Since the $Li^6(p,\gamma)Be^7$ angular distributions of Warren, Alexander, and Chadwick[16] near 1 Mev indicate the presence of a large $\cos^2\theta$ term, the situation can at best be only partially helped by the inclusion of the s-wave $J=1/2^+$ state suggested by Lane.[4] Thus the theoretical situation leaves room for further experimental studies in this energy region. A fruitful experimental approach would seem to be a study of the elastic scattering of protons by Li^6.

At the highest bombarding energies investigated the angular distributions could not be explained in terms of s and p waves alone. In order to obtain an angular distribution more accurate than the four-point distributions which were adequate at the lower energies, measurements were made at 3 additional angles at 2.91 Mev. The angular distribution obtained is shown in Fig. 7. The form of this curve suggests that either angular momenta greater than one are becoming effective in the formation of compound nucleus states or that some sort of a direct interaction process is taking place.[15] Measurements at higher bombarding energies will be necessary in order to clarify this point.

[16] Warren, Alexander, and Chadwick, Phys. Rev. **101**, 242 (1956).

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Gamma Radiation from Co^{56} and Co^{58}

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The gamma rays following the decay of Co^{56} and Co^{58} have been observed by means of a large NaI(Tl) crystal scintillation spectrometer. Relative intensities of the Co^{56} gamma radiation are presented as well as ratios of orbital electron capture to positron emission for both Co^{56} and Co^{58}.

INTRODUCTION

THE availability of large NaI(Tl) crystals has made possible the measurement of gamma-ray spectra from sources too weak to produce statistically significant results in other spectrometers. As long as very good resolution is not required, measurement of the area of the full-energy peak, with appropriate corrections, gives a good measure of the gamma-ray intensity[1,2] relative to other gamma rays in the same spectrum.

In the current measurements a cylindrically-shaped NaI(Tl) crystal, four inches high and four inches in diameter, and a DuMont type-6364 photomultiplier tube were used to observe the gamma radiation. The resulting pulse-height distribution was recorded on a Bell-Kelly type 20-channel analyzer, operated so that the spectrum covered a total of 100 channels.

The sources were placed exterior to a lead housing surrounding the crystal-photomultiplier system and observed by the crystal through a collimating aperture $\frac{1}{2}$ inch in diameter and 8 inches long.

COBALT-56

Source Preparation

Two different sources of Co^{56} were used for this experiment. One was prepared in the University of Washington cyclotron by the $Fe^{56}(p,n)Co^{56}$ reaction on a stainless steel foil used by the Seattle group as exit window for their cyclotron.[3] The other was prepared by the same reaction in the University of California 60-in. cyclotron.[4]

The sources were encapsulated in the end of either a glass or brass container in a space adequately small so that they could be considered point sources. The brass capsule was made especially for this purpose with walls just thick enough to stop all positrons. Thus, the full-energy peak from the annihilation radiation may be used to determine positron intensity.

Analysis of Data

The pulse-height distribution from one of the Co^{56} sources is shown in the lower histogram of Fig. 1. It is a spectrum typical of either source. The upper distribution is the statistical error for this particular set of data. Analysis of relative intensities has been made by a series of successive subtractions of normalized spectral shapes, as indicated in Fig. 2, these shapes having been determined experimentally for a series of monoenergetic gamma rays from Cs^{137}, Nb^{95}, Zn^{65}, K^{42}, and Na^{24}. For the lower energy radiations, a high-gain set of data (Fig. 3) was obtained and analyzed in the same manner. This distribution was used to determine the relative

[1] R. S. Foote and H. W. Koch, Rev. Sci. Instr. **25**, 736 (1954).
[2] G. M. Griffiths, Can. J. Phys. **33**, 209 (1955).
[3] This source was obtained from Dr. D. J. Farmer, who had the required chemistry performed to extract the cobalt fraction.
[4] This source was obtained from Dr. C. D. Jeffries, who initially prepared the source for studies of the paramagnetic resonance fine structure of Co^{56}; see Jones, Dobrowski, and Jeffries, Phys. Rev. **102**, 738 (1956).

amounts of orbital electron capture and positron emission in Co^{56}.

