Experimental Evidence for Orbital Electron Emission Accompanying Beta-Decay*

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Experiments are described which indicate the existence of a mode of beta-disintegration in which the energy emitted is shared by three particles: beta-particle, neutrino, and ejected orbital electron. The energy spectrum of the orbital electrons ("IB electrons") from Sc^{44} has been measured over the range 30 to 150 kev. The "IB internal conversion coefficient"—that is, the ratio of the measured number of IB electrons to the number of internal bremsstrahlung (IB) predicted by the theory of Knipp and Uhlenbeck, and Bloch—is found to be essentially constant over the measured energy range, and equal to 4.3. The frequency with which the three-particle disintegration takes place is about 0.04 times that of ordinary decay into a beta-particle and a neutrino. The measurements have an estimated accuracy of +3 percent, −20 percent.

INTRODUCTION

I

THE validity of the Fermi theory of beta-decay[1] now appears to be well established. Experimental measurements of the beta-spectra of both allowed and forbidden transitions have been made down to extremely low energies and are in agreement with the theory over the entire measurable energy range.[2] In addition, the beta-spectra of forbidden transitions have been investigated so thoroughly that the type of interaction which takes place between the decaying nucleon and the electron-neutrino field has been determined uniquely.[3] Although there remain a few cases which are not yet completely explained (e.g., C^{14}, RaE), it seems certain that their explanation will require no revision of the basic theory.

On the other hand, it is becoming increasingly evident that the Fermi theory is, in a sense, incomplete. That is to say, given two neighboring isobars differing in mass by an amount W_0, the theory does not describe all of the ways in which the nuclear transition can occur. The theory takes into account only the possibility that the available energy is shared between two emitted particles, *viz.*, the electron and neutrino; it does not consider possible events in which the energy is shared by more than two particles: electron, neutrino, and photon, for example.[4]

The first experimental evidence for the latter process was actually found before Fermi proposed his theory. Aston,[5] in 1927, discovered weak continuous gamma-radiation accompanying the beta-disintegration of RaE. This phenomenon has since been observed in other isotopes by a number of people,[6–11] most recently by Wu.[11] Such gamma-radiation has been given the name "internal bremsstrahlung" (henceforth denoted by IB).

A theory for IB was given in 1936 simultaneously by Knipp and Uhlenbeck[12] and Bloch[13] (henceforth denoted by KUB), who showed quantum-mechanically that continuous radiation of the observed order of magnitude, i.e., approximately $\alpha=1/137$ quanta per beta-particle, could be attributed to the sudden change in nuclear charge which occurs when the beta-particle is created and leaves the nucleus. They obtained the probability per unit time $S(k)$ for emission of a quantum of energy k by a second-order perturbation calculation, corresponding to the following two-step process: (1) the transition from initial to intermediate state consisting of the nuclear transformation accompanied by the creation of a beta-particle and a neutrino; (2) the transition of the electron from its intermediate state to a final state by emission of a photon of energy k. For the interaction hamiltonian in step (1) KUB chose the polar vector interaction for an allowed transition, and for the interaction in step (2) they used the coupling term between the electron and the quantized electromagnetic radiation field.

The radiation spectrum which they obtained can be written in the form,

$$S(k)=\int_{1+k}^{W_0} dW_e P(W_e)\Phi(W_e, k).$$

Here $P(W_e)dW_e$ is the probability that a beta-particle be created with an energy in the interval W_e to W_e+dW_e, and is to be taken as the theoretical distribution given by the Fermi theory. $\Phi(W_e, k)$ is the probability that a beta-particle of energy W_e will radiate a gamma-quantum of energy k; they found

$$\Phi(W_e, k)=\frac{\alpha p}{\pi p_e k}\left\{\frac{W_e^2+W^2}{W_e p}\ln(W+p)-2\right\},$$

