Al^{27} below 6 Mev, it is clear that absorption techniques are not likely to be adequate to establish the decay scheme from the highly excited states produced by proton capture in Mg^{26}.

Casson[13] has measured the gamma-ray energies at the 336- and 314-kev resonances with a scintillation spectrometer. At the 336-kev resonance he found 5.8- and 2.8-Mev gamma rays, while the gamma rays from the 314-kev resonance had an energy of about 4.3 Mev. Our measurement at the 450-kev level indicated a 6.0-Mev gamma ray, a value in good agreement with the 6.2 Mev reported by Tangen.[3] These values are compatible with the possibility of an initial transition to the well-known 2.8-Mev level.

V. ACKNOWLEDGMENTS

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[13] H. Casson, Phys. Rev. 89, 809 (1953).

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Decay Scheme of Co^{56}

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The decay scheme of Co^{56} was studied by means of a magnetic lens spectrometer and a gamma-gamma coincidence scintillation spectrometer. The positron spectrum consists of two groups of maximum energies of 1.50 Mev and 0.44 Mev, relative abundance of 96 percent and 4 percent, respectively, leading to a second and third excited state of Fe^{56}. Orbital electron capture also takes place involving several other excited states. Both of the beta-ray spectra involved appear to have the "allowed" shape of the Fermi plot. The energies of the gamma rays emitted by the Fe^{56} nucleus were determined by studies of the photoelectron spectrum and scintillation spectrum. The energies determined were 0.845 Mev, 1.24 Mev, 1.75 Mev, 2.30 Mev, 2.60 Mev, and 3.25 Mev, respectively. These gamma rays were fitted into the decay scheme by means of beta spectrum analysis and gamma-gamma coincidence experiments.

INTRODUCTION

IT was first reported by Livingood and Seaborg[1] that Co^{56} had a half-life of about 72 days. Cook and McDaniel,[2] using absorption and coincidence methods, reported that the disintegration took place by K capture and a single positron emission with an upper energy limit of 1.20 Mev. The average energy for the several gamma rays present was 1.74 Mev. Elliott and Deutsch[3] using a magnetic lens spectrometer and coincidence methods, reported a positron spectrum of a maximum energy of 1.50 Mev; they found the Fermi plot to be a straight line down to 0.48 Mev. The presence of the other cobalt isotopes prevented the investigation of the spectrum beyond this point. Six gamma rays ranging in energy from 0.845 Mev to 3.25 Mev were also reported.

In the present work the aim was to study Co^{56} without interference from Co^{57} and Co^{58}. For this purpose, a sample of ferric oxide enriched in Fe^{56} (99.84 percent) was obtained from Oak Ridge National Laboratory and bombarded in the cyclotron of the University of California. The target was under bombardment by 10-Mev protons for six hours, the protons being accelerated as hydrogen molecule ions. The total irradiation was 28 microampere hours. A carrier-free sample of Co^{56} was obtained and its mode of decay was studied by both a magnetic lens type spectrometer and a gamma-gamma coincidence scintillation spectrometer.

SOURCE PREPARATION

The bombarded ferric oxide was dissovled in $6N$ hydrochloric acid and treated with a few drops of bromine water, the latter acting as an oxidizing agent for the iron. The solution was evaporated to dryness and the residue dissolved in $6N$ hydrochloric acid. The solution was cooled to 5 degrees centigrade and transferred to a separatory funnel along with an equal volume of chilled ether. The two phases were shaken together and the aqueous phase containing the radioactive cobalt and some iron was extracted. The aqueous phase was then evaporated almost to dryness, diluted to 25 ml with triple distilled water, and the pH adjusted to 1.5. The solution was gently heated, then dilute ammonium hydroxide was added until the pH was approximately 4.5. After allowing 2 hours for the hydrous ferric oxide to settle, the solution was filtered, evaporated to dryness, and the ammonium chloride sublimed. The small residue remaining was dissolved in 1 ml of $0.01N$ hydrochloric acid and ammonium hydroxide added until the pH of the solution was ap-

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[1] J. J. Livengood and G. T. Seaborg, Phys. Rev. 60, 913 (1941).
[2] C. S. Cook and P. W. McDaniel, Phys. Rev. 62, 412 (1942).
[3] L. G. Elliott and M. Deutsch, Phys. Rev. 64, 321 (1943).

