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A Magnetic-Lens Electron Spectrometer: Radiations from 5.3 Year Cobalt^{60}

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An improved magnetic-lens spectrometer, similar in principle to that described by Deutsch, Elliott, and Evans [1] has been constructed. The structure, operation, and method of calibration, using a ThB+C deposit, is described. Results of measurements of the primary beta-ray spectrum of Co^{60} and of the gamma-ray spectrum converted in a uranium radiator are given. These give an end point of 0.310 for the value reported by Deutsch, Elliott, and Roberts[2] of 0.308 ±0.008 million electron volt (Mev). Two gamma rays were measured at 1.16 and 1.32 Mev, likewise in agreement with the values of 1.10 ±0.03 and 1.30 ±0.03 Mev, given by the same authors.

I. Introduction

An electron spectrometer for the study of radiations from radioactive substances has been constructed and put into use at the Bureau. The spectrometer is of the magnetic thin-lens type, similar in principle to that built by Deutsch [3] and his coworkers at the Massachusetts Institute of Technology. Many of the modifications incorporated in the Bureau instrument are based on those introduced by R. Wilkinson and W. Rall in the instrument they assembled at Clinton Laboratories in Oak Ridge. A description of some of these features, following that given by them in their classified report on the instrument, is included.

Radiations from 5.3 yr Co^{60} were studied as the initial work.

II. Description of the Spectrometer

The spectrometer tube consists of a cylindrical vacuum chamber. On the axis of the chamber is mounted at one end a source of radioactive material; at the other end is a thin-window Geiger-Müller counter, which acts as a detector. The lens coil is mounted coaxially with the chamber (see fig. 1). The electrons travel down the spectrometer tube, with their paths restricted by a set of baffles.

Electrons of different energies are focused on the counter window by using different currents in the lens coil. Information about the radiations from the source can then be obtained by varying the current through the coil and recording the

[1] M. Deutsch, L. G. Elliott, and R. D. Evans, Rev. Sci. Instr. **15**, 178 (1944).
[2] M. Deutsch, L. G. Elliott, and A. Roberts, Phys. Rev. **68**, 193 (1945).
[3] See footnote 1.

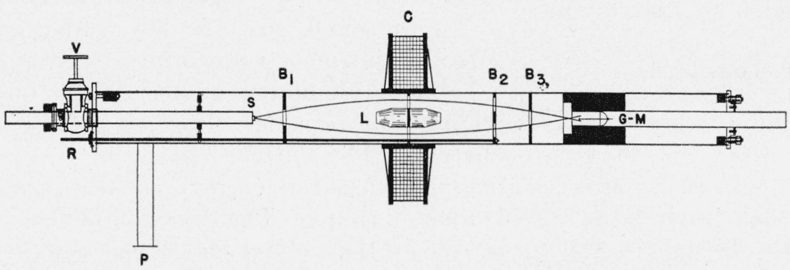

FIGURE 1.—*Longitudinal section of thin magnetic-lens spectrometer.*

B_1, B_3, fixed baffles; B_2, adjustable baffle moved from outside by rod, *R*; *C*, lens coils; *L*, lead baffle at center of lens; *P*, connection to pumps; *S*, source; *V*, gate valve with rubber gasket to close vacuum chamber. *GM*, Geiger-Müller counter with mica window.

number of counts registered by the detector at each current setting.

1. Spectrometer Chamber

The chamber consists of a brass tube 6½ in. in outside diameter, ⅛-in. wall thickness, and about 6½ ft in length. The end plates are grooved and provided with rubber gaskets to make the vacuum seals. The opening through the source end plate is provided with a Wilson seal, through which passes a 1½-in. brass tube on which the radioactive source is mounted. A gate valve with a small chamber at this end, which can be evacuated, provides a means for inserting or removing sources without destroying the vacuum in the main chamber.

