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Disintegration Schemes of Radioactive Substances VIII. Co^{60}

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The radiations emitted in the decay of the two isomers of Co^{60} have been studied by means of a magnetic lens spectrometer and coincidence methods. The five-year isomer decays by emission of negatrons of maximum energy 0.308±0.008 Mev, followed by two gamma-rays in cascade, of energies 1.10±0.03 Mev and 1.30±0.03 Mev, respectively. At least 90 percent of the disintegrations of the 10.7-minute isomer proceed by an isomeric transition of energy 0.056±0.003 Mev, presumably to the five-year level. In the remaining disintegrations negatrons of maximum energy 1.25±0.06 Mev are emitted, probably followed by a single gamma-ray of 1.50 Mev. It is shown that the decay of both isomers is consistent with accepted selection rules for beta- and gamma-ray transitions, indicating a high angular momentum quantum number—four or more—for the five-year level and a low one for the 10.7-minute level. It is pointed out that slow neutron capture by Co^{59} should lead predominantly to the five-year level. Co^{60} is a convenient substance for laboratory gamma-ray standards because of its long half-life and practically homogeneous radiation.

INTRODUCTION

THE two species of cobalt produced by slow neutron or deuteron bombardment of cobalt must be assigned to the mass number 60 since Mitchell, Brown, and Fowler[1] have shown stable cobalt to consist of the single species Co^{59}. Livingood and Seaborg[2] found half lives of 10.7 minutes and 5.3 years, respectively, for the two isomers of Co^{60}. They also reported[3] that the five-year isomer emits negatrons with a main group of maximum energy about 0.2 Mev and a weak group extending to about 0.8 Mev. The energy of the gamma-rays as found by lead absorption was given by them as 1.3 Mev. Of the radiations emitted with the 10.7-minute period, they state that they consist mostly of soft internal conversion electrons.

Nelson, Pool, and Kurbatov[4] studied the beta-rays of the 10.7-minute activity in a semi-circular focusing beta-ray spectrometer and reported finding only a continuous spectrum. From an extrapolation of the Fermi plot they found a maximum energy of 1.35 Mev, but the spectrum actually seemed to extend to about 1.6 Mev. The gamma-rays emitted by the short period were found by them to have an energy of 1.7 Mev, while the long period was reported to emit gamma-rays of 1.5 Mev. In a paper[5] read

* Now with the Canadian National Research Council, Montreal.
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[1] J. J. Mitchell, H. S. Brown, and R. D. Fowler, Phys. Rev. **60**, 359 (1941).
[2] J. J. Livingood and G. T. Seaborg, Phys. Rev. **60**, 913 (1941).
[3] J. J. Livingood and G. T. Seaborg, Phys. Rev. **53**, 847 (1938).
[4] M. E. Nelson, M. L. Pool, and J. D. Kurbatov, Phys. Rev. **62**, 1 (1942).
[5] M. Deutsch and L. G. Elliott, Phys. Rev. **62**, 558 (1942).

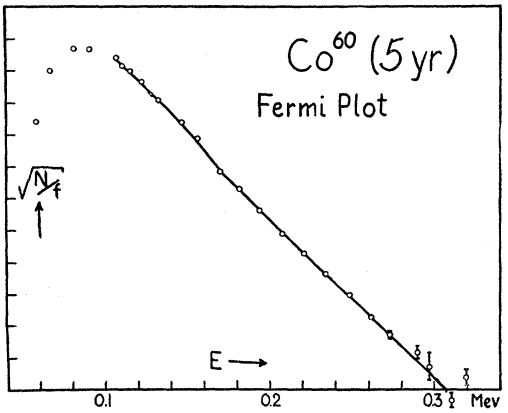

FIG. 1. Fermi plot of the beta-ray spectrum of the 5-year isomer.

to the Physical Society we have reported the results of a study of Co^{60} by means of coincidence and spectrometer techniques described in previous papers of this series.[6] In this paper we shall describe the experiments leading to those results and report some further findings. Although the results, particularly those concerning the 10.7-minute period, are not as complete as those obtained with other activities,[6] we are presenting them at this time because the pressure of other work has prevented the continuation of these studies.