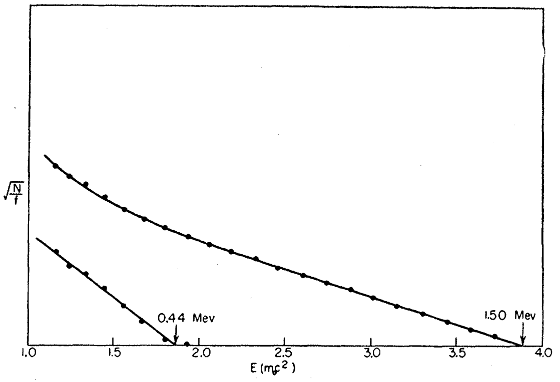

FIG. 1. Fermi plot of the positron spectrum of Co^{56} obtained with a solenoidal spectrometer.

proximately 8.5. The solution was allowed to stand several hours, filtered to remove the remaining hydrous ferric oxide, and evaporated to dryness. After volatilizing the ammonium chloride, the invisible quantity of radioactive cobalt was dissolved in hydrochloric acid and transferred to a spectrometer mount for spectroscopic studies.

THE BETA SPECTRUM

The beta spectrum was measured using a solenoidal type spectrometer. The spectrometer was equipped with a "thin window" Geiger-Müller tube. The window was made of zapon film weighing 120 μg/cm² and reinforced by a nylon fiber grid. The source, weighing approximately 40 μg/cm², was mounted on a zapon backing of 50 μg/cm². Figure 1 shows the Fermi plot of the positron spectrum. It can be seen that the spectrum is complex, consisting of two components with the end-point energy of the main group 1.50 Mev±0.01 Mev and that of the second group 0.44 Mev±0.03 Mev. Their relative abundances were determined to be 96 percent and 4 percent, respectively. The second beta component must be considered as requiring further experimental verification, because of the low abundance and low energy end point. The main component has an end-point energy in agreement with that previously reported.[3] The possibility of the presence of other cobalt isotopes, Co^{57} and Co^{58}, was checked by attempting to detect the presence of the conversion electron peaks at 0.119 Mev and 0.133 Mev characteristic of Co^{57} and the conversion electron peak at 0.805-Mev characteristic of Co^{58}. There was no indication that these isotopes were present. Thus, the lower-energy positron group may be attributed to the radioactive isotope Co^{56}.

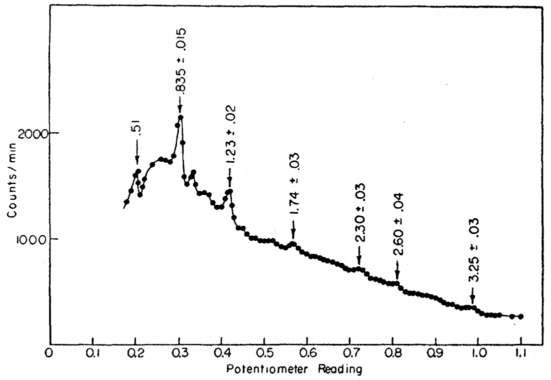

FIG. 2. Photoelectron spectrum produced in a 70-mg/cm² uranium radiator by the gamma rays of Co^{56} obtained with a spectrometer of thick-lens type with moderate resolution.

