Isomerism in Co^{58}

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An isomer of Co^{58} has been identified which decays with a half-life of 8.8 hours by emission of a 24.9 ± 1.0 kev γ-ray. The ratio of the K and L conversion coefficients was 1.9 ± 0.2. The relative cross section for formation of the isomeric and ground state of Co^{58} by α-particle bombardment of manganese was found to be 1.7. The conversion coefficient of the 805 kev γ-ray of Fe^{58} was 2.5×10^{-4}. Possible decay schemes are presented.

I. INTRODUCTION

WHEN a manganese metal target was bombarded with 40-Mev α-particles from the 60-inch cyclotron, a weak 8.8 hour activity appeared in the chemically separated cobalt fraction, in addition to the expected long half-lives of Co^{56} (72 days), Co^{57} (270 days) and Co^{58} (72 days). A similar period was found in cobalt fractions from nickel and cobalt bombarded with 18 Mev deuterons and fast neutrons, and from copper placed in the circulating deuteron beam of the 184-inch cyclotron. These cobalt samples were followed with a 3.2 mg/cm^2 end window Victoreen counter. When a 71 mg/cm^2 aluminum absorber was placed between the counter and the samples, no 8.8 hour activity could be detected; when a 210 mg/cm^2 absorber was used, the samples grew with a half-life of approximately 9 hours. The results of the investigation reported here show this new period to be associated with an isomer of Co^{58}. The main part of the work was carried out with a magnetic lens spectrometer of the type described by Siegbahn,[1] calibrated with annihilation radiation.

II. ISOTOPIC ASSIGNMENT

The α-particle bombardment of manganese was found to be the most convenient method of production of the unknown activity; the only other period of comparable half-life formed in this case was the 2.6 hour Mn^{56}. The low measured intensity of the 8.8 hour activity made formation from target impurities suspect. A thorough chemical investigation (see the Appendix) therefore had to be carried out, and different manganese compounds in addition to the metal were used as targets. The bulk of the 8.8 hour activity under investigation followed the cobalt fractions and we can conclude that the new period belongs to that element.

The isotopic assignment is made by considering the momentum spectrum of the cobalt fraction obtained from manganese bombarded with 40 Mev α-particles. This spectrum showed the characteristic radiations[2] of Co^{58}, Co^{57}, and Co^{56} formed by (α, n), $(\alpha, 2n)$ and $(\alpha, 3n)$ reactions. In addition a conversion line was found at 530 gauss-cm which decayed with an 8.8 hour half-life; this corresponds to electrons whose range is only slightly larger than the 0.4 mg/cm^2 thickness of the nylon counter window. As will be seen in the next section, this line is due to L electrons, the K electrons being absorbed in the counter window. At the same time part of the continuous spectrum grew, and an analysis showed the characteristic β^+-continuum of Co^{58} to be responsible for the growth. The activity associated with the conversion line thus decayed to Co^{58}.

Verification of this assignment was accomplished by reducing the α-energy to 17 Mev with aluminum absorbers, so that Co^{57} and Co^{56} [formed by $(\alpha, 2n)$ and $(\alpha, 3n)$ reactions] were not present. The resulting spectrum is shown in Fig. 1. At low values of $H\rho$ are two peaks due to K and L conversion electrons as obtained with a thin zapon window (Section III). In the center can be seen the continuous β^+-spectrum of Co^{58} that grew as the two low energy conversion peaks decayed (Section IV); the insert at high values of $H\rho$ magnifies the conversion electrons of the 805 kev γ-ray of Fe^{58} (Section V). Any possible contamination by products of an $(\alpha, 2n)$ reaction would have been noticed as conversion electrons of the 117 kev and 130 kev γ-rays emitted in the decay of Co^{57}: no such lines were observed. These results show the existence of an 8.8 hour isomer of Co^{58} decaying to the 72-day ground state.

III. PROPERTIES OF THE ISOMER

In order to study the conversion electrons associated with the new isomer, a thin counter window was constructed with a single zapon film supported by a wire grid. With the counter connected to a 2 liter reservoir, leakage was small enough so the counting characteristics did not change appreciably over 3 hour periods. This fact was checked by taking frequent counts with a standard. The cobalt sulfide sample, prepared from manganese bombarded with 17 Mev α-particles, was placed on a thin zapon film and was estimated to have less than 0.1 mg/cm^2 thickness. The observed K and L conversion peaks are shown in Fig. 1. The width at half-maximum checks the known resolution of the spectrometer and the two lines are well separated. Possible M conversion electrons could not be resolved and are included under the L peak.

