The Second-Forbidden Beta Spectra of Co^{60} and Sc^{46}†*

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A hitherto unreported high-energy beta-ray component has been found in the decay of Co^{60}. Its abundance and end point are (0.15±0.01) percent and 1.48±0.02 Mev, respectively. The abundance and end point of the Sc^{46} high-energy component are (0.096±0.01) percent and 1.25±0.02 Mev, respectively. Both the Co^{60} and Sc^{46} spectra can be fitted with the C_{2T} correction factor corresponding to $\Delta J=2$ and no parity change. The log ft values, uncorrected for the forbidden shape, are: $Co^{60}=12.6$, and $Sc^{46}=11.3$. The decay schemes are discussed.

I. INTRODUCTION

RECENT studies of beta spectra have shown the existence of several types of forbidden transitions. Excellent review articles are given by Konopinski and Langer[1] and Wu.[2] The theory of forbidden spectra is discussed by Konopinski and Uhlenbeck.[3]

The work reported here is concerned with second-forbidden transitions characterized by a spin change of two units and no parity change. Spectra of this type are not unique in that one parameter may be adjusted to obtain agreement with experiment. Only transitions involving a spin change of one unit more than the degree of forbiddenness yield unique spectra.

The second-forbidden spectra with $\Delta J=2$ (no) have been satisfactorily fitted with the approximate form of the tensor correction factor;[1] *viz.*,

$$\hbar^2 C_{2T}=\sum|T_{ij}|^2(\alpha Z/2R)^2(p^2+4q^2)+\sum|A_{ij}|^2(p^2+q^2) -\sum(T_{ij}A_{ij}^*+c.c.)(\alpha Z/2R)(p^2+2q^2), \quad (1)$$

where p and q are the electron and neutrino momenta, respectively.

Longmire and Messiah[4] have shown that the ratio of the matrix elements $\rho=A_{ij}/T_{ij}$ is real, and independent of both the z components of the spins and i, j. Hence, (1) reduces to

$$C_{2T}\sim(p^2+k^2q^2), \quad (2)$$

where

$$\rho=\frac{\alpha Z}{2R}\left(\frac{k-2}{k-1}\right). \quad (3)$$

It must be mentioned that the same correction factor results from the polar-vector interaction, and that the polar-vector–axial-vector combination is not excluded. Further, admixtures of scalar and pseudoscalar to the tensor interaction do not alter the form of Eq. (2).[1] However, for comparison with other work, it is convenient to express the results in terms of the particular ratio stated in Eq. (3). Cs^{137}, Tc^{99}, Cl^{36}, Cs^{135}, and I^{129} exhibit spectra which fall into this category.[2]

Cobalt-60 (5.2y) decays principally to the second excited state of Ni^{60} by the emission of a 0.32-Mev beta ray.[5] Two prompt gamma rays are in cascade to the ground state of Ni^{60}. The existence of a weak high-energy beta transition to the first excited state of Ni^{60} has not been mentioned hitherto in the literature, although Siegbahn and Deutsch[6] observed electrons beyond the main beta spectrum which were attributed to the Compton effect.

Scandium-46 (85d) decays to Ti^{46} in a manner[7] similar to that of Co^{60}. The existence of a high-energy beta component was first suspected by Walke;[8] since then numerous studies of its intensity and end-point energy have been made.[7,9] The more recent[10,11] measurements give 0.1 to 0.2 percent and 1.25 Mev for these quantities.

II. EXPERIMENTAL METHOD

A. Spectrometer

A uniform magnetic field solenoidal spectrometer with a ring image was used to measure the beta spectra. Several improvements were made in the spectrometer baffle since the original description[12] in order to facilitate study of the very weak beta components in the presence of intense gamma and low-energy beta radiation.

