength to obtain the maximum number of β particles. If the

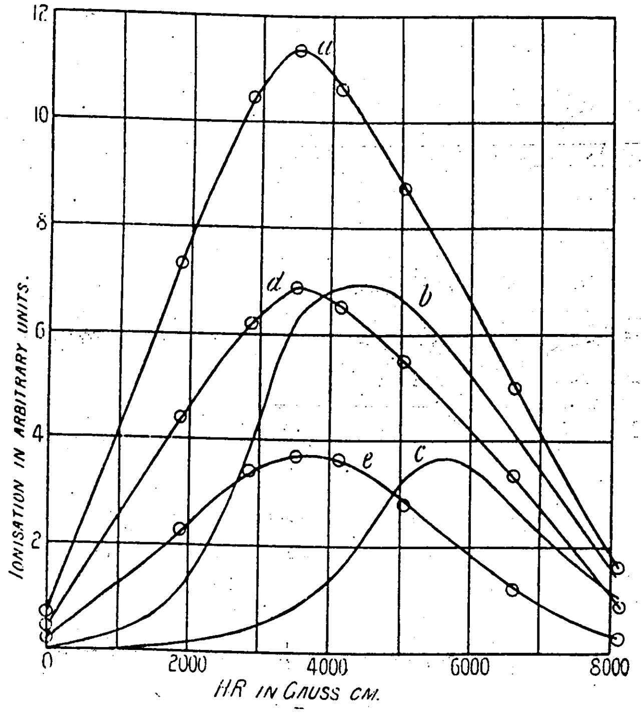

Fig. 9. Ionization as a function of momentum for different thicknesses of absorber. Curves *a*, *b*, and *c* are for aluminum absorbers of thickness 0, 0.489, and 1.219 mm, respectively, placed just under the electroscope in figure 7. Curves *d* and *e* are for thicknesses of 0.489 and 1.219 mm placed at J (figure 7, left side) just before entering the magnetic field. If the β rays lose velocity in passing through matter, then curves *d* and *e* should be shifted to the left. They are. Source: Wilson, "On the Absorption of Homogeneous β-Rays by Matter, and on the Variation of the Absorption of the Rays with Velocity" (ref. 21), p. 626.

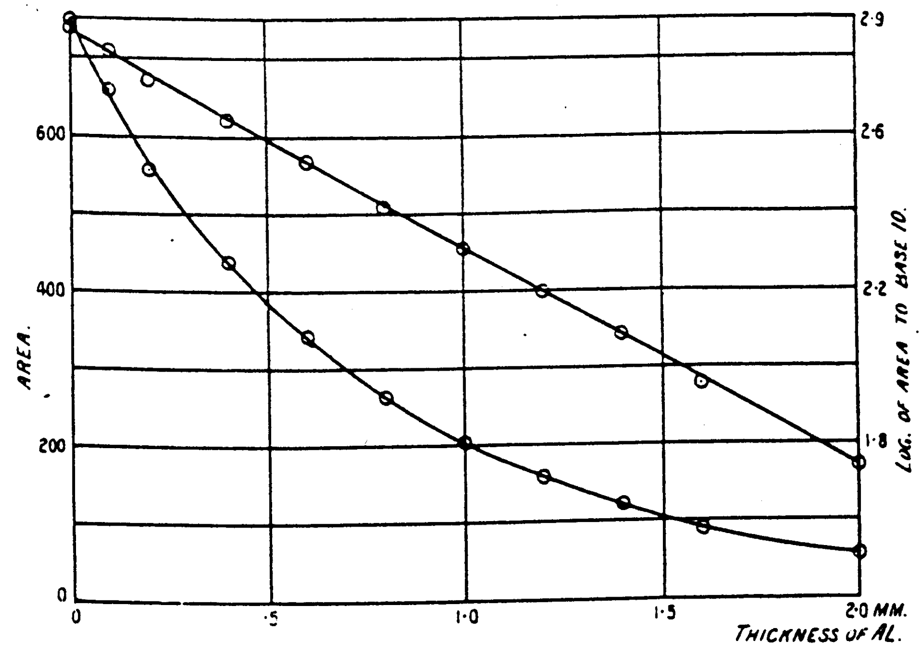

Fig. 10. Wilson's calculated absorption curves assuming an inhomogeneous energy spectrum for the emitted β rays. Wilson calculated values of the intensity as a function of absorber thickness using an initially inhomogeneous beam of electrons. The upper curve plots the intensity, whereas the lower curve is the logarithm of the intensity. The absorption is predicted to be linear, not exponential. Source: Wilson, "On the Absorption of Homogeneous β-Rays by Matter, and on the Variation of the Absorption of the Rays with Velocity" (ref. 21), p. 623.

velocity had not changed in passing through the absorber, then that value would be H_o. It was. This certainly cast doubt on Wilson's result that the β particles lost energy in passing through matter, a result he needed to show why others had found an exponential absorption law.

Wilson showed that although Schmidt's experimental result was correct, his interpretation of that result was incorrect. Wilson measured the absorption of β rays as a function of momentum for various absorber thicknesses. The measurements were made under two different sets of conditions. For curves *a*, *b*, and *c* in figure 10 the absorber (thickness 0, 0.489 mm, and 1.219 mm, respectively) was placed just under the electroscope (see figure 8). For curves *d* and *e* (0.489 mm and 1.219 mm) the absorber was placed at J, before the electrons entered the magnetic field. If electrons do not change velocity in passing through matter, curves *d* and *e* should be identical to curves *b* and *c*. They clearly are not and the fact that the curves are shifted to the left demonstrates that electrons lose velocity (energy) in passing through matter.

In Wilson's own words:

> In fig. [9], curve *a*, is shown the connection between ionisation and the electroscope and the strength of [magnetic] field when a certain preparation of radium is used as a source of radiation. As in the case of uranium rays we can determine the shape of this curve after the rays have passed through various thicknesses of matter. Curves shown at *b* and *c* for the rays after passing through 0.489 and 1.219 mm. of aluminum were obtained experimentally by varying the field while sheets of aluminum were placed under the electroscope. The rays from the radium were then allowed to pass through screens of these thicknesses placed at J (fig. [7, right side]) *before entering the field.*
>
> If the particles do not decrease in velocity in passing through matter the curves obtained in this case connecting ionisation with strength of magnetic field should fall on *b* and *c*. If the velocity decreases, however, they should fall to the left of these. This was found to be the case, the curves being shown in the figure at *d* and *e*, and the particles therefore decrease in velocity as they pass through matter.[32]

Once again Wilson provided an explanation of an incorrect interpretation of an experimental result.

