finds to first order in α,

$$\eta_1^{\pm}=\eta_1\pm\alpha[C+\log(2kr_0)-\mathrm{Ci}(2kr_0)\cos(2\eta_1)+\mathrm{si}(2kr_0)\sin(2\eta_1)], \quad (4)$$

$$C_1^{\pm}=1\mp\alpha[\mathrm{Ci}(2kr_0)\sin(2\eta_1)+\mathrm{si}(2kr_0)\cos(2\eta_1)] \quad (5)$$

with

$$\mathrm{Ci}(x)=-\int_x^\infty \frac{\cos x}{x}dx, \quad \mathrm{si}(x)=-\int_x^\infty \frac{\sin x}{x}dx,$$

$$C=\text{Euler's constant}=0.5772.$$

$\eta_3^{\pm}$ and $C_3^{\pm}$ have an identical expression in η_3. Similar expressions could be worked out for the η's and C's belonging to the p-waves.

For α of the order of 10^{-2} or smaller ($\alpha=1.25\times10^{-2}$ for 35 Mev pions) and not too small η_1, the α-terms in (4) and (5) are quite small and a good approximation is obtained by putting $\alpha=0$ in all expressions P, Q, R; the Coulomb effects reduce then to the α-term in Eq. (1).

To show the order of magnitude of the Coulomb effects for 35 Mev pions, the differential cross sections have been plotted for two choices of phase shifts: $\eta_3=\pm10°$, all other η's$=0$ (Fig. 1), and $\eta_{33}=\pm7°$, all other η's$=0$ (Fig. 2). These phase shifts correspond in each case to a total π^+ scattering cross section of the order of 18×10^{-27} cm^2, (in agreement with the data available so far).[4] The solid lines correspond to positive phase shifts, the dotted lines to negative ones. The difference between positive and negative phase shifts for $\pi^-\rightarrow\pi^0$ scattering at all angles and $\pi^-\rightarrow\pi^-$ or $\pi^+\rightarrow\pi^+$ scattering for $\theta>\pi/2$ is small and has been neglected. It is interesting to note that the effects are as large as 50 percent for θ below 50°, where θ is the scattering angle in the center-of-mass system.

A more detailed account of this work is available as a University of Rochester report (NYO-3223). The author wishes to thank Professor R. E. Marshak for suggesting this investigation and for many valuable discussions. He is indebted to Mr. R. Grover for computational help.

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[4] Barnes, Clark, Perry, and Angell, Phys. Rev. 87, 669 (1952).

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Disintegration Scheme of Fe^{59}†

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The radiations accompanying the disintegration of Fe^{59} have been investigated using lens spectrometer and scintillation counter techniques. Three beta-ray spectra of end points 1560±8 kev (0.3 percent), 462±3 kev (53.9 percent), and 271±3 kev (45.8 percent) lead to the ground state, to 1098-kev and 1289-kev excited states of Co^{59}. The 1560-kev spectrum has a forbidden shape; the shapes of the other partial spectra are allowed. Gamma-rays of 191±2 kev (2.8 percent), 1098±6 kev (56.7 percent) and 1289±6 kev (43 percent) represent all the transitions possible between the three Co^{59}-states. The conversion coefficients characterize the 191-kev and the 1098-kev transitions as magnetic dipoles, the 1289-kev transition as electric quadrupole.

A disintegration scheme is presented in which spins and parities are assigned to all the levels involved. The single-particle orbitals corresponding to the assigned spins and parities agree with those of the spin-orbit coupling shell model. Accordingly, the first excited state (1098-kev) of Co^{59} is an $f_{5/2}$ state, and its 1098-kev energy difference from the $f_{7/2}$ gound state represents the spin-orbit splitting of the f-levels, which is responsible for the existence of a closed shell at N or $Z=28$.

The angular correlation of the 191 kev–1098 kev gamma-gamma cascade was measured and found to support the proposed spin assignment.

INTRODUCTION

THE radiations of 46-day Fe^{59} were studied by Deutsch and co-workers in 1942.[1] They analyzed the beta-ray spectrum into two components of approximately equal intensities with end points of 257 and 460 kev. They showed that the low energy beta-ray group is followed by a 1.30-Mev gamma-ray, the high energy group by a 1.10-Mev gamma-ray.

As the two high energy gamma-rays are not in coincidence with one another, Fe^{59} proved to be a very useful source with which to test gamma-gamma angular correlation equipment and similar arrangements for spurious coincidences due to scattering. When such a test was run without the usual lead absorbers in front of the counters, a small number of gamma-gamma coincidences was observed and traced back to a weak gamma-gamma cascade in the Fe^{59} decay, i.e., in Co^{59}.[2]

A subsequent investigation of the angular correlation in this gamma-gamma cascade did not allow an unambiguous assignment of spins to the levels involved. However, it was felt that most of the ambiguities could

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† Supported in part by the joint program of the ONR and AEC.

* Now with the Bartol Research Foundation, Swarthmore, Pennsylvania.

[1] Deutsch, Downing, Elliott, Irvine, and Roberts, Phys. Rev. 62, 3 (1942).

[2] F. R. Metzger, Phys. Rev. 85, 727 (1952).

be eliminated by a study of the internal conversion of the gamma-rays and of the intensities of the beta-ray transitions. When, in the summer of 1951, high specific activity Fe^{59} became available through the radioisotopes program of the AEC, it was decided to reinvestigate the radiation emitted in the decay of Fe^{59}.