THE FIVE-YEAR ISOMER

Sources of the long-lived species of Co^{60} were prepared by prolonged deuteron bombardment of cobalt metal. The sources usually contained traces of Co^{58} (Paper VII) produced by $(n, 2n)$ and possibly (d, H^3) reactions. The method of chemical purification followed the lines described[6] in paper VI. The specific activity of the material was not high enough for the preparation of a sufficiently strong source which could be considered thin for electrons of such low energy. The shape of the beta-ray spectrum is therefore distorted at low energies by scattering in the source and near the endpoint by the low resolution of the spectrometer which is necessary because of the low intensity available. Figure 1 shows a Fermi plot of the spectrum observed in the short lens spectrometer. A very weak high energy "tail" extending to about 1 Mev was shown to be due to secondary electrons ejected from the source by gamma-rays since its intensity was increased when the source was covered by a thin copper foil. These electrons were subtracted before plotting Fig. 1. The maximum energy of the spectrum as obtained from Fig. 1 is 0.308 $\pm$0.008 Mev.

Figure 2 shows a spectrum of the secondary electrons ejected by the gamma-rays of Co^{60} from a thin lead radiator and from the copper capsule containing the source. The two photoelectron peaks are clearly due to the K electrons of lead ejected by gamma-rays of 1.10 Mev and 1.30 Mev quantum energy, respectively.

The similarity of the spectrum shown in Fig. 2 with that produced by the gamma-rays of Fe^{59} (Paper IV) is rather striking. However, coincidence studies showed the disintegration schemes to be quite different. The number of beta-gamma coincidences per recorded beta-ray of Co^{60} was found to be $3.12\pm0.09\times10^{-3}$ and independent of beta-ray energy. This number is just twice the value observed with a source of Fe^{59} placed in the same standard coincidence arrangement (Paper V). Gamma-gamma coincidences were also observed in the case of Co^{60}, and their number was $1.60\pm0.08\times10^{-3}$ per recorded gamma-ray. Thus there can be no doubt that the two gamma-rays are emitted in successive rather than in alternate transitions. The ratio 2:1 of the fractional beta-gamma and gamma-

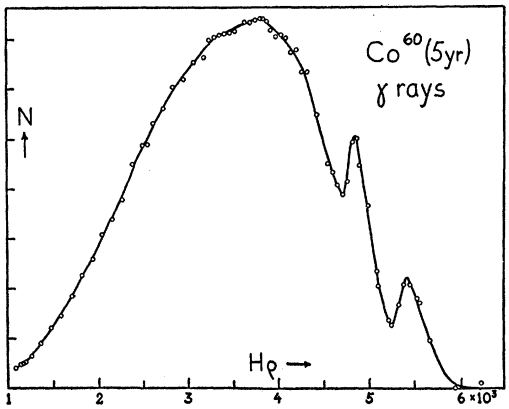

FIG. 2. Secondary electrons ejected by the gamma-rays of the 5-year isomer.

[6] Reference to the earlier papers will be found in paper VI: L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943), reference 1. The short lens spectrometer has been described by M. Deutsch, L. G. Elliott, and R. D. Evans, Rev. Sci. Inst. **15**, 178 (1944).

gamma coincidence rates is, of course, just what one would expect in this case. Sources of Co^{60} are quite convenient gamma-ray standards because of the almost monochromatic radiation and the long lifetime. Co^{60} also provides one of the calibration points of the gamma-ray counter efficiency curve (Paper V). Figure 3 shows the disintegration scheme of Co^{60}. The order of emission of the two gamma-rays is not determined by our experiment.

THE 10.7-MINUTE ISOMER

The half-life of the short-lived isomer is somewhat too short for a thorough study by our usual methods. However, a certain amount of information was gained about its mode of decay.

Since the short half-life does not permit careful chemical purification, we prepared most sources by a slow neutron capture process, using a Szilard-Chalmers process. Sources prepared by deuteron bombardment of cobalt behaved in every way like those prepared by neutron capture, but occasionally radioactive impurities were introduced from the cyclotron chamber.

About 40 grams of potassium cobalticyanide were prepared and dissolved in 500 cc of water. Before exposure about 2 mg of $CoCl_2$ were added as carrier. After exposure the radioactive atoms were collected with the carrier by precipitation with NaOH and H_2O_2. The cobalticyanide had to be purified frequently by precipitation with alcohol, because the peroxide used in the separation seemed to cause formation of interfering compounds.

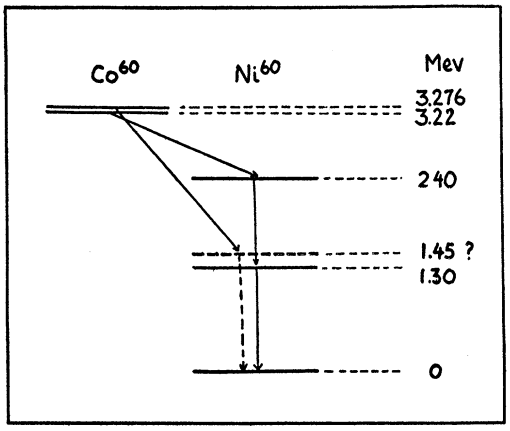

FIG. 3. Probable decay scheme of Co^{60}. The excitation of the level indicated by the dotted line is probably 1.50 Mev. The isomeric transition not clearly indicated in the figure constitutes 90 percent of the disintegrations.

