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The Nuclide Ni^{56}†

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Ni^{56} has been produced by the bombardment of the separated isotope Fe^{54} with 39-Mev alpha-particles. It is a 6.4±0.1 day orbital electron capture activity with less than 1 percent positrons. Growth of its daughter Co^{56} makes the mass assignment certain and confirms the 6.4-day half-life. Gamma-rays of the following energies in Mev (and relative intensities) have been found: 0.17 (1.0), 0.28 (0.3), 0.48 (0.4), 0.81 (0.8), 0.96 (0.1), 1.33 (0.05), 1.58 (0.15), and 1.75 (0.02). The half-lives of most of these gamma-rays have been followed individually and agree with the half-life quoted. The large number of gammas indicates that the decay scheme is complex. Coincidences have been found between the cobalt K x-rays and the gammas as well as between the gamma-rays themselves. There is less than 10^{-4} alpha-branching.

I. INTRODUCTION

SEVERAL people, including Mayer,[1] have suggested that a study of Ni^{56} would be significant because both the neutron and proton numbers indicate possible closure of shells. Also Ni^{56}, having equal numbers of protons and neutrons, may be considered an alpha-particle nucleus. Alpha-particle nuclei below Ca^{40} have long been known to be unusually stable. The stability of Ni^{56} may throw some light on this stability effect in nuclei above Ca^{40}. Friedlander[2] has observed a smaller amount of longer-lived activity along with the 36-hour Ni^{57} produced in an alpha-bombardment of iron. This evidence together with its expected stability because of shell closure at 28 neutrons and 28 protons was an indication that a long-lived Ni^{56} might exist. The alpha-bombardment of iron would appear to be one of the best methods of producing this activity with the expected reaction being $Fe^{54}(\alpha,2n)Ni^{56}$. Since the natural isotopic abundance of Fe^{54} is only 5.9 percent, however, it seemed advisable to obtain an enriched stable isotope for alpha-bombardment.

II. EXPERIMENTAL

A sample of Fe_2O_3 showing 84.3 percent Fe^{54}, 15.3 percent Fe^{56}, <0.5 percent Fe^{57}, and <0.2 percent Fe^{58} was obtained from the Stable Isotopes Research and Production Division of Oak Ridge National Laboratory. It was bombarded with an external beam of 62.28 microampere hours of 39±1-Mev α-particles from the University of California's 60-inch cyclotron. The sample was dissolved in concentrated HCl and a nickel-cobalt-iron separation performed according to a procedure of Moore and Kraus[3] using an anion exchange column. The anion exchange column employed Dowex A-2 (a diethanol methyl quaternary amine) resin (100 mesh) which had been carefully screened, washed, treated with ethyl alcohol and dried. Elution with 10 normal HCl removed the nickel, leaving the cobalt and iron fractions on the resin. Further elution with 2 normal HCl removed the cobalt from the iron, which stayed on the resin. To check for completeness of separation, a sample of nickel was separated using the conventional dimethylglyoxime precipitation. The gamma-ray spectrum of this sample was identical with that of the sample from the ion exchange separation. The separated nickel sample was counted in a beta proportional counter, a Geiger-Mueller counter, and an integrating scintillation counter. In the beta proportional counter an absorption curve was obtained which indicated a large intensity of very low energy electrons which were totally absorbed in 0.22 mg/cm² of aluminum. The half-life measurements obtained on the integrating scintillation counter did not agree with those

† This nuclide has also been studied by W. J. Worthington, Jr., Phys. Rev. 87, 158 (1952).
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[1] M. Goeppert-Mayer, Phys. Rev. 78, 16 (1950).
[2] Friedlander, Perlman, Alburger, and Sunyar, Phys. Rev. 80, 30 (1950).
[3] G. E. Moore and K. A. Kraus, J. Am. Chem. Soc. 74, 843 (1952); 72, 5792 (1950).