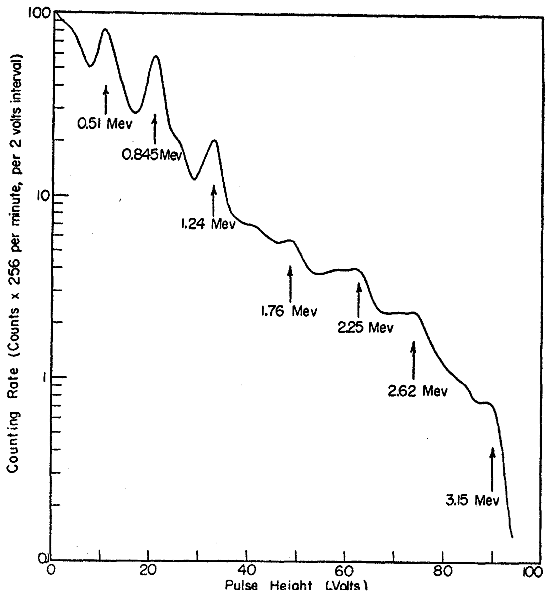

FIG. 3. Pulse-height spectrum of Co^{56} on NaI(Tl) scintillation spectrometer.

THE GAMMA-RAY SPECTRUM

Figure 2 shows the spectrum of secondary electrons produced in a 70-mg/cm² uranium radiator by the gamma rays of Co^{56}. The gamma-ray spectrum was also studied using a gamma-ray scintillation spectrometer. Seven gamma rays were observed, including the 0.511-Mev positron annihilation radiation. The scintillation spectrometer was equipped with a thallium-activated sodium iodide crystal (diameter 1.0 in., length 1.0 in.). Figure 3 is a plot of the data obtained. Table I is a summary of these results and those obtained by Elliott and Deutsch.[3] The intensities of the

TABLE I. Gamma-ray spectrum of Co^{56}.

		Investigation			Previous work[a]	
Gamma ray	Photo-spectrum	Scintillation-spectrum	Selected value	Intensity	Photo-spec.	Intensity
1st	0.835 ±0.015	0.845 ±0.015	0.845 ±0.015	1.00	0.845	1.0
2nd	1.23 ±0.02	1.24 ±0.02	1.24 ±0.02	0.55	1.26	0.5
3rd	1.74 ±0.03	1.76 ±0.04	1.75 ±0.04	0.24	1.74	0.2
4th	2.30 ±0.03	2.25 ±0.04	2.30 ±0.03	0.12	2.01	0.1
5th	2.60 ±0.04	2.62 ±0.04	2.60 ±0.04	0.14	2.55	0.2
6th	3.25 ±0.03	3.15 ±0.05	3.25 ±0.03	0.24	3.25	0.2

[a] See reference 3.

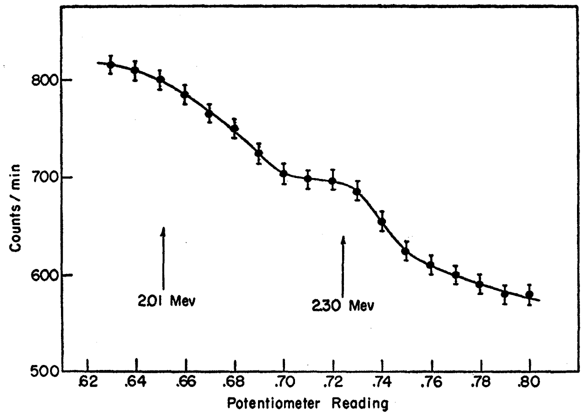

FIG. 4. Photospectrum near the region of 2.30-Mev gamma ray of Co^{56}. The energy indicated in the figure is the sum of photoelectron energy and the K binding energy of uranium.

gamma rays were estimated from the photoelectron spectrum except for the first and second gamma rays. These were determined from the scintillation spectrum corrected for counting efficiency. This was necessary since the photopeak of the 0.835-Mev gamma ray was so distorted by the thickness of the radiator that an accurate intensity estimate was difficult. The fourth column of Table I is the value for gamma-ray energies selected by the authors. The results of scintillation-spectrum are chosen for the values of first and second gamma-ray energy, because the 70-mg/cm^2 radiator is too thick for precise measurement of energies about 1 Mev or less. The energy of the third gamma ray is the mean value, and the energies of the fourth, fifth, and sixth gamma rays are those from the results of the photospectrum, since it is very difficult to determine correctly many high-energy gamma rays from a complex scintillation spectrum.