where α is the fine structure constant, p_e and W_e are

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1 E. Fermi, Z. Physik **88**, 161 (1934).
2 See Langer, Motz, and Price, Phys. Rev. **77**, 798 (1950).
3 L. M. Langer and R. D. Moffat, Phys. Rev. **82**, 635 (1951).
4 It should, perhaps, be emphasized that these particles are created simultaneously in the processes under consideration here.
5 G. H. Aston, Proc. Cambridge Phil. Soc. **23**, 935 (1927).
6 S. Bramson, Z. Physik **66**, 721 (1930).
7 C. J. Sizoo and D. J. Commore, Physica **3**, 921 (1936).
8 Sizoo, Eickman, and Green, Physica **6**, 1057 (1939).
9 E. Stahel and D. J. Commore, Physica **2**, 707 (1935).
10 E. Stahel and J. Guillessen, J. phys. et radium **1**, 12 (1940).
11 C. S. Wu, Phys. Rev. **59**, 481 (1941).
12 J. K. Knipp and G. E. Uhlenbeck, Physica **3**, 425 (1936).
13 F. Bloch, Phys. Rev. **50**, 472 (1936).

the momentum and energy of the electron when it is "born," and p and W are the momentum and energy of the electron after radiating the photon. W_0 is the end-point energy of the beta-spectrum. The relativistic units are used: $\hbar = m = c = 1$.

Since Φ behaves roughly as $1/k$, $S(k)$ suffers an "infrared catastrophe," i.e., becomes infinite at $k=0$. For this reason it is customary to plot the IB energy distribution in the form $kS(k)$ *versus* k. Figure 1 shows the spectrum predicted for $W_0=3.860$. In the same figure is plotted the number of quanta, $N(k)$, having energy greater than k per electron. This number is given by

$$N(k)=\int_k^{W_0-1} dx S(x).$$

These calculations have been extended by Chang and Falkoff[14] in two directions. First, since the polar vector interaction used by KUB is but one of the five linearly independent, relativistically invariant interactions which might be used in the beta-decay theory, they made the calculations for the other four interactions. Second, they extended the calculations to forbidden beta-transitions. Their method of calculation was that used by KUB.

From the very small differences in $S(k)$ which their results indicate for the different kinds of beta-spectra, it is clear that one could not hope to distinguish degrees of forbiddenness or types of interaction by measuring IB spectra.

Actually, an IB spectrum has never been measured, but absorption experiments indicate that the radiation is continuous and inhomogeneous. Wu found the total energy of the IB from P^{32} to be about 0.002 mc^2 per beta-particle, in agreement with the KUB theory.

II

One might suspect the existence of a phenomenon similar to IB, in which an orbital electron (instead of a photon) carries off part of the available energy.[15] These electrons might be termed "internally converted IB" or, more simply, "IB electrons." Such a phenomenon would certainly have been undetected in the experiments on IB simply because the apparatus was so designed as to be insensitive to electrons. Since the Fermi theory is so well substantiated, one can predict that this effect will be small and will give rise principally to low energy electrons.

For the purpose of observing this process it is clear that only positron emitters would be suitable, because in a negatron emitter the ejected orbital electrons would be indistinguishable from the beta-particles. Also, it would seem more promising to seek a suitable isotope

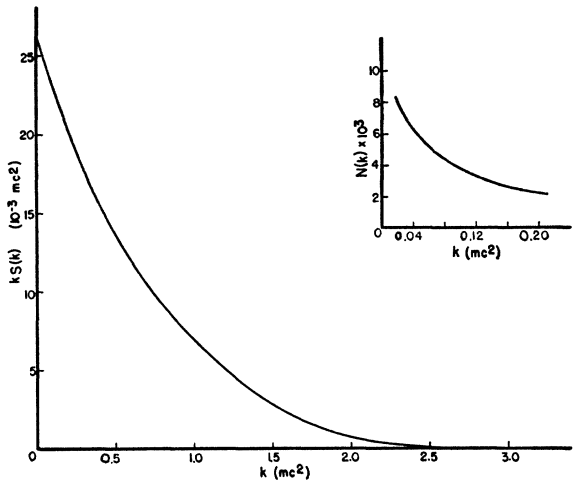

FIG. 1. IB spectrum predicted by KUB theory for $W_0=3.860$. k is the IB energy and $S(k)$ the IB intensity. The inset shows the variation with energy of the number, $N(k)$, of IB per beta-particle having energies greater than k.

at the lower end of the periodic table because of the following considerations. High Z positron emitters are rare, K-capture being the predominant mode of decay. In addition, Auger electrons from high Z atoms have energies in the range in which one would like to make measurements; this is not the case for $Z<25$. Finally, when a theory is proposed for the process, it will probably be based upon a Born approximation, which becomes less valid with increasing Z. Comparison of experiment and theory would thus be facilitated by the use of a low Z isotope. Other desirable features of the isotope are that it be easy to obtain, have a reasonably long life, and have a simple, high energy mode of decay.