SOURCE MATERIAL

The first coincidence and scintillation spectrometer measurements[2] were carried out with low specific activity Fe^{59} (0.06 mC/g). All the experiments reported in this paper were performed with two shipments of high specific activity Fe^{59}, catalog item 26-PX of the Isotopes Division AEC. This Fe^{59} had been produced in a nuclear reactor by (n,γ)-reaction with enriched Fe^{58}.

Most of the final data were taken with a one millicurie shipment having a specific activity of 770 mC/g. This is to be compared with a specific activity of 1.3 mC/g available to Deutsch *et al.*[1]

COINCIDENCE EXPERIMENTS

Using NaI scintillation detectors in a coincidence arrangement of 10^{-7} seconds resolving time a small number of true gamma-gamma coincidences was observed in a Fe^{59} source. These coincidences were still present when two inches of lead separated the two counters; they therefore could not be attributed to Compton scattering from one counter to the other. The coincidence rate decreased with a half-life of 45±3 days which agrees with the half-life reported for Fe^{59},[3] indicating that a cascade in Co^{59} is the origin of these gamma-gamma coincidences.

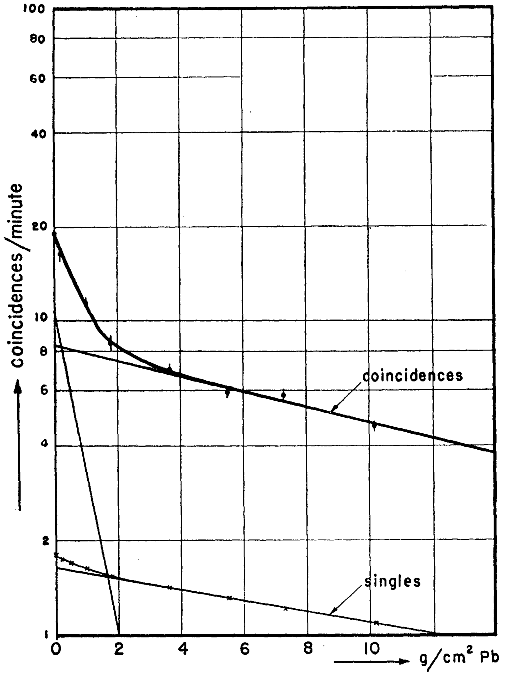

FIG. 1. Absorption of the γ-γ coincidences by lead absorbers in front of one counter. The absorption curve of the singles is included for comparison.

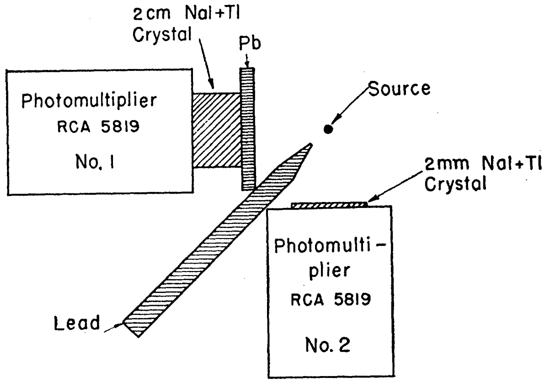

FIG. 2. Arrangement of the scintillation counters for the coincidence experiments.

Three g/cm² of lead in front of each counter reduced the single counting rates by about fifteen percent, but decreased the coincidence rate by a factor of thirty. This proves that one of coinciding components is a low energy gamma-ray.

The two coincident gamma-rays were clearly separated in a coincidence absorption experiment using lead absorbers in front of one of the two detectors. Figure 1 shows the coincidence absorption curve and its analysis into two components. The difference of the zero absorber values of the two components is due to a difference in the energy dependence of the detection efficiencies of the two scintillation detectors which differed somewhat in size and in the setting of the discriminators. From the absorption coefficient of the soft component one estimates a gamma-ray energy of about 200 kev. The absorption of the hard coincident gamma-ray follows closely the absorption of the bulk of the singles (Fig. 1). The slightly larger slope of the coincidence absorption curve is easily understood if one assumes that the 1.1-Mev gamma-ray is responsible for the coincidences, whereas a mixture of 1.1- and 1.3-Mev gamma-rays determines the absorption properties of the singles.

In order to determine the intensity of the 200-kev, 1.1-Mev cascade, coincidences were measured with the arrangement shown in Fig. 2. A NaI crystal, 2 cm thick and 3 cm in diameter with 5 g/cm² lead in front, detected the hard gamma-rays only. Another NaI crystal, No. 2, 2 mm thick and 3 cm in diameter, favored the soft gamma-ray.

The ratio of true coincidences to single counts in No. 1, N_{12}/N_1, is simply equal to $\alpha\cdot\omega_2\cdot\epsilon_2$, where α is the intensity of the cascade (per disintegration), $4\pi\omega_2$ is the solid angle in steradians subtended by the 2-mm crystal and ϵ_2 is the efficiency of the 2-mm crystal for

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[3] See *Nuclear data*, National Bureau of Standards Circular No. 499 (1950), p. 52.