The results are in good agreement with those of the previous workers with the exception of the energy of the fourth gamma ray. The authors found the energy to be 2.30 Mev. (See Fig. 4.)

COINCIDENCE MEASUREMENTS

A gamma-gamma coincidence scintillation spectrometer was used as an aid in determining the disintegration scheme. Two 5819 photomultiplier tubes mounted with thallium-activated sodium iodide crystals were arranged at 180 degrees to each other. The time constant of the coincidence circuit was measured as 5×10^{-7} second. An example of the coincidence spectrum is shown in Fig. 5. The gate of one channel was adjusted to admit the annihilation peak and the threshold of the other channel was varied throughout the energy range. It was found that the annihilation radiation was in coincidence with the 0.845-Mev gamma ray and the 1.24-Mev gamma ray. This confirms the decay scheme proposed by Elliott and Deutsch. Table II shows the results of the coincidence experiments.

TABLE III. Gamma-gamma coincidence of Co^{56}. Energies are in Mev. "O" means that a coincidence was observed, "X" that it was not.

	0.845	1.24	1.75	2.30	2.60	3.25
0.511	O	O	—	—	—	X
0.845		O	O	O	O	O
1.24			O	X	X	X

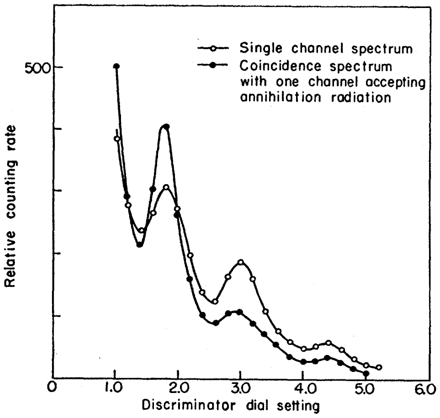

FIG. 5. Single-channel and coincidence spectra of gamma rays of Co^{56}. The prominent peaks are due to gamma rays at 0.511 Mev (annihilation radiation), 0.845 Mev, and 1.24 Mev.

THE DISINTEGRATION SCHEME OF Co^{56}

Figure 6 shows the disintegration scheme of Co^{56} based on the beta-ray analysis, the gamma-ray measurements, and the coincidence experiments. This scheme is similar to the tentative disintegration scheme proposed by the M.I.T. group which was based on gamma-ray intensity measurements. The main beta-ray group decays to the 2.09-Mev second excited level of Fe^{56} which de-excites to the ground state, emitting successively 1.24-Mev and 0.845-Mev gamma rays.

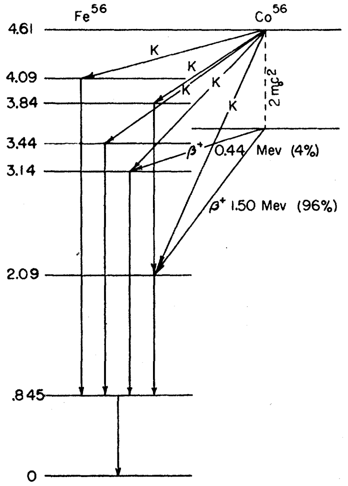

FIG. 6. Disintegration scheme of Co^{56}.

The second beta-ray group decays to the third, 3.14-Mev, excited level of Fe^{56} which de-excites to the ground state by successive emissions of 2.30-Mev and 0.845-Mev gamma rays. The maximum energy of the second positron group, 0.45 Mev, deduced from the main positron group and the 1.24-Mev and 2.30-Mev gamma rays (see Fig. 6), agrees within the range of experimental error with that found by beta-ray analysis, 0.44 Mev. The 1.75-Mev gamma-ray de-excites to the second excited level, 2.09 Mev, and the other two gamma rays, 2.60 and 3.25 Mev de-excite, to the first excited level, the 0.845-Mev level. These three gamma rays arise from three excited levels of Fe^{56}, 3.44 Mev, 3.84 Mev, and 4.09 Mev, respectively, resulting from the decay of Co^{56} by K capture. There is some possibility of decay to the 3.44-Mev level by positron emission but this may be of very low intensity because of the competition of electron capture as the available energy is small, 0.14 Mev. The confirmation of this latter positron group is outside the range of the instrument.

