the activity of each foil was followed for over a week and a decay curve plotted for each foil. As explained earlier, the end activity in each foil was quite probably due mainly to the 180-hr. Ag^{111} isotope. The initial activity of the 180-hr. period in each foil was plotted as a function of the bombarding energy. These data for the 180-hr. silver activity are shown by the solid circles in Fig. 4. The curve through these points corresponds to a reaction involving proton capture (i.e., deuteron in, neutron ejected).

By subtracting the 180-hr. activity from the decay curve for each foil, a new family of curves is obtained, each ending in a straight line corresponding to the 13-hr. palladium activity. By extending these curves back to the time at which the bombardment was ended, the relative values of the initial 13-hr. Pd^{109} activities for each foil are obtained. These are shown as open circles in Fig. 4 and the curve through them corresponds to a reaction involving neutron capture (i.e., deuteron in, proton ejected).

While following the activity of the foils, the electrometer was continually calibrated in terms of a known uranium standard. The initial activity of the top foil for the 13-hr. palladium was about 1.70 microcuries and for the 180-hr. silver about 0.092 microcuries.

To facilitate comparison of the two excitation curves, they are arbitrarily adjusted to the same value at an energy of 5.8 Mev. Although too much significance should not be attached to these curves, it seems reasonably certain that as the energy of the incident particle decreases, the activity in the silver falls off somewhat more rapidly than in the palladium. This is contrary to what might be expected from the Bohr model of the nucleus, since it indicates less probability for neutron ejection from the excited nucleus than for proton ejection. It would, however, be more in accord with the Oppenheimer-Phillips[7] consideration, which is concerned with the probabilities of the particles entering the nuclei.

We are greatly indebted to B. R. Curtis for work with the cloud chamber and to D. W. Stewart and E. Rosenbaum for making the many chemical separations.

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[7] Oppenheimer and Phillips, Phys. Rev. **48**, 500 (1935).

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Neutron-Induced Radioactivity of Long Life in Cobalt

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When cobalt is bombarded by neutrons, an activity of long half-life is obtained. The radioactive element has been shown by a chemical analysis to be an isotope of cobalt. The radiations emitted in the disintegration of this element have been investigated, principally by the absorption method. A gamma-ray is observed with a mass absorption coefficient in Pb of about 0.047 cm^2/g, and a spectrum of soft beta-rays with an estimated limiting range of 30 mg/cm^2 of aluminum, representing an energy of 160 kv. A group of more penetrating particles completely absorbed only by about 0.65 g/cm^2 of aluminum is also indicated. This group may represent a relatively infrequent disintegration process, in which the total energy is carried off by the beta-particle and no gamma-ray is emitted. Results of a measurement on the half-life indicate that it is 2.0 ± 0.5 years.

AN activity of half-life over a year was discovered in cobalt bombarded with neutrons by Sampson, Ridenour and Bleakney.[1] Results of activation of only a few weeks with the neutrons of 55 mC of Ra+Be slowed down by water indicated that a very strong activity would be obtained if bombardment were continued for a time comparable to the half-life.

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[1] Sampson, Ridenour and Bleakney, Phys. Rev. **50**, 382 (1936).

The large capture cross section (35×10^{-24} cm^2) found by Dunning and co-workers[2] leads one to expect a strong activity in cobalt bombarded by slow neutrons. The other known activity due to slow neutrons is a weak short-lived one found by Rotblat,[3] the period of which has been given as 11 minutes by Heyn[4] and others.[5, 6] It is probable therefore that the capture process leading to the production of the long-lived radioelement is responsible for the large slow neutron cross section.