Since any small permanent value of $H\rho$ in the spec-

[1] K. Siegbahn, Phil. Mag. **37**, 162 (1946).
[2] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).

trometer is important at the low energies involved here, Auger electrons of Cd^{111} were used to check the calibration of the machine in this region. Values of 17.0 kev and 24.1 kev were obtained for the energies of the K and L cobalt conversion electrons; the E_L-E_K difference of 7.1 kev agrees within the expected error with the cobalt value of 6.9 kev, and the energy of the isomeric transition is given as 24.9 kev. The position of the L line was also measured by reversing the current and taking the average of the two values. The result was 24.2 kev. The energy with estimated uncertainty of the isomeric transition is thus given as 24.9±1.0 kev. Considering this energy value and the half-life of 8.8 hours, a $\Lambda=4$ transition is indicated, according to Axel and Dancoff.[3]

The ratio of the K to L conversion coefficients has been obtained by comparison of the intensities of the two lines. Lawson and Cork[4] have shown that the ratio of the experimental peak heights (before division of the counting rate by $H\rho$) should be equal to the ratio of the normalized areas (after division of the counting rate by $H\rho$). Experimental values given by these two methods are shown in Table I. The close agreement indicates that self-absorption and back-scattering in the source, if not negligible, at least affect both peaks equally. That the thickness of the counter window did not appreciably influence the ratio was shown by placing zapon films prepared from the same solution as the window over the source. With one film covering the sample a decrease of 2 percent in the relative peak height was observed; with two films this decrease amounted to 7 percent. The contribution of M electrons to the L peak is unknown but is believed to be small. Table I also lists theoretical values for a $\Lambda=4$ transition obtained from the paper by Hebb and Nelson.[5] The isomeric transition thus appears to be caused by a mixture of magnetic 2^3 and electric 2^4 pole radiation.

The 72-day decay of the ground state of Co^{58} has been investigated by Deutsch and co-workers.[6,7] They have

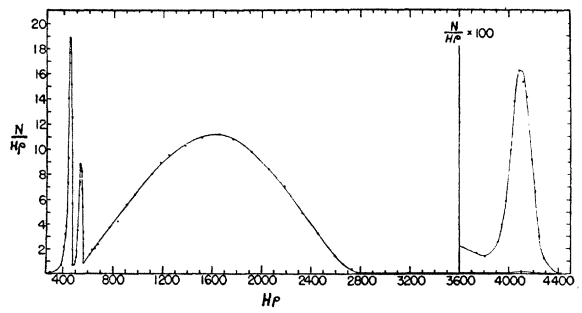

FIG. 1. Momentum distribution of beta-rays of Co^{58} showing internal conversion lines of the Co^{58} isomer and of Fe^{58}.

TABLE I. Experimental and theoretical values for a $\Lambda=4$ transition of the ratio of the conversion coefficients in the K and L shells for the 24.9 kev γ-ray of Co^{58}.

Experiment		Magnetic 2^3 pole	Electric 2^4 pole
from peak heights	from area		
1.93±0.10	1.89±0.19	6.6	0.41

shown that the decay proceeds 14.5 percent by β^+-emission and 85.5 percent by K-capture to an excited state of Fe^{58} from which the ground state is reached by emission of an 805 kev γ-ray. The β^+-spectrum has an end point of 0.47 Mev. It is concluded that the β^+-transition occurs with an angular momentum change of unity or zero, with the parity change undetermined. No decay to the ground state of Fe^{58} was observed by these investigators, which means that this transition must be at least twice forbidden by comparison with Co^{56} whose decay has this degree of forbiddennesss according to Konopinski.[8]

No evidence for the decay of the isomer of Co^{58} to the ground state of Fe^{58} was found. This would have appeared as high energy β^+-particles decaying with the 8.8 hour half-life. Transitions from the isomer to the excited state of Fe^{58} would have been hard to detect due to the small energy difference between the two states of Co^{58}; however, such transitions must be very rare as indicated in the following section.

IV. RELATIVE CROSS SECTION

During the bombardment of a thick manganese target with 17 Mev α-particles both 8.8 hour isomeric and 72-day ground state of Co^{58} are formed. The continuous β^+-spectrum grows therefore as the isomer decays after the sample is introduced into the spectrometer. This was observed by following the activity at the $H\rho=1500$ gauss-cm point with time; since the length and intensity variation of the bombardment is known, the ratio of the cross section for the formation of the isomer σ_1 to the cross section for formation of the ground state σ_2 can be calculated and a value of $\sigma_1/\sigma_2=1.7$ is obtained. The result would be in serious error if an appreciable number of transitions occurred between the isomer and the excited state of Fe^{58}. This is highly improbable since even if such a transition were of the allowed or first forbidden type it would have a partial half-life comparable to the 72 days of the ground state; however possible spin assignments discussed in Section VI make such a decay very highly forbidden.