The opening through the end plate of the main chamber is also equipped with a Wilson seal to accommodate a 2-in. brass tube, in which the Geiger-Müller counter is mounted. The position of the detector can thus be adjusted without breaking the vacuum in the main chamber.

The pumping system consists of an oil diffusion pump backed by a Cenco Megavac pump. A pressure of about 5×10^{-5} mm of Hg can easily be attained. It was found that for most purposes a pressure of about 10^{-2} mm of Hg, attainable with the Megavac alone, was quite adequate.

The baffle system shown in figure 1 serves to define the transmitted beam and to reduce the undesirable effects due to scattering. The adjustable baffle, B_3, may be moved by means of a ¼-in. rod, R, attached to it and passing through a Wilson seal in the radiation source end plate of the spectrometer chamber. The position of this baffle affects the width of the annulus through which focused electrons pass, and thus the resolution of the instrument. The solid lead cylinders, L, on the axis of the spectrometer reduce the gamma-ray background in the counter.

2. Lens Coil

The coil was wound on a brass spool, providing a coil width of 10 cm. No. 14 glass-insulated copper wire was used, each layer containing about 52 turns. Leads were brought out to a terminal board after the first 1,326 turns, the next 1,020, the next 867, and the last 765. The coil as a whole has an inner radius of 10 cm and an outer radius of about 25 cm. Each of the four sections has a resistance of about 9 ohms, and the separate terminals to each of them provide for their use in various combinations.

During the winding, a sheet of copper of 22-mil thickness was placed over the winding every four layers. These copper sheets, 19 in all, have tongues projecting through slots in the sides of the brass spool. The tongues are soldered into brass blocks that are water-cooled. This arrangement allows for the dissipation of about 1,500 w in the coil without an excessive temperature rise in the copper winding.

3. Regulation of the Coil Current

The current for the lens coil is provided by a separate motor-generator set. This current is regulated by a method similar to that used in connection with the Berkeley cyclotron. The regulation and control circuits are shown in figures 2 and 3.

The generator field requires current up to 1 amp. This current forms the plate current of 10 6L6 tubes connected in parallel. Regulation of the output of the generator is attained by causing the output current to control the grids of the 6L6's, as explained below.

As can be seen from figure 2, the grid voltage of the 6L6's will vary with the grid of the 6SJ7. The grid of the 6SJ7 is connected to a network containing a 920 twin-photocell tube, so that its voltage will depend on the relative illumination of the two photocells. Illumination of the photocells is provided by a galvanometer lamp, and the circuit containing this galvanometer is shown in figure 3. A double-pole, double-throw switch provides for either shorting the galvanometer or putting it into the circuit. A 1,000-ohm potentiometer provides for adjustment of the sensitivity and damping of the galvanometer.

When the galvanometer is in the circuit it is in series with the low-voltage winding of a 6.3-v filament transformer (or part of it selected by a 10K potentiometer), with a 0.001-ohm shunt, and a variable voltage, V_1, (from 0 to about 30 mv). The output current of the generator (i. e. the lens-coil current) is fed through the 0.001-ohm shunt. The direction of this current is such that the voltage developed across the shunt opposes V_1. The galvanometer coil then assumes a position determined by the balance between these two voltages.

