Beta-Ray Spectra of Scandium

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The positron spectrum of Sc^{44}, and the electron spectrum of Sc^{48} have been measured by a spectrometer of high resolution. A Kurie plot of the spectra shows that neither satisfies the Fermi distribution for an "allowed disintegration." The maximum energy of the positrons is 1.45 ± 0.01 Mev, and of the electrons 640 ± 4 kev. Other activities in scandium were too weak to be measured. The spectra have been corrected for width of the slits of the spectrometer, and an experimental check on the accuracy of the correction obtained. The positron decay curve may be resolved into two components, of 4-hr. and 52-hr. half-life, due to a 52-hr. γ-ray transition to the 4-hr. Sc^{44} positron-emitting level. The conversion coefficient of the γ-ray is 0.070 ± 0.012, corresponding to a change of angular momentum of 3 units in the transition. The excitation energy of the γ-ray for deuteron bombardment has been obtained as 4.0 ± 0.2 Mev.

THE well-known Fermi theory of β-decay[1] gives an explicit expression for the shape of the β-spectrum of radioactive disintegrations for allowed transitions. The distribution function is seen to be rather sensitively dependent upon the maximum energy of the radioactive transition. Recently, Uhlenbeck and Konopinski[2] have been able to formulate the theory for forbidden transitions, which is given in the form of a correction factor to the Fermi distribution function. To be able to classify a given radioactive disintegration as allowed, or forbidden, it is then necessary to measure both the shape of the spectrum, and its upper end point with the maximum precision possible.

An isotope of scandium was one of the first elements to be formed by an artificial disintegration due to bombardment,[3] and a considerable amount of work in the identification and classification of the radioactive isotopes of scandium has already been reported. Scandium is interesting in that it has only one stable isotope, Sc^{45}, whereas the latest systematic classification gives it at least seven radioactive ones, of weights 41, 42, 43, 44, 46, 48, 49.[4,5] Where measured at all, the spectra had been observed by cloud-chamber methods. It seemed worth while to re-examine the spectra more exactly, namely by the β-ray spectrometer. Preliminary results have been reported previously.[6] The instrument used is a high resolution 180° focusing type, with radius of curvature of the β-particles 12 cm and has previously been described.[7]

Preliminary deuteron bombardments of calcium, alpha-particle bombardments of potassium and calcium, and irradiation of titanium with neutrons from the (Be-n) reaction, showed that the calcium-deuteron reactions were the only ones which gave intensities of radioactive spectra great enough to be measured accurately in the beta-ray spectrometer. No bombardments were made of scandium because of the requirement of a very thin sample for the spectrometer. No activities were found which conflict with the final assignments of the isotopes made by Walke.[4]

Calcium, in the form of the metal, or the oxide or hydroxide, was bombarded with 9.5 Mev deuterons at average beam currents of 8–10 microamperes, irradiations lasting for as long as 175 microampere hours. The entire sample was dissolved in a minimum of concentrated HCl, and after a preliminary filtering to remove any traces of dust and other impurities which were not acted on by the HCl; 0.1 mg carrier was added, and the scandium deposited as the hydroxide by filtering through a funnel whose base, held tightly against a filter paper, was formed into a slit of the desired size. The filter paper weighed about 3 mg/cm^2. The active

* Now with Corning Glass Works, Corning, New York.
[1] E. Fermi, Zeits. f. Physik **88**, 161 (1934).
[2] G. E. Uhlenbeck and E. J. Konopinski, Phys. Rev. **60**, 308 (1941).
[3] M. Zyw, Nature **134**, 64 (1934).
[4] H. Walke, Phys. Rev. **57**, 163 (1940).
[5] L. D. P. King and D. R. Elliot, Phys. Rev. **59**, 168A (1941).
[6] G. P. Smith, Phys. Rev. **59**, 937A (1941).
[7] J. L. Lawson and A. W. Tyler, Rev. Sci. Inst. **11**, 6 (1940).