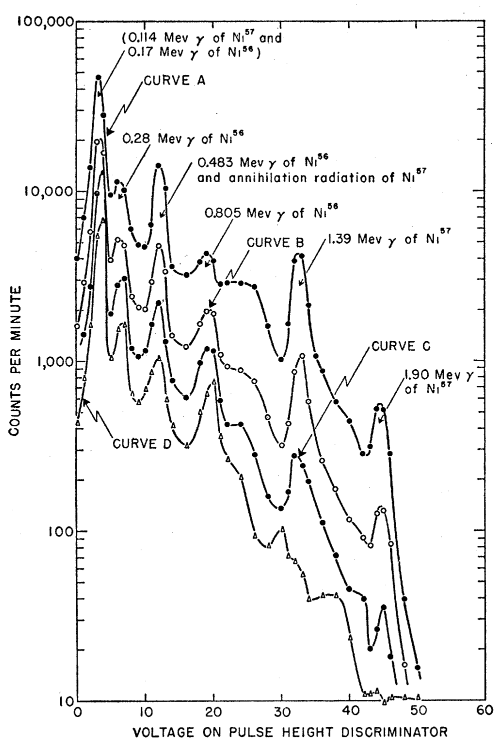

FIG. 1. Gamma-ray spectra of Ni^{56} and Ni^{57} as a function of time.

Curve	Hours after separation	Hours after bombardment
A	3	102
B	74	173
C	147	249
D	291	390

obtained with the beta proportional counter and the Geiger-Mueller counter. Gamma-ray spectra were obtained as a function of time using a sweep-type differential and integral discriminator similar to the one already described by Fairstein.[4] The gamma-rays showed two half-lives. The first was the 36-hour half-life of Ni^{57} which is well known. The second half-life was a new 6.4-day activity.

Some of the gamma-ray spectra as a function of time are shown in Figs. 1 and 2. The gamma-ray spectra in Fig. 1 show a Ni fraction containing a considerable amount of Ni^{57} as well as the 6.4 day Ni, whereas the gamma-spectra in Fig. 2 were chosen to show the decay of the 6.4-day activity and the growth of its daughter. Spectra utilizing greater resolution have been obtained to separate gamma-rays in the low energy region not shown as separated in Figs. 1 and 2. Gamma-rays at 0.114, 1.39, and 1.90 Mev were attributed to Ni^{57}; these compare with 0.128, 1.375, and 1.91 Mev found by Canada and Mitchell.[5] All the gamma-rays associated with the 6.4-day nickel activity, together with their relative intensities when it was possible to determine them, are listed in Table I. The gamma-rays with energies of 170, 281, 483, 805, and 1575 kev have been shown to decay with a half-life of approximately 6.4 days. The gamma-rays of 960, 1330, and 1750 kev are almost certainly associated with the decay of this new nickel isotope although it was not possible to measure their half-lives accurately because they appear as strong shoulders on other peaks of the gamma-ray spectra. There also appeared to be a weak gamma-ray at 370 kev which is not listed in Table I because it is less definitely established than the others. An absorption spectrum using a Geiger-Mueller counter was obtained for this new nickel activity after the majority of the Ni^{57} had decayed away. The absorption curve is shown in Fig. 3. Coincidence measurements indicated that this activity occurred in coincidence with the gamma-rays attributed to the 6.4-day activity and that some of these gammas were in coincidence with each other.

III. MASS ASSIGNMENT OF THE NICKEL ACTIVITY

After the Ni^{57} (identified by its gamma-ray spectrum, the energy of its positron, and its half-life) had been allowed to decay away, a nickel separation was made. Then from time to time cobalt milkings were carried

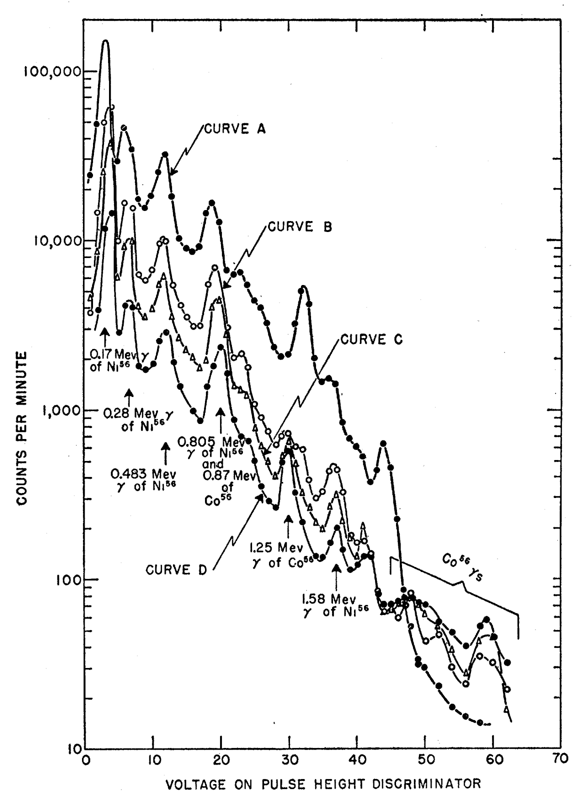

FIG. 2. Gamma-ray spectra of Ni^{56} (with a small amount of Ni^{57} present) and Co^{56} growing in.