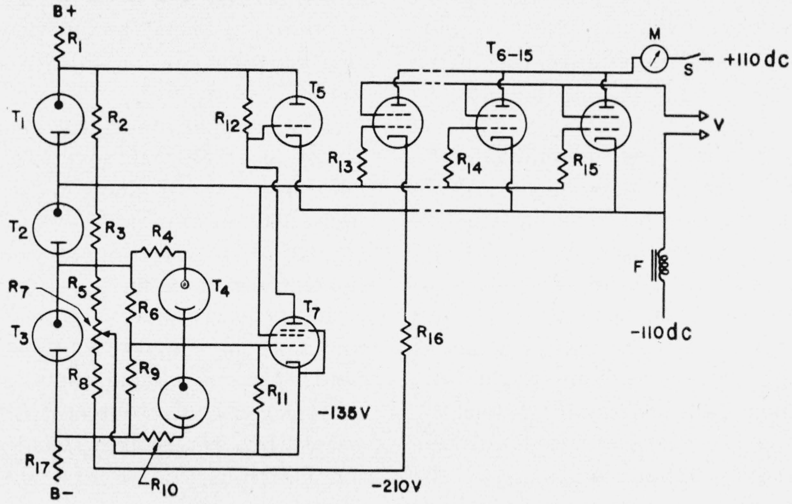

FIGURE 2.—*Diagram of circuit for stabilizing current in the lens coils of the spectrometer.*

R_{11}, R_{17}, 2,500 ohms, 10 w.; R_2, R_3, 50,000 ohms; R_4, R_{10}, 3 megohms; R_5, R_8, 10,000 ohms; R_7, 5,000 ohms; R_6, R_9, 10 megohms; R_{11}, 20 megohms; R_{12}, 100,000 ohms wire wound precision; R_{13}, R_{14}, R_{15}, . . ., 0.5 megohm; R_{16}, 200,000 ohms; T_1, T_2, T_3, VR105; T_4, 920 phototube; T_5, 6C5; T_7, 6SJ7. $T_6$15—6L6. *F*, generator field; *M*, ammeter; *V*, separate voltage supply for screen grids of 6L6 tubes.

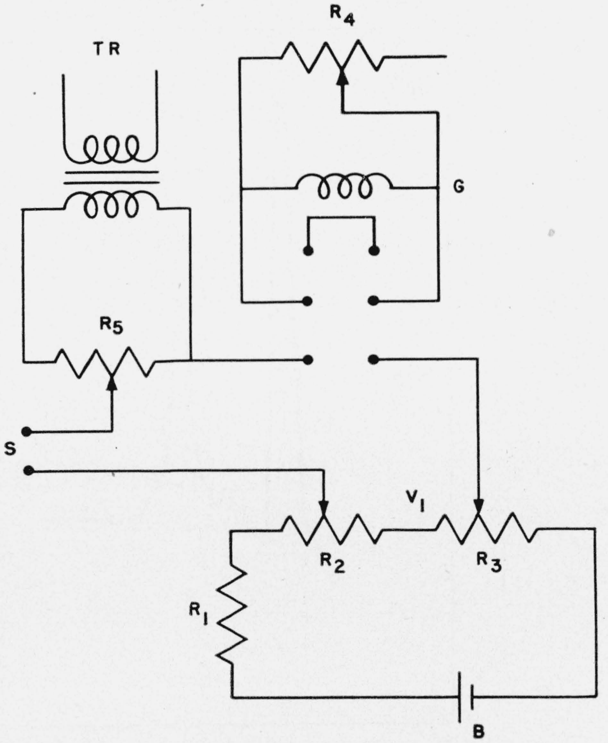

FIGURE 3.—*Diagram of circuit for the photocell galvanometer.*

R_1, 50,000 ohms; R_2, 70 ohms; R_3, R_4, 1,000 ohms; R_5, 10,000-ohm potentiometer; *TR*, transformer with 6.3 v secondary winding. *B*, 1.5 v dry cell. *G*, galvanometer coils. *S*, connection to 0.001-ohm shunt in series with generator armature and coils of spectrometer.

If the lens current tends to change, the balance in this circuit is upset so as to change the deflection of the galvanometer coil. The resulting change of illumination on the photocells changes the grid voltage of the 6SJ7 and hence the cathode voltage of the 6L6's, so as to change the generator field current to counteract the original change of the generator output. The lens current is in this way stabilized to about 0.1 percent. The presence of the low-voltage winding of a 6.3-v filament transformer is for the purpose of reducing fluctuations that might result from a tendency of the circuit to overcompensate.

Various settings of the lens current are obtained by selecting various values of V_1. The current is measured by passing it through an accurately calibrated shunt and measuring the voltage drop across it with a potentiometer.

