tude may be compared with those calculated theoretically. In all these cases the theoretical magnitudes are too large, quite outside of experimental error. Thus, although the theory provides a good approximation to the magnetic moments, exact agreement is not obtained. The discrepancy may presumably be attributed to second-order effects, such as polarization of the core by the odd particle, which have not been included in the theory. Rasmussen and Chiao have shown that the theoretical magnetic moments of several deformed nuclei may be brought into better agreement with experiment by assigning quenched g factors for the intrinsic spin of the odd particle.[19] We note that use of quenched g factors for the odd neutron in Dy^{155} and Dy^{157} would improve the agreement between experiment and theory in both cases.

ACKNOWLEDGMENT

It is a pleasure to acknowledge the assistance of Professor John O. Rasmussen, who suggested this experiment and read the manuscript.

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PHYSICAL REVIEW VOLUME 123, NUMBER 1 JULY 1, 1961

Positron Spectra of Co^{56}†

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(Received February 27, 1961)

The positron spectrum of Co^{56} has been carefully studied with a magnetic spectrometer. Two positron groups were observed. The maximum energies and intensities of the two groups are 1.464±0.015 Mev and 0.440±0.030 Mev and ⩾90% and ⩽10%, respectively. No evidence for any other groups was found. In particular, an upper limit of 1% was set for the presence of any group with maximum energy 0.9–1.0 Mev. The high-energy spectrum has essentially an allowed shape. However, the inclusion of a shape factor such as $(1+0.3/W)$ offers a more consistent fit to all the data.

INTRODUCTION

THE decay of Co^{56} to Fe^{56} has been studied by Kienle and Segel who report that all the Co^{56} positron-emission and electron-capture transitions, which are allowed on the basis of spins and parities of the levels, have relatively high ft values.[1] The intense positron decay ($E_0 \simeq 1.5$ Mev) from the 4+ ground state of Co^{56} to the 4+ second excited state of Fe^{56} has a $\log ft$ of 8.7. This is markedly higher than those of the other allowed transitions in Co^{56} (with $\log ft$ from 6.1 to 7.3). All these transitions have ft values which are larger than those of normal allowed decays.

Recently, the beta-gamma directional correlation between the 1.46-Mev positron group and the two cascade gamma rays which de-excite the second excited state of Fe^{56} was measured.[2] A maximum anisotropy of 2.5–3.3% for $A=[n(\pi)-n(\pi/2)]/n(\pi/2)$ was observed (n is the coincidence counting rate at the given angle). This is only the third anisotropy reported in allowed beta decay and this is much larger than the other two[3,4] (0.2% and 1%, respectively, for Na^{22} and F^{20}).

The unusually high ft value and the anisotropic beta-gamma directional correlation of the 1.46-Mev positron group suggest that deviations from the normal allowed beta-decay theory might also be observed in the shape of the beta spectrum. No detailed investigation in search of possible subtleties in the shape of the spectrum has been made. Indeed, there are disagreements among previous investigators as to the existence and characteristics of other possible positron groups from the Co^{56} decay.[1,5–10]

† Supported in part by the joint programs of the Office of Naval Research and the U. S. Atomic Energy Commission and by a grant from the National Science Foundation.

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Careful studies of the positron spectra from the decay of Co^{56} have been made in the present investigation. The high-energy group is found to have a nearly statistical shape down to about 470 kev where a second group begins. However, the best fit to the data includes a shape factor of the form $(1+0.3/W)$ or something equivalent. No evidence for the reported 0.9–1.0-Mev end-point group[6,7] was observed. The only group observed, other than the 1.46-Mev group, has an end-point energy of $\simeq$440 kev.

SPECTROMETERS

The positron spectra were measured in a 40-cm radius of curvature, 180° focusing, shaped magnetic field spectrometer.[11] Modifications of the equipment and its operation are discussed elsewhere. (See reference 12.)