The lead baffle nearest the source was removed, and additional lead was placed in the main support tube. A lead shield two inches thick was placed around the

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[1] E. J. Konopinski and L. M. Langer, Ann. Rev. Nuclear Sci. **2**, 261 (1953).
[2] C. S. Wu, Physica **18**, 989 (1952).
[3] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).
[4] C. L. Longmire and A. M. L. Messiah, Phys. Rev. **83**, 464 (1951).
[5] Deutsch, Elliot, and Roberts, Phys. Rev. **68**, 193 (1945); C. Y. Fan, Phys. Rev. **87**, 252 (1952).
[6] K. Siegbahn and M. Deutsch, Arkiv Fysik **2**, 9 (1950) and Phys. Rev. **77**, 680 (1950).
[7] I. Feister and L. F. Curtiss, J. Research Natl. Bur. Standards **38**, 411 (1947); C. Peacock and R. G. Wilkinson, Phys. Rev. **72**, 251 (1947); A. E. Miller and M. Deutsch, Phys. Rev. **72**, 527 (1947).
[8] H. Walke, Phys. Rev. **57**, 163 (1940).
[9] C. E. Mandeville and M. V. Scherb, Phys. Rev. **73**, 141 (1948); C. L. Peacock and R. G. Wilkinson, Phys. Rev. **74**, 297 (1948); Sorenson, Dale, and Kurbatov, Phys. Rev. **79**, 1007 (1950); F. T. Porter and C. S. Cook, Phys. Rev. **81**, 298 and 640 (1951).
[10] Whalen, Porter, and Cook, Phys. Rev. **89**, 902 (1953).
[11] F. H. Schmidt and G. L. Keister, Phys. Rev. **91**, 483 (1953).
[12] F. H. Schmidt, Rev. Sci. Instr. **23**, 361 (1952).

counter. Another lead shield approximately one-half inch thick was mounted directly behind the ring-slit.

Six helical baffles were mounted along the electron trajectories between the delimiting and ring baffles to provide discrimination between positrons and electrons. Further discrimination was achieved by a turbine-like baffle consisting of $\frac{1}{32}$-in. thick copper blades placed immediately behind the ring focus slit. In addition to positron-electron discrimination, these baffles reduced the background due to Compton and photoelectrons produced in the baffle structure.

The spectrometer was calibrated with the F line[13] of thorium B. Internal conversion electrons from Ni^{60} provided a check calibration.[14] The sources were maintained at ground potential by means of a hot-cathode source discharger.

The solid angle subtended at the source by the opening of the delimiting baffles was set to 4 percent of the total sphere. The actual transmission of the instrument was reduced to 2.7 percent by the helical baffle system. The inverse momentum resolution under these conditions for the source size used was 1.7 percent full width at half-maximum.

An end-window G-M Counter served as the detector. A 0.6-mg/cm^2 rubber hydrochloride window allowed complete transmission of electrons down to 50 kev.

B. Scattering in the Spectrometer

The spectrometer was checked for possible electron scattering in several ways. The spectrum of Pm^{147}, which is known to yield a linear Kurie plot,[15] was examined. A thin source on a Zapon backing produced a linear Kurie plot down to 50 kev; with a thin Zapon counter window linearity was achieved to 20 kev. The P^{32} spectrum also gave a linear Kurie plot consistent with the thickness of the source backing.

Very strong Pm^{147} and P^{32} sources were studied in the neighborhood of the end-point energies. These sources gave counting rates at the peaks of the spectra of more than 10 000 counts/sec.[16] In addition to a small instrumental curvature due to the finite resolution, a "tail" of electrons was observed which extended to $B\rho$ values some 20 percent greater than the end point. The tail is entirely negligible for most purposes, but does produce a slight distortion in the high energy spectra of Co^{60} and Sc^{46} near the end-points of the main branches. It is probably due to scattering from baffle edges. Figure 1 shows the tail of the Pm^{147} spectrum. For comparison a corresponding section of the Co^{60} spectrum is shown.