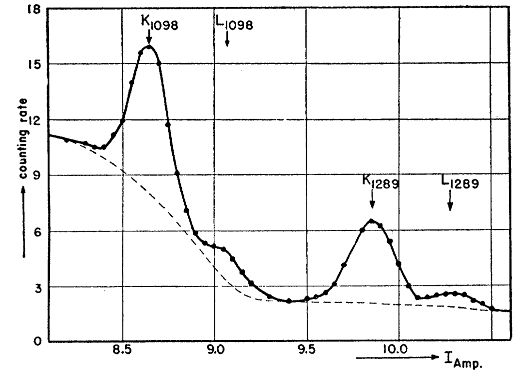

FIG. 3. Photoelectron spectrum of Fe^{59} using a gold converter. The dashed line represents the Compton background.

the detection of the 200-kev component. The measured values were $N_{12}=14.6/\text{min}$, $N_1=74{,}500/\text{min}$, $\omega_2=2.8\times10^{-2}$. For ϵ_2 we have used the value 0.25, which is close to the theoretical efficiency and in agreement with previous experience with this crystal. With these values one calculates $\alpha=(2.8\pm0.8)\times10^{-2}$. The error is tentative and mainly reflects the uncertainty in the efficiency value.

The above value of α is consistent with the analysis of a carefully measured singles absorption curve taking into account the energy dependence of the detection efficiency.

PHOTOELECTRON SPECTRUM

a. Energies of the Co^{59} Gamma-Rays

The spectrum of the electrons ejected by the Co^{59} gamma-rays from a 4.9 mg/cm^2 gold foil was measured in a lens spectrometer of 2.5 percent resolution and 0.5 percent transmission.

Superimposed on the Compton distribution, the photoelectron lines due to gamma-rays of 191±2 kev, 1100±6 kev, and 1287±6 kev were identified. The spectrometer had been calibrated using the photoelectron lines of the 1172.9- and 1333.2-kev[4] Ni^{60} gamma-rays. If one accepts the 191-kev radiation as the transition between the 1287- and the 1100-kev levels, the best values for the energies of the Co^{59} gamma-rays are 191±2, 1098±6, and 1289±6 kev.

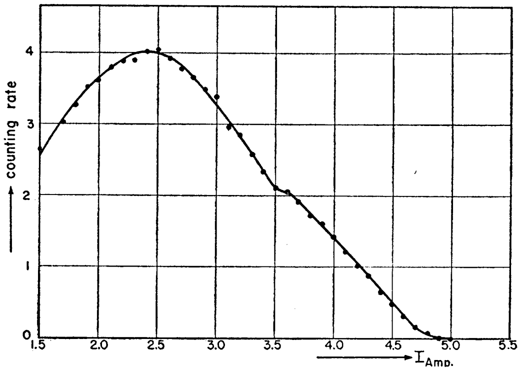

FIG. 4. β-ray spectrum of Fe^{59} in the energy region between 60 and 500 kev.

b. Intensity Ratio of the High Energy Gamma-Rays

The relative intensity of the 1.10- and 1.29-Mev gamma-rays is very important for the interpretation of the conversion data.

The intensity ratio can be inferred from the height of the photoelectron lines if the energy dependence of the gold converter efficiency is known. From previous experiments with gamma-rays above 550 kev the efficiency of our arrangement was known to be very nearly inversely proportional to the square of the gamma-ray energy. This was again checked using the two Ni^{60} gamma-rays, which have equal intensities for all practical purposes. With gold converter foils of thickness 25 mg/cm^2 and 4.9 mg/cm^2 a ratio of 1.29 ±0.05 was measured for the peak heights of the 1.17- and 1.33-Mev gamma-rays. This agrees with the ratio $(1.333/1.173)^2=1.29$ calculated by the inverse square law.

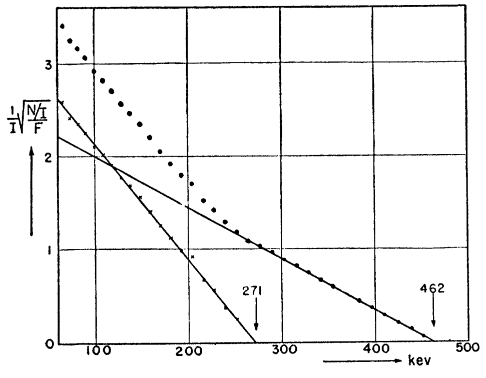

FIG. 5. Fermi plot of the β-ray spectrum of Fe^{59}. Circles represent the measured points, crosses the result of the subtraction of the 462-kev spectrum.

If the two Co^{59} gamma-rays were of equal intensities, one would expect a ratio $(1.289/1.098)^2=1.38$ for the photoelectron peaks. The measured peak heights are in a ratio of 1.78±0.08. The 1.1-Mev transition is therefore $1.78/1.38=1.29\pm0.06$ times more intense than the 1.29-Mev transition.

A typical measurement of the photopeaks of the Co^{59} gamma-rays, using a 25-mg/cm^2 gold converter, is reproduced in Fig. 3. The presence of a strong Compton background renders the analysis more difficult. However, checks with a 4.9 mg/cm^2 gold foil and without any foil permit the background to be determined quite accurately.

THE BETA-RAY SPECTRUM

Beta-ray sources of one-quarter inch diameter were prepared by drying a drop of $FeCl_3$ solution on a Nylon-

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[4] Latest energy values according to a private communication from Professor Du Mond.