In assembling the circuit, the photocell and its galvanometer are mounted separately on a wall bracket. This prevents any vibrations associated with operating the controls from upsetting the equilibrium of the galvanometer.

The 10 6L6's are mounted on a separate chassis. This chassis also contains a power pack supplying all voltages for the photocell circuit. A second chassis contains a power supply which provides screen voltage for the 6L6's. The rest of the circuit, including the meter, *M*, which indicates the field current (the plate current of the 6L6's), the switch, S, for the 220-v d-c line, and the V_1 voltage supply, are mounted on a third chassis, the control chassis (which contains the three VR105 tubes, the 6SJ7 and 6C5, and their associated resistors).

When the circuit was first assembled the cathodes of the 6*L*6's (rather than the grids, as shown in fig. 2) were tied down to the point marked zero voltage (between the first and second VR105 tubes). Difficulty was encountered, however, because of the tendency of the circuit to go into high-frequency oscillation despite the presence of separate half-megohm resistors in the grid circuits of the 6L6's. When the points at which the grids and cathodes of the 6L6's are tied into the control circuit were interchanged (to give the circuit shown in fig. 2), this difficulty was eliminated.

In adjusting the circuit for operation, one proceeds as follows: V_1 is set at zero. The galvanometer position is adjusted to illuminate both photocells approximately equally. Switch S is then closed (the switch in the output circuit of the generator is kept open during this adjustment), and the grid of the 6SJ7 is adjusted by moving the tap on the 5,000-ohm potentiometer so that the plate current of the 6L6's has just begun to rise. Before closing the switch in the output circuit of the generator, the following test should be made. As V_1 is increased the light from the galvanometer lamp will sweep across the "increase" photocell (there being no opposing voltage from the 0.001-ohm shunt) until it leaves the photocell surfaces completely. As this takes place the plate current should pass through its maximum and then down to a value not far from 0. A low 6L6 plate current with zero illumination provides against a sudden large current rise should the galvanometer lamp burn out or its light leave the photocell surfaces for some other reason. The maximum 6L6 plate current should be adjusted in accordance with the arrangement of coil sections that is being used, by adjusting the 6L6 grid voltage through the tap on the 5,000-ohm potentiometer.

III. Radiations From 5.3 Yr Co^{60}

1. Calibration

For the initial work the source and detector were placed 100 cm apart, corresponding to a focal distance of 25 cm. The Geiger-Müller counter, which serves as a detector, has an opening 5 mm in diameter, and the mica window, which seals this opening, has a surface density of approximately 3.5 mg/cm^2.

The momentum of the focused electrons is expressible as $H\rho$, where ρ is the radius of the circular orbit these electrons would have in a uniform magnetic field, H. As the electron paths in the thin-lens spectrometer are quite complicated, no attempt is made to use the spectrometer as an absolute instrument. Instead, use is made of the fact that the lens coil contains no iron, so that the field, H, is proportional to the current, I. Hence, for a given source-detector arrangement, we may write $H\rho = kI$. k may be determined by studying electrons, whose momentum is well known. For this purpose the conversion electrons from a deposit of thorium B were used. Curves obtained with such a source are shown in figures 4 and 5.

In obtaining the data for figure 4, the four sections of the lens coil were connected in parallel. With such an arrangement of coils and a 100-cm