III

It is the purpose of this research to investigate the existence of a mode of beta-disintegration in which the energy released by the nucleus is shared among three particles: beta-particle, neutrino, and orbital electron. The method of the research is to determine the existence, energy distribution, and relative intensity of the orbital electrons ejected during the decay of a positron emitting isotope.

EXPERIMENTAL APPARATUS AND PROCEDURE

The isotope chosen for the experiments was Sc^{44}. The decay scheme of Sc^{44} is believed to be thoroughly understood[16] (see Fig. 2), and it has most of the desirable properties discussed above.

Two 180° focusing, shaped magnetic field spectrometers were employed in these studies, one[17] having a 15-cm radius of curvature, and the other[18] having a 40-cm radius of curvature (hereafter referred to as the "small" and "large" spectrometers, respectively).

[14] C. S. Wang Chang and D. L. Falkoff, Phys. Rev. **76**, 365 (1949).

[15] An electron distribution which might be the result of such a process has been observed by L. M. Langer and R. D. Moffat, Phys. Rev. **80**, 651 (1950).

[16] J. A. Bruner and L. M. Langer, Phys. Rev. **79**, 606 (1950).

[17] J. A. Bruner and F. R. Scott, Rev. Sci. Instr. **21**, 545 (1950).

[18] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).

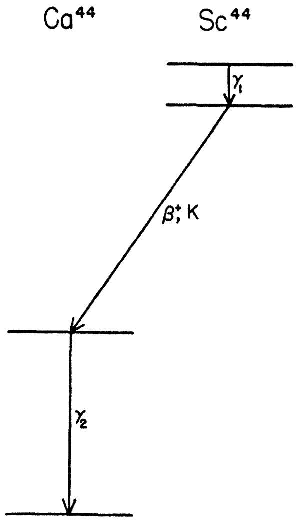

FIG. 2. Decay scheme for Sc^{44}. γ_1 has an energy of 271 kev and a period of 57 hr; the 4.0-hr positron group has an end-point energy of 1.463 Mev ($W_0 = 3.860\ mc^2$); γ_2 has an energy of 1.16 Mev.

Essentially three different experiments were performed; these will be described separately, but all three had the following features in common. Sc^{44} was produced by the reaction $K^{41}(\alpha,n)Sc^{44}$. An enriched sample (99 percent K^{41}, 1 percent K^{39})[19] of K^{41} in the form of KCl was bombarded with 17-Mev alpha-particles in the cyclotron. Scandium was then separated chemically from the KCl in the manner described in the Appendix, but with the differences noted below.

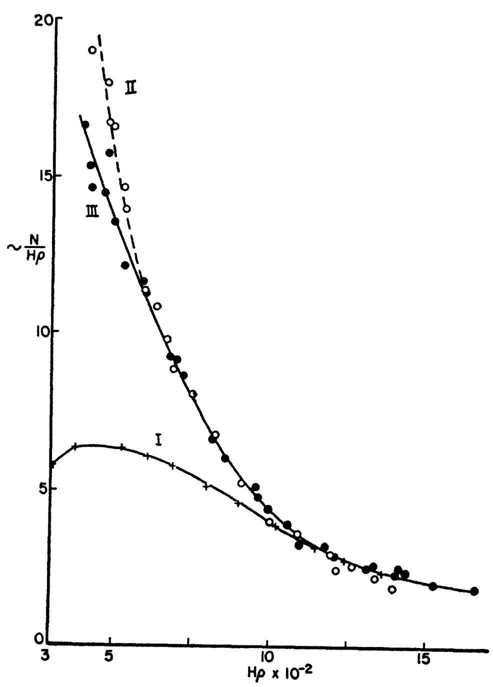

FIG. 3. Momentum spectrum of IB electrons from Sc^{44}. Crosses represent data from Experiment I, open circles from Experiment II, and closed circles from Experiment III. Curves are normalized to equal positron intensity.

[19] Supplied by the Y-12 Plant, Carbide and Carbon Chemicals Corporation, on allocation by the Isotopes Division of the United States AEC.