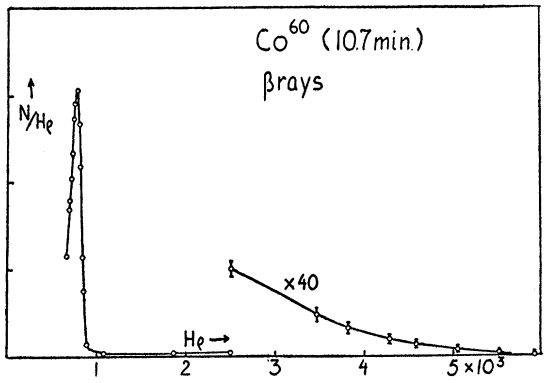

FIG. 4. Beta-ray spectrum of the 10.7-minute isomer. No correction for absorption in the counter window has been applied.

An absorption curve of the beta-rays emitted by the 10.7-minute isomer showed a very soft component of great abundance and another component of maximum range 470 mg/cm². This value corresponds to a maximum energy of 1.15 Mev. Unfortunately the half life of 10.7 minutes is too short to permit careful preparation of sources for spectrometer observations. Sources were prepared by cutting a piece of the filter paper holding the oxide precipitate. Figure 4 shows that, although these sources were rather thick, they allowed us to identify the two components of the beta-radiation. The soft component is seen as a peak of conversion electrons. Its relative intensity is greatly reduced by absorption in the counter window and in the source. The peak occurs at an energy of 48.5 ± 2 Kev. The K and L peaks are not resolved because of the thickness of the source. If the conversion occurs mostly in the K shell, as seems likely from theoretical considerations, the energy of the converted gamma-ray is 0.056 ± 0.003 Mev. If L conversion should be abundant, the gamma-ray energy may be slightly lower. The hard component of the beta-rays is a continuous spectrum. The maximum energy, as found from the rather inaccurate data of Fig. 4, appears to be 1.28 ± 0.06 Mev. This is in fair agreement with the absorption data.[7] We estimate that there are at least ten times as many conversion electrons as

[7] In the preliminary report (reference 5), this value was erroneously given as 1.5 Mev.

disintegration electrons. K x-rays of cobalt were also found.

Since gamma-rays of about 1.7 Mev had been reported to accompany the decay of the 10.7-minute isomer,[4] we studied coincidences between beta-rays and these hard gamma-rays. The conversion electrons were found to be unaccompanied by gamma-rays. The beta-rays, on the other hand, showed $1.3\pm0.4\times10^{-3}$ beta-gamma coincidences per recorded beta-ray, in agreement with the assumption that each beta-ray is accompanied by one gamma-ray of about 1.5 Mev.

The isomeric transition of 0.056 Mev probably leads to the five-year level since no other periods have been observed. The beta-decay, with maximum energy 1.25 ± 0.06 Mev, leads to an excited state of Ni^{60} with an excitation energy of 1.50 ±0.1 Mev as calculated from the energy balance in the scheme shown in Fig. 3. It seems rather unlikely that this excitation energy could really be 1.30 Mev, involving the same state as the decay of the five-year isomer, but the possibility cannot be entirely excluded without an actual spectrometer measurement of the gamma-ray energy for which sufficient source strength was not available.

DISCUSSION

The disintegration scheme of the five-year level (probably the ground state) of Co^{60} seems quite well established except for the order of emission of the two gamma-rays. The main features of the decay of the 10.7-minute level are also probably correctly given by the scheme shown in Fig. 3.

It seems interesting to investigate whether the decay of both levels can be adequately described by known selection rules for electromagnetic and beta-ray transitions. The ground state of Ni^{60} probably has an angular momentum zero. If we assume that the transition probability for electric dipole and quadrupole radiations is of the same order of magnitude, then the state with 2.4 Mev excitation must have an angular momentum quantum number of at least three, while the intermediate state, with 1.1 Mev or 1.3 Mev excitation, must have angular momentum one or more, with appropriate parity assignments for all states. If the 2.4 Mev level had angular momentum zero, also possible according to selection rules for gamma-ray emission, beta-transitions to the ground state should certainly occur with observable abundance. The five-year beta-decay is probably "first forbidden," involving parity change, and must occur with an angular momentum change of at least one in order to forbid transitions to the intermediate excited state. Thus the five-year level of Co^{60} must have an angular momentum quantum number of at least four. If the beta-decay is of the allowed type, this could be reduced to three. On the other hand, the beta-decay of the 10.7-minute level may be an allowed transition. This is true if the ratio of 1:10 for the ratio of beta-decay to isomeric transition is correct, since the beta-decay rate corresponds then to a half-life (in the absence of the competing transition) of 107 minutes. Since, furthermore, the de-excitation of the resulting state of Ni^{60} seems to proceed by the emission of a single quantum, the angular momentum of the 10.7-minute level of Co^{60} may be low, even zero.