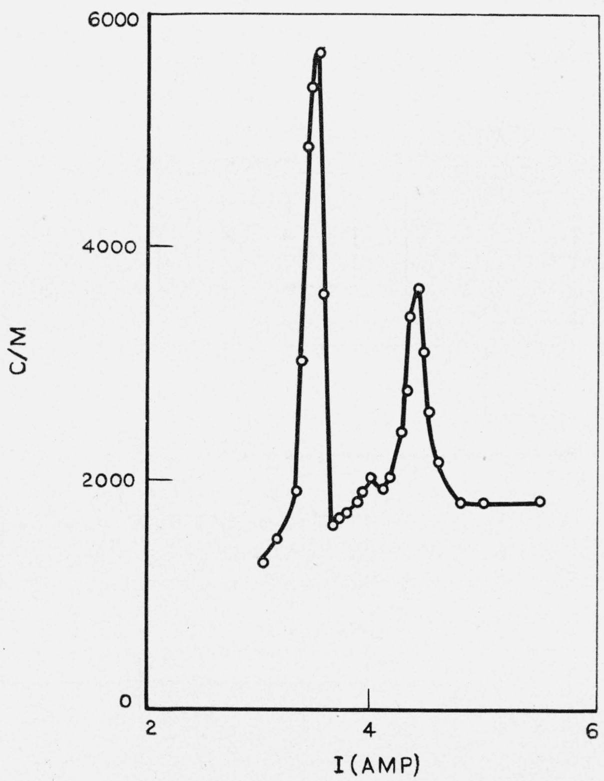

FIGURE 4.—*Spectrum of conversion electrons from* ThB+C *deposit used for calibration.*

All four coils in parallel. ThB No. 6; 4 coils parallel.

source-detector distance, electrons up to an energy of 2.5 Mev (with the present cooling provisions for the coil) can be studied. Higher energies are obtained by increasing the source-detector distance, but at a sacrifice in resolution.

In the spectrometer paper by Deutsch,[4] the $H\rho$ values for the two pronounced lines shown in figure 4 are given as 1,385 and 1,750. The first line has its peak at 3.48 amp, giving a k value ($H\rho$ per ampere) of 398. The second line has its peak at 4.38 amp. This corresponds to a coil constant of 399, and is a good check.

As an additional check some preliminary data have been obtained on the high-energy conversion line from the thorium source (from thorium C). The peak occurs at about 25.1 amp. If we use the $H\rho$ value of 10,080 given by Rutherford, Chadwick, and Ellis,[5] we again obtain a coil constant of 399. This serves to establish the linearity of the instrument throughout its range. This result is to be expected, as care was taken in construction to exclude any iron from the vicinity of the coil; the magnetic field and coil current are then related linearly throughout the range.

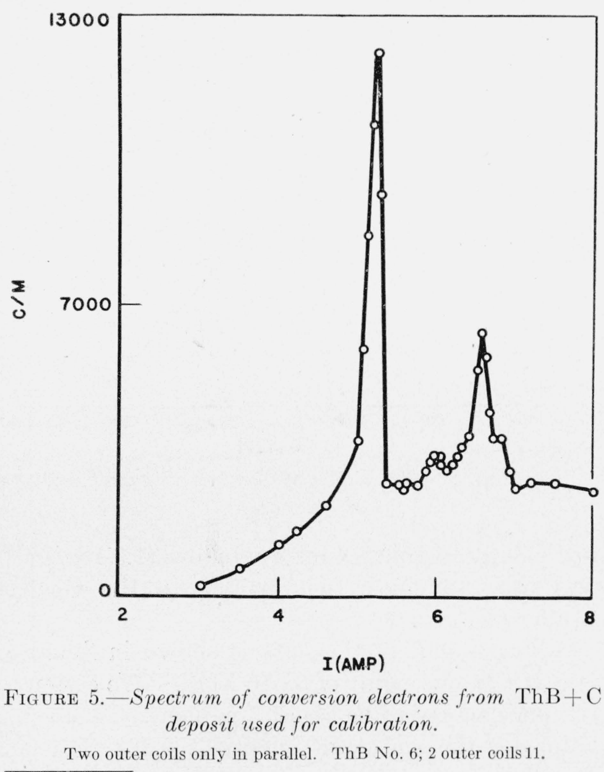

FIGURE 5.—*Spectrum of conversion electrons from* ThB+C *deposit used for calibration.*

Two outer coils only in parallel. ThB No. 6; 2 outer coils 11.

[4] See footnote 1.

[5] E. Rutherford, J. Chadwick, C. D. Ellis. Radiations from radioactive substances, p. 369 (Cambridge Univ. Press, London, 1930).