To determine gamma-ray intensity, the area of the full-energy peak was measured. Three corrections were then applied. The first was the peak-efficiency correction, determined experimentally as a function of energy for the particular NaI(Tl) crystal used in this experiment. With the use of this correction, the total number of gamma rays observed by the crystal may be determined from the number seen as part of the full-energy peak. The second correction was a calculation to correct for those gamma rays which pass through the crystal without undergoing a Compton, photoelectron, or pair-production interaction, sometimes called the $(1-e^{-\mu x})$ correction. The third is a calculation, which has been checked experimentally, which corrects for the greater porosity of the collimator for higher energy gamma rays caused by gamma-ray transmission through the collimator edges. This correction becomes less pronounced the farther the source is placed above the collimator.

Results

The relative intensities of the gamma rays following the decay of Co^{56} are given in Table I. The same gamma rays, in essentially the same ratios, were observed in both sources. The errors include, in addition to the expected statistical error, an error derived from the consistency of results from different sets of data from the two sources.

The 0.975-Mev radiation is observed (see Fig. 3) only as a widening of the full-energy peak of the 1.02-Mev radiation. For this reason there is considerable uncertainty in both its energy and its intensity. The 1.35-Mev gamma ray reported by Howard *et al.*[5,6] appears as a high-energy tail on the 1.22-Mev radiation.

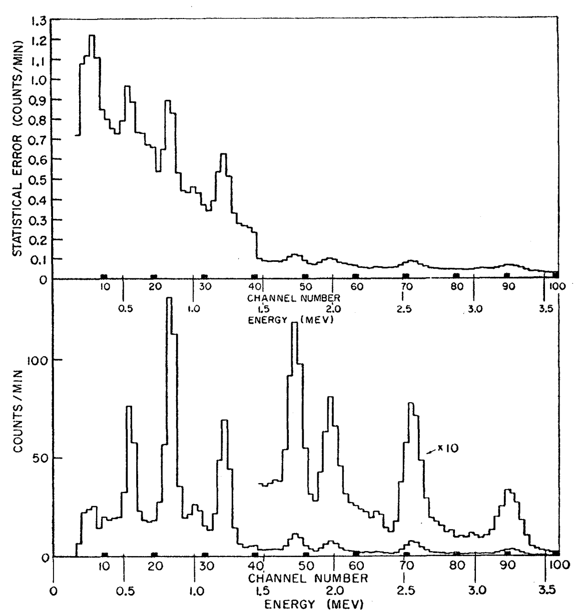

FIG. 1. A typical pulse-height distribution from one of the Co^{56} sources (lower histogram). Statistical errors for this particular set of data (upper histogram) are typical of other such data.