> This experiment also explains why the experiments of Schmidt apparently show no change in the velocity of the rays. According to the views expressed in this paper he was dealing with heterogeneous rays and the position of the maximum should therefore move to the higher fields if the velocity of the rays does not change. The actual decrease in velocity, however, brings the maximum point back to practically the same position as before.[33]

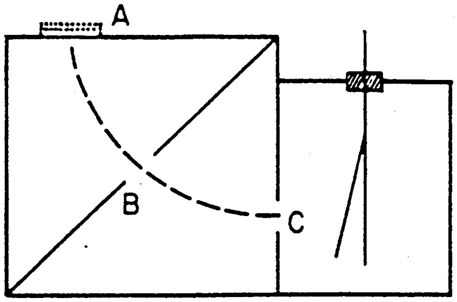

Fig. 11. Schmidt's apparatus for demonstrating that β rays do not change velocity in passing through matter. The β rays were deflected by a magnetic field perpendicular to the plane of the paper so that they passed through the semicircular canal ABC. Schmidt measured the magnetic field that provided the maximum intensity with and without an absorber placed over the radioactive source at A. If the velocity does not change, the value of the magnetic field will be unchanged. It was. Source: Heilbron, "The Scattering of α and β Particles and Rutherford's Atom" (ref. 77), p. 268.

The Immediate Reaction of the Physics Community

Wilsons' negative result on the exponential absorption of β rays received support from further work by Schmidt.[34] Schmidt inferred from his data that electrons did change their velocity in passing through matter, confirming one of Wilson's assumptions, and also found that the electrons were not always absorbed exponentially. He did not mention or cite Wilson's results, however. This was not the case in the adjacent paper by Hahn and Meitner.[35] Hahn and Meitner argued that Wilson's results showed rather that the β-decay electrons were monoenergetic and did not lose energy in passing through matter. Wilson responded and argued that his differences with Hahn and Meitner did not concern their respective experimental results, but rather the interpretation of those results.[36]

The issue whether the electrons emitted in β decay were monoenergetic or had a continuous energy spectrum would not be resolved until the experimental work of C. D. Ellis and W. A. Wooster.[37]* The question of whether electrons lose energy in passing through matter was immediately investigated, however, and resolved in favor of Wilson. J. Arnold Crowther soon reported results on that very question.[38] He noted that there already existed a considerable amount of indirect evidence on the subject, citing the work of both Wilson and Schmidt. He noted that Schmidt's 1907 experiment, discussed earlier, "seemed to prove conclusively that the β-rays suffered no change in velocity even when transmitted through very considerable thicknesses of absorbing material."[39] He also noted, however, that "W. Wilson has given considerable indirect evidence to show that the β-rays from a single radio-active substance are not homogeneous [monoenergetic], and in this case, Schmidt's curves could only be explained on the assumption that there was a definite decrease in velocity as the rays passed through increasing thicknesses of absorbing material."[40] Crowther proposed to investigate the question directly by measuring the velocity of electrons before and after they passed through an absorbing layer. His apparatus is shown in figure 12. Radium was placed at either A or B, depending on whether a parallel beam of electrons was needed, and the entire apparatus placed in a magnetic field. "Two chambers were made and placed so that the window A of the one came directly opposite the window B of the other. The two magnetic fields [each apparatus had its own, separately adjustable magnetic field] were arranged so that the rays of the proper velocity would be deflected round the two systems and emerge finally into an ionization chamber of the usual pattern."[41]

> Fig. [13] shows the effect of interposing a sheet of aluminum 0.47 mm in thickness between the two systems, for two different velocities of the incident beam. The upper curve in each case is the curve obtained for the incident beam in the absence of the absorbing sheet. The ordinates represent the intensity of the rays passing through the two systems, as measured by the ionization produced; the abscissae measure the magnetic field acting upon the second system.
>
> It will be seen that in each case the introduction of the absorbing sheet produces a very definite displacement of the curve in the direction of smaller velocities … .

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* For details see Franklin (ref. 1).

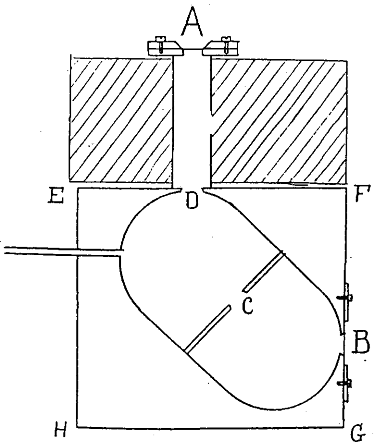

Fig. 12. One of Crowther's chambers for investigating whether electrons lost velocity in passing through matter. Two chambers were placed so that the window A of one chamber was opposite window B of the other. There were separately adjustable magnetic fields perpendicular to the plane of the paper in each chamber. Source: Crowther, "On the Transmission of β-rays" (ref. 38), p. 446.

> It is evident therefore that there is a small, but perceptible decrease in the velocity of the β-rays as they pass through absorbing media.[42]

Crowther also tested the hypothesis of exponential absorption, again noting the disagreement between Wilson and others. He found conflicting results. For an aluminum absorber he stated that the absorption curve, although not in exact agreement with Wilson's results, was definitely not exponential. For a platinum absorber, however, he found exponential absorption. He concluded:

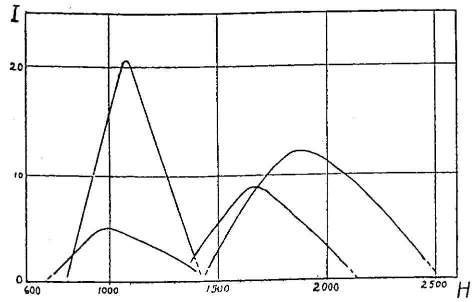

Fig. 13. Electron intensity as a function of magnetic field for two different initial electron velocities. The two curves on the right correspond to a high initial velocity. The upper and lower of these curves were obtained with 0 and 0.47 mm of aluminum absorber, respectively. Not only is the intensity reduced, but the lower curve is shifted to a lower magnetic field value, demonstrating that the electrons have lost velocity in passing through the absorber. Similarly for the curves for the initially lower velocity electrons on the left. Source: Crowther, "On the Transmission of β-rays" (ref. 38), p. 447.