In figure 5 the thorium B spectrum is shown for another arrangement of the coil sections, namely, the two outer sections alone, in parallel. This arrangement is useful in the study of lower-energy radiations. With a 100-cm source-detector distance, electron energies up to 0.65 Mev can be studied with the present coil-cooling system. The two-section arrangement gives higher resolution than that of the four-section coil, or, for a given resolution, higher counting rates can be obtained when using the two-section arrangement.

In figure 5 the two strong thorium B lines occur at 5.20 and 6.55 amp. These give coil constants for this arrangement of 266 and 267 $H\rho$ per ampere, respectively.

2. Gamma Rays From 5.3 yr Co^{60}

The 5.3 yr Co^{60} isotope was found useful in determining some of the characteristics of the spectrometer. The supply of this isotope consisted of 50 mg of cobalt metal that had been irradiated for about 6 weeks in the pile at Clinton Laboratories.

For the spectrometer study a radiation source having a gamma-ray strength equivalent to about 5 millicuries of radium was prepared. The active material is placed in a brass capsule having a minimum wall thickness of 1 mm, so that all beta rays are absorbed. The radiator, from which the gamma rays eject photoelectrons, is placed as close as possible to the active material (in the present case about 1 mm). The radiator is placed in the same position as the thorium deposit used in the calibration work.

The photoelectrons from the radiator are focused by the spectrometer. The photoelectron peaks are superimposed upon a broad distribution of Compton electrons, ejected mostly from the brass capsule. The determination of the energy of the photoelectrons enables a determination of the gamma-ray energies. The radiations from 5.3 yr Co^{60} have been reported by Deutsch.[6] A curve showing data on the gamma rays from this isotope is given in figure 6.

For this curve all four coil sections, in parallel, were used. The radiator was a uranium foil of surface density 23 mg/cm ^{2}. The curve shows L photoelectron peaks for the two gamma rays in

[6] M. Deutsch, L. G. Elliott, and A. Roberts, Phys. Rev. **68**, 193 (1945).

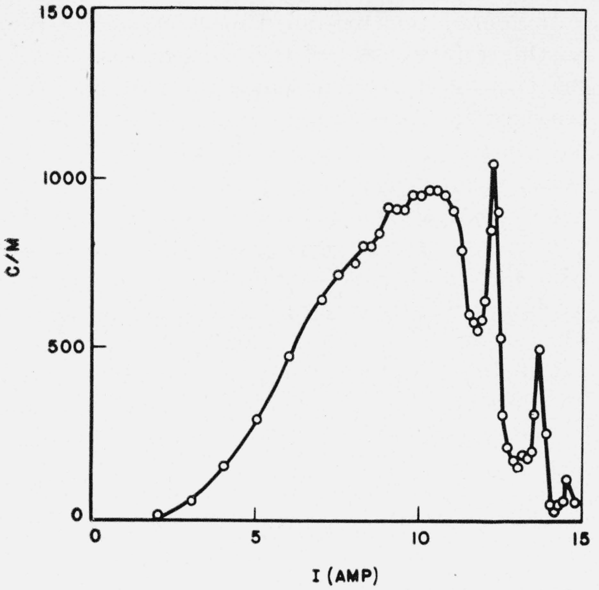

FIGURE 6.—*Spectrum showing the conversion spectrum for* Co^{60} *gamma rays in uranium radiator, of thickness 23 mg/cm²*.

Four coils in parallel. Co^{60} γ No. 2; V–23 radiator; 4 coils parallel.

addition to the pronounced K groups. The more complete structure in this curve over that of Deutsch is probably due to the use of uranium as radiator material instead of lead. The strength of the source made it possible to use a baffle arrangement giving fairly high resolution. The photoelectron peaks in figure 6 have a half-width ($\Delta\, p/p$, where p is the momentum) of about 0.02.