A continuous flow, loop anode proportional counter with an aluminum-coated Mylar window was used as the detector. This window has a cutoff energy at about 20 kev and gives essentially complete transmission above 100 kev.

The gamma-ray spectra were measured on a single channel analyzer. The detector was a NaI(Tl) crystal $2\frac{1}{2}$-in. diam$\times$2-in. thick optically coupled to a Du Mont 6363 photomultiplier. Gamma-gamma coincidence spectra were also measured with a fast-slow coincidence unit[13] with $2\tau=2\times10^{-8}$ sec. The second detector was a 3 in.$\times$3 in. NaI(Tl) crystal coupled to a Du Mont 6363 photomultiplier.

SOURCE PREPARATION

The Co^{56} was produced by the $Fe^{56}(p,n)Co^{56}$ reaction with 20-Mev protons in the ORNL cyclotron. The target was an iron foil weighing approximately 2 g. This was dissolved in concentrated HCl. Then the iron was extracted from the cobalt with ether. This was done three times; each time the cobalt solution was used for the next extraction. This separated cobalt fraction was further purified with ion exchange columns of Dowex 1 resin (50–100 mesh). The cobalt was absorbed on the column in concentrated HCl. The cobalt was then eluted in 4*M* HCl. After passing through the large (1 cm diam$\times$20 cm long) column, this was repeated with a small (2 mm diam$\times$5 cm long) column for final purification.

The first source was vacuum evaporated onto an aluminum coated Zapon backing 50 μg/cm^2 and covered with a Zapon film of less than 10 μg/cm^2. The source, completely invisible, was less than 10 μg/cm^2 thick. The evaporation yield was poor, however, and this source was relatively weak.

A second source was prepared on a similar backing by liquid deposition of the activity and covered with a similar Zapon film. This source was prepared about 10 days later from the remaining cobalt solution and was not as thin. Its thickness was 50–100 μg/cm^2.

Later, a source of the same separated Co^{56} was prepared on a Mylar backing for the scintillation spectrometer. A source of Co^{58} was prepared from a Co^{58} solution obtained from ORNL. This source was used for comparison in this spectrometer of the Co^{58} and Co^{56} spectra.

TREATMENT OF DATA

Four measurements of the positron spectrum were made from 200 kev to 2.1 Mev which is well beyond the 1.5-Mev end point of the highest energy group. The first two measurements were with the evaporated source and the other two with the liquid deposited source. In addition, less detailed runs were made with the evaporated source to check on the decay of the 470-kev group. Each run consists of two sets of data taken on repeated cycles of the magnetic field. Most of the points have a 1% statistical accuracy in the counting rates.

The half-life of the source was checked with a fraction of the separated solution. This fraction was checked for a period of 200 days and was found to decay with a half-life of 80 days. This is in agreement with the reported half-life of 77.3 days.[14] From a knowledge of the target foil and the chemistry performed (as well as the analysis of the beta spectrum), it was concluded that Co^{58} was the only possible contamination. Co^{58} does have a positron spectrum with a $\simeq$470-kev end point. Decay checks on the spectrum of the 470-kev group did not indicate a half-life different from that of the main group. This is difficult to determine, however, since the source was getting weaker and Co^{56} and Co^{58}

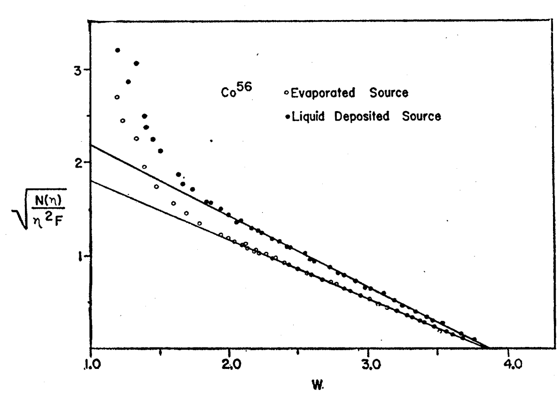

FIG. 1. Fermi-Kurie plots of the Co^{56} data from the evaporated source (open circles) and the liquid deposited source (closed circles).