Curve	Hours after separation	Hours after bombardment
A	29	271
B	153	395
C	317	559
D	533	775

[4] E. Fairstein, Rev. Sci. Instr. **22**, 76 (1951).
[5] R. Canada and A. C. G. Mitchell, Phys. Rev. **83**, 955 (1951).

out on this nickel fraction and decay curves on the resulting nickel fractions were followed; Fig. 4 is an example of one of these curves. The cobalt activity which grows into the nickel fraction is certainly that of Co^{56}. Gamma-rays of the following energy in Mev have been observed in the Co fraction milked from the Ni: 0.87, 1.25, 1.73, 2.04, and 2.53. These compare with 0.845, 1.26, 1.74, 2.01, and 2.55 Mev reported by Elliot and Deutsch.[6] In addition, the 1.5-Mev positron has been identified by absorption measurements. The cobalt growth curve in Fig. 4 has been normalized to give equal counting efficiencies for the parent and daughter. It is consistent with a 6.4-day half-life for Ni^{56} and an 80-day half-life for Co^{56}. Because the identification of the daughter Co^{56} is so definite, the mass assignment of this nickel activity as Ni^{56} seems unequivocal.

IV. DECAY CONSTANT AND MODE OF DECAY

Although a half-life of approximately 6.4 days was obtained for the various gamma-rays followed (see Figs. 1 and 2), this half-life varied considerably as may be seen in Table I, because of the background of Ni^{57} and due to the growth of cobalt activities. A more precise determination of the half-life was possible from the data obtained using the repeated separations of the nickel and the integrating scintillation counter (of which Fig. 4 is an example). The half-life so determined is 6.4 ± 0.1 days. An attempt was made to determine the possible existence of a positron activity by absorption measurements. These measurements using aluminum absorbers showed the existence of a radiation with a half-thickness of 8.5 ± 0.5 mg per cm^2 of aluminum (see Fig. 3); this half-thickness is consistent with that expected for a *K* x-ray of cobalt.[7] It was not possible to obtain a large enough number of absorbers to determine accurately the half-thickness of Be. However, in view of the much greater half-thickness in Be, these results cannot be interpreted as a weak positron but only as *K* x-rays of Co. Absorption measurements

TABLE I. Gamma-rays associated with Ni^{56}, their energies, relative intensities, and observed half-life when available.

γ-ray	Energy in Mev	Relative intensity[a]	Half-life
1	0.17	1.0	6.7
2	0.28	0.3	6.38
3	0.48	0.4	6.8
4	0.81	0.8	6.0
5	0.96	0.1	
6	1.33	0.05	
7	1.58	0.15	7.6[b]
8	1.75	0.02	

[a] The relative intensities were obtained with a scintillation counter which had been calibrated with samples which had been coincidence counted. (The spectrometer was assembled and calibrated by A. R. Brosi, B. H. Ketelle, and H. Zeldes.)
[b] Half-life strongly affected by Co^{56} at 1.73 Mev.

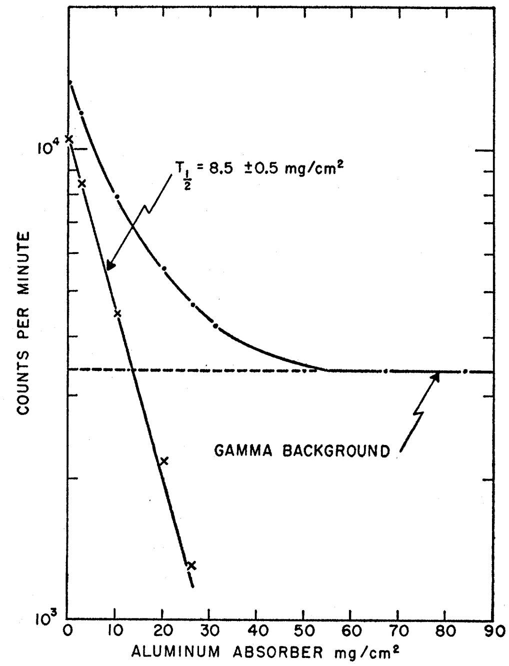

FIG. 3. Absorption of Ni^{56} radiations by aluminum.