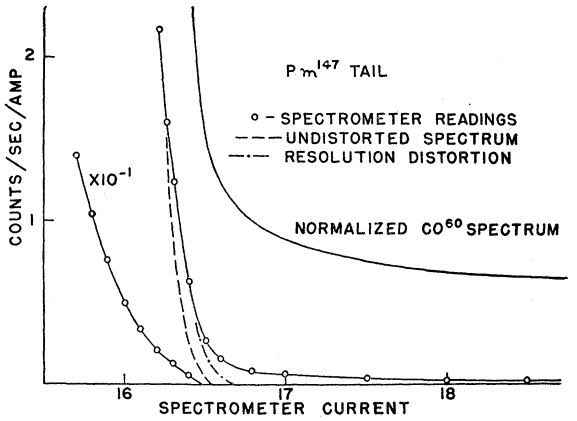

FIG. 1. Instrumental distortion observed with a very strong Pm^{147} source. Co^{60} is shown for comparison.

C. Gamma-Ray Background

The gamma-ray background from the strong sources used in this investigation was troublesome. Although the measures discussed in Sec. II-A materially reduced the background, it was still far from negligible. The gamma-ray background was measured by reversing the spectrometer current.[17] The reversed-current discrimination of the helical and turbine baffle was better than one in 2×10^5. The background obtained by closing off the ring slit opening was slightly less than that obtained by reversing the current. This is due to absorption of degraded gamma radiation in the $\frac{1}{4}$-in. aluminum and brass shutter. The gamma-ray background counting rate was about equal to the maximum counting rates of the weak high-energy beta spectra.

D. Secondary Effects in Baffle System

The high gamma-ray flux produces many Compton and photoelectrons in the baffle. Depending upon the point of creation, such electrons could conceivably pass through the ring slit and reach the counter for current values both above and below the energy of the gamma-ray or internal conversion lines.

In order to study the effect, a strong source of Mn^{52} was made in the University of Washington 60-inch cyclotron.[18] Mn^{52} ($6d$) decays by positron emission and K capture. Three gamma rays, 0.73, 0.94, and 1.46 Mev, are in cascade.[19]

The electron spectrum of Mn^{52} was examined in the spectrometer. The source was chemically deposited and consequently quite non-uniform in thickness. Hence, many Compton electrons were observed which were produced in the source. However, above the Compton limit for the 1.46-Mev gamma ray, no electrons other than those due to internal conversion were found. The

[13] G. Lindström, Phys. Rev. **83**, 465 (1951); D. I. Meyer and F. H. Schmidt, Phys. Rev. **89**, 908 (1953).
[14] Alburger, Hedgran, and Lindström, Phys. Rev. **89**, 1303 (1953).
[15] Langer, Motz, and Price, Phys. Rev. **77**, 798 (1950).
[16] Measured by closing all but a very small known fraction of the ring-slit. This was done by means of the sector baffle. See reference 12.
[17] Positrons from internal pair conversion of the 1.33-Mev gamma ray of Co^{60} have a maximum energy of 0.33 Mev; hence, they introduced no error.
[18] F. H. Schmidt *et al.*, Rev. Sci. Instr. (to be published).
[19] W. C. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946).

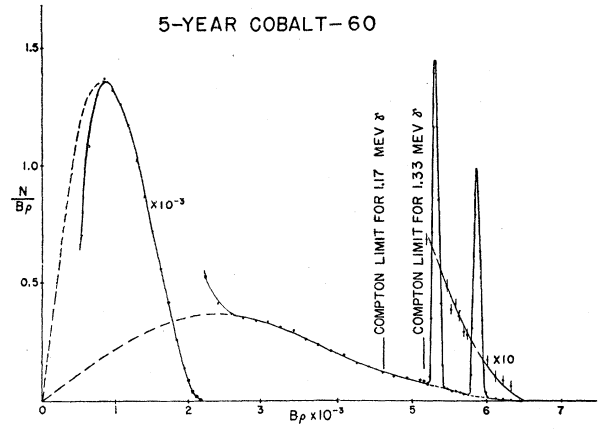

FIG. 2. The electron momentum spectrum of Co^{60} source C-1. The dashed portions were obtained from extrapolation of the Kurie plots.

counting rate on the high-energy side of the 1.46-Mev internal conversion line was indistinguishable from background. In contrast, a significant electron count extends beyond the higher energy internal conversion line of Co^{60} (see Fig. 2).