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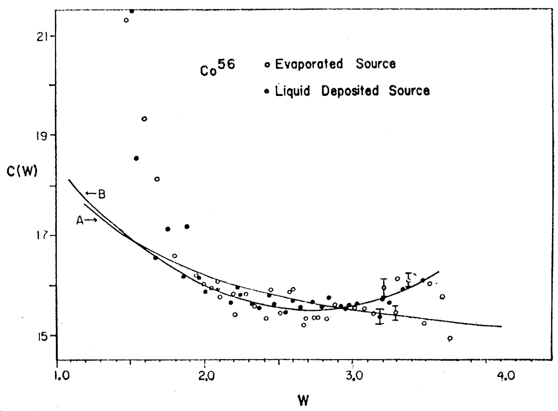

FIG. 2. Shape-factor plots of $C(W) \sim N(\eta)/\eta^2 F(W_0-W)^2$ vs W for the evaporated source (open circles) and the liquid deposited source (closed circles). The plots for the two sets of data are normalized. The curves correspond to empirical shape factors $(1+0.3/W)$ and $(1-0.24W+0.044W^2)$ normalized to the data.

have similar half-lives (77.3 days[14] and 71.3 days,[15] respectively).

Fermi-Kurie (F-K) plots of the data were made with the aid of tables[16] and the Indiana University computer. The outer screening correction is negligible at this Z value and these energies, as is the finite de Broglie wavelength correction. Least-squares fits to the F-K plots and the shape-factor plots were made with the Vanderbilt University computer.

RESULTS

In Fig. 1 are seen the F-K plots of runs 1 and 2 made with the evaporated source, and runs 3 and 4 made with the liquid deposited source. The straight lines are least-squares fitted to the data for $2.6 \leqslant W \leqslant 3.6$. The end-point energy is $W_0 = 3.865\ m_0c^2$ (1.464 ± 0.015 Mev). The F-K plots are nearly linear from the maximum energy down to about 470 kev. Another group is clearly seen below this energy. No indication is found in the F-K plots for a positron group of maximum energy 0.9–1.0 Mev.

If a weak positron group with maximum energy about 0.9–1.0 Mev exists, it should be seen more clearly in a plot of the shape factor. In Fig. 2 are given shape-factor plots of $C(W) \sim N(\eta)/\eta^2 F(W_0-W)^2$ vs W. Data are plotted for both sources. Typical statistical limits of errors in the counting rates are shown. Except for the final two or three points, which are very sensitive to the determination of W_0, the shape factor is well fitted by a straight line from about 600 kev out. There is a slight rise in the data between 470 and 600 kev. There is no evidence for another beta group with end-point energy 0.9–1.0 Mev. As a check on the possible existence of such a group, the following analysis was carried out. The positron spectrum of Zr^{89} ($E_0 = 897$ kev) was recently measured in this spectrometer.[12] A plot of $N(\eta)$ vs $H\rho$ of the Zr^{89} data was made. This plot was normalized to have an intensity of 1% of a similar plot for the Co^{56} data. Then, the 1% Zr^{89} spectrum was added to the Co^{56} total spectrum. Next, this Zr^{89} spectrum was subtracted from the Co^{56} total spectrum. From a comparison of these three plots (the Co^{56} spectrum, the Co^{56} spectrum with a 1% Zr^{89} spectrum added, and the Co^{56} spectrum with a 1% Zr^{89} spectrum subtracted), an upper limit of 1% can be set for the intensity of a positron group with maximum energy about 900 kev.