Since almost nothing is known about this radioelement, it seemed desirable to measure the period and determine the nature of the radiations emitted by it, as well as to ascertain by chemical test whether it is an isotope of cobalt. Bombardment of about ten weeks with neutrons from the 55 mC source, slowed down by water, produced an activity in a sheet of very pure cobalt metal (about 50 cm^2 in area and 0.4 g/cm^2 thick) great enough to obtain a fairly accurate estimate of the energy of the beta-ray spectrum from its absorption in aluminum as well as to detect the presence of accompanying gamma-radiation and measure the absorption coefficient of the latter in Pb. The activity was not sufficient to use methods of greater precision. To obtain great activity in an element of this half-life, a very large source of neutrons is required unless the bombarding time is made very long.

1. Identity of the Radioelement

For the chemical analysis a solution of cobalt nitrate in water which had been exposed to the neutrons of the 55 mC source for several months, and which showed the long period activity, was used. After adding small quantities of soluble manganese and iron salts, these elements were successively separated by the usual procedures of qualitative analysis.[7] The cobalt itself was then precipitated. The iron and manganese precipitates showed no activity but the cobalt precipitate carried the activity with it. It is therefore concluded that the radioactive element is an isotope of cobalt.

The abundant stable isotope of cobalt is Co^{59}. Co^{57} is also believed to exist, the ratio Co^{57}/Co^{59} being about 1/600.[8] Neutron capture by both Co^{57} and Co^{59} to form radioactive isotopes, Co^{58} and Co^{60}, could be expected. It would seem reasonable to attribute the stronger long period activity to Co^{60}, formed from the more abundant isotope Co^{59}, and the 11-minute activity to Co^{58}. This avoids the necessity of assigning to Co^{57} a cross section about 600 times 35×10^{-24} cm^2. This contingency however is not ruled out because cross sections larger than 21×10^{-21} have been observed.[2] A long period activity due to a cobalt isotope has been observed by Livingood, Fairbrother and Seaborg[6] in Fe bombarded by deuterons, as well as in cobalt bombarded by neutrons. The only way that Co^{60} could be formed by deuteron bombardment of iron is by capture of the whole deuteron by Fe^{58}, the highest mass found in iron, present to less than a percent. The process is regarded as very unlikely, so that this evidence favors the assignment of the 11-minute activity to Co^{60} and the long period to Co^{58}, which could be formed from iron with deuterons by the reaction $Fe^{57}(d, n)Co^{58}$. Evidence favoring this assignment is the failure so far to report the 11-minute period from cobalt bombarded by fast neutrons[4, 9] and by gamma-rays.[10] Both reactions should yield Co^{58}. Less convincing evidence is the failure to find any activity of short half-life in manganese bombarded by 7 Mev alpha-particles in this laboratory.[11] The formation of Co^{58} by the reaction $Mn^{55}(\alpha, n)Co^{58}$ would be expected. A check by the fast neutron reaction $Cu^{63}(n, \alpha)Co^{60}$ [1] is impossible because the 10-minute activity of Cu^{62} from the reaction $Cu^{63}(n, 2n)Cu^{62}$ would obscure the 11-minute period of Co^{60} if it were present. The reaction $Ni(n, p)Co$, which yields the 11-minute period,[3, 4] cannot be used as evidence, because both Co^{58} and Co^{60} can be formed in this way.

[2] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).
[3] Rotblat, Nature **136**, 515 (1935).
[4] Heyn, Physica **4**, 160 (1937).
[5] Kikuchi, Takeda and Ito, Proc. Phys.-Math. Soc. Japan **19**, 43 (1937).
[6] Livingood, Fairbrother and Seaborg, Phys. Rev. **52**, 135 (1937).
[7] A. A. Noyes, *Qualitative Chemical Analysis.*
[8] Sampson and Bleakney, Phys. Rev. **50**, 732 (1936).
[9] Pool, Cork and Thornton, Phys. Rev. **52**, 239 (1937).
[10] Bothe and Gentner, Zeits. f. Physik **106**, 236 (1937).
[11] Ridenour and Henderson, paper in publication.