E. Correction for Compton Electrons Produced in the Sources[11]

The number of Compton electrons produced in a lamina exposed to gamma radiation is proportional to the thickness x of the lamina. If the lamina consists of a source of gamma radiation of constant specific activity then the number of gamma rays is also proportional to x. Hence, the number of Compton electrons produced in a laminar source, and counted in a spectrometer is $N_c=\Omega Sax^2$, where S=source strength per unit thickness, a=a constant for a given electron energy, and Ω=spectrometer transmission. If the source lamina is not uniformly thick, one must sum over the various thicknesses to obtain $N_c=\Omega Sa\langle x^2\rangle_{Av}$.

If the source also emits a beta spectrum, the total count detected is

$$N=\Omega S[a\langle x^2\rangle_{Av}+b\langle x\rangle_{Av}], \tag{4}$$

where b=the beta spectrum distribution function.

If two sources equal in size but differing in thickness are made from material of uniform specific activity, the two spectrometer counting rates at a given energy will be

$$\begin{aligned} N_1&=\Omega S[a\langle x_1^2\rangle_{Av}+b\langle x_1\rangle_{Av}],\\ N_2&=\Omega S[a\langle x_2^2\rangle_{Av}+b\langle x_2\rangle_{Av}]. \end{aligned} \tag{5}$$

Eliminating a from Eq. (5), and solving for the true beta counts of source No. 1

$$b\Omega S\langle x_1\rangle_{Av}=\frac{N_1[\langle x_2^2\rangle_{Av}/\langle x_1^2\rangle_{Av}]-N_2}{\langle x_2^2\rangle_{Av}/\langle x_1^2\rangle_{Av}-r}, \tag{6}$$

where the ratio of the source strengths$=r=\langle x_2\rangle_{Av}/\langle x_1\rangle_{Av}$. If the two sources are uniform in thickness, then $\langle x_2^2\rangle_{Av}/\langle x_1^2\rangle_{Av}=r^2$, and Eq. (6) becomes

$$b\Omega Sx_1=\frac{1}{r}\left(\frac{N_1r^2-N_2}{r-1}\right). \tag{7}$$

In this case Eq. (4) is a true quadratic. Experimentally, the counting rates at one value of momentum for three sources of known relative strengths are sufficient to determine a quadratic dependence; such a dependence indicates that the sources are adequately uniform for application of this method of correction.

III. SOURCE PREPARATION

Cobalt-60 sources were prepared by electroplating active cobalt metal onto 0.6-mg/cm² rubber hydrochloride films. High specific activity (>3 curies/gram) cobalt was obtained from Oak Ridge.

A layer of gold (~0.1 mg/cm²) was vacuum-evaporated onto the rubber hydrochloride. Its resistance was about 10 ohms per square. The film was placed in a jig which pressed the gold section gently against the bottom of a short piece of glass tubing. A plating solution of $CoCl_2$ and boric acid was pipetted into the tube. A platinum wire anode was inserted into the solution. A current of 5 ma/cm² for 14 seconds to 10 minutes was used to prepare the sources of various required strengths. A similar recipe has been described by Dunn.[20]

Four Co^{60} sources $\frac{7}{32}$ inch in diameter were prepared. Data for them are listed in Table I. The low-energy beta spectrum of the weakest source was measured in the spectrometer; the source strength was found by integrating over the spectrum. The gamma radiation of the other three sources was compared with the weakest source. Source thicknesses were obtained from the charge passed through the plating cell. Due to a small amount of gas formation at the cathode the thicknesses listed in Table I are upper limits.

Scandium-46 sources were prepared by precipitation of scandium hydroxide onto rubber hydrochloride films. High specific activity (>15 C/g) scandium was obtained from Oak Ridge.

Vacuum evaporation was tried but proved impractical for preparation of strong sources. The following method[19] proved most satisfactory: $Sc(NO_3)_3$ solution was placed on the rubber hydrochloride film over an area defined by insulin. The solution was exposed to ammonia vapor and a white gelatinous hydroxide appeared. After evaporation a thin and fairly uniform layer of scandium hydroxide and ammonia salt remained.