DISCUSSION

The 3.14-Mev excited state of Fe^{56} was established by photoelectron measurements and the analysis of the positron spectrum. This level is higher than the 2.85-Mev level found by the M.I.T. group and is also higher than the 2.98-Mev level deduced by the study of the disintegration scheme of Mn^{56} by the same group. From the present work it is difficult to state if these two levels are identical.

The comparative lifetimes of beta-ray transitions were determined by the following method. The 0.845-Mev internal conversion electron peak was measured along with the positron spectrum. Assuming the radiation to be electric quadropole according to Goldhaber's[4] empirical rule, the internal conversion coefficient of the 0.845-Mev gamma ray is given as 2.8×10^{-4} from Rose's table.[5] By using this factor, the intensity of the positron to the 0.845-Mev gamma ray can be determined from the comparison of the two areas of the spectra. This ratio was found to be 0.23. As all the gamma rays are known to de-excite to the 0.845-Mev level according to the present disintegration scheme, the partial lifetime of the main positron disintegration may be estimated as 3.12×10^{7} seconds which was determined from an average half-life of 76 days. A $\log ft$ value of 8.64 was determined by using Feenberg and Trigg's[6] chart. The relative half-life of the lower-energy group was deduced from the following formula:

$$(\tan\alpha_1)^2/(\tan\alpha_2)^2=(f_2t_2)/(f_1t_1),$$

where α is the slope of the Fermi line to the energy coordinate. The $\log ft$ of this group was 7.73. This simple and rapid method of ft-value determinations of a complex beta spectrum is very convenient, especially for the relative $\log ft$ values of each group. The K/β^+ ratio was determined roughly from gamma-ray intensities. The intensity of the K capture involved in the 1.50-Mev positron disintegration is determined by the following expression:

$$\begin{aligned} K_c\ (\text{intensity}) &= (\text{1.24-Mev gamma-ray intensity}) \\ &\quad -(\text{1.50-Mev positron intensity}) \\ &\quad -(\text{1.75-Mev gamma-ray intensity}). \end{aligned}$$

The ratio of the K/β^+ is found to be 0.35. This value may be compared with the theoretical value of the allowed transition, 0.1.[6] However, it is noted that the accuracy of the intensity estimation may be no greater than 20 percent. If the intensity of the 1.24-Mev gamma ray is assumed to be 0.5 as reported by the M.I.T. group, then the K/β ratio is 0.13. The above argument is only considered as one piece of evidence for the presence of K electron capture involved in the 1.50-Mev positron transition. The K/β^+ ratio involved in the lower-energy positron transition is also deduced from the same argument by taking into account the 4 percent branching ratio determined from the analysis of the beta spectrum. The ratio was found to be 12.

Since Co^{56} may have the nuclear configuration $f_{7/2}-p_{3/2}$ from the nuclear shell model,[7] it is probable that the ground state of Co^{56} has a spin of 5 from the Nordheim empirical rule.[8] The positron disintegration appears to be l- or first-forbidden according to Nordheim's classification. If the second (2.09-Mev) excited level and the third (3.14-Mev) excited level are assumed to have spins of $+4$ and $+6$, respectively, according to Goldhaber's rule,[4] the $\Delta I=1$, $\Delta I=2$ characterisitc may be applied to both disintegrations. So far as the $\log ft$ value is concerned, the 1.50-Mev positron has, most likely, the characteristic $\Delta I=2$, yes.[8] At the present there is insufficient experimental evidence to confirm either of these.

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[6] E. Feenberg and G. Trigg, Revs. Modern Phys. **21**, 399 (1950).

[7] M. Mayer, Phys. Rev. **78**, 16 (1950).

[8] L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).