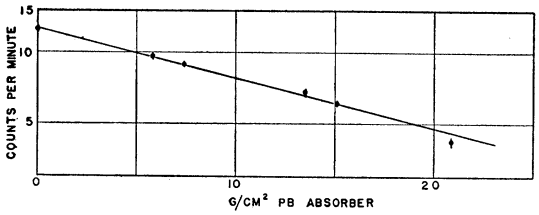

FIG. 1. Absorption in Pb of the gamma-radiation from cobalt. Ordinates represent response of gamma-ray counter in counts per minute above background.

2. GAMMA-RADIATION

For the remaining experiments the activated sheet of cobalt metal was used. When this was placed closely around a gamma-ray tube counter having a wall thickness of about 0.9 g/cm², there was an increase in the counting rate of three times the background. The radiation producing this effect showed an absorption in Pb of exponential character with a mass absorption coefficient of about 0.047 cm²/g. The curve obtained is shown in Fig. 1. A radiation of this penetrating character is doubtless gamma-radiation.

For obtaining the absorption curve of Fig. 1, the cobalt sheet was placed around the counter in the form of a coaxial cylinder, and cylindrical absorbers were inserted between. A large enough number of counts were taken that the estimated statistical errors in the points are as shown by the small vertical lines on the figure. From the value of the absorption coefficient one would attribute to the gamma-ray an energy of 1.5 to 2.0 Mev.[12] A determination of the absorption in copper indicated the correctness of assigning the lower of the two possible energy values associated with this one value of the absorption coefficient. This energy value is not to be taken too seriously, however, because the accurate determination of an absorption coefficient demands a geometry for eliminating scattered radiation from the direct beam which cannot be attained with a low intensity source. For this reason the value 0.047 is probably too low and the estimated energy too high. Nevertheless, the absorption coefficient is given here because a knowledge of the gamma-ray energy would be desirable in connection with an interpretation of the beta-ray spectrum and because it indicates at least that the gamma-ray is fairly hard.

[12] Gentner, J. de phys. et rad. **6**, 274 (1935).

3. THE BETA-RAY SPECTRUM

The principal constituent of the beta-ray spectrum is a group of low energy beta-particles which is completely absorbed by about 30 mg/cm² of aluminum. The wall of the ordinary beta-ray tube counter is of about this thickness, so that for dealing with this group a special experimental arrangement had to be devised to avoid the use of a window that would itself absorb an appreciable fraction of the incident particles. This consisted of a wire screen tube counter mounted axially on the inside and at one end of a glass containing tube, which could be evacuated and filled with dry air at a suitable pressure (8 cm). The cobalt sheet was mounted with a bit of wax to the inside wall of the glass tube so that it completely surrounded the wire screen counter. Cylindrical absorbing foils of aluminum could be inserted between the cobalt and the wire screen, but in the absence of a foil there was no absorber between the cobalt and the sensitive volume of the counter except air of stopping power equivalent to about 1 mm at NTP.

The counter and its containing tube were mounted vertically. By moving iron counterweights in side tubes with a small magnet absorbing foils of three different thicknesses could be lowered into place between cobalt and counter, and removed again, without changing the pressure in the counter. Hence three points on the absorption curve beside that for zero absorber could be taken. The counter then had

TABLE I. *Results of measurements on the absorption of the soft component of the beta-ray spectrum, showing average counting rate of wire screen counter for each absorber thickness and total number of counts taken in determining this average.*

THICKNESS OF Al IN MG/CM²	TOTAL NUMBER OF COUNTS TAKEN	AVERAGE COUNTING RATE IN MIN.⁻¹
No Absorber	53,548	213
2.4	35,096	176
4.6	33,800	155
6.5	30,520	141
10.6	63,188	134
14.7	44,064	129
19.3	35,536	124
29.4	34,484	118
44.1	30,012	112
58.8	22,292	109
221.	10,964	83

to be opened to the air to replace the foils. Once the counter had been opened and refilled with air at its working pressure, its sensitivity at a given working voltage was slightly different. Hence, each time a new set of foils was put in, one of the old set was retained and its absorption was used to fit the new series of readings to the preceding ones.