Zapon film of approximately 20μg/cm^2. The beta-ray spectrum was then investigated in the lens spectrometer using a 195-μg/cm^2 window on the Geiger counter.

a. The Major Intensity Partial Beta-Ray Spectra

Figure 4 gives the beta-ray spectrum obtained with a source of about 3 μC strength. The break at 3.6 amp (277 kev) is rather pronounced and indicates the existence of two partial spectra. This is in agreement with Deutsch *et al.*,[1] but is contrary to the result of Mann and Hanson.[5] The Fermi plot, Fig. 5, shows the decomposition very clearly and yields for the end point energies 462±3 kev and 271±3 kev.

From a measurement of the areas under the two partial spectra it follows that 55 percent of the Fe^{59} disintegrations proceed via the 462-kev spectrum, whereas 45 percent take place through the 271-kev branch.

Preliminary experiments with sources of low specific activity had indicated the large influence of scattering, i.e., source thickness on the measured branching ratio. In order to estimate the magnitude of this effect, the beta-ray spectrum was measured with three sources of 3, 8 and 30 μC. The relative strengths of these sources had been determined to better than one percent by gamma-ray counting with a scintillation counter. Using the gamma-ray values for the relative strengths the measured counting rates were normalized to the same source strength and plotted in Fig. 6. The agreement of the three-spectra is very satisfactory in the upper part of the spectrum. The Fermi plot for the 462-kev spectrum, which is assumed to have an allowed shape below 271 kev, is therefore practically identical for all three sources. The contribution from the scattering is very substantial in the lower parts of the spectrum, especially for the 30 μC source. Consequently the Fermi plot of the 271-kev partial spectrum will strongly depend on the source thickness, as also will the intensity attributed to the 271-kev branch.

From the data of Fig. 6 it was estimated that the error in the area of the 271-kev spectrum due to scattering in the sources was between one and two percent for the 3 μC source. This correction has already been taken into account in the intensities stated earlier.

Using a half-life of 46 days and a 45 to 55 intensity ratio one calculates log*ft* values of 5.9 for the 271-kev spectrum and of 6.7 for the 462-kev branch. The implications of these *ft* values will be discussed later.

b. Low Intensity, High Energy Beta-Ray Spectrum

With the 3 μC source the counting rates at energies higher than 480 kev did not vary by more than a few counts per minute. However, when a 100 μC source was used for the investigation of the conversion lines of the high energy gamma-rays, the counting rate above 480 kev was considerably larger than the background rate expected for a source of this strength. With a Co^{60} source of comparable strength and of comparable specific activity, the normal background counting rate was observed. The different behavior of the two sources is illustrated in Fig. 7. The counting rate at 12.5 amperes has been subtracted from all the measured points as normal background. The plateau-like regions to the left of the conversion peaks are due to Compton effect in the sources themselves. For the Co^{60} source the counting rate drops to zero in the region between the two conversion lines, whereas for the Fe^{59} source a residual counting rate of about 50 counts/minute is observed.

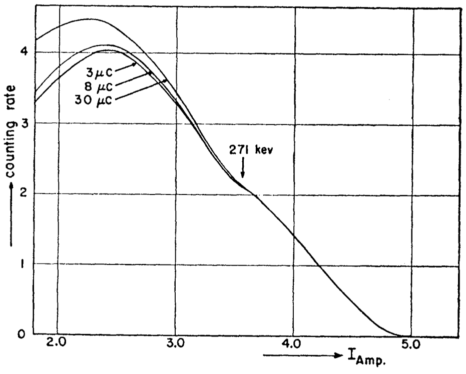

FIG. 6. The influence of source thickness on the shape of the β-ray spectrum of Fe^{59}. The three curves were normalized to the same source strength.

From the evidence summarized in Fig. 7 it is concluded that a high energy beta-ray spectrum is connected with the decay of Fe^{59}. Visual inspection suggests for the end point of this spectrum a current value of about 12 amperes, which corresponds to 1554 kev. This energy is very close to the total energy available for the $Fe^{59}-Co^{59}$ decay, namely, 462+1098=1560 kev. The high energy beta-ray spectrum is therefore considered to be the transition to the gound state of Co^{59}.

With the use of a 0.5 mC beta-source, the high energy

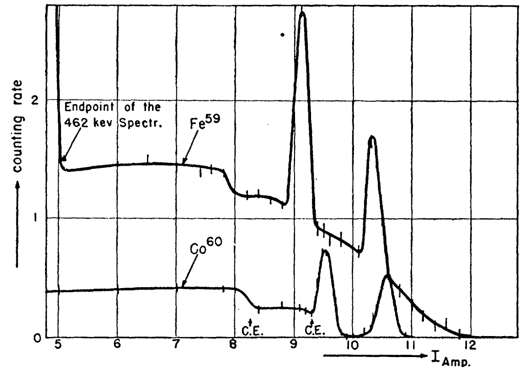

FIG. 7. High energy portion of the electron spectra of Fe^{59} and Co^{60}. Arrows indicate the maximum energies of the Compton electrons due to the Ni^{60} γ-rays.

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[5] K. C. Mann and G. H. Hanson, Phys. Rev. 83, 893 (1951).