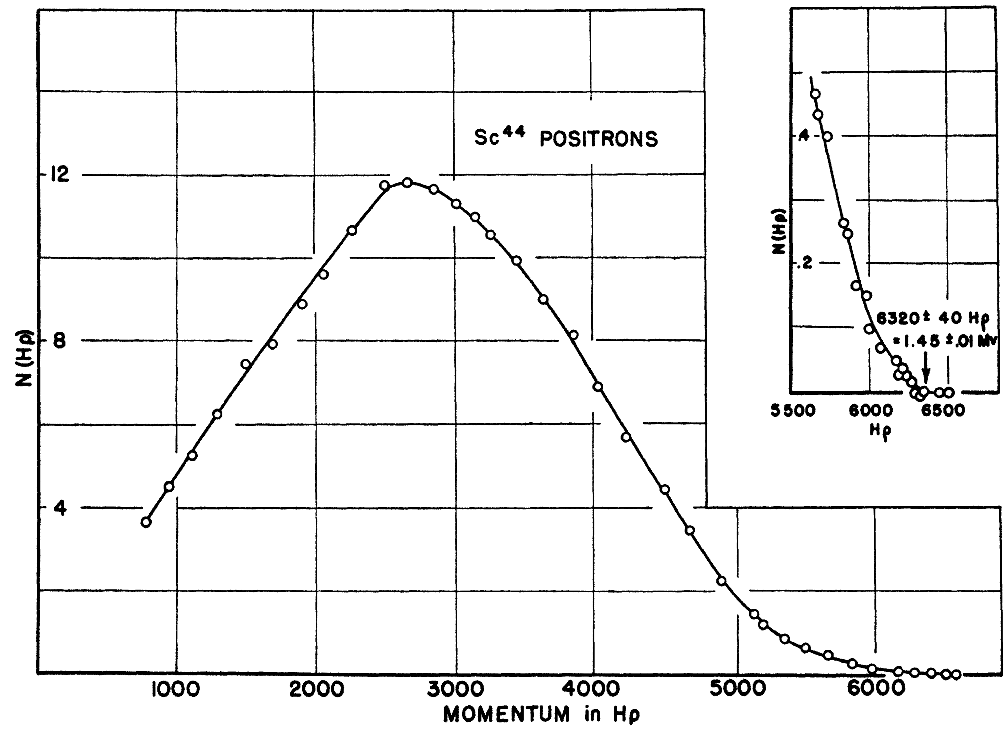

FIG. 1. The positron spectrum of Sc^{44}.

scandium deposit was covered with a very thin layer (<0.05 mg/cm²) of collodion, and placed in the spectrometer. Experiments of Lawson[8] have shown that the scattering due to the filter paper and collodion is probably negligible.

When examined in the spectrometer, both electron and positron spectra were found, along with a line of conversion electrons. They are shown in Figs. 1 and 2. Each has been corrected for background counting rate, efficiency of the counter, absorption in the counter window, counting losses in the scale-of-64 recording circuit, and decay of the source during observation. Decay curves of the various components of the observed spectra are shown in Fig. 3.

THE SPECTRUM OF Sc^{44}

The positron spectrum of the separated scandium has an end point at 1.45 ± 0.01 Mev, and by measuring the activity as a function of time for a particular value of $H\rho$, a decay curve with two components, 4.1 ± 0.1 hr., and 52 ± 2 hr., was obtained. To identify these two components, previously suggested to be isomers,[4, 9] several tests were made, from which the following conclusions may be drawn:

1. The shape of the observed spectrum does not change with energy of the bombarding deuterons. This indicates that there is only one responsible isotope; the excitation functions of two different isotopes are almost certainly widely different, and the shape of the spectrum, if complex, should change with bombardment energy.

2. The shape of the decay curves taken for several different values of $H\rho$ remains the same. If there were two superposed spectra, with presumably different half-lives and different maximum energies, the decay rate would be dependent on the $H\rho$ of the point considered.