> We are thus led to the following result. When β-rays are emitted by any substance, whether due to its own radio-active properties, or excited by external radiation of a single definite type, the absorption of the rays emitted follows an exponential law. On the other hand the absorption of a homogeneous beam of β-rays by a substance such as aluminum which does not emit any large amount of true secondary radiation of its own, follows a law the precise nature of which remains to be determined, but which is certainly not exponential.[43]

Crowther had shown that electrons lost energy in passing through matter and also that electron absorption, at least for aluminum, was not exponential. His results supported those of Wilson. Further support was provided by the experiments of J. A. Gray who, along with Wilson, was working in Manchester with Ernest Rutherford. Gray summarized the situation as follows:

> Hahn has found by the electrical method that β-rays from a simple radioactive substance are absorbed very nearly according to an exponential law, and has utilised this property to decide whether the source of β-rays consists of one or more products emitting β-particles. [Note that Hahn was assuming that one substance emitted one monoenergetic electron]. This method, in the hands of Hahn and Meitner, has proved very fruitful in bringing to light new and unsuspected β-ray products. In addition, it has been assumed by many writers that the exponential law of absorption is a proof that the rays are homogeneous, *i.e.*, that the β-particles are emitted initially at an identical speed and, further, that the velocity of the β-particles does not change appreciably in traversing matter.
>
> W. Wilson has attacked this question from another direction. Using radium emanation, he has sorted out the rays from the active deposit by means of a magnetic field, and obtained rays which, if not homogeneous, cover a small range of velocities. Testing these rays by means of an electroscope, he found that when the ionisation was plotted against the thickness of absorbing matter, the curve obtained was not exponential, but very nearly a straight line. This indicated that the absorption of very nearly homogeneous rays was not a constant, but increased with the thickness of matter traversed. Such a result can only be explained by a loss of velocity in β-rays as they pass through matter. It also shows that an exponential law of absorption does not signify homogeneous β-rays, but rather rays with a particular distribution of velocities.
>
> This point of view has been a matter of discussion between Hahn and Meitner and Wilson, and the former in their paper supported the view that an exponential law of absorption is a proof that the β-particles are homogeneous, and do not decrease appreciably in velocity in passing through matter. It has been the object of the experiments described in this paper to obtain independent evidence on this important question by deflecting the β-rays from some radioactive substance in a magnetic field.[44]

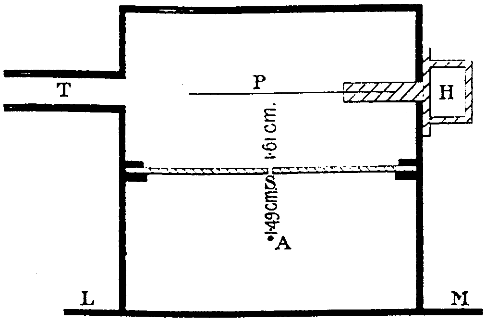

Fig. 14. Gray's apparatus for investigating the absorption of β rays. Electrons from the radioactive source A passed through the slit S and struck a photographic plate at P. The entire apparatus was placed in a magnetic field so that electrons of different velocities would follow different paths. Source: Gray, "The Distribution of Velocity in the β-Rays from a Radioactive Substance" (ref. 44), p. 140.

To avoid difficulties arising from the decay of several elements in the same source, Gray used RaE (^{214}Bi), a single element source. His apparatus is shown in figure 14. Electrons from the radioactive source A passed through the slit S and struck a photographic plate at P. The entire apparatus was placed in a magnetic field so that electrons of different velocities would follow different paths. Gray's results are shown in figure 15 and "there was no sign of a set or sets of homogeneous β-rays. The narrow band is caused by the undeflected rays in the absence of a magnetic field. The other band, or magnetic spectrum as it may be called, shows no sign of bands, the spectrum being quite continuous."[45] The results also show a broad spectrum of electron velocities or energies. Gray also measured the absorption of these electrons, and his results are shown in figure 16 (A). The logarithm of the intensity as a function of the thickness of the aluminum absorber "is practically a straight line," indicating exponential absorption. "[We] see that β-rays, which are very nearly absorbed according to an exponential law, are by no means homogeneous."[46] This conformed to Wilson's view on exponential absorption.

To obtain results in a reasonable time, Gray had used a thick RaE source. He noted:

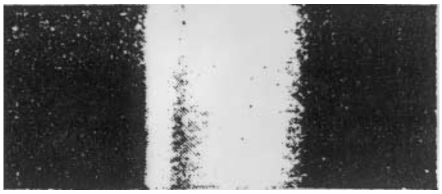

Fig. 15. Gray's photograph of the intensity of electrons of different velocities. No evidence of a single energy or of a line spectrum is seen. "The narrow band [on the left] is caused by the undeflected rays in the absence of a magnetic field. The other band, [on the right] or magnetic spectrum as it may be called, shows no sign of bands, the spectrum being quite continuous." Source: Gray, "The Distribution of Velocity in the β-Rays from a Radioactive Substance" (ref. 44), p. 140.

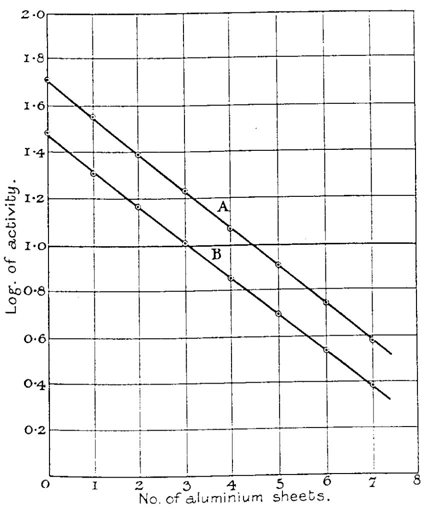

Fig. 16. Gray's results for the absorption of inhomogeneous β rays, for two different experimental conditions. The logarithm of the intensity of electrons as a function of absorber thickness is plotted as a function of absorber thickness. Both curves are straight lines, indicating an exponential absorption law. Source: Gray, "The Distribution of Velocity in the β-Rays from a Radioactive Substance" (ref. 44), p. 140.