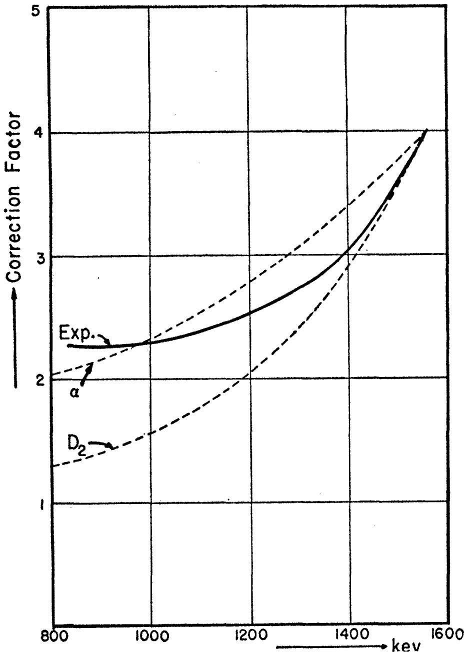

FIG. 8. Correction factors for Fe^{59} electrons. The full line represents the experimental correction factor for the 1560-kev spectrum. The dashed lines correspond to the unique correction factors for α-type ($\Delta I = 2$, yes) and D_2 type ($\Delta I = 3$, no) transitions. Ordinate scale is arbitrary.

spectrum was investigated in great detail. Unfortunately, only the regions from 1150 to 1210 kev and from 1340 kev to the end point are accessable and free from special corrections. In the upper third of the spectrum the conversion lines cover an appreciable portion of the beta-ray spectrum. Below 1100 kev (9.15 amp) the determination of the spectral shape is rendered uncertain by the presence of Compton electrons ejected out of the source material by the high energy gamma-rays. This effect was corrected for by using the shape of the distribution of Compton electrons suggested by the Co^{60} data of Fig. 7.

The Fermi plot obtained after applying all the necessary corrections indicated that the 1560-kev spectrum has a forbidden shape. Using a reasonable continuation of the Fermi plot to low energies, the 1560-kev spectrum was integrated and found to comprise 0.3±0.1 percent of the Fe^{59} disintegrations. This intensity leads to a log*ft* of 10.9±0.2, which classifies the transition as second forbidden.

In Fig. 8 the experimental shape correction factor for the high energy beta-ray spectrum is compared with the unique correction factors for the first forbidden α-type ($\Delta I = 2$, yes) and the second forbidden D_2 type ($\Delta I = 3$, no) transitions. Both these shapes are excluded by the measurements. The correct assignment for the high energy spectrum is therefore $\Delta I = 2$, no.

The shell model assignment $f_{7/2}$ to the ground state of Co^{59} is in agreement with the measured spin and the new value for the magnetic dipole moment[6] of this nucleus. The character of the high energy beta-ray spectrum then determines the spin and parity of the Fe^{59} ground state as $\frac{3}{2}$, odd. A $p_{3/2}$ ground state for Fe^{59} with 33 neutrons is in accordance with the $p_{3/2}$ assignment for ${}_{33}As^{75}$ and for most of the nuclei with N or Z equal to 29, 31, 33, and 35.

It should be added that $h_{11/2}$ is another assignment for the ground state of Fe^{59} which is consistent with the existence of the high energy beta-ray spectrum. However, spins as high as 11/2 seem to occur only for much larger values of Z and N and even then only for excited states.

The results reported in this section are summarized in Table I.

CONVERSION ELECTRON SPECTRUM

a. Conversion of the 1.1- and 1.29-Mev Gamma-Rays

The theoretical K-conversion coefficients[7] for 1.1- and 1.29-Mev gamma-rays and different multipole orders are summarized in Table II.

$E2$ and $M1$, which do not involve a parity change, are with respect to their conversion, not only clearly separated from $E3$ or $M2$, but also from $E1$, which demands a parity change. Moderately accurate conversion data can therefore decide whether or not the high energy transitions in Co^{59} involve parity changes and they might also give some indication as to the electric or magnetic character of the transitions.

The same 0.5 mC source which had served in the investigation of the high energy beta-ray spectrum was used for the conversion measurements. The existence of the high energy spectrum and the presence of the "Compton step" due to the 1.29-Mev gamma-ray rendered the determination of the conversion line intensities more difficult. The best data obtained are presented in Fig. 9. From a comparison of peak heights as well as areas a value of 1.79±0.06 was obtained for the relative number of 1.1- and 1.3-Mev conversion electrons.

In order to determine the conversion coefficients of the two transitions, the number of conversion electrons must be compared with the number of unconverted

TABLE I. Properties of the partial beta-ray spectra of Fe^{59}. "Allowed" f-values have been used throughout.

Endpoint energy (kev)	Intensity (percent of disint.)	log*ft*	Shape
271±3	44.9±2	5.9	allowed
462±3	54.8±2	6.7	allowed
1560±8	0.3±0.1	10.9	forbidden $\neq \alpha$, $\neq D_2$

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[6] W. G. Proctor and F. C. Yu, Phys. Rev. **77**, 716 (1950).