Sources were prepared by depositing the radioactive solution on a backing of 6 $\mu g/cm^2$ Zapon and drying it. The sources were electrically grounded at one end with 0.18 mg/cm^2 aluminum leaf. Sources for the small spectrometer measured 2 cm by 0.3 cm, and those for the large spectrometer 2.7 cm by 0.6 cm. Unfortunately, source thicknesses could not be measured accurately, partly because $ScCl_3$ is hygroscopic, and partly because the laboratory balance has a sensitivity of only 0.1 mg. Source intensities were of the order of 1 millicurie.

The G-M counters had windows of about 3 $\mu g/cm^2$ Zapon and were filled with about 2.7 cm of a 2–1 ethylene-argon mixture.

In each case the negatron spectrum was measured over the range of about 10 to 150 kev, and several points were taken on the positron spectrum to determine the magnitude of the positron decay process. Negatron measurements were not extended much beyond 150 kev because of the very low counting rates encountered. The decay of the source material was followed automatically in the manner described before.[16]

Experiment I

About 380 mg KCl was bombarded for 4 hours with a total of 150 microampere hours of alpha-particles. In the chemical separation 50 μg Sc carrier was added.

The electron momentum distribution was measured in the small spectrometer over the range 300 to 1400 $H\rho$; this distribution is labeled I in Fig. 3. The maximum counting rate was about 2500 per minute—roughly 5 times the background rate. At least 1000 real counts were taken at each point.

An end window counter was employed, in which the glass bead was 1 cm behind the window. The source thickness was estimated to be about 80 $\mu g/cm^2$.

Experiment II

Somewhat less than 380 mg KCl was bombarded for 4.5 hours with a total of 100 μamp hr of alpha-particles. In the chemical separation 20 μg carrier was added.

The electron momentum distribution was measured in the large spectrometer over the range 400 to 1400 $H\rho$; this distribution is labeled II in Fig. 3. The maximum counting rate was about 250 per minute—roughly 10 times the background rate. At least 1000 real counts were taken at most points.

A side window counter was used in order to determine the transmission of the gas in the "dead space" of the end window counter used in Experiment I. The source thickness was estimated to be about 50 $\mu g/cm^2$.

Experiment III

About 300 mg KCl was bombarded for 5 hours with a total of 120 μamp hr of alpha-particles. In the chemical separation only 10 μg carrier was added; this was not quite sufficient to remove all the activity. In addition, no NH_4OH was required to produce alkalinity: the dissociation of the KCl by the bombardment and the subsequent escape of chlorine left an excess of positive potassium ions which combined with water to produce enough KOH for alkalinity. The consequent absence of ammonium salts is believed to have reduced the source thickness substantially. The source thickness was estimated to be no more than 20 $\mu g/cm^2$.

The electron momentum distribution from 400 to 1650 $H\rho$ was measured in the small spectrometer using a side window counter; this distribution is labeled III in Fig. 3. The maximum counting rate was about 1000 per minute—roughly 8 times the background rate. At least 3000 real counts were taken at most points.

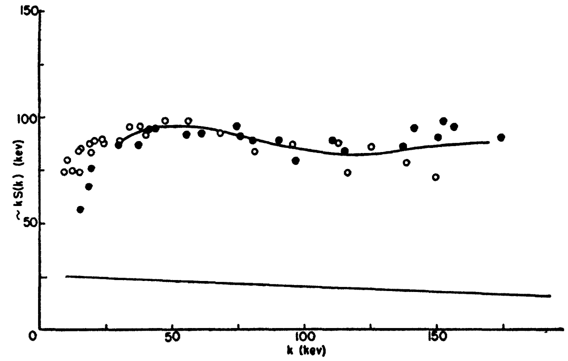

FIG. 4. Data plotted in the manner suggested by KUB. Open circles are from Experiment II, closed circles from Experiment III. The lower curve is a section of the theoretical IB spectrum shown in Fig. 1.

RESULTS

A. Momentum Distribution

The measured momentum distributions are shown in Fig. 3. The three curves are normalized to the same intensity relative to the intensity of the positrons. The agreement between Experiments II and III is very good over the range above about 650 $H\rho$, but both are in disagreement with Experiment I below 1100 $H\rho$. Below 650 $H\rho$ curves II and III also diverge. As will be shown later, spectrum I is distorted because of variable counter sensitivity; henceforth, unless otherwise stated, we shall restrict our attention to Experiments II and III.