> The above experiments do not prove directly that the β-rays from RaE are not initially expelled at an identical speed, for it is possible that the β-rays coming from the lower layers of the active material may be so changed in velocity that an exponential law of absorption results from the mixture. However, in this case we could not expect that the rays from a thin film of RaE would be absorbed exponentially, and we should expect a different coefficient of absorption for the thin layer. An absorption curve was taken of the β-rays from a thin film of the material used in taking the photographs. In this film the absorption of the rays in the active material is very small, and care was taken that very little secondary β-radiation entered the electroscope, yet the rays from RaE are absorbed exponentially. The result in shown in curve B, fig. [16], … . *It is therefore practically certain that the β-rays from RaE are initially expelled, not at an identical speed, but with widely different velocities. The experiments with radium emanation gave similar evidence with respect to the β-rays from RaB and RaC.*[47]

Surprisingly, Gary did not emphasize the continuous energy spectrum of the electrons emitted in β decay, which seemed to be indicated by his results. One might speculate that this was due, in part, to concentrating on electron absorption, as Wilson had also done. Gray concluded:

> Summing up the experiments, which as we have seen, confirm Wilson's results, we may say that –
>
> 1. β-rays, which are absorbed according to an exponential law, are not homogeneous.
> 2. β-rays must fall in velocity in traversing matter.[48]

In an adjacent paper, Wilson presented further evidence to support his view that electrons lost velocity in passing through matter. His experimental apparatus was similar to that used by Crowther. "The general idea of the experiment was to separate out a beam of approximately homogeneous rays by means of a magnetic field, and to determine the velocity of these rays after passing through various sheets of matter by means of a second field."[49]

His apparatus is shown in figure 17. Electrons emitted by a radioactive source A were bent in a circular path by a uniform magnetic field C.* If the electrons followed a circular path of a certain radius they would pass through hole O. The electrons that passed through hole O were then bent by a uniform magnetic field D and detected in electroscope E. Absorbers of various thicknesses were placed at Q, and the velocity change, if any, measured.** Wilson described the experiment as follows:

> By passing currents of known strength though the electromagnets C and D, approximately homogeneous radiation was allowed to pass through the hole O

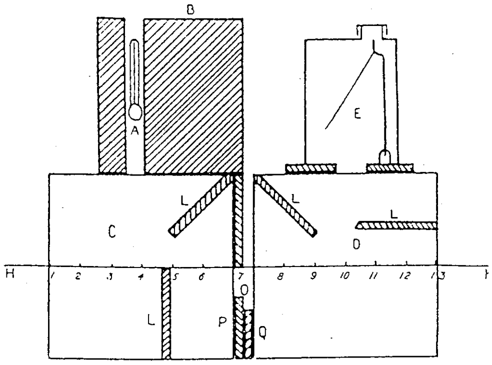

Fig. 17. Wilson's apparatus for investigating whether electrons lose velocity in passing through matter. It is similar to that used by Crowther (figure 12). A radioactive source is placed at A and the emitted electrons bent in a circular path by separately adjustable magnetic fields in each chamber. Absorbers of varying thickness were placed at Q. Source: Wilson, "The Decrease of Velocity of the β-Particles on Passing through Matter" (ref. 49), p. 142.

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* Wilson checked that the magnetic fields C and D were indeed uniform.

** There was an important experimental problem: "The field in each electromagnet is a function of the current in both. Thus, if the current through the electromagnet C was kept constant and that in D made to vary, changes took place in both the fields C and D. Now, in the present case, it is required that the field in electromagnet C should be kept constant, while that in D is made to vary, so that changes in the currents in both electromagnets are necessary. The system was therefore calibrated as follows: – The current in the electromagnet C was kept constant and that in D varied and the strengths of the fields in each were determined by means of a Grassot fluxmeter, for each value of the current in D. A similar set of readings was taken for about ten different values of the current in C. From the results thus obtained, curves could be drawn from which the values of the currents in C and D could be adjusted so that the field in C was kept constant while that in D was made to vary" (ref. 49), pp. 143–144.

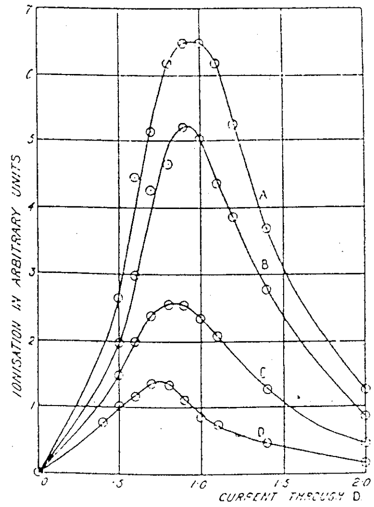

Fig. 18. Wilson's results on whether electrons lose velocity in passing through matter. The intensity of electrons is plotted as a function of the current in the magnet in chamber D, after the absorber, for various absorber thicknesses and for different initial velocities. As the absorber thickness is increased (curves A–D), the intensity is reduced and the peak is shifted to lower fields, demonstrating that the electrons have lost velocity in passing through the absorber and that the loss is larger for thicker absorbers. Source: Wilson, "The Decrease of Velocity of the β-Particles on Passing through Matter" (ref. 49), p. 144.

> into the magnetic field D. The field in D was varied, while that in C was kept constant, so that the same bundle of approximately homogeneous rays passed through the hole O during the whole of the experiment. The ionisation in the electroscope was determined for each value of the field in D, and the values thus obtained were plotted against the current in D. The rays were then made to pass through various sheets of aluminum placed in the slot in Q before they entered the second magnetic field and the experiments repeated.[50]

Wilson's results for various increasing absorber thicknesses are shown in figure 18 (A–D). "It will be noticed that these maximum points move to the lower fields as the sheets of aluminum are interposed in the path, *proving conclusively that the velocity of the rays decreases by an appreciable amount as they pass through matter.*"[51]*

Wilson further concluded, "The experiments show that the velocity of the β-particles is appreciably reduced as they pass through matter … ."[52]

Meitner, Hahn, and von Baeyer made improvements in their experimental apparatus (figure 19) to increase the energy resolution in their β-ray spectra. 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

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* Wilson also repeated his explanation of Schmidt's result, discussed earlier, which had seemed to show that the velocity of the electrons remained constant as they passed through matter.