[7] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report, ORNL 1023 (unpublished).

gamma-rays. In view of the very small conversion the number of unconverted gamma-rays is practically the same as the number of transitions. The combined intensities of the two gamma-transitions equals the combined intensities of the 271-kev and 462-kev beta-ray spectra. The 1.1-Mev transition is fed by the 462-kev beta-ray spectrum and by the 2.8 percent abundant 191-kev gamma-ray. The number of 1.29-Mev transitions is equal to the number of 271-kev beta-transitions reduced by the number of 191-kev gamma-rays. Using the beta-ray intensities of Table I, the 1.1-Mev transitions thus comprise $54.8+2.8=57.6$ percent of all Fe^{59} disintegrations, whereas the 1.29-Mev transitions comprise $44.9-2.8=42.1$ percent. The relative intensity of the two high energy transitions is therefore $57.6/42.1=1.37\pm0.09$. From the analysis of the photoelectron spectrum a ratio of 1.29 ± 0.06 was derived. The average is 1.32 ± 0.05. This corresponds to 56.7 percent 1.1-Mev transitions and 43 percent 1.29-Mev transitions. The conversion coefficient of the 1.1-Mev transitions is then obtained by dividing the number of 1.1-Mev conversion electrons by 56.7 percent of the total number of beta-rays. Likewise the conversion coefficient of the 1.29-Mev transition is obtained by dividing the corresponding number of conversion electrons by 43 percent of the total number of beta-rays.

The total area under the beta-ray spectrum of the 0.5 mC source could not be determined directly as the counting rates in the main spectrum were too high and in addition the source was rather thick. On the other hand, the beta-ray spectrum of the 3 μC source had been carefully investigated and the total area under the beta-ray spectrum had been determined. It was therefore only necessary to compare the strengths of the two sources by gamma-ray counting. This was done with the help of a third source of intermediate strength.

Combining all of this information the following total conversion coefficients were obtained:

$$\alpha_{\text{total}}(1.1\text{ Mev})=(18.3\pm0.7)\times10^{-5},$$
$$\alpha_{\text{total}}(1.29\text{ Mev})=(13.5\pm0.6)\times10^{-5}.$$

If a K/L ratio of 10 and an L/M ratio of 3 are assumed, the K-conversion coefficients become

$$\alpha_K(1.1\text{ Mev})=(16.1\pm0.6)\times10^{-5},$$
$$\alpha_K(1.29\text{ Mev})=(11.9\pm0.6)\times10^{-5}.$$

Comparing these values with the theoretical coefficients of Table II, one can immediately exclude $E1$, $M2$, $E3$, and $M3$ for both gamma-rays, leaving $M1$ and $E2$ as the only alternatives. Neither $M1$ nor $E2$ involve a change of parity. The $f_{7/2}$ ground state of Co^{59} and the 1.1-Mev and 1.29-Mev excited states have therefore all the same parity, namely, odd. Spin $\frac{1}{2}$ is excluded for either excited state of Co^{59}, because $E3$ and $M3$ are ruled out.

TABLE II. K-conversion coefficients of the high energy Co^{59} gamma-rays for different multipole orders (according to Rose *et al.*, reference 7).

	$E1$	$E2$	$E3$	$M1$	$M2$	$M3$
$10^5\times\alpha_K(1.1\text{ Mev})$	6.7	16.2	33.0	14.9	31.0	60.0
$10^5\times\alpha_K(1.29\text{ Mev})$	5.5	11.2	20.7	10.1	20.1	37.5

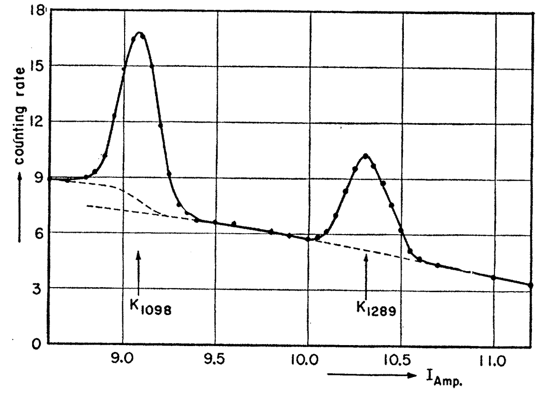

FIG. 9. Electron spectrum of Fe^{59} in the energy region between 1 Mev and 1.4 Mev. Dashed line represents background from 1560-kev β-ray spectrum and from Compton distribution of the 1.29-Mev γ-ray.

If the experimental K-conversion coefficients are accepted at face value, then both transitions are electric quadrupoles. However, when the difference between various assignments becomes so small, the absolute values might not be a very good guide. For example, the experimental values might change slightly owing to changes in some of the corrections and the theoretical values might change if screening is taken into account.[8] Most of these changes would presumably affect the absolute values much more than they would the ratio of the two coefficients. Moreover, the ratio is obtained more directly from experiment and is therefore more accurate. In order to decide between $M1$ and $E2$, it appears preferable therefore to consider the ratio of the conversion coefficients.

With the value 1.79 ± 0.06 for the relative number of conversion electrons and the value 1.32 ± 0.05 for the ratio of the gamma-ray intensities, the ratio of the total conversion coefficients becomes 1.36 ± 0.07. The K/L ratios for $M1$ and $E2$ transitions of very small Z^2/E are not known. It will be assumed that they are approximately equal and that the ratio 1.36 is also the ratio of the K-conversion coefficients of the 1.1 and 1.29-Mev gamma-rays. The ratios expected for the different possible assignments are compared with the experimental value in Table III.