Knowing the binding energies of the K and L electrons in uranium, we can compute the energies of the two gamma rays from 5.3 yr Co^{60}. For the low-energy gamma ray, the K-electron peak is at 12.25 amp. Using the coil constant of 399 $H\rho$ per ampere, we get an $H\rho$ value for these photoelectrons of 4,890, or an energy of 1.045 Mev. Adding the K-binding energy of uranium, 0.115 Mev, there is obtained a gamma-ray energy of 1.16 Mev. The L-electron peak occurs at 13.125 amp, corresponding to an $H\rho$ of 5,240, and energy of 1.14 Mev. Adding the L-binding energy of uranium, 0.022 Mev, we again get a gamma-ray energy of 1.16 Mev. Similarly, the K and L electron groups from the high-energy gamma ray give us a value of 1.32 Mev for the gamma-ray energy. We estimate the values to be correct within 3 percent. The values given by Deutsch are 1.10 ± 0.003 Mev and 1.30 ± 0.03 Mev.

Figure 7 shows a graph of the beta-ray spectrum of 5.3 yr Co^{60}. The source was made by evaporating a solution of cobalt nitrate on an aluminum foil having a surface density of 2 mg/cm.[2] The active material itself was also estimated to be about 2 mg/cm.[2] As the beta rays are of fairly

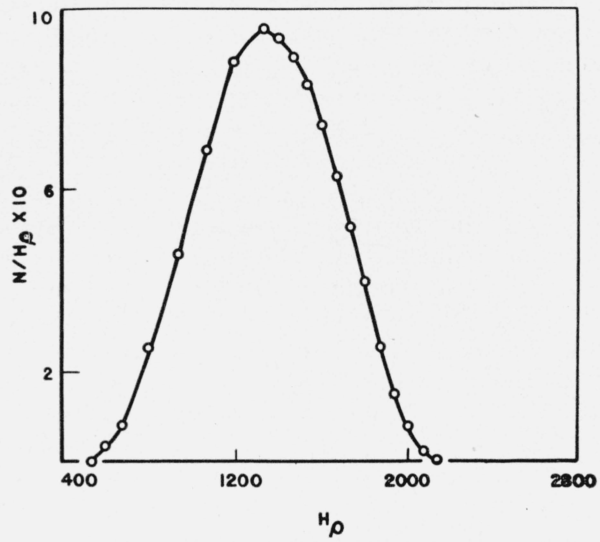

FIGURE 7.—*Beta-ray spectrum of* CO^{60}.

Co 6 No. 3.

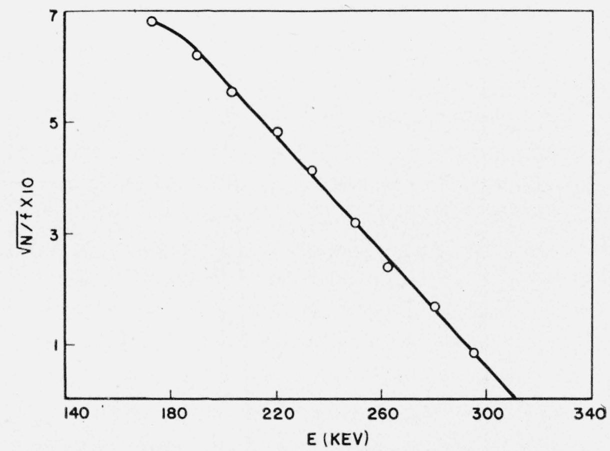

FIGURE 8.—*Fermi plot of* Co^{60} *beta-ray spectrum.*

Co^{60}; Fermi plot.

low energy, a thinner mica window (1.3 mg/cm ²) was used to cover the opening in the Geiger-Müller counter.

A Fermi plot of the data is shown in figure 8. It gives an end point of 0.310 Mev. We estimate the uncertainty to be about 3 percent. Deutsch's value for the end-point energy is 0.308 ± 0.008 Mev.

WASHINGTON, October 24, 1946.