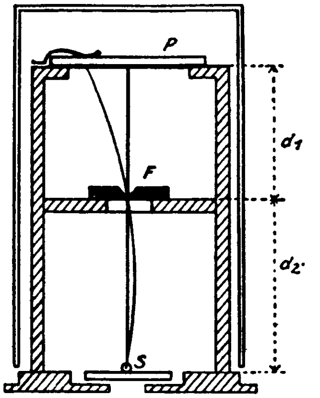

Fig. 19. The experimental apparatus used by Meitner, Hahn, and von Baeyer. The β rays emitted by the source S are bent by a magnetic field, pass through a slit at F and strike the photographic plate P. Source: Hahn, *A Scientific Autobiography* (ref. 20), p. 55.

the same energy would follow the same path and produce a single line on the photographic plate. The results showed a line spectrum and still seemed to support the view that there was one homogeneous 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 20). There were some problems, however. There are some weak lines in the photograph that are difficult to explain on a one-energy line one-element view. The experimenters wrote, "The present investigation shows that,

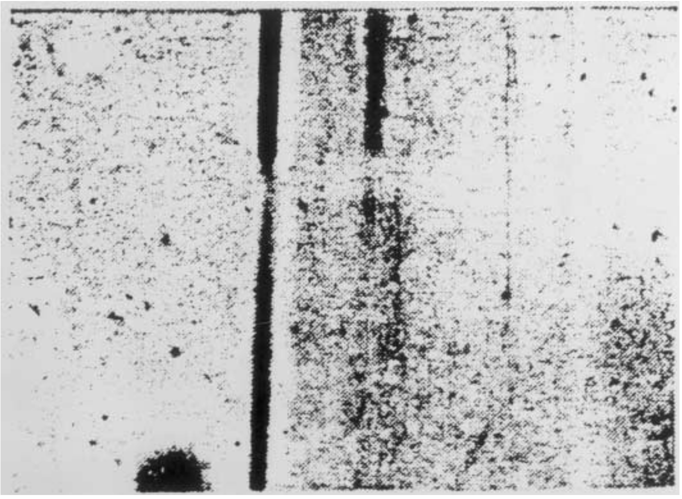

Fig. 20. The first line spectrum for β decay published by Meitner, Hahn, and von Baeyer. The two observed lines were thought to be produced by the two radioactive elements present in the source. Source: von Baeyer, Hahn, and Meitner, "Uber die β-Strahlen des aktiven Niederschlags des Thoriums" (ref. 16), p. 279.

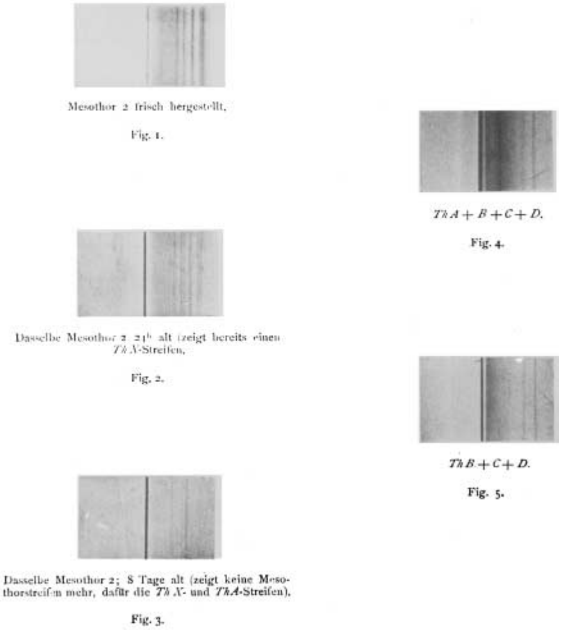

Fig. 21. The complex β rays energy spectra obtained by Meitner, Hahn, and von Baeyer with their improved apparatus. A large number of lines are seen. 1. Mesothorium-2, freshly prepared. 2. Mesothorium-2, 24 hours old, showing a faint line from thorium-X. 3. Mesothorium-2, 8 days old. The mesothorium lines have disappeared, but lines from thorium-X and thorium-A begin to show. 4. Thorium A + B + C + D. 5. Thorium B + C + D. Source: Hahn *A Scientific Autobiography* (ref. 20), following p. 72.

in the decay of radioactive substances, not only α-rays but also β-rays leave the radioactive atom with a velocity characteristic for the species in question. This lends new support to the hypothesis of Hahn and Meitner … ."[53]

Further improvements to the apparatus, including stronger and thinner radioactive sources, improved the quality of the photographs obtained, but showed a complexity of electron velocities that made it difficult to argue for the Hahn-Meitner hypothesis (figure 21). As Hahn later wrote, "Our earlier opinions were beyond salvage. It was impossible to assume a separate substance for each beta line."[54] The beta spectrum was just too complex. Meitner, Hahn, and von Baeyer admitted, however, that the exponential absorption law "could not be a criterion for the homogeneity of the radiation as Hahn and Meitner, in contrast to other scientists[55]* have assumed."[56]

Gray and Wilson[57] proved the heterogeneity of electrons emitted from a thick layer of RaE. They remarked on the recent discussions and experimental evidence concerning the exponential absorption of electrons and on the decrease in velocity

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* There was a specific reference to the work of Alois F. Kovarik, but adjoining papers on the same subject were by Kovarik and Wilson and by Gray and Wilson. The latter paper is discussed in detail below.

of electrons in passing through matter. They concluded that, "It follows as a necessary consequence of these results that β rays which are absorbed exponentially by aluminum are not homogeneous."[58] They noted, however, that recent work by von Baeyer and Hahn had shown "that the β rays from several radioactive products possess a considerable degree of homogeneity [a reference to the line spectra that had been found]" and went on to state:

> We have no definite evidence so far that the rays from such thin layers as they used are absorbed according to an exponential law. Gray by the same method showed that the β rays from a thick layer of radium E are distinctly heterogeneous, although they are absorbed according to an exponential law by aluminum. In view of the experiments of v. Baeyer and Hahn the following experiments were performed.[59]

Surprisingly, they did not mention Gray's own very recent result, discussed above, that the electrons from a thin film of RaE were emitted with widely different velocities.

The experimental apparatus of Gray and Wilson is shown in figure 22. Electrons from a RaE source at B were bent in a circular orbit of fixed radius by a magnetic field, passed through holes O and P, and were detected by electroscope E. The ionization in the electroscope was measured as a function of magnetic field. The experiment was repeated with aluminum absorbers of various thickness placed just below the electroscope. The results are shown in figure 23, with curves *a*, *b*, *c*, *d*, and *e* for aluminum thicknesses 0, 0.067, 0.245, 0.489, and 0.731 mm, respectively. The graph clearly shows that lower-field (velocity or energy) electrons are absorbed more easily. "It will be noticed that the rays which produced the maximum ionization when no aluminum was placed under the electroscope are practically all

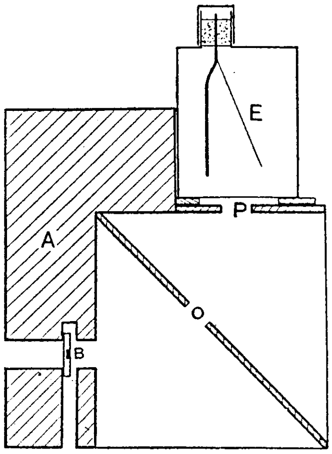

Fig. 22. The apparatus of Gray and Wilson for investigating the absorption of β rays. Electrons from a RaE source at B were bent in a circular orbit of fixed radius by a magnetic field, passed through holes O and P, and were detected by electroscope E. Source: Gray and Wilson, "The Heterogeneity of the β Rays from a Thick Layer of Radium E" (ref. 57), p. 871.