The only theoretical ratio agreeing within the limits of error with the experimental value is the one assigning $M1$ to the 1.1-Mev transition and $E2$ to the 1.29-Mev transition. The $E2$–$E2$ and $M1$–$M1$ assignments are improbable, and the $E2$–$M1$ combination is definitely ruled out.

$M1$ for the 1.1-Mev transition leaves the possi-

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[8] J. R. Reitz, Phys. Rev. **77**, 10 (1950).

TABLE III. The ratios of the theoretical K-conversion coefficients for the four possible assignments of multipole orders to the Co^{59} gamma-rays in comparison with the experimental value.

1.1-Mev gamma-ray	1.29-Mev gamma-ray	α_K(1.1 Mev)/α_K(1.29 Mev)
$M1$	$M1$	1.48
$M1$	$E2$	1.33
$E2$	$M1$	1.60
$E2$	$E2$	1.45
Experiment		1.36±0.07

bilities 7/2 and 5/2 for the spin of the first excited state of Co^{59}.[9] A spin of 7/2 would call for an α-type shape of the 462-kev beta-ray spectrum in contradiction with experiment. The first (1.1-Mev) excited state of Co^{59} has therefore spin 5/2, odd parity. If the single-particle model still holds at this excitation, spin and parity characterize the level as $f_{5/2}$.

$E2$ for the 1.29-Mev transition leads to a spin of $\frac{3}{2}$ and odd parity for the second excited state, $p_{3/2}$ being the appropriate single particle level.

It might be added that conversion measurements on Co^{60} yielded a value 1.34±0.09 for the ratio of the conversion coefficients of the Ni^{60} gamma-rays in very good agreement with the theoretical ratio 1.32 calculated for the accepted $E2$–$E2$ assignment.

b. Conversion of the 191-kev Gamma-Ray

The theoretical conversion coefficients of a 191-kev gamma-ray in Co are given in Table IV for different multipole orders. $E2$ and $M2$ are very well separated from $E1$ and $M1$ with regard to their conversion coefficients. If either $E2$ or $M2$ was the correct assignment, the counting rate in the conversion line should amount to five percent of the counting rate in the beta-ray spectrum on which the conversion line is superimposed. In the $E1$ or $M1$ case the contribution of the conversion line should be about 0.8 percent of the total counting rate. A quick survey did not reveal any conversion line, indicating that the contribution of the conversion line was smaller than two percent. After a careful investigation of the beta-ray spectrum, during which at least 10^5 counts were taken in every point, the conversion line of the 191-kev gamma-ray could be identified. The number of conversion electrons was found to be 0.02 percent of the total number of beta-rays. With a 2.8 percent abundance of the 191-kev transition one calculates a conversion coefficient of $(7\pm3)\times10^{-3}$, in very good agreement with the theoretical coefficients for either $E1$ or $M1$. As all Co^{59} levels have the same parity, $E1$ is excluded and the unique assignment to the 191-kev transition is $M1$. The same conclusion was reached on the basis of the conversion of the high energy gamma-rays. The measured value of the conversion coefficient restricts the maximum amount of $E2$ admixture to the 191-kev transition to 10 percent.

ANGULAR CORRELATION EXPERIMENTS

The existence of the 191-kev gamma-ray offers the possibility of measuring the angular correlation in the 191–1098-kev gamma-ray cascade of Co^{59}. However, one cannot expect to obtain a unique spin assignment from such an experiment with an odd-even nucleus where both transitions can be mixtures of magnetic and electric multipoles. By a suitable choice of the mixing ratios the coefficients of the angular correlation can be varied within wide limits,[10] and thus the same experimental data can be fitted with different spin assignments. Lifetime considerations will exclude some mixtures, but in general, they are not a very reliable guide in view of the large scatter observed in the magnitude of the nuclear matrix elements.[11]

If, on the other hand, the spins of the three cascade states are already known, the angular correlation can be used as a very sensitive means for determining the degree of mixture present in the transitions.

Using NaI crystals in a coincidence arrangement of 1.2×10^{-7} seconds resolving time the first correlation experiments were carried out with low specific activity Fe^{59} (0.06 mC/g). Due to the low coincidence rate obtainable with the weak (2.8 percent) cascade the data were rather inaccurate, and, although suggesting a small correlation, could not rule out the absence of any correlation. Thus, the preliminary correlation experiments could not exclude any assignment attributing spin $\frac{1}{2}$ to the intermediate level of the Co^{59} cascade. At this point it was decided that conversion measurements would answer the question of spin $\frac{1}{2}$ more directly and in addition would provide information concerning the parities of the Co^{59} states.

After most of the investigation described in the preceding sections had been completed and the assignment 3/2–5/2–7/2 had been established, the angular correlation of the 191–1098-kev cascade was measured again by Mr. Schiff of this laboratory using NaI crystals and an improved coincidence arrangement of 1.5×10^{-8} second resolving time. High specific activity Fe^{59} sources were used for these measurements. The correlation was studied between 90 degrees and 180 degrees in angular steps of 15 degrees. The measured points can be fitted with a $1+A_2\cos^2\theta$ distribution using a value of $A_2=0.080\pm0.016$, which definitely

TABLE IV. Theoretical K-conversion coefficients for a 191-kev gamma-ray in Co (according to Rose *et al.*, reference 7).