B. Comparison with the Predicted IB Spectrum

In Fig. 4 the data from Experiments II and III are plotted in the manner suggested by KUB, and underneath is the theoretical curve for IB. The data and theoretical curve are adjusted to the same positron intensity.

C. IB Internal Conversion Coefficient

One can define a conversion coefficient, γ, for IB as

$$\gamma(k)=N_e(k-K)/N_{IB}(k),$$

where $N_e(k-K)$ is the measured number of electrons with energy $k-K$, $N_{IB}(k)$ the predicted number of IB with energy k, and K the binding energy of an electron in the K-shell (we neglect conversion in higher shells). Figure 5 shows the results of such calculations. For comparison purposes, in the same figure is presented the electric dipole K-shell conversion coefficient for $Z=20$. (This curve is extrapolated from the calculated values of Reitz.[20]) It should be mentioned that this particular coefficient has no special significance other than to illustrate the rapid variation with energy which is characteristic of conversion coefficients of all multipole orders. The contrast between the two curves is apparent; the IB coefficient is essentially constant over the range measured, while the dipole coefficient varies by a factor of about 200.

[20] J. R. Reitz, Phys. Rev. 77, 10 (1950).

DISCUSSION OF RESULTS

In order to interpret the results accurately, one must examine all the possible sources of error and evaluate the probable error contributed by each.

A. K-Capture

Morrison and Schiff[21] have calculated theoretically that IB is to be expected from K-capture transitions with a total probability of $\alpha(W_0+1)^2/12\pi$ per K-capture event. There is a striking difference, however, in the predicted IB intensity distribution compared to that accompanying beta-emission: the predicted spec-

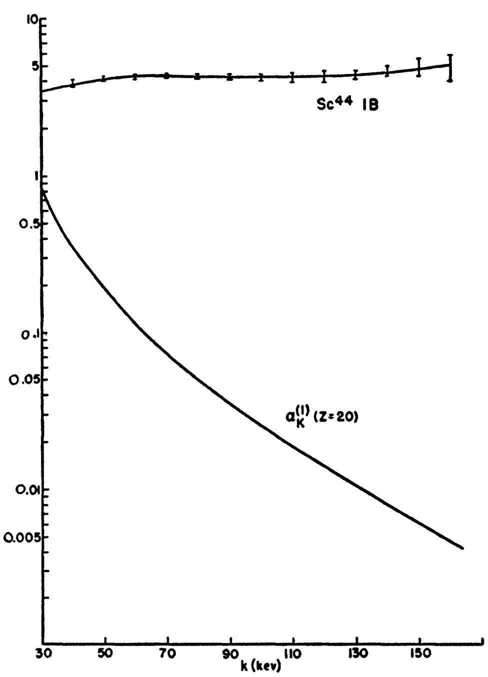

FIG. 5. Comparison of Sc^{44} "IB internal conversion coefficient" with the conversion coefficient for ordinary nuclear electric dipole radiation. The "error" symbols represent the spread in the experimental data.

[21] P. Morrison and L. I. Schiff, Phys. Rev. 58, 24 (1940).

tral shape for IB from K-capture is given by

$$S(k)dk=\alpha\{1-k/(W_0+1)\}^2kdk/\pi.$$

The intensity is clearly zero at $k=0$ and $k=W_0+1$, and has a maximum at $k=(W_0+1)/3$. For Sc^{44}, then, it turns out that the number of IB per K-capture is 0.6α, and that only 5 percent of the IB have energies less than 200 kev.

From the intensity measurements on the photoelectrons from the positron annihilation radiation and the 1.16 Mev gamma-ray,[16] it was concluded that the K-capture-to-positron ratio is about 0.5. With these values we are now in a position to calculate the relative numbers of IB with energies in the range 0 to 200 kev to be expected from K-capture and positron emission. For K-capture the number is $0.05(0.6\alpha)(0.5)=0.015\alpha$, and, as we have seen, the number for positron emission is about α. Hence it follows that less than 2 percent of all Sc^{44} IB of energy less than 200 kev will have their origin in K-capture events.