Four Sc^{46} sources $\frac{7}{32}$ inch in diameter were prepared. Their strengths, as listed in Table I, were determined in the same manner as the Co^{60} sources. The two strongest sources were weighed in order to determine their thicknesses. Thicknesses of the other two were inferred from their gamma-ray intensities.

[20] R. W. Dunn, Nucleonics **10**, No. 7, 8 (1952).

TABLE I. Source data.

Source material	Cobalt-60				Scandium-46			
Source No.	*C*-1	*C*-2	*C*-3	*C*-4	*S*-1	*S*-2	*S*-3	*S*-4
Strength mC	0.47	0.28	0.099	0.014	0.46	0.34	0.20	0.0094
Thickness mg/cm²	<1.32	<0.66	<0.026	<0.004	~3.5	~2.9	~1.6	~0.07
Backing thickness mg/cm²	0.7	0.7	0.7	0.1	0.6	0.6	0.6	0.6
Relative intensity by ionization chamber measurement	1.00	0.60	0.21	0.029	1.00	0.75	0.46	0.023

IV. RESULTS

A. Co^{60}

The electron momentum spectrum of the strongest Co^{60} source, *C*-1, is shown in Fig. 2. The end of the spectrum beyond the 1.33-Mev internal conversion line is shown to expanded scale. No electrons were observed beyond the 1.46-Mev Mn^{52} internal conversion line. (See Sec. II-D.) Its intensity was comparable with the Co^{60} lines. A very small hump which may be due to Compton electrons lies just below the 1.17-Mev conversion line. The dashed portion of the high-energy spectrum is extrapolated from the best fit using the C_{2T} correction factor.

In Fig. 3 are plotted counting rates *vs* source strength for various points on the electron spectrum. The absence of a quadratic component within experimental error shows that the sources are thin enough to make the Compton correction term in Eq. (4) negligible. Hence, for the Co^{60}, no corrections for Compton electrons were made.[21]

Over a period of two months there was no evidence that the high-energy beta-component decayed with a half-life different from that of the main component.[22]

Figure 4 shows Kurie plots[23] of the high-energy and the low-energy spectra of Co^{60} obtained from source *C*-1. The low-energy component exhibits linearity down to ~150 kev.[24] Hence, it is unlikely that the high-energy component would be distorted above 400 kev.

The high-energy spectrum in Fig. 4 exhibits a forbidden shape similar to that of Cs^{137}.[25] The curve is calculated using the C_{2T} correction factor from Eq. (2) with k^2 adjusted to give the best fit to the experimental points. The value of k^2 so obtained is 5.79; the ratio of the matrix elements, ρ, obtained from Eq. (3) is 2.0. The nuclear radius was assumed $=1.4\times10^{-13}A^{\frac{1}{3}}$.

The end point of the high-energy Co^{60} spectrum is 1.48±0.02 Mev. From the integral of the momentum spectra of Fig. 2, the abundance of the high energy branch is found to be (0.15±0.01) percent. The log of the comparative half-life[26] of the transition is 12.6.

The high-energy Co^{60} spectrum could not be fitted with the unique correction factor for second-forbidden spectra corresponding to $\Delta J=3$ (no), as is shown in Fig. 4.

B. Sc^{46}

Figure 5 shows the electron spectra obtained from the three strongest Sc^{46} sources. The curves are normalized to source *S*-1 by the source strengths listed in Table I. Again, electrons are observed beyond the 1.12-Mev conversion line. At the Compton limit for the 0.89-Mev gamma ray there appear "humps" characteristic of Compton spectra.