	$E1$	$E2$	$M1$	$M2$
$\alpha_K\times10^3$	6.2	41.5	7.1	43.5

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[9] The ft-values of the main beta-ray spectra exclude spins larger than 7/2 for the excited states of Co^{59} if one discards spin $h_{11/2}$ for the ground state of Fe^{59} in favor of $p_{3/2}$.

[10] D. S. Ling and D. L. Falkoff, Phys. Rev. **76**, 1639 (1949).

[11] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

excludes spin $\frac{1}{2}$ for the first excited state of Co^{59} in agreement with the conversion experiments.

The measured coefficient is compatible with the assignments 3/2–3/2–7/2 and 3/2–5/2–7/2 without the need of a mixture. The combination 5/2–5/2–7/2 would give rise to the observed correlation if about three percent $E2$ were admixed to the 1098-kev $M1$ transition. Such an admixture cannot be excluded, although from Weisskopf's lifetime formulas[12] one expects only about 0.1 percent $E2$. The cascade 5/2–3/2–7/2 cannot fit the experiment as long as the admixture of $E2$ to the 191-kev transition is kept below ten percent, the limit given by the conversion coefficient of the 191-kev line. Thus, of the four spin combinations compatible with the *ft* values of the beta-ray spectra and with the $E2$ or $M1$ character of the gamma-rays, the angular correlation eliminates one definitely, renders one unlikely, and leaves two as equally probable choices.

The experiment restricts the coefficient A_2 to values ranging from 0.064 to 0.096. Only an $A_2=0.077$ would give pure transitions for the 3/2–5/2–7/2 cascade. In order to match the other values, mixtures must be considered. As the admixture of $E2$ becomes more probable with increasing energy, it is assumed for reasons of simplicity, that only the 1098-kev transition is a mixture, the 191-kev gamma-ray being pure $M1$. Actually one expects from the lifetime relations[12] 0.002 percent $E2$ for the 191-kev gamma-ray and 0.1 percent $E2$ for the 1098-kev transition. Using the formulas given by Ling and Falkoff,[10] one finds that the admixture of $E2$ varies from 0.02 percent to zero percent and back to 0.06 percent as A_2 changes from 0.064 over 0.077 to 0.096. Thus the admixture of $E2$ to the 1098-kev transition is smaller than the 0.1 percent expected from Weisskopf's formulas. However, a factor of ten or even hundred in the transition probability is not considered serious, especially when it points in the direction of reduced $E2$ intensity.

CONCLUSIONS

Based on the experiments discussed in the preceding sections, the disintegration scheme shown in Fig. 10 is proposed. It agrees in the most intense radiation with that of Deutsch *et al.*[1] The intensities given in Fig. 10 are the adjusted values obtained by combining the beta-ray measurements with the gamma-ray data. The intensities of Table I, which are slightly different, were based on the beta-ray experiments alone.

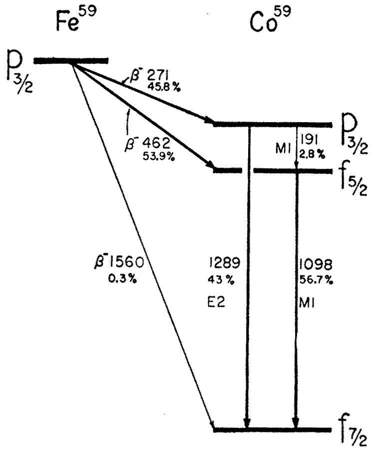

FIG. 10. Proposed disintegration scheme of Fe^{59}. Transition energies are given in kev.

If the excited levels of Co^{59} are single particle levels, the 1.098-Mev gamma-ray represents the splitting of the *f*-levels which, in the *jj*-coupling model of Mayer[13] and of Haxel, Jensen, and Suess,[14] gives rise to the shell at N or $Z=28$.

As all the levels involved in the decay of Fe^{59} have the same parity (odd), the beta-ray transitions can only be allowed or second forbidden. The log*ft* value of 5.9 for the 271-kev spectrum is consistent with an allowed transition. The log*ft* value of 6.7 of the 462-kev spectrum exceeds the range usually attributed to allowed transitions. However, the 462-kev spectrum involves a change of two units of orbital angular momentum; it therefore belongs to the *l*-forbidden group,[15] the extreme example of which is C^{14} with a log*ft* value of 9.

According to our decay scheme the 191-kev $M1$ gamma-ray competes with the 1.29-Mev $E2$ transition. From Weisskopf's formulas[12] one would expect the 191-kev transition to be about twice as strong as the 1.29-Mev transition. Experimentally, however, the 1.29-Mev gamma-ray is fifteen times as intense as the 191-kev gamma-ray. The 191-kev $M1$ transition is probably thirty times weaker than expected because it involves a change of two units of orbital angular momentum. According to Sachs and Ross[16] such $\Delta l=2$ transitions, which would be forbidden for ordinary magnetic dipole effects, are allowed for certain forms of the interaction moment, but are expected to be somewhat weaker than the transitions involving no change in orbital angular momentum.

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[12] V. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[13] M. G. Mayer, Phys. Rev. **75**, 1946 (1949); **78**, 16 (1950).

[14] Haxel, Jensen, and Suess, Phys. Rev. **75**, 1766 (1949).

[15] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951); and L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).

[16] R. G. Sachs and M. Ross, Phys. Rev. **84**, 379 (1951).