The results of the absorption measurements taken under these conditions are shown in Table I and Fig. 2. The curve shows a rapid drop for thicknesses up to about 10 mg/cm^2 after which there is a transition to a portion of more gradual slope. This last gradually sloping portion also has the characteristics of an absorption curve for beta-particles but it does not flatten out until absorber thicknesses of about 0.65 g/cm^2 of aluminum (Fig. 4) are reached. Absorption curves of beta-ray spectra known to consist of only one component, like that of RaE, do not exhibit the spread out character relative to the half-value thickness of this complete absorption curve. It therefore seems reasonable to attribute the gradually sloping portion of the curve of Fig. 2 to a distinct group of particles of higher energy and to take as the upper limit of the low energy spectrum the point where the first rapid drop merges into it. This point is estimated to be at 30 mg/cm^2 corresponding to an energy of approximately 160 kv.[13]

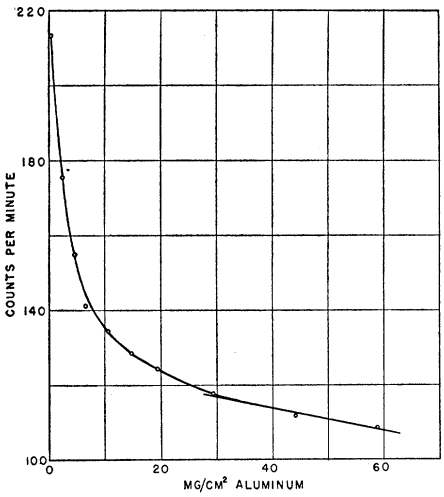

FIG. 2. Absorption in aluminum of the soft component of the beta-ray spectrum. Wire screen counter used as detector.

[13] Results of Madgwick; see Rutherford, Chadwick and Ellis, p. 422.

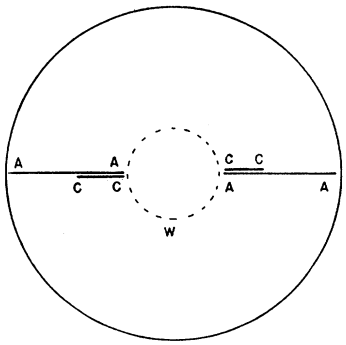

FIG. 3. Schematic diagram of cross section of the magnetic deflection apparatus used in determining the sign of the soft beta-rays. *W*, wire screen tube counter; *CC*, cobalt strips; *AA*, thick Cu supports. Field perpendicular to plane of paper.

It was shown that these low energy particles are negative electrons by a magnetic deflection method. The activity of the source was not great enough to obtain reliable information from a cloud chamber. A modified wire screen counter arrangement which could be placed in the field of a large water-cooled solenoid was used. A cross section of the apparatus perpendicular to the field and to the axis of the wire screen counter is shown in Fig. 3. *W* is the counter; *CC* are strips of cobalt parallel lengthwise to the axis of the counter; *AA* are supporting strips of copper through which the beta-particles could not pass. It can be seen that some particles from the cobalt could enter the counter in the absence of a field but that the number entering could be increased by applying a field of suitable magnitude and sense. The nature of the charge on the particles was then known from the sense of the field causing the increase. For a source of low intensity this simple arrangement was found preferable to ones in which the beam of particles entering the counter was more narrowly defined.

The results showed that the particles were negatively charged. With a counting rate for zero field of about 45 per minute, fields of 800 to 1000 gauss out of the paper on Fig. 3 increased it by 15 to 18 percent, while there was a slight decrease for fields in the opposite direction. Although it is difficult to take into account the disturbing action on the field of the magnetic cobalt strips, the geometry indicates that the radius of curvature for particles leaving the surface of the cobalt normally and entering the