The 1.46-Mev group was treated as if it had a linear F-K plot and then subtracted from the total. An F-K plot of the data after this subtraction is seen in Fig. 3. The data were obtained with the evaporated source. Note, there appear to be two discontinuities. The strongest group has an end point at about 470 kev. If the points beyond 470 kev are treated as a beta group, the end-point energy would be about 720 ± 70 kev. Such a group is inconsistent with any previous reports. The intensity of the 470-kev group relative to the total is about 10%. The intensity of the other distribution treated as a beta spectrum is about 1%. Other evidence is strongly against the existence of such a higher energy group. (See discussion, next section.)

However, if the 1.46-Mev group is not assumed to have a linear F-K plot, then evidence for the 720-kev "group" disappears (Fig. 4). Indeed, with its high ft value, the 1.46-Mev group might be expected to show some deviation from the allowed spectrum. Previous studies of allowed beta spectra (both positron and electron) with much lower ft values have suggested the necessity for an empirical shape correction factor of the form $1+b/W$ (with $b \simeq 0.3$) or $1+C_1W+C_2W^2$. (See reference 12.) The shape correction factor $(1+0.3/W)$ normalized to the data is shown in Fig. 2. Also shown is a shape factor $(1-0.24W+0.044W^2)$ obtained from a least-squares fit to the data with $1.9 \leqslant W \leqslant 3.6$ and normalized to the data. Both of these are reasonable

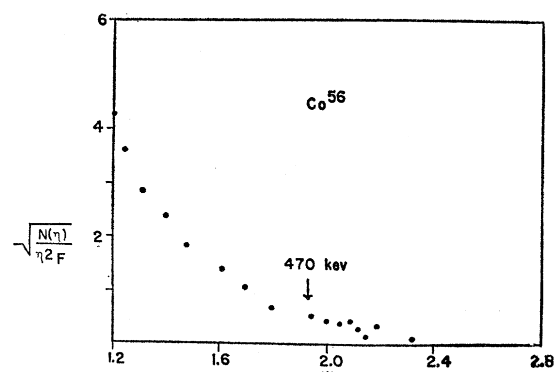

FIG. 3. Fermi-Kurie plot of the Co^{56} data taken with the evaporated source after the 1.46-Mev group, assumed to have a statistical shape, was subtracted.

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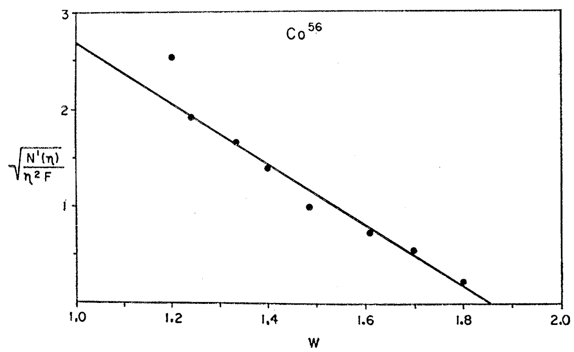

FIG. 4. Fermi-Kurie plot of the Co^{56} data taken with the evaporated source after the 1.46-Mev group, assumed to have a shape factor $\sim(1+0.3/W)$, was subtracted.

fits to the spectrum in the energy range above 470 kev. Note that since the high-energy points are very sensitive to the choice of W_0, not as much weight was given to the last two or three points. If a shape-correction factor is applied to the 1.46-Mev group, only the 470-kev group remains after subtraction of the main group (see Fig. 4). When the shape factor is applied to the 1.46-Mev group, the intensity of the low-energy group is reduced from 10% to 7–8% and the energy from 470 to 440 kev.

The singles gamma-ray spectrum of Co^{56} was measured with particular interest in the energy region around the strong 845-kev transition in the decay of Co^{56}. Co^{58} has a strong gamma ray at 810 kev. The Co^{58} spectrum was carefully measured in this region also. Then combined plots of the Co^{56} and Co^{58} gamma-ray spectra were constructed with the Co^{58} fraction representing 5, 10, and 25% of the Co^{56} decays.