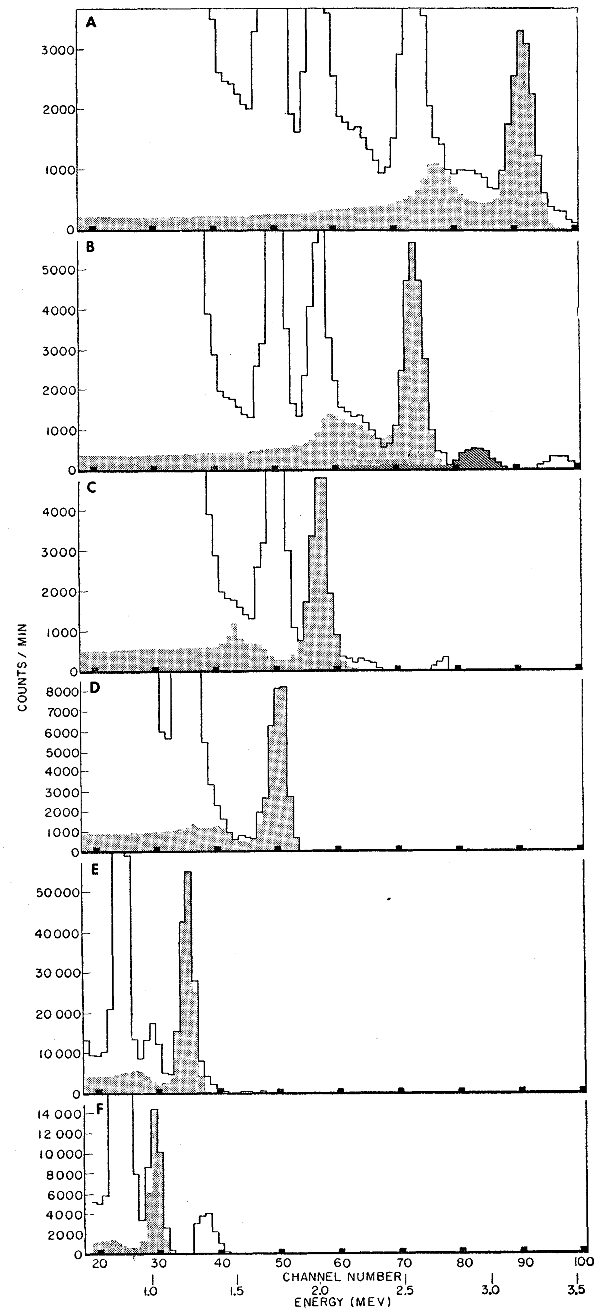

FIG. 2. Series of histograms showing unfolding of data by successive subtractions of pulse-height distributions for monoenergetic gamma rays.

[5] Howard, Pond, and Jastram reported by K. Way *et al.* in *Nuclear Level Schemes*, $A=40-A=92$, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955), p. 55. Reference to other work on both Co^{56} and Co^{58} may be found in *Nuclear Level Schemes*.

[6] K. P. Howard and C. R. Dulgeroff (private communication).

Any 1.5-Mev radiation is not obvious and, if it exists, appears to have an intensity less than one percent that of the 0.845-Mev radiation. At the lower energies, after several subtractions have been made, relatively large statistical errors would be associated with results quoted for any low-intensity radiations.

The 1.73-Mev line is of the proper width to be a single line. If two gamma rays exist near this energy,[5,6] they are so close that they do not produce any widening of the full-energy peak.

The counts observed just above Channel 60 in Fig. 2 may be contributed by a 2.17-Mev radiation,[5] but at least some of these counts are probably caused by the second escape peak from pair production of the 3.25-Mev radiation.

The intensity of the annihilation radiation is such that the relative amount of orbital electron capture to positron emission is 4.3±0.2, assuming that all Co^{56} disintegrations pass through the 0.845-Mev level. This agrees well with the value obtained by Sakai *et al.*[7] from a comparison of the positron spectral intensity with the internal conversion of the 0.845-Mev radiation. If the 3.47-Mev gamma ray is a transition from Sakai's 3.44-Mev level to the ground state of Fe^{56} as suggested in Table I, the value of ϵ/β^+ will be changed only slightly because of the low intensity of the 3.47-Mev transition.