V. CONVERSION COEFFICIENT OF THE Fe^{58} γ-RAY

The conversion electrons of the 805 kev γ-ray emitted following β^+-emission by the ground state of Co^{58} are shown in the insert of Fig. 1. A relatively thick source of about 1 mg/cm² and a 0.4 mg/cm² Nylon counter window were used to measure the β^+-continuum and

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[5] M. H. Hebb and E. Nelson, Phys. Rev. **58**, 486 (1940).
[6] M. Deutsch and L. G. Elliot, Phys. Rev. **65**, 211 (1944).
[7] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
[8] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).

TABLE II. Experimental and theoretical values of the interna conversion coefficient in the K shell for the 805 kev γ-ray of Fe^{58}: $\alpha_K \times 10^4$.

Experiment	Electric pole 2^1	Electric pole 2^2	Magnetic pole 2^1	Magnetic pole 2^2
2.5	1.3	3.4	2.4	5.9

the high energy conversion line in order to obtain large enough counting rates. The continuous background between the end of the β^+-spectrum and the 805 kev line was probably due to Compton electrons from the source and parts of the spectrometer. The width at the half-intensity point of the line agrees with the known 4 percent resolution of the spectrometer; however the maximum counting rate on the peak was only twice the normal counter background. This makes the result sensitive to the inevitable background variations. The contribution from photo-electrons produced in the sample should amount to only a few percent. To check on this possible source of error a 2.8 mg/cm^2 nickel foil was placed over the source and no significant change in peak height observed.

To obtain the desired conversion coefficient the ratio of the area under the line to 6.9 times the area under the continuous β^+-spectrum must be taken. The latter is distorted below 150 kev by scattering in the sample and counter window. Above this energy a Fermi plot gives a straight line. This line was extrapolated to zero momentum and the result used to obtain the area under the β^+-spectrum. The conversion peak contains both K and L electrons. According to Hebb and Nelson[4] the latter amount to 8 percent of the total number. This correction was applied to the observed area under the line. Thus the value quoted in Table II is obtained.

This table also lists theoretical values of the conversion coefficient as interpolated from recent calculations by M. E. Rose.[9] Comparison with the experimental result indicates a magnetic dipole transition, although the estimated accuracy of the measurement is not such as to exclude electric quadrupole radiation. In either case the transition occurs with no change in parity.

VI. DISCUSSION

Figure 2 represents a decay scheme of Co^{58} which is possible on the basis of the results of Deutsch *et al.*,[6,7] summarized in Section III, and the work reported in this paper. The spin of the ground state of Fe^{58}, an even-even nucleus, is undoubtedly zero and the parity was taken as positive on the basis of the shell model. The spin and parity assignments in Fig. 2 are made by assuming the β^+-decay of Co^{58} to be of the allowed type and appear to be the only possible ones if the excited Fe^{58} state decays by magnetic dipole radiation. If electric quadrupole radiation is responsible for this transition, then the assignments for the 0.805 Mev, 1.785 Mev, and 1.810 Mev levels could be 2+, 2+, and 5+, or 2+, 3+, and 6+, respectively. Values of 2+, 3−, and 6− for these levels appear probable if a first forbidden transition is responsible for the β^+-spectrum. In any case the isomeric state has a higher spin value than the ground state.

This is verified by the measured relative cross sections for formation of the two states of cobalt. According to the statistical theory this is given by

$$\sigma_1/\sigma_2=(2I_1+1)/(2I_2+1),$$

where σ_1 and σ_2 are the cross sections for the formation and I_1 and I_2, the spin values of the isomeric and ground states respectively. This formula is only expected to apply to the case of high excitation energy and heavy nuclei as discussed by Segrè and Helmholz.[10] As was just seen, two sets of choices for I_1 and I_2 appear possible. These give theoretical values for the relative cross section of 2.20 and 1.86. These are close to the experimental result of $\sigma_1/\sigma_2=1.7$.

It is of interest to compare the properties of the isomers of Co^{58} and Co^{60}. The latter has been investigated by Deutsch, Elliot, and Roberts[11] and more recent work is quoted by Axel and Dancoff.[3] From these the following conclusions can be drawn.

(1) The Co^{60} isomer decays to the ground state by emission of a mixture of 2^3 magnetic and 2^4 electric pole radiation; this is similar to Co^{58} as shown in Section III. Thus the same spin difference exists between the two levels of each isotope.

(2) The spin I_1 of the isomeric state in Co^{60} is lower than the spin I_2 of the ground state; the opposite is true for Co^{58}. It is possible that corresponding spin values are the same for the two isotopes, but this cannot be ascertained from the available data. The reversal of the spin order might indicate a crossing of energy levels as two neutrons are added to Co^{58}.