3. The upper end point was also constant with time. Within the statistical fluctuations of the very weak activity near the maximum energy, the end-point energy is the same for the 4.1-hr. and the 52-hr. periods.

Since, therefore, the 4.1-hr. and the 52-hr.

[8] J. L. Lawson, Phys. Rev. **56**, 131 (1939).

[9] J. M. Cork and R. L. Thornton, Phys. Rev. **53**, 866 (1938).

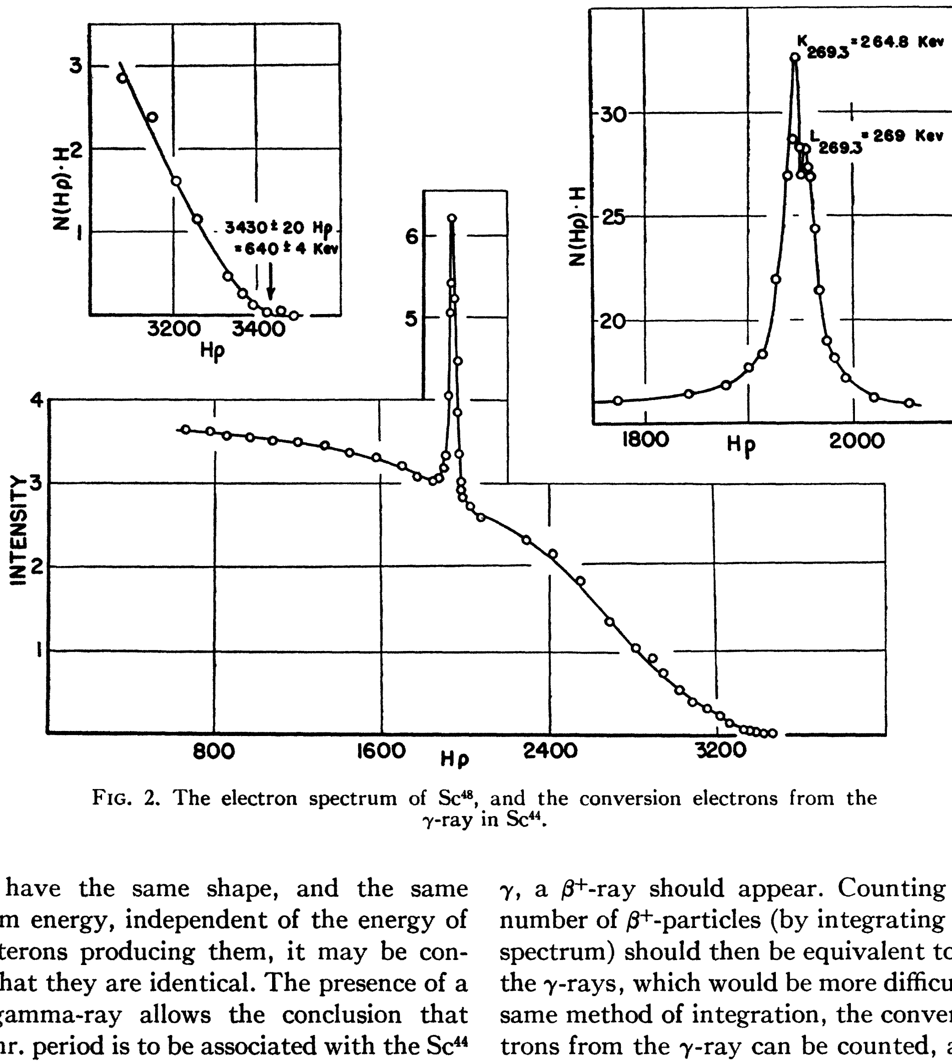

FIG. 2. The electron spectrum of Sc^{48}, and the conversion electrons from the γ-ray in Sc^{44}.