B. Purity of Source

(1) *Purity of separated isotope.*—The mass analysis accompanying the sample of KCl listed the relative percentages of potassium isotopes as follows: K^{39}, 1.04 ± 0.03; K^{40}, 0.023 ± 0.005; K^{41}, 98.94 ± 0.03. The spectrographic analysis yielded the following percentages of impurities: Cu, less than 0.04; Mg, less than 0.02; Na, 0.15; Li, less than 0.15. The only isotope in this sample which, after an alpha-particle bombardment, would yield radioactivity detectable in the present experiments is K^{41}.

(2) *Purity of source material.*—The bulk of the activity produced by alpha-bombardment of the target material is, of course, Sc^{44}. However, the measurements of the positron spectrum[16] of Sc^{44} showed that about 10 percent of the nuclear transmutations were by $K^{41}(\alpha,2n)Sc^{43}$. In addition, Ga^{66} and Ga^{68} are produced in the copper target plate, and a small amount of copper is scraped loose when the target material is removed from the plate. The gallium activity, while detectable, was always less than 1 percent of the total.

Sc^{43} has a period (4 hr) comparable to that of Sc^{44}, so that it was not feasible to permit it to decay away before starting measurements, but its positron end point (1.13 Mev) is considerably lower than that of Sc^{44}, thus giving rise to a lower relative IB intensity. It is safe, therefore, to set an upper limit of 10 percent to the error caused by impurities in the source.

C. Scattering

(1) *Outside the vacuum chamber.*—Although the counter was shielded from the source by lead blocks and the thick magnet core, the intense gamma-radiation was still sufficient to raise the background counting rate by a factor of from 3 to 10 over the normal rate. The background was always closely monitored, however, so that its sole contribution to error lay in raising the standard deviation of the computed IB electron counting rate.

(2) *Inside the vacuum chamber.*—Under the heading of "scattered electrons" in this section are included: positrons scattered from vacuum chamber walls; scattered conversion electrons from the Sc^{44} gamma-rays; Compton and photoelectrons produced by radiation from the annihilation of positrons in the walls; electrons from pair production by the 1.16-Mev gamma-rays in the walls—in short, any electrons which enter the counter from the vacuum chamber and either do not originate in the source material or originate in the source material and undergo one or more collisions outside the source before being counted.

Three effects served to indicate that essentially all the electrons entering the counter from the vacuum chamber were "focused" (that is to say, unscattered) electrons. The first of these effects was found by chance. In the course of an experiment with the small spectrometer it was discovered that the detector slit was displaced radially from its optimum position. To rectify this, the slit width was doubled, so as to include more of the focal area. Now if the electrons were scattered electrons, one would expect the counting rate to be exactly doubled. In fact, the counting rate increased by a factor considerably greater than 2, indicating that at least a large fraction of the electrons were not the result of scattering.

The two most cogent arguments, though, arise from comparing the measurements made in the two different spectrometers. First, the measured shapes of the negatron spectrum agreed very closely over the accurately measurable energy range. Second, the measured relative intensities (that is, relative to the positron intensity) of the negatrons were the same within the experimental error of about 2 percent. Now since the scattering processes are dependent upon the geometry of the vacuum chamber, both the energy distribution and the relative intensity of scattered electrons will be different in the two spectrometers. It must be concluded, therefore, that scattered electrons make a very small contribution to the measured negatron intensity.

D. Possible Alternative Negatron Origins

Having ascertained that the electrons originate in the source material, we must now examine the evidence that they have their origin in the IB process. The evidence is of an indirect kind; we consider, and hope to be able to discount, the other possibilities for the electron origin.

(1) *β^- spectrum.*—The obvious question to be answered initially is whether the electrons are true beta-particles. The answer is equally obvious, however, from the momentum spectrum. The spectrum does not resemble a beta-spectrum; on the contrary, the electron intensity increases monotonically with decreasing energy. Hence we can safely say that the electrons are not beta-particles.

(2) *Internal conversion of K−L x-rays (Auger electrons).*—X-radiation following K-capture will be highly internally converted, but the conversion electrons will all have energies (approximately) equal to the difference in binding energy of electrons in the K and L shells. For calcium ($Z=20$) this difference is only about 4 kev, which is below the measured energy range.