These plots were then compared with the singles and coincidence Co^{56} spectra. The coincidence spectra were obtained by looking at the energy region around 845 kev, while gating the coincidence analyzer on the 1.24-Mev gamma ray which is in prompt coincidence with the 845-kev gamma ray in the Co^{56} decay. From the difference in the appearance of the 845-kev gamma ray photo-peak in the Co^{56} singles spectrum and coincidence spectrum, it was estimated that a 810-kev gamma ray was possibly present in the Co^{56} sample and that the intensity of this gamma ray relative to that of the 845-kev gamma ray in Co^{56} was $\lesssim 5\%$. This number has a large uncertainty, however. Unfortunately, when the conversion electron spectrum was measured, the beta-ray source was too weak to observe conversion electrons of an 810-kev transition with the above intensity. From this work, the possible contribution of Co^{58} to the Co^{56} positron spectrum is $\lesssim 5\%$.

DISCUSSION AND CONCLUSIONS

First consider the possibility of groups other than the intense 1.46-Mev group. From our results, an upper limit of 1% relative to the total has been set for the intensity of a group with maximum energy 0.9–1.0 Mev. Such a group has been reported[6,7] and questioned.[8,9] An upper limit of 1% for the intensity of such a group has also been made from beta-gamma coincidence measurements.[1,10] If this group does exist, it would correspond to a twice forbidden $(4+ \rightarrow 2+)$ transition in the accepted decay scheme. A twice forbidden transition would be much too weak to compete with the allowed transitions even though the ft values are high. On the basis of all the evidence, the upper limit of 1% for a group with maximum energy 0.9–1.0 Mev is quite safe.

It is emphasized again that there has been no real evidence for other beta groups with end-point energies between 550 and 1250 kev. Such groups would also be inconsistant with the decay scheme as discussed above. Furthermore, beta-gamma coincidence studies should have indicated the presence of another group in this range if one exists. Thus, the high-energy tail on the 470-kev beta group (Fig. 3) is not another beta group.

Now look at the evidence for the 440–470-kev group. A 440-kev group with an intensity of 4% of the total was first reported[5] and then not observed $(0.44\beta^+ < 2\%$ of $1.46\beta^+)$.[9] Diddens *et al.* set an upper limit of 0.6% for the intensity of a 450-kev positron group relative to the 1.46-Mev group.[10] This conclusion was reached, however, by measuring coincidences between positrons with an energy of 230 kev and gamma rays with an energy of 2.1–2.3 Mev. It has been shown that positrons of this energy, while not in coincidence with these high-energy gamma rays with any observable intensity, are in coincidence with the 1.04-Mev gamma rays.[1] The intensity of this group was reported only as weak.[1] Thus the existence, but not the intensity, of a positron group with maximum energy about 440–470 kev is established.

In our studies, a positron group with an end point 440–470 kev was observed. The intensity of this group is 10% of the total if the 1.46-Mev group has a strictly statistical shape. The 1.46-Mev spectrum, as will be discussed later, is better fitted with a weak energy-dependent shape factor. When this is included in the analysis, the intensity of the 470-kev group is reduced to about 7–8%. Even this intensity seems rather high in view of the other evidence. Neither this group nor its intensity as measured in this work is associated with source thickness problems, as has been suggested.[9] The shape of the low-energy region of the spectrum and the relative intensity are the same for the data obtained with evaporated source ($<10\ \mu g/cm^2$ source thickness) as for that obtained with the thicker (50–100 $\mu g/cm^2$) liquid deposited source. If these low-energy electrons of the 470-kev group did arise from source thickness problems, then there should have been a marked difference in the data from the two sources and there was no difference. Thus, this observed 470-kev group must arise from beta decay.