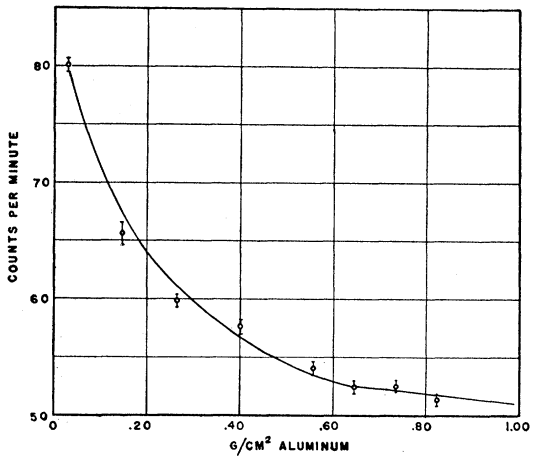

FIG. 4. Absorption in aluminum of the more penetrating beta-rays. Thin-walled counter used as detector.

counter was of the order of a centimeter, giving $H\rho$ values of the order of 1000, corresponding to electron energies in the neighborhood of 100 kv.

The curve of Fig. 4 is a plot of the results obtained by continuing the absorption measurements to greater thicknesses of aluminum, using a beta-ray counter with a thin cylinder of Dow metal. For the first point the wall of the counter acted as absorber. This curve can scarcely represent a tailing-off portion of the curve of Fig. 2, as mentioned before. If, as supposed, it is due to a distinct group of particles, this group is less numerous than that of the soft beta-particles, the ratio being less than 1/30 when the relative absorption of the two groups in the material of the source is considered. (To allow a comparison of Figs. 2 and 4 it should be mentioned that the wire screen counter was somewhat larger than the Dow metal counter, and the natural backgrounds, which were not subtracted here, were about 30 and 25, respectively.) From the curve the upper limit of this higher-energy spectrum is estimated to be 0.65 ± 0.05 g/cm² corresponding to an energy of 1.45 ± 0.10 Mev.[14]

It is difficult to account for the presence of two groups of particles without a more exact knowledge of the gamma-ray energy. Intensity considerations make it seem unlikely that it is a line spectrum due to internal conversion of the gamma-ray. It is suggested that it probably represents a rarer mode of disintegration in which the beta-transition leaves the product nucleus in the ground state and no gamma-radiation is emitted.

[14] Feather, Phys. Rev. **35**, 1559 (1930).

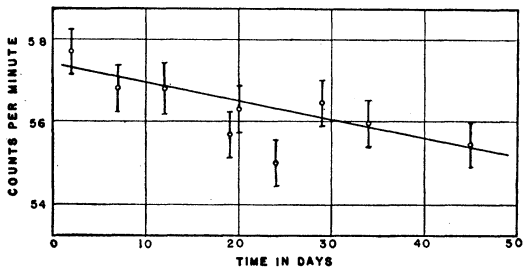

FIG. 5. Decay of the activity of the cobalt sample with time. Ordinates represent response of gamma-ray counter in counts per minute above background.

4. THE HALF-LIFE

Counter measurements of the gamma-ray activity of the cobalt sheet were made over a period of six weeks in an attempt to determine the half-life. A plot of the results is shown in Fig. 5, where the ordinates represent the average counting rate of the counter above background. The ordinate scale is logarithmic. Here, as in the previous cases, the estimated statistical errors, represented by vertical lines through the points, are obtained from the square root of the total number of counts taken in a reading divided by the time, and include the background error. Before each measurement the sensitivity of the counter was checked for constancy against a small source of Ra at a fixed distance. The slope of the decay curve, as drawn in the figure, corresponds to a half-life slightly more than 800 days. It is felt that a half-life value of 2.0 ± 0.5 years represents a conservative estimate consistent with the data.

The writer wishes to take this opportunity to express appreciation to the members of the Princeton faculty for many stimulating discussions during the progress of the investigation. Special acknowledgment is due Professor Walker Bleakney for the suggestion and general supervision of the problem and Professors L. A. Turner and R. Ladenburg, and Dr. L. N. Ridenour for helpful advice and criticism.