(3) *Photoelectrons and Compton electrons produced in the source material by the Sc^{44} gamma-rays.*—Simple calculations show that, of these processes, the production of Compton electrons by the 271-kev gamma-ray is by far the most probable; the probability of such a gamma-ray producing a Compton electron is 0.11 per g/cm^2 source thickness. For the sources used, this probability is of the order of 10^{-5} or less. In addition, the measured distribution does not resemble a Compton distribution, and the photoelectrons would not have energies in the measured range.

(4) *Photo- and Compton electrons produced in the source material by IB.*—These effects are more probable than the immediately preceding ones, because both the photo- and Compton cross sections increase with decreasing gamma-ray energy. At energies less than 80 kev the photoelectrons will be the more intense. Assuming the theoretical IB distribution to be correct, and using the known photoelectric cross sections, it can easily be shown that the number of photoelectrons per IB per mg/cm^2 source thickness varies from 10^{-1} at 10 kev to 10^{-3} at 45 kev to 10^{-5} at 160 kev. The total contribution of photoelectrons and Compton electrons to the measured electron intensity has a maximum of at most 0.3 percent at 10 kev and is considerably less at higher energies.

(5) *Internal pair production by the 1.16-Mev gamma-ray.*—The probability of this phenomenon occurring, as calculated by Rose and Uhlenbeck[22] and Jaeger and Hulme,[23] is about 5×10^{-5} pair per gamma-ray. The energy distribution of the negative electrons decreases roughly linearly from 10^{-4} per gamma-ray at zero energy to 0 at about 150 kev. The maximum contribution to the measured negatron intensity is about 4 percent at about 75 kev; it is about 1 percent at 10 kev and 0 at 150 kev.[24]

(6) *Internal pair production by the Sc^{44} positrons.*—According to Bradt,[25] this process is about 100 times less probable than the last one mentioned above.

(7) *Recoil electrons from the scattering of Sc^{44} positrons in the source material.*—We should like to know how many of the detected electrons were ejected from the source material because of collisions with the Sc^{44} positrons. To compute this number we would need to know the form of the interaction between positron and negatron. Unfortunately, to quote Heitler,[26] "In the present theory of the positive electron this interaction is not included in a satisfactory way." As a result we must base our argument on less quantitative grounds.

The number of scattering processes occurring would certainly vary directly as the source thickness. In these experiments sources were used which differed in thickness by a factor of about 2 to 3; hence one would expect a 2- to 3-fold increase in the number of spurious counts. What actually was observed, however, was essentially no difference in the measured spectra down to an energy of about 35 to 40 kev. As we shall see, the deviation at this point can be explained satisfactorily in another manner. Hence we conclude that the number of recoil electrons is inappreciable.

(8) *Rearrangement of atomic electrons.*—During positron emission the atomic number decreases by one, and therefore the binding energy of all the atomic electrons also decreases. One might wonder if this energy release would be sufficient to accelerate an electron into the measured energy range. A simple computation shows, however, that the available energy is less than 1 kev.

E. Additional Causes for Possible Spectrum Distortion

In the preceding section we have presented the evidence that most of the detected electrons had their origin in the IB-type process. Next we must determine to what extent the measured spectra were distorted by other causes.

The mere fact that the spectra, as measured in different spectrometers using sources of different thicknesses, agree so well down to an energy of about 35 kev is strong evidence that the measured spectrum is the correct one over the range of about 35 to 150 kev.

(1) *The effects of source thickness.*—The increased number of low energy electrons in Experiment II is believed to be caused by backscattering in the thicker source used. This is substantiated by the following considerations. Hamilton and Gross,[27] by examining all data through July, 1949, on negatron activities for which good information on source thickness is available, have determined an empirical relation between source thickness and the energy at which deviations from a straight line Fermi plot occur. This relation is

$$V_k = 1700(Z^2t/A)^{\frac{1}{2}},$$

where V_k is the critical energy in kev, and t is the source thickness in g/cm^2. For $ScCl_3$, the average Z and A are 18 and 38, respectively. Substituting $V_k=35$ and solving for t, we find $t=50\ \mu g/cm^2$, which is better agreement with the estimated value than one has any right to expect. For the thinner source, substituting $t=20\ \mu g/cm^2$, we find $V_k=22$ kev. It is, therefore,

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[22] M. E. Rose and G. E. Uhlenbeck, Phys. Rev. **48**, 211 (1935).
[23] J. C. Jaeger and H. R. Hulme, Proc. Roy. Soc. (London) 148, 708 (1935).
[24] These numbers are based on the assignment (see reference 16) of an *EQ* or *MD* character to the gamma-ray.
[25] H. Bradt, Helv. Phys. Acta **17**, 1 (1944).
[26] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1944), second edition, p. 198.
[27] D. R. Hamilton and L. Gross, Rev. Sci. Instr. **21**, 912 (1950).

believed that in Experiment III the spectrum is undistorted by source thickness down to at least 25 kev.