spectra have the same shape, and the same maximum energy, independent of the energy of the deuterons producing them, it may be concluded that they are identical. The presence of a 52-hr. gamma-ray allows the conclusion that the 4.1-hr. period is to be associated with the Sc^{44} level. After the active atoms originally on the Sc^{44} level have all decayed, the level is still being supplied with Sc^{44} atoms from the γ-ray transition with a 52-hr. half-life from Sc^{*44}, 269 kev above the Sc^{44} level. Since Sc^{44} has a relatively short half-life the positrons then appear with the half-life of the parent, 52 hours. Intensities extrapolated to the end of bombardment of the 52-hr. and 4.1-hr. components indicate that both scandium levels are formed in the bombardment.

INTERNAL CONVERSION OF THE GAMMA-RAY

After all the excited nuclei originally on the Sc^{44} level have disintegrated with the 4.1-hr. period, every positron which appears should have been produced by a γ-transition, and so for each γ, a β^+-ray should appear. Counting the total number of β^+-particles (by integrating under the spectrum) should then be equivalent to counting the γ-rays, which would be more difficult. By the same method of integration, the conversion electrons from the γ-ray can be counted, and hence the internal conversion coefficient for the γ-ray obtained. Three samples gave 0.064 ± 0.015, 0.10 ± 0.02, and 0.077 ± 0.010, of which the last is seen to be the most accurate.[10]

Hebb and Uhlenbeck,[11] and others[12] have calculated the probability that a γ-ray of given energy in a transition between two states whose angular momentum difference is known, will be

[10] A. C. Helmholz [Phys. Rev. **60**, 415 (1941)] has estimated the conversion coefficient of this γ-ray by comparing the number of conversion electrons with the number of photoelectrons from lead. He obtained $\alpha = 0.5$ corresponding to $l = 4$. The half-life of the radiation does not agree with computed λ's for any l, and hence cannot be used to determine uniquely the spin change.

[11] M. H. Hebb and G. E. Uhlenbeck, Physica **7**, 605 (1938).

[12] S. M. Dancoff and P. Morrison, Phys. Rev. **55**, 122 (1939).