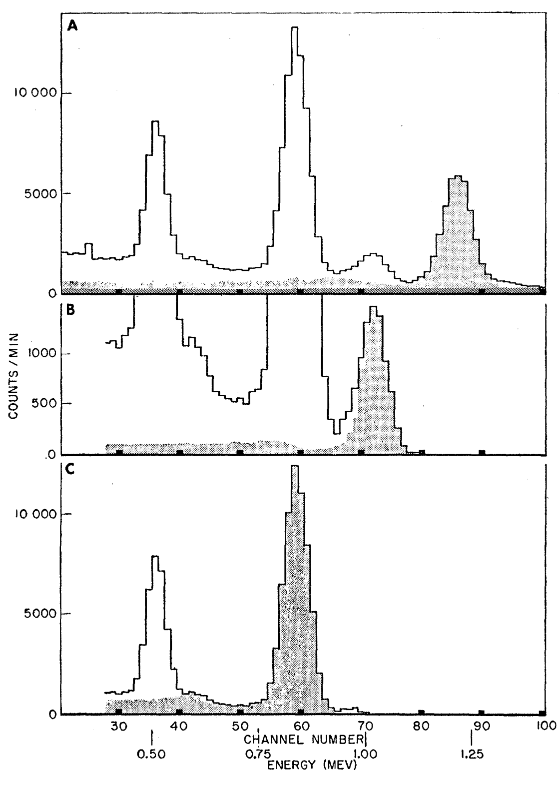

FIG. 3. Low-energy pulse-height distribution from Co^{56}, showing successive spectral unfolding subtractions. Diagonally shaded area in upper histogram is Compton distribution from all higher energy gamma radiation.

[7] Sakai, Dick, Anderson, and Kurbatov, Phys. Rev. **95**, 101 (1954).

TABLE I. Relative intensities of the gamma rays following the decay of Co^{56}.

Gamma-ray energy	Relative intensity	Possible transition in energy level scheme[a] (Mev)
0.845	1.000	0.845→0
0.975	0.018±0.012	4.10 →3.14
1.025	0.158±0.016	3.14 →2.09
1.22	0.703±0.017	2.09 →0.845
1.35	0.057±0.016	3.44 →2.09
1.76	0.169±0.008	3.84 →2.09
2.02	0.115±0.003	4.10 →2.09
2.56	0.156±0.008	3.44 →0.845
2.98	0.019±0.005	3.84 →0.845
3.25	0.116±0.003	4.10 →0.845
3.47	0.011±0.001	3.44 →0

[a] Based upon the energy level scheme proposed by Sakai (reference 8) and Poppema *et al.* (reference 10).

Conclusions

The relative intensities of gamma radiations following the decay of Co^{56} have been determined by means of a large NaI(Tl) crystal scintillation spectrometer. There still appears to be some disagreement[5–9] as to the number and energies of the positron transitions from Co^{56}.

The gamma radiation observed in the present experiment can be relatively easily fitted into the level schemes proposed by Sakai[8] and by Poppema *et al.*[10] The appropriate transitions are listed in Table I.

Within the limits of error, the four gamma rays of energy 1.22, 2.56, 2.98, and 3.25 Mev account for all transitions to the 0.845-Mev level.

That there is very little, if any, 2.30-Mev radiation between the 3.14-Mev level and the 0.845-Mev level makes the assignment[10] of 3+ to the 3.14-Mev level somewhat in doubt. An assignment of 5+ would appear more appropriate. Otherwise the assignments of spins and parities by Poppema *et al.*[10] appear consistent with these data.

COBALT-58

Source Preparation

The Co^{58} source was obtained from Oak Ridge, having been prepared by a $Ni^{58}(n,p)Co^{58}$ reaction.[11] Also present was some Co^{60} from the $Ni^{60}(n,p)Co^{60}$ reaction. The Co^{60} radiation, however, was present only in small quantities and was concentrated in the two gamma-ray lines at 1.17 and 1.33 Mev.

[8] M. Sakai, J. Phys. Soc. Japan **10**, 729 (1955).
[9] Kurbatov, Sathoff, Hisatake, and Sakai, Bull. Am. Phys. Soc. Ser. II, **1**, 163 (1956).
[10] Poppema, Siekman, Van Wageningen, and Tolhoek, Physica **21**, 223 (1955).
[11] This source was also supplied by Dr. C. D. Jeffries, who used it for studies of the paramagnetic resonance fine structure of Co^{58}.