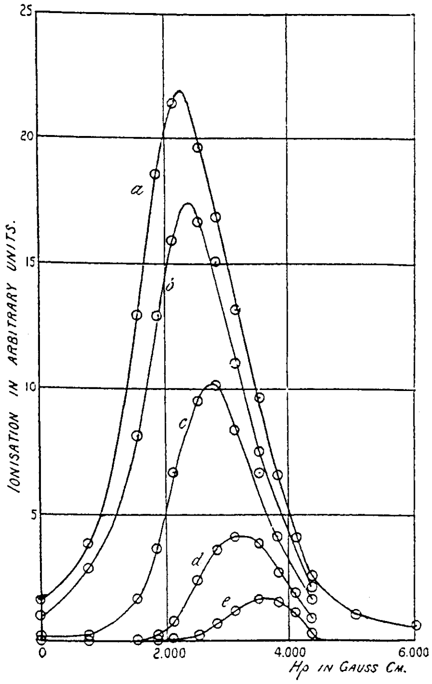

Fig. 23. The ionization in the electroscope (electron intensity) plotted as a function of electron momentum. The experiment was repeated with aluminum absorbers of various thickness placed just below the electroscope. Curves *a*, *b*, *c*, *d*, and *e* were obtained with aluminum thicknesses 0, 0.067, 0.245, 0.489, and 0.731 mm, respectively. The graph clearly shows that low momentum (energy) electrons are absorbed more easily. Source: Gray and Wilson, "The Heterogeneity of the β Rays from a Thick Layer of Radium E" (ref. 57), p. 872.

absorbed by a thickness of 0.73 mm Al, while for rays corresponding to the higher fields appreciable quantities are still transmitted."[60]

Gray and Wilson also measured absorption curves for electrons of different energies directly. They found, once again, that the lower-energy electrons were more easily absorbed and that the absorption for such almost monoenergetic electrons was not exponential. They concluded that, "It has been shown above that from a pencil of β rays which is absorbed according to an exponential law, rays of widely different penetrating powers can be separated out. It follows, therefore, that absorption of β rays according to an exponential law is no criterion of homogeneity."[61] By 1911, Hahn, Meitner, von Baeyer, Gray, Wilson, Crowther and, no doubt, everyone else in the physics community were in agreement. Monoenergetic electrons were not absorbed exponentially and exponential absorption was not an indication that they were monoenergetic, but rather of a spread in energies.

The *coup de grace* was performed by Wilson. 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 that an inhomogeneous beam of electrons was absorbed exponentially.[62] He began with a monoenergetic beam of electrons and showed once again that it did not obey an exponential absorption law. He then modified the 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 24), similar to the one he had calculated previously. He concluded, "The fact that β-rays, initially homogeneous, are absorbed according to an exponential law after passing through a small thickness of platinum has been confirmed, and it has been shown that this is not due to mere scattering of the rays, but to the fact that the beam is rendered heterogeneous in its passage through the platinum."[63]

Wilson, with some evidential support from others, had demonstrated clearly that monoenergetic electrons were not absorbed exponentially. He also had shown that exponential absorption, rather than indicating that the electrons were monoenergetic, actually showed that the electrons had a spectrum of energies. Following this work the method for investigating the energy of β-decay electrons changed. Magnetic spectrometers with different detectors – electroscopes, photographic plates, and later the newly developed Geiger counters – were used. This was an important early step in the investigation that ultimately led to the conclusion that the energy spectrum in β decay was continuous, and to Wolfgang Pauli's suggestion of the neutrino. It is not surprising that citations to Wilson's work soon disappeared. Scientists do not often discuss the reasons why they did not choose a particular experimental technique. What is surprising is that after having done such

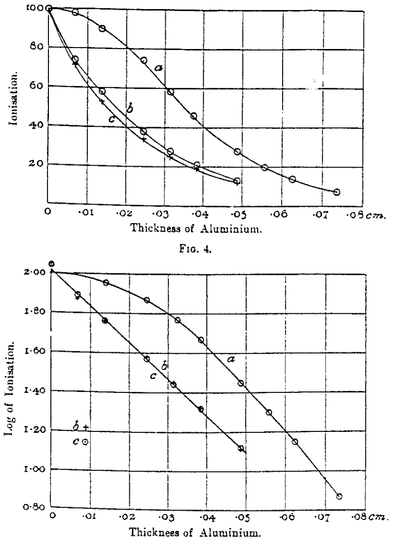

Fig. 24. Wilson's experimental plots on the absorption of a beam of electrons. Curves *b* and *c* in the upper graph show the intensity of homogeneous electrons as a function of absorber thickness after they have passed through a platinum sheet rendering them inhomogeneous. Curve *a* shows the absorption of the homogenous electrons. In the lower graph the logarithm of the ionization is plotted. The curves for *b* and *c* are straight lines, indicating exponential absorption for *inhomogeneous* electrons. Curve *a*, for monoenergetic electrons, is clearly not an exponential. Source: Wilson, "On the Absorption and Reflection of Homogeneous β-Particles" (ref. 62), p. 317.

"important" (Ernest Rutherford) or even "revolutionary" (Frederick Soddy) work, Wilson soon left the field of radioactive decay. I now discuss the reasons for this.

Some Personal Glimpses

William Wilson's research on radioactivity and electron absorption was of very high quality, as we have seen, and was completed while he was a relatively young scholar. Wilson was born on March 29, 1887, and enrolled as an undergraduate at the University of Manchester in 1904. He had a distinguished undergraduate record. In 1906 he was appointed a Hatfield Scholar, which was awarded to a physics student after his second year, and was tenable in the third year and for a year after graduation, and he received a first-class honors degree in 1907. Even before his graduation Wilson was doing publishable research under the guidance of Ernest Rutherford.[64] He received an M.Sc. in 1908 and was an honorary research fellow in the physics department, possibly unpaid.* In his report to the council of the university in 1909, Rutherford described Wilson's work on the absorption of β rays and on the velocity dependence of that absorption as "important." It was.