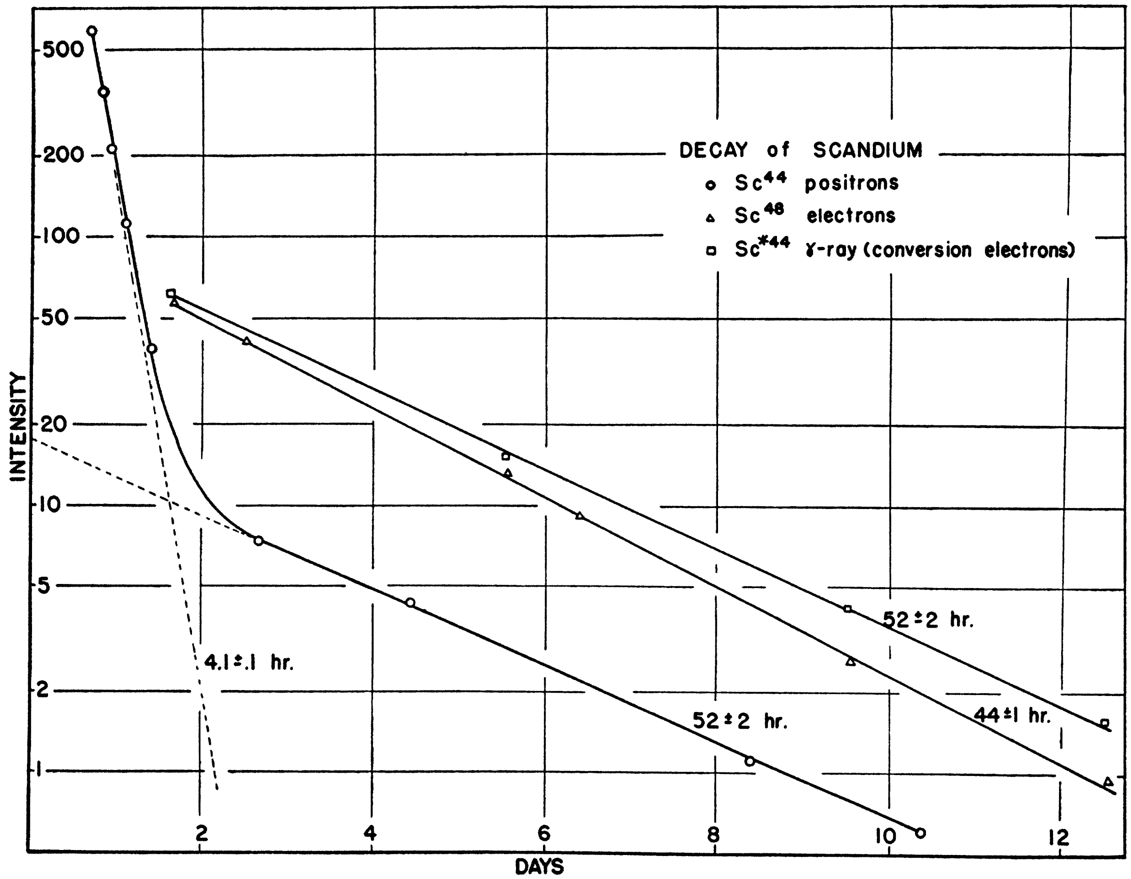

Fig. 3. Decay curves of the scandium isotopes.

internally converted. For light nuclei, up to $Z\sim30$, the probability may be computed non-relativistically. For scandium, $Z=21$, and for a γ-ray transition between two states of energy difference 269.3 kev, the expected ratio of electrons to γ-ray quanta depends on the change in angular momentum in the following way:

l	1	2	3	4
N_e/N_q	0.00084	0.0047	0.084	0.308

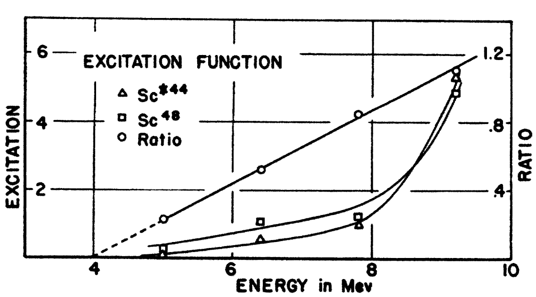

Fig. 4. Excitation energy of the 269-kev γ-ray.

for conversion in the K shell only. Conversion in the L shell must be added to this, which would increase the ratio somewhat. Curves drawn by Hebb and Nelson give for a γ-ray of 269 kev in scandium, the ratio $\alpha_K/\alpha_L=11$, with a possible error of 10–20 percent, and almost independent of the angular momentum change. From the known shape of electron conversion lines in the spectrometer, the observed conversion electron spectrum may be approximately resolved into two components due to conversion in the orbital electron shells. This gives $\alpha_K/\alpha_L=8\pm50$ percent, in fair agreement with theory. The corrected experimental value of N_e/N_q is then 0.070 ± 0.012, which when compared with the values given in the table above, indicates that this is an electric octopole radiation; change of angular momentum $=3$.

EXCITATION ENERGY OF THE γ-RAY

The spectrometer affords an accurate method of measuring the excitation energy of the Sc^{*44}