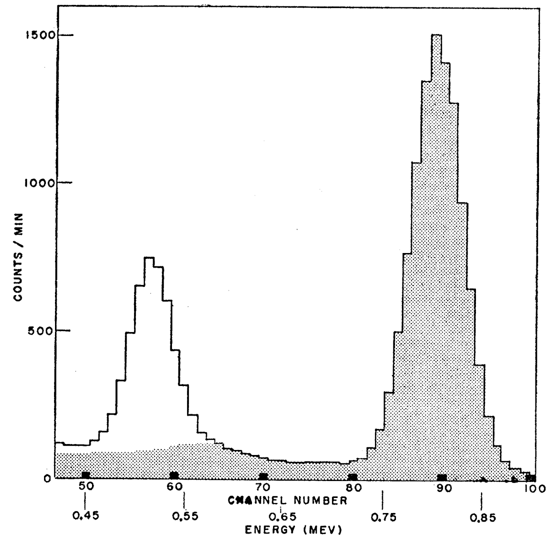

FIG. 4. Pulse-height distribution from Co^{58} showing the 0.805-Mev peak and annihilation radiation peak.

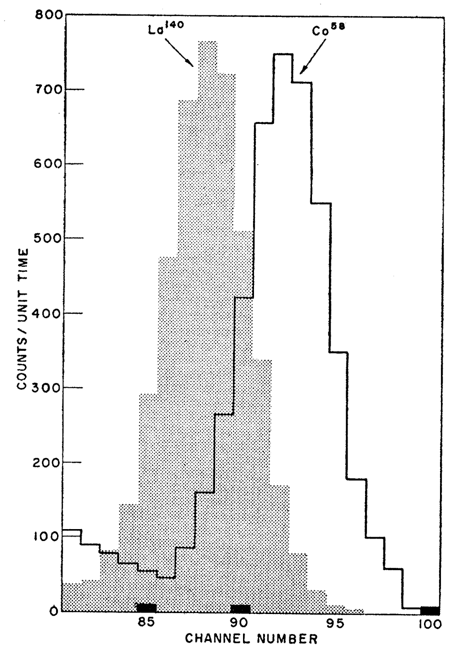

FIG. 5. The Co^{58} high-energy peak is superposed over the La^{140} 1.60-Mev full-energy peak. From this it is determined that the high-energy Co^{58} gamma ray has an energy of 1.67 Mev.

Results and Discussion

The pulse-height distribution and analysis for the 0.805-Mev radiation and annihilation radiation are shown in Fig. 4. On the basis of this analysis, a value of 5.9 ± 0.2 is obtained for the ratio of orbital electron capture to positron emission. This is in excellent agreement with the earlier experimentally determined ϵ/β^+ ratio.[12]

The 1.67-Mev radiation, with an intensity 0.005 that of the 0.805-Mev radiation, is confirmed.[13,14] That its energy is 1.67 Mev is indicated in Fig. 5, where its full-energy peak is superimposed over a La^{140} pulse-height distribution in the vicinity of the La^{140} 1.60-Mev full-energy peak. Thus, the transition between the 1.67 Mev level in Fe^{58} and the 0.805-Mev level should take place through a 0.865-Mev gamma ray. The center of this peak should thus appear in Channel 95 of Fig. 4. Under these circumstances it would appear that, if present, the intensity of an 0.865-Mev gamma ray is less than 2% that of the 0.805-Mev gamma ray. This, too, is in agreement with the findings of Rossi *et al.*[14]

The assistance of Mr. R. A. Taylor and Mr. P. L. Phelps with the electronics has contributed greatly to the success of this series of experiments.

[12] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
[13] B. L. Robinson and R. W. Fink, Bull. Am. Phys. Soc. Ser. II, **1**, 40 (1956).
[14] Rossi, Frauenfelder, Levine, and Singer, Bull. Am. Phys. Soc. Ser. II, **1**, 163 (1956).