In 1910 Wilson was awarded an 1851 Exhibition Scholarship for two years of research anywhere in the world. These scholarships were given to those students who already had made significant research contributions and had exceptional promise. Their regulations stated:

> The Scholarships are intended, not to facilitate attendance on ordinary collegiate studies, but to enable Students who have passed through a College curriculum and have given evidence of capacity for original research, to continue the prosecution of Science with the view of aiding its advance, or its application to the industries of the country … .
>
> The Candidate must indicate high promise of capacity for advancing Science or its applications by original research. Evidence of this capacity is strictly required, this being the main qualification for a Scholarship. The most suitable evidence is a satisfactory account of a research already performed, and the Commissioners will decline to confirm the nomination of a Candidate unless such an account is furnished, or there is other equally distinct evidence that he possesses the required qualification.[65]

This was an extremely prestigious award. Summarizing the awards made during the first seventy years,** the chairman of the Science Scholarships Committee wrote, "It is some indication of the distinction which characterizes the Record that it contains the names of 99 Fellows of the Royal Society, including two past

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* Wilson may have been supported by his Hatfield Scholarship.

** The scholarships were offered from 1891 until 1921. Interestingly, neither Cambridge nor Oxford were allowed to nominate candidates. In 1922 the awards were changed to what we would call postdoctoral fellowships and Oxford and Cambridge candidates became eligible.

Presidents, and of 8 Nobel Laureates."[66] The Nobel Laureates included Ernest Rutherford and James Chadwick. The 1851 Scholars also included J. A. Gray, who also worked at Manchester and collaborated with Wilson on research. Wilson used his scholarship to continue his studies on radioactivity and electron absorption with J. J. Thomson at the Cavendish Laboratory in Cambridge. He was "accompanied by sufficient scholarships to create a *cause celebre*, for in the same year he did the completely unexpected thing and won not only the Langworthy Scholarship but also the 1851 Exhibition Scholarship, which was open to anyone in the British Empire – with the result that the rules were changed, so that no equally brilliant successor could ever again hold both scholarships."[67]

Wilson's arrival in Cambridge necessitated the building of new experimental apparatus, and it seems to have taken some time for him to get it operating properly.* That done, he continued his work on the absorption and scattering of β rays. Rutherford commented that, "These investigations added materially to our information on this subject, and cleared up several outstanding points of interest."[68] J. J. Thomson concurred, "I am glad to be able to report that he [Wilson] has worked well and made good progress and obtained interesting results."[69]**

In May 1912, nearing the end of his tenure as an 1851 Exhibition Scholar, Wilson wrote to Rutherford concerning his future. Sidney Chapman, one of Wilson's colleagues at Cambridge, had received an offer of a Lectureship at the University of Toronto, but had decided to turn it down. James McLennan, the group leader at Toronto, had asked Chapman to recommend an alternate, and Chapman asked Wilson if he was interested. Wilson asked Rutherford what he thought about the position, and also asked him for a letter of recommendation. One of Wilson's reasons for considering the position seriously was that opportunities for advancement in academia for young scholars in England were not very good. (This seems to be a continual problem, not only in Britain, but elsewhere.) Wilson wrote, "The prospects here do not seem very bright. There are twenty or thirty men here practically all looking for jobs and of course quite a number with you and in different parts of the country."[70] He thought that Canada, with its increasing population, offered better prospects.

There were other, more personal, reasons.

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* In his evaluation of Wilson's performance as an 1851 Exhibition Scholar, Ernest Rutherford remarked that, "His [Wilson's] first year was mainly occupied in getting his apparatus in thorough working order and in obtaining preliminary results."

** J. J. Thomson seems to have been fond of playing jokes on his students. Soon after Wilson arrived in Cambridge in 1910 he was further investigating Crowther's recently reported result on the exponential absorption of β rays in platinum. In a letter to Rutherford, Wilson remarked that, "He [Thomson] came to me with the stock joke that Slobodowsky working in the University of Tophlis had done my work beforehand, but the names were a little too far-fetched and the time between Crowther's paper and the present too short" (W. Wilson, letter to Rutherford, October 24, 1910). Wilson also reported that a similar ploy had, in fact, worked on one of his colleagues who "went round both the University and Philosophical libraries" in his search for the purported results. Needless to say the colleague couldn't find the reference, but "told J.J. that the work had been done by a German but he didn't remember the paper it was in."

> Another fact which influences me to a slight extent is that I got engaged during the vacation and think that I would feel better if I were settled down in a post.
>
> Please don't think me rash and foolish for taking such a step before I am definitely settled for I have had the young lady in question in my mind's eye for about twelve years and since we are both 25 years of age and various other "mind's eyes" seemed to be wandering around in that direction I thought it was best to get the matter definitely fixed up.[71]

Wilson also consulted Thomson, who thought he "would be well advised to take it and has written to McLennan recommending me."[72]

Wilson was offered, and accepted, a position as Lecturer in Physics at the University of Toronto, and took up his duties in the fall of 1912. (A year later his brother Harry joined him in the electrical engineering department.) He was very happy with both his new job and with his new location. "At the present moment I feel as if I don't want to live in England again. There's something in the air here which makes me feel awake, a feeling that I've only had at odd moments during the past six years."[73]* Wilson reemphasized his view a little later. "This place suits me down to the ground and I feel about ten times as energetic as I have done for the last four or five years."[74]**

Wilson found that his teaching duties went well and wrote to Rutherford that although he hadn't as yet started doing research, he thought it might be a good idea to work in a different area of physics. He remarked that he had begun reading recent research reports on light. By November 17, 1912, Wilson had changed his mind. He wrote to Rutherford that he was intending to begin work on the reflection of homogeneous β rays and asked Rutherford for advice about handling the radioactive sources necessary for that work. He also remarked that McLennan had recommended him for a research post in Pittsburgh, which involved making luminescent screens for use with radioactive materials. The salary for the post was $3000 per year, a considerable increase from his lectureship at $1250 per year, and quite attractive for a prospective bridegroom. Wilson was considering a career in industry.

In 1913 Wilson received his doctorate from Manchester, and in 1914 he married his fiancée, Ada Edlin. That year he, along with his brother, also accepted a position as a research physicist with the Western Electric Company in Pittsburgh. Wilson began working on radio transmission, particularly on radio telephony. "When the first long-distance trials of radio-telephony were made from the United States Naval Station at Arlington, Virginia, Wilson set up the receiving station at

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* Wilson also liked the climate. "So far the climate is Manchestery (if one can coin so ugly a word) but is a great improvement on that of Cambridge" (Wilson to Rutherford, September 28, 1912, University of Cambridge Library).