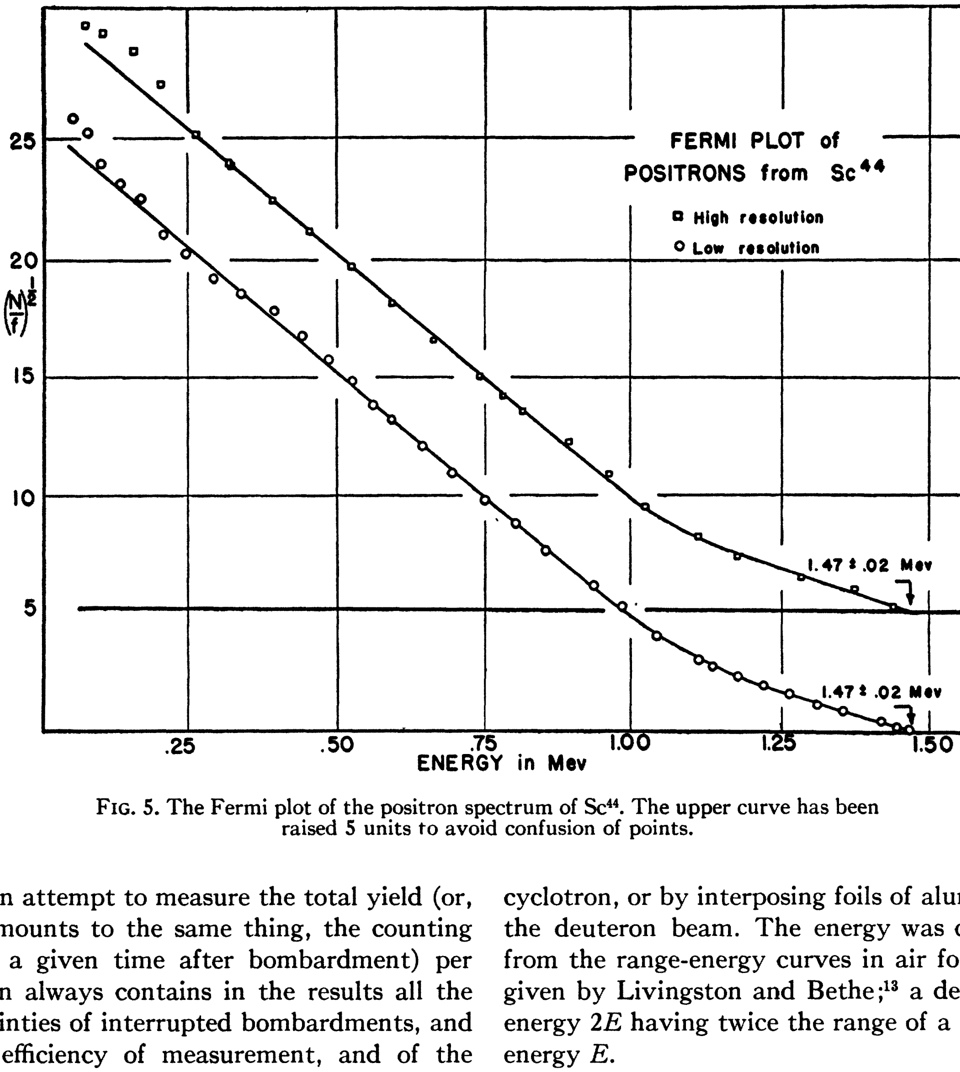

FIG. 5. The Fermi plot of the positron spectrum of Sc^{44}. The upper curve has been raised 5 units to avoid confusion of points.

level. An attempt to measure the total yield (or, what amounts to the same thing, the counting rate at a given time after bombardment) per deuteron always contains in the results all the uncertainties of interrupted bombardments, and of the efficiency of measurement, and of the efficiency of the chemical separation. However, in the spectrometer, the γ-ray of the Sc^{*44}—Sc^{44} transition appears superposed on the continuous spectrum of Sc^{48}. In measuring the two spectra, the same uncertainties, (and of the same amount and sign) are present in both. The ratio of the two then results in considerably more significant data than either taken separately, especially as the general excitation energy curve goes to zero somewhat asymptotically. Figure 4 shows the counting rate per microampere hour of bombardment, for Sc^{*44}, Sc^{44}, and their ratio. The indicated energy of excitation by deuterons for the Sc^{*44} level is seen in Fig. 4 to be 4.0±0.2 Mev. The bombarding energy was changed by either changing the wave-length of the oscillators of the cyclotron, or by interposing foils of aluminum in the deuteron beam. The energy was computed from the range-energy curves in air for protons given by Livingston and Bethe;[13] a deuteron of energy $2E$ having twice the range of a proton of energy E.