The question arises as to whether this $\lesssim 10\%$ group is the result of an impurity. On the basis of half-life measurements and the chemistry performed, Co^{58} is the only likely impurity. As a check on this, the gamma-ray spectrum was carefully studied in search of the prominent 810-kev transition in Co^{58}. From the analysis of the gamma-ray measurements, a value of $\lesssim 5\%$ was obtained for the possible contribution of Co^{58} to the Co^{56} spectrum. A more definite value for the Co^{58} contribution was difficult to obtain. This introduces a large uncertainty in the intensity of this beta group in Co^{56}. The intensity of a Co^{56} beta group with energy 440–470 kev may be from 2–10% on the basis of our work, but the lower values are to be preferred when all the evidence is considered.

Now consider the intense 1.46-Mev positron group. The shape of this spectrum is nearly allowed. For the shape to differ from statistical would not be surprising in view of the high log*ft* value of 8.7 and the large beta-gamma directional correlation. Although an allowed shape cannot be completely excluded on the basis of these measurements, the data are fitted much more consistently by including an energy-dependent shape factor. The F-K plots and experimental shape factors exhibit a small excess of low-energy electrons over the allowed distribution before the 470-kev group begins. This is seen more clearly in the data above 470 kev when the 1.46-Mev group is subtracted as an allowed spectrum. This tail on the 470-kev group disappears if the 1.46-Mev group is subtracted as a nonstatistical spectrum.

It has been found necessary to include a shape factor of the form $(1+b/W)$ or $(1+C_1W+C_2W^2)$ to explain other allowed beta spectra.[12] Such shape factors normalized to the data are shown in Fig. 2. Either of these two equations offers a good fit to the data for b values between 0.2 and 0.3 or C_1 about -0.24 and C_2 about 0.04.

The necessity to include in the Co^{56} 1.46-Mev spectrum a shape factor of the same form and magnitude as has been observed in other positron and electron spectra perhaps gives added weight to the other measurements.[12] One significant fact here is the high *ft* value of this Co^{56} group. It has been thought that the deviations reported earlier in positron spectra[12] might be connected with the higher than usual *ft* values (log*ft* of 7.4 and 6.1 for Na^{22} and Zr^{89}, respectively) although the Zr^{89} *ft* value is only just outside the limits of normal allowed values. For this Co^{56} group, the log*ft* value is 8.7. The fact that the shape factor of the strongly hindered Co^{56} positron spectrum does not differ observably from those of Na^{22} and Zr^{89} suggests that whatever the nature of the deviations observed in Na^{22}, Zr^{89}, and Co^{56}, they are of a form that does not depend on the magnitude of the *ft* value.

It was pointed out in the angular correlation work[2] and is emphasized again here that with such a large beta-gamma correlation and with more detailed information now available about the beta spectrum, the 1.46-Mev group in the Co^{56} decay should be a good case to compare theory and experiment for higher-order effects which may occur when the normal allowed matrix elements are reduced. More theoretical work is needed for such a large *ft*, allowed decay. Such an analysis might hold a clue to understanding the deviations observed.

It should be pointed out that, as in the Zr^{89} spectrum, the 1.46-Mev transition proceeds by both Fermi and Gamow-Teller radiations. The deviation requiring the $(1+b/W)$ correction factor may still arise only from the Gamow-Teller part as in Na^{22}, P^{32}, In^{114}, and Y^{90} and may not be associated with the Fermi part of the radiation.

ACKNOWLEDGMENTS

The authors wish to thank Dr. R. E. Segel for pointing out the unusually high *ft* value of the 1.46-Mev group and suggesting further studies of this decay.

We wish to thank Dr. H. Rolf and the Vanderbilt University Computing Center for their help, and to acknowledge the National Science Foundation's support of the computer work. W. Croft is thanked for his assistance in the chemical preparation of the sources and D. Camp for help in carrying out the experiment. The assistance of Mrs. A. Hankla in the data analysis is also gratefully acknowledged. J. Mann is thanked for his work on the gamma-ray spectra.