** Wilson also liked his accommodations. "I have a splendid room in the Faculty Residence. Of course it has a bed in one corner but it is really quite large and nice, and only costs me $3.50 a week while my board at the Faculty Union costs $4.50" (Wilson to Rutherford, September 28, 1912, University of Cambridge Library). A total expenditure of $8 per week on room and board with a yearly salary of $1250 was not bad.

San Diego, California; his brother was at the Arlington end of the transmission. He did important research on vacuum tubes, and later in general problems of radio and wire communication."[75]

Wilson went on to become Assistant Director of Research at Bell Telephone Laboratories, the successor to Western Electric, in 1928 and held that position until his retirement, because of ill health, in 1942. By 1945 his health had improved and he accepted an appointment as professor of physics at North Carolina State College in Charlotte. He died in 1948.

Discussion

The reader may ask why I have devoted an entire paper to the work William Wilson.* After all, Wilson did not make any discoveries that led to future work. All he did was to show that what others believed about the connection of monoenergetic electrons with exponential absorption was wrong. That was, in a sense, a dead end, and citations to his work soon disappeared. Such a view does not do justice to Wilson's work. His results on exponential absorption changed the method by which other researchers in the field investigated both absorption and the β-ray energy spectrum. Previously, measurements of the range of electrons in matter had been one method of determining their energy.** After Wilson's results were reported, magnetic spectrometers with various different detectors, such as electroscopes, photographic plates, and Geiger counters, became the apparatus of choice. In fact, Chadwick,[76] using a magnetic spectrometer with either an electroscope or a Geiger counter as a detector, first showed that the energy spectrum in β decay was continuous.*** (Chadwick's result did not establish the continuous energy spectrum. Most physicists still believed that the observed spectrum resulted from a discrete line spectrum for the electrons, with the electrons losing energy as they left the radioactive source. Only after Ellis and Wooster showed that this was not the case was the continuous energy spectrum accepted.)

Wilson has received mixed treatment from historians of science. There are very good, albeit rather brief, technical discussions of Wilson's work by John Heilbron, Abraham Pais, and Ruth Sime.[77] Pais entitled his discussion of Wilson's work, "A Revolutionary Conclusion," and Heilbron remarked that "Wilson's results were shattering." By contrast, Otto Hahn in his *Scientific Autobiography*[78] makes no mention of Wilson. Neither does Patricia Rife in her recent biography of Lise Meitner.[79] Wilson deserves better. His work was important in the methodological and epistemological sense, and he was an excellent scientist. In presenting his "revolu-

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* As discussed below, other historians have offered only brief discussions of Wilson's work.

** Range continued to be used as a measure of the maximum energy of electrons emitted in β decay through the early 1930s.

*** To be accurate, Chadwick showed that there are discrete lines superimposed on a much larger continuous energy spectrum. For details see Franklin (ref. 1), chapter 1.

tionary" results, he argued very carefully for their credibility. In addition, he provided a calculation that explained why his results differed from others who had found exponential absorption. He showed that the experimental results were correct, but that they had been misinterpreted. Rather than showing that the β rays were monoenergetic, he showed that the results demonstrated that the electrons actually had a continuous energy range. He was not satisfied, however, with just a calculation. He later showed experimentally that initially monoenergetic electrons, made heterogeneous by passing through matter, were exponentially absorbed. Wilson had shown that the Emperor, in fact, was not wearing any clothes. Unlike the case in Anderson's fairy tale, in which the Emperor's attendants continued to hold his nonexistent train, Wilson's colleagues believed him.

Acknowledgments

Much of this work was done while I was a Miegunyah Distinguished Fellow in the Department of History and Philosophy of Science of the University of Melbourne. I am grateful to Rod Home, head of the department, not only for his hospitality, but also for sharing with me his knowledge of late-nineteenth-century science and its institutions. My discussions with him were invaluable. I also had many valuable discussions with my colleagues at Melbourne, Howard Sankey, Neil Thomason, Maureen Christie, and Manuel Thomaz, another visitor in the department. I also thank the Royal Commission for the 1851 Exhibition and its archivist, Mrs. V. C. Phillips, for providing information and documents about the 1851 Exhibition Scholarships. Barry White and Chris Gibson, of the University of Manchester library, also provided much very valuable information about William Wilson, and Professor Robin Marshall of the Department of Physics and Astronomy, University of Manchester, provided the photograph of William Wilson. Copies of William Wilson's letters to Rutherford were provided by Adam Perkins of the University of Cambridge library.

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No Place Like Home

A. S. Russell explained how, while in Manchester, he learned about Ernest Rutherford's pride in being a New Zealander:

> One day at a formal luncheon a bishop started to tell me a story of how he had met my professor at an earlier meal. Knowing that Rutherford was a New Zealander, he had asked him how many people there were in the South Island. He had been quite genuinely surprised to learn in answer that it was only about 250,000. He had imagined till then that the population was of the order of three or four millions. To indicate his surprise, and to get confirmation of the smallness of his figure, he compared it to Rutherford with the population of an English town. "As I spoke to him of this", continued the Bishop to me, "I saw your professor's face flush. You could almost see the blood flowing up the neck and flooding the face…". Just at that interesting point the chairman at the luncheon proposed the health of the King. We rose, and I never heard the end of the story – at least from the bishop. A few days later, however, as I arrived a little late for the laboratory tea, I came in at the professor's words: "…bishop in gaiters. It was perfectly ludicrous. He thought there ought to be about four million there. 'Quarter of a million?', he said to me incredulously. 'Do you mean to say there are only 250,000 there? Only about the population of Stoke-on-Trent?'" It was then that I realized why Rutherford had got excited in the bishop's story. The idea of comparing his lovely South Island with some place in England like Stoke-on-Trent? So I waited for the conclusion of the bishop's story. And it came. "So I said to him", continued Rutherford, and then he paused and looked kindly at us all. "I hope there are none of you here from Stoke-on-Trent. So I said to him: 'Maybe the population is only about that of Stoke-on-Trent. But let me tell you, sir, that every single man in the South Island of New Zealand could eat up the whole population of Stoke-on-Trent, every day, before breakfast, and still be hungry'."

A. S. Russell, "Lord Rutherford: Manchester, 1907–19: a Partial Portrait," in *Rutherford by Those Who Knew Him*: *Being the collection of the first five Rutherford lectures of the Physical Society* (London: The Physical Society, 1954), p. 66.