(2) *The effects of absorption in counter gas and counter window.*—In a side window counter, once an electron passes through the window it is counted. In every experiment the Zapon window thickness was 3 $\mu g/cm^2$; such windows have effectively 100 percent transmission down to at least 20 kev.

In the end window counter used in Experiment I, electrons were required to traverse about 50 $\mu g/cm^2$of counter gas before entering the region in which they were counted. The resulting effect on the counting rate is shown in Fig. 3. The transmission of the counter gas varies from 100 percent at about 100 kev to 50 percent at about 30 kev. (Part of this effect, however, is probably caused by increased source thickness.)

F. Final Judgment of Accuracy

In view of the possible sources of error discussed, the accuracy of the measured electron spectrum between 30 and 150 kev is judged to be: +3 percent, −20 percent.

G. Balance of Energy

So far we have presented the evidence for the assertion that the electrons detected were actually formed in the IB process and that the energy spectrum measured is the correct one. At this point it might be well to consider another question: that of the balance of energy. If, as these experiments indicate, the beta-decay process involves three emitted particles about 4 percent[28] of the time, could one detect the difference between the resulting beta-spectrum and that predicted on the basis of purely two-particle emission? The answer is, probably not. The average energy decrease per positron is about 5 kev;[28] the decrease is less at low energies and greater at high energies. The point is that the energy loss is so "smoothed out" over the spectrum that it is unlikely to be detected in experiments of present day precision.

H. Internal Conversion Coefficient

The measured IB internal conversion coefficient and its energy dependence bear no resemblance to a conversion coefficient for any multipole order nuclear gamma-radiation. Is this to be expected or not?

An argument that it is not to be expected in the following. The de Broglie wavelength, $\lambdabar = \hbar/p$, for positrons of energy greater than 5 kev is less than the radius of the Sc^{44} K-shell; that is, all positrons with more than 5-kev energy are created within the K-shell. One might expect, then, that the electromagnetic field experienced by a K electron would not be greatly different from that produced by the nucleus before beta-emission.

[28] This number will no doubt vary from one isotope to another.

The experiments show, however, that either this argument or the KUB theory is wrong. The former seems to be the more probable. Certainly, an exact theoretical treatment of the phenomenon is desirable.

CONCLUSIONS

These experiments indicate the existence of a mode of beta-disintegration in which the energy emitted is shared by three particles: beta-particle, neutrino, and orbital electron. The energy spectrum of the ejected orbital electrons (IB electrons) from Sc^{44} has been measured over the range 30 to 150 kev. The IB internal conversion coefficient—that is, the ratio of the measured number of IB electrons to the number of IB predicted by the KUB theory—was found to be essentially constant over the measured energy range, and equal to 4.3. The frequency with which the three-particle disintegration takes place is about 0.04 times that of ordinary decay into a beta-particle and a neutrino. The measurements have an estimated accuracy of +3 percent, −20 percent.

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APPENDIX.

CHEMISTRY OF SCANDIUM

To separate scandium from KCl:

(1) Prepare 20 cc of carrier solution of Sc_2O_3 in HNO_3, containing 10 to 50 μg Sc.
(2) Dissolve KCl in this solution.
(3) Precipitate $Sc(OH)_3$ by adding NH_4OH.
(4) Filter through a fritted glass funnel, and wash with 50 cc hot H_2O. Remove filtrate and save.
(5) Wash precipitate with hot H_2O to remove NH_4 salts.
(6) Dissolve precipitate in 15 cc hot 6 N HCl, and wash with a small account of H_2O to remove all HCl.
(7) Evaporate to dryness, then dissolve in 2 or 3 drops H_2O.