Now let us consider the electromagnetic "isomeric transition." The observed decay constant for this transition is about $\lambda=10^{-3}$ sec.$^{-1}$. Using for the gamma-decay constant the formula given by Segrè[8] (quoted by Helmholtz) and for the conversion coefficients the values given by Hebb and Nelson,[9] we find for electric 2^3-pole radiation $\lambda_3^{(\gamma)}=4\times10^{-2}$ sec.$^{-1}$. The internal conversion coefficient is about 100, giving a total $\lambda_3=4$ sec.$^{-1}$, with K conversion preponderant by a factor of 5. 2^3-pole radiation requires parity change and an angular momentum change of 2 or 3 units. For 2^4-pole radiation we find similarly $\lambda_4^{(\gamma)}=2\times10^{-9}$ sec.$^{-1}$, with the internal conversion coefficient 1000, giving a total $\lambda_4=2\times10^{-6}$ sec.$^{-1}$. Again K conversion would be greater than L conversion by a factor of 3. Electric 2^4-pole radiation involves no parity change and an angular momentum change of 3 or 4 units. The relativistic formula of Dancoff and Morrison (their Eq. (18)) gives values of the conversion coefficients larger by a factor of 3 for 2^3-pole and by a factor of 8 for 2^4-pole radiation. This gives

[8] A. C. Helmholtz, Phys. Rev. 60, 415 (1941).

[9] M. H. Hebb and E. Nelson, Phys. Rev. 58, 486 (1940); also S. M. Dancoff and P. Morrison, Phys. Rev. 55, 121 (1939).

predicted decay constant $\lambda_3=12$ sec.$^{-1}$ and $\lambda_4=1.6\times10^{-5}$ sec.$^{-1}$, as compared with the observed value $\lambda=10^{-3}$ sec.$^{-1}$. One may conclude that if the theory means anything at all, the angular momentum difference between the two states of Co^{60} should be between two and four, and that there is evidence that it is three or four. This is quite consistent with the evidence from the independent beta-decay of the two states, as discussed above, where it was also shown that the five-year level is probably the one with higher angular momentum.

This apparent agreement with accepted selection rules leads us to consider the neutron capture process by Co^{59}, whose normal state is known[10] to have a nuclear angular momentum quantum number 7/2. This means that upon capture of a slow neutron the excited compound nucleus Co^{60} must be in a state with angular momentum 3 or 4, depending on the relative orientation of the neutron spin. It would, therefore, seem likely that the five-year level should be populated more heavily by the ensuing gamma-ray emission. If the number of steps in which this emission takes place is small, then the known selection rules favor a small angular momentum change. If a large number of gamma-rays is emitted in cascade, then the final result of random changes in angular momentum should still tend to be small, favoring transitions to the five-year level which seems to have angular momentum near four. This effect should be enhanced by the greater statistical weight of states of larger angular momentum. Unfortunately, the available data are very unreliable, because it is not known what fraction of the radiations of the two isomers were detected by the various observers. Horvath and Salant[11] report a total neutron capture cross section 600 times as great as the production of the 10.7-minute isomer, while Sinma and Yamasaki[12] find a ratio 40:1. Granting the great uncertainty of the neutron capture experiments, the results seem to support our assumptions concerning the angular momenta of the two states.

From the disintegration scheme shown in Fig. 3, one can calculate the mass difference between neutral atoms $Co^{60}-Ni^{60}=2.92\times10^{-3}$ a.m.u.

It is a pleasure to acknowledge the friendly cooperation of Professor M. S. Livingston and the cyclotron crew and of Professor J. W. Irvine, Jr. who helped with the chemical procedures. We also wish to thank Professor R. D. Evans for his continued interest.

[10] K. R. More, Phys. Rev. **46**, 470 (1934).

[11] W. J. Horvath and E. O. Salant, Phys. Rev. **59**, 154 (1941).

[12] K. Sinma and F. Yamasaki, Phys. Rev. **59**, 502 (1941).