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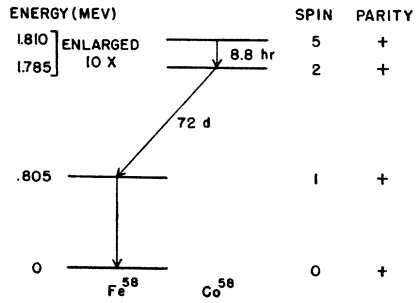

FIG. 2. Proposed decay scheme of Co^{58}.

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[10] E. Segrè and A. C. Helmholz, Rev. Mod. Phys. **21**, 271 (1949).

[11] Deutsch, Elliot, and Roberts, Phys. Rev. **68**, 193 (1945).

gested several of the chemical separations. Thanks are also due Mr. Bernie Rossi and the 60-inch cyclotron crew for carrying out the bombardments.

APPENDIX. CHEMICAL PROCEDURE

To the solution of Mn in HCl 10 mg amounts of Co, Cu, Fe, Ni, Zn carriers were added. The 1*N* solution was saturated with $(NH_4)_3SCN$ and shaken with a 50 percent mixture of diethyl ether and amyl alcohol. After several washings the alcohol-ether extract was found to be free of Mn. The remaining metals were removed from the extract by shaking with an ammoniacal solution, the copper precipitated as sulfide in 0.3*N* acid solution, the nickel separated as the dimethyl glyoxime, the zinc obtained as sulfide in nearly neutral solution, the iron precipitated as the hydroxide and finally the cobalt separated as sulfide in a basic solution or precipitated by nitroso-β-naphthol. This procedure in parts or as a whole was repeated several times. After the assignment to the element had been established, 1 mg amounts of Co carrier were extracted from a solution of the manganese target with the alcohol-ether mixture, and directly precipitated as the sulfide from an ammoniacal solution.

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Decay Constants of K^{40}

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New measurements have been made of the decay constants of K^{40} for beta-ray emission and for electron capture, and a decay scheme is proposed on the basis of these measurements and the previous data. Special counters adapted to the measurement of low levels of activity were developed for making the measurements. The results obtained were 28.3 ± 1.0 beta-rays per gram of K per sec. and 13.5 ± 4.0 electron captures per 100 beta-rays, corresponding to a total half-life of $12.7\pm0.5\times10^8$ yr., with 88 percent of the decays by beta-ray emission and 12 percent by electron capture. A previous measurement of the gamma-ray intensity in K^{40}, by the present authors, gave 3.6 ± 0.3 gamma-rays per gram of K per sec., or about 12.7 gamma-rays per 100 beta-rays. Since the numbers of gamma-rays and of electron captures in the decay of K^{40} are essentially the same, and since previous measurements indicate that the gamma-energy is greater than the beta-energy, it is proposed that the gamma-ray be associated with the electron-capture decay, a gamma-ray following each electron capture.

I. INTRODUCTION

POTASSIUM 40 is known to decay by beta- and gamma-ray emission and by electron capture, but recent measurements of the decay constants have been in rather poor agreement. The most reliable recent measurements[1–6] of the beta-half-life have given values ranging from 12.0 to 17.8×10^8 yr., with an average value of about 14.4×10^8 yr. The most ingenious method was that of Stout,[4] who mixed into his potassium sources an accurately known activity of Na^{24}, which has nearly the same beta-energy as K^{40}, and measured the ratio of K^{40} to Na^{24} counting rates. Knowing the specific activity of the Na^{24}, he was then able to determine the K^{40} activity directly, without corrections, and obtained 13.1×10^8 yr.

There is even more disparity between the recent estimates of electron-capture intensity, the values ranging from 5 to 190 electron captures per 100 beta-rays. The discrepancies here can be attributed to the uncertainties inherent in the methods used in making the measurements. The measurement of Bleuler and Gabriel[7] was made with a counter arranged to admit gaseous absorbers to absorb selectively the x-rays resulting from the electron-capture decay. Most of the counting rate was due to beta-rays from K^{40}, and the reduction in counting rate when the absorber was introduced was only about two percent. Scattering of the beta-rays in the gaseous absorber may have caused a large part of the two percent change in their counting rate, and the result of 190 electron captures per 100 beta-rays is probably considerably too large. The other determinations[2,8,9] of electron-capture intensity were made from the amount of argon trapped in potassium-bearing minerals, on the assumption that the argon had been produced by decaying potassium. The most refined of these measurements was that of Aldrich and Nier,[10] who used the mass spectrograph to analyze the ratio of A^{40} to A^{36} in minerals. They found that A^{40} was relatively more abundant in potassium-bearing minerals than in present-day atmospheric argon, and from their data they estimated that there are about 10 electron captures per 100 beta-rays in K^{40}.

New measurements of the decay constants for beta-ray emission and for electron capture were undertaken.

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