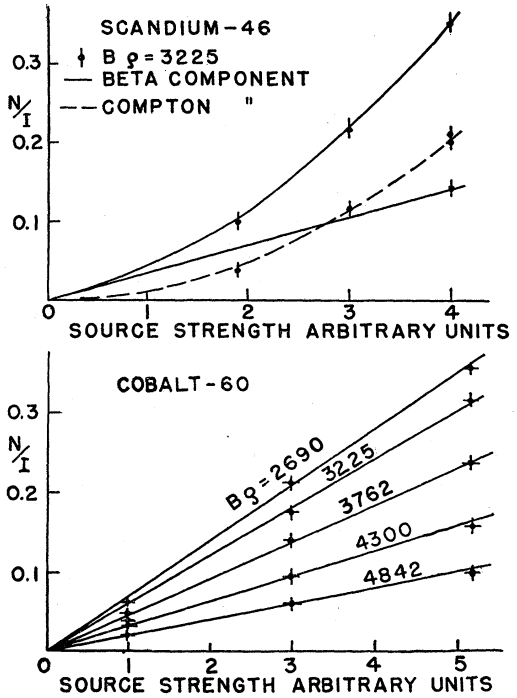

FIG. 3. Analysis of the Compton electron background. The linearity of the Co^{60} curves indicates a negligible Compton component; the quadratic dependence for Sc^{46} shows the presence of Compton electrons.

[21] It is interesting to note that a chemically deposited Co^{60} source of strength comparable to *C*-1 exhibited strong Compton electron spectra similar to those of Sc^{46}, as shown in Fig. 5.

[22] A very remote possibility exists that Co^{61} is present as a contaminant. Smith, Haslam, and Taylor [Phys. Rev. 84, 482 (1951)] have found that Co^{61} (99 min) emits two beta-rays (1.00 and 1.43 Mev) and an ~0.5-Mev gamma ray. In order for Co^{61} to be produced in a secondary reaction in the pile and remain as a contaminant, it would have to exist in a long half-life low-energy isomeric state which fed the 99-min Co^{61} ground state.

[23] *Tables for the Analysis of Beta Spectra,* National Bureau of Standards, Applied Mathematics Series No. 13 (U. S. Government Printing Office, Washington, 1952).

[24] The weakest source, *C*-4, showed linearity down to 50 kev.

[25] L. M. Langer and R. J. D. Moffat, Phys. Rev. 82, 635 (1951).

[26] S. A. Moszkowski, Phys. Rev. 82, 35 (1951).

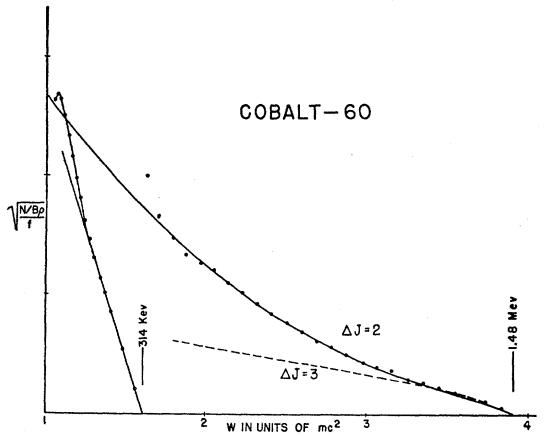

FIG. 4. Kurie plots of the Co^{60} spectra. The solid line on the higher energy spectrum is the best fit obtained from the C_{2T} correction factor. The dashed curve is the unique shape for $\Delta J=3$.

In Fig. 3 is plotted the counting rate at one value of momentum as a function of source strength. The quadratic component predicted by Eq. (4) for uniform sources is apparent. From similar curves for each momentum value the appropriate correction factors are found. Curve A, Fig. 5, is the corrected spectrum found by application of Eq. (7).

The high-energy Sc^{46} spectrum was observed for a period of two months. Its half-life was the same as that of the main beta component. This result is in agreement with the observations of Porter and Cook.[9]

Figure 6 shows the Kurie plot of both Sc^{46} spectra. The high-energy component is that obtained from curve A, Fig. 5. The low-energy component is linear down to ~175 kev. The high energy spectrum of Sc^{46} is similar to that of Co^{60}. The curve is calculated from Eq. (2) with $k^2=7.70$. Hence, $\rho=2.59$, the end-point energy$=1.25\pm0.02$ Mev, and the abundance$=(0.096\pm0.010)$ percent.[27] The log of the comparative half-life of the transition is[26] 11.3.