EFFECT OF SLIT WIDTH ON THE SHAPE OF THE SPECTRUM

The observed spectra have also been corrected for the effect of a finite slit width, by choosing a suitable average radius of curvature of the particles. To test this quantitatively, sources were prepared for a slit width of 3 mm and of 1 mm and the positron spectra of each measured separately in the spectrometer. The positrons were measured, rather than the electrons, because of their greater intensity. However, it was impossible to get a source strong enough for the 1 mm slit to give results statistically as good as

[13] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 268 (1939).

for low resolution. The Kurie plot of the two spectra appears in Fig. 5. The two curves have been displaced by one unit on the graph to show more clearly the points on each. They are seen to be parallel, and to have the same extrapolated upper end point, indicating that the effect of a finite slit width may be satisfactorily corrected for in obtaining the true shape of the spectrum.

THE SPECTRUM OF Sc^{48}

The electron spectrum has an upper end point of 3430 ± 30 $H\rho$, corresponding to an energy of 640 ± 4 kev. A plot of the Kurie approximation to the Fermi function gives the curve shown in the Fig. 6. The decay in the spectrometer shows a single half-life 44 ± 2 hr. No electrons of energy greater than 650 kev, either from a continuous spectrum or a converted γ-ray were found.[14] The observed conversion electrons from the K shell occur at 1943 $H\rho$, or 264.8 kev. The conversion in the L shell is seen to be incompletely resolved from the K conversion electrons, but an approximate separation in which the known shape of a conversion line in the spectrometer is used gives for the electrons from the L shell, $H\rho = 1962$, or $E = 269.2$ kev. By adding the binding energies of the K and L electrons obtained from x-ray data, 4.5 and 0.5 kev, respectively, one obtains the energy of the γ-ray as 269.3 ± 1 kev. By subtracting the continuous electron background (which decays with a different half-life) from the conversion electrons, the half-life of the electron line, and hence of the γ-ray, is found to be 52 ± 2 hr.

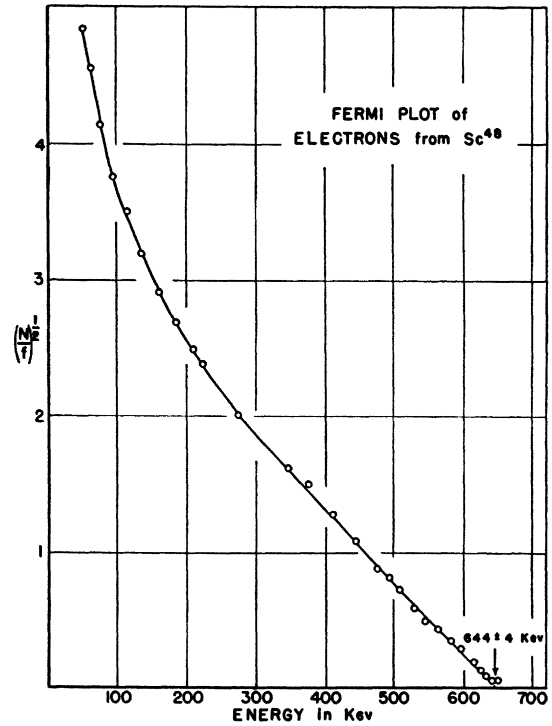

FIG. 6. The Fermi plot of the electron spectrum of Sc^{48}.

I wish to acknowledge the cooperation of Professor J. M. Cork, under whose direction this research was carried out. I am grateful for helpful discussions of theory with Professor G. E. Uhlenbeck. Mr. R. J. Bessey has performed some of the calculations.

[14] Compare H. Walke, reference 4.