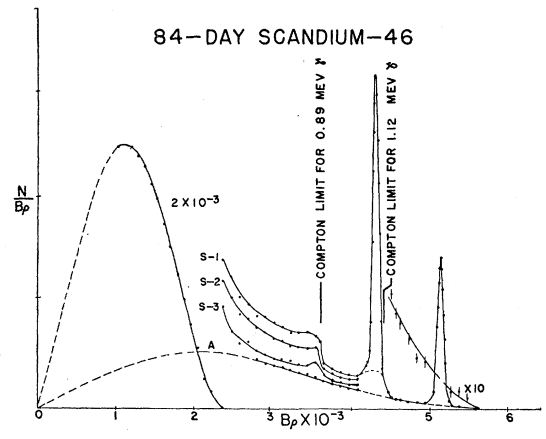

FIG. 5. The electron momentum spectra of three Sc^{46} sources normalized to source S-1. Curve A shows the higher energy spectrum obtained after correction for Compton electrons.

As in the case of Co^{60}, it was not possible to fit the Sc^{46} spectrum with the unique correction factor corresponding to $\Delta J=3$ (no).

DISCUSSION

The high-energy beta component in Sc^{46}, and the newly discovered high-energy component in Co^{60}, exhibit second-forbidden spectra characterized by $\Delta J=2$ (no). These conclusions are supported by the log ft values for the transitions. It is perhaps interesting to note that of the five previously known examples of this type, Cl^{36} is the only other even-A nucleus.

These results, coupled with other work,[28] enable one to make unambiguous spin and parity assignments to the ground states of Co^{60} and Sc^{46}. Angular-correlation and polarization studies of the gamma rays emitted by Ni^{60} and Ti^{46} have resulted in assignment of 0, 2, 4 for the spins and even parity for the first three levels of these even-even nuclei. Since the higher-energy spectra require $\Delta J=2$ (no), and the ft values for the low-energy spectra are consistent with either allowed or first-forbidden, it follows that the spins and parities of the ground states of both Co^{60} and Sc^{46} are 4+. Hence, the low-energy transitions are both allowed.

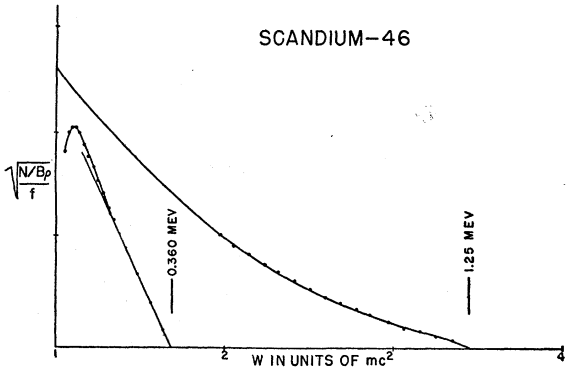

FIG. 6. Kurie plots of the Sc^{46} spectra. The solid line on the higher energy spectrum is the best fit obtained from the C_{2T} correction factor.

Therefore, the present data supports earlier proposals for the decay scheme[28] of Sc^{46} shown in Fig. 7. The gamma-ray order is in agreement with the more recent work.[10,11] The shell model predicts[29] an $f_{7/2}-f_{7/2}$ configuration for the odd proton and neutron, and hence even parity for the ground state. The spin of 4 is consistent with Nordheim's rule[30] for coupling of odd-neutron and odd-proton groups belonging to the same Schmidt group.

[27] The value (0.22 ± 0.5) percent given in a preliminary report (reference 11) was incorrect due to an instrumental error in estimating the intensity of the low-energy branch.

[28] M. G. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[29] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

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

For Co^{60} the assignment of 4+ to the ground state is not in full agreement with other decay scheme proposals. Deutsch and Goldhaber[31] measured the abundance of the beta-transition from the 10.7-min isomeric state of Co^{60} to the first excited state of Ni^{60} relative to the gamma-ray intensity. No evidence for a transition to the ground state was found. Accordingly, 2+ was assigned to the isomeric level. The K/L internal conversion ratio, and the half-life of the isomeric state, indicates a spin change of three[28] between the isomeric and ground states of Co^{60}. These considerations led to the assignment of 5+ to the ground state. The angular-correlation studies at low temperature by Grace and Halban[32] are consistent with a spin of 5, but do not exclude 4.

Figure 8 shows proposed new spin assignments of the Co^{60} decay scheme. A 1+ state has been assigned to the isomeric level. The shell model predicts that the

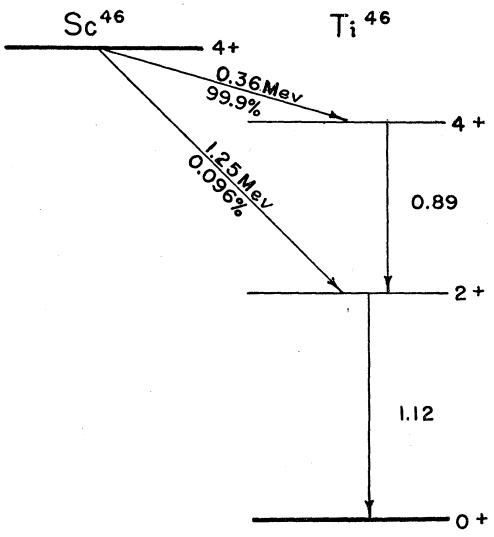

FIG. 7. Sc^{46} decay scheme.

odd proton and odd neutron of the Co^{60} ground state are in $f_{7/2}$ and $p_{3/2}$ states, respectively.[29] Since these belong to the same Schmidt group, the assignment of

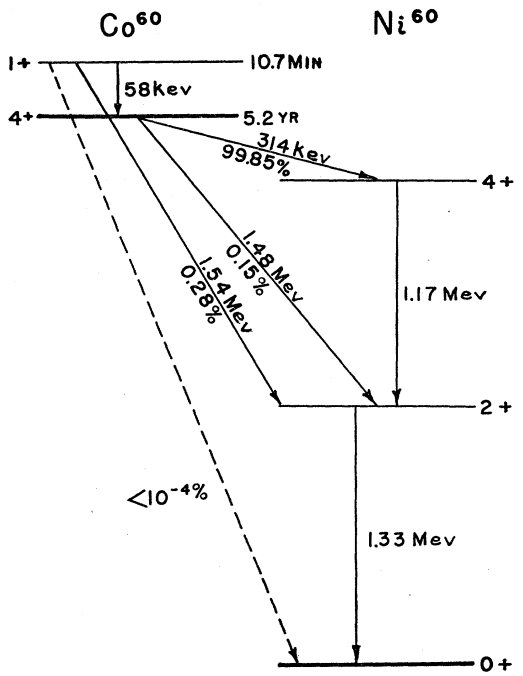

FIG. 8. Co^{60} proposed decay scheme.

4+ is consistent with Nordheim's rule for this case. The isomeric state may be formed by merely shifting a $p_{3/2}$ neutron to the next shell; *viz.*, the $f_{5/2}$. Now the odd-proton and odd-neutron groups belong to different Schmidt groups. Accordingly, the resultant spin will be the difference;[26] i.e., $J=1$.

The log ft values for the 0.31- and 1.54-Mev allowed transitions are 7.46 and 7.15, respectively.[28] The assignment of the proton and neutron orbitals for the ground state of Co^{60} produces l-forbiddenness in the 0.31-Mev transition; however, such is not the case for the 1.54-Mev transition from the isomeric state. The much larger log ft value (>9.67)[31] for the beta transition from the isomeric level to the ground state of Ni^{60} is even harder to understand. It remains inconsistent with the spin assignments proposed here.

We wish to express our appreciation to T. J. Morgan and the University of Washington cyclotron group for the production of Mn^{52}, and to J. S. Blair for helpful discussion.

[31] M. Deutsch and G. Scharff-Goldhaber, Phys. Rev. 83, 1059 (1951).
[32] M. A. Grace and H. Halban, Physica 18, 1227 (1952).