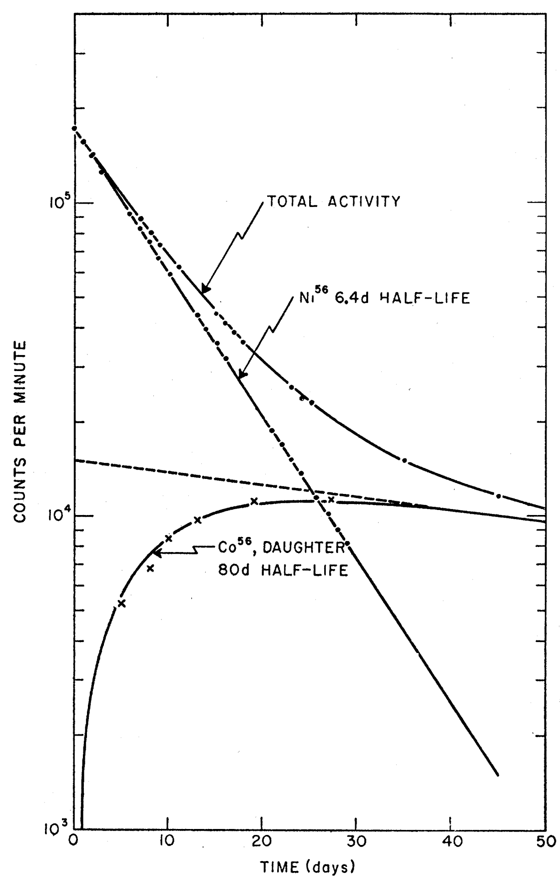

FIG. 4. Ni^{56} decay, Co^{56} growth curves; Ni^{56} half-life: 6.4 days; Co^{56} half-life: 80 days. Typical nonequilibrium case where half-life of parent is shorter than half-life of daughter.

[6] L. G. Elliot and M. Deutsch, Phys. Rev. **63**, 321 (1943).
[7] Brosi, Borkowski, Conn, and Griess, Jr., Phys. Rev. **81**, 391 (1951).

indicated no other activity except the very low energy electrons and the gamma-rays; the former are probably to be explained as due to a partial internal conversion of the K x-rays. In this way, it was possible to show that there was less than 1 positron for every 95 positrons of Co which grow into the Ni activity in a period of 20 days. Since the Co^{56} activity never reaches a value greater than 10 percent of the Ni activity (assuming equal counting efficiencies) a very conservative upper limit of less than 1 percent positron activity is suggested. If equal counting efficiencies are assumed, an upper limit of 0.1 percent positron activity obtains. The fact that no annihilation radiation was observed supports the low limit on positron branching although the gamma-ray at 0.45 Mev makes this an insensitive test. Since it has not been possible to observe positrons in this activity, whereas there is a very complex gamma-ray spectrum along with Co K x-rays, the existence of the discrepancy between the decay rate as obtained by a Geiger-Mueller or beta proportional counter and an integrating scintillation counter may be understood. The decay rate using a proportional or Geiger-Mueller counter was less than 6 days but on repeated separations approached ever nearer 6 days as the remaining Ni^{57} died away whereas, as may be seen in Fig. 4, the decay constant obtained by using an integrating scintillation counter is very constant and, therefore, would appear to be reliable. In view of the fact that Ni^{56} is an alpha-particle nuclide, the possibility of its being an alpha-emitter was considered. A very intense sample was placed in a methane-type gas-flow counter, and no alpha-counts were observed. In this way it was possible to set an upper limit of 10^{-4} on the alpha-branching ratio.

V. DISCUSSION

While the existence of coincidences between the Co K x-rays and the gammas and between some of the gammas themselves has been established, it has not been possible to describe a unique decay scheme due to the complexity of the gamma-ray spectrum, i.e., several different decay schemes explain the present data equally well. The complexity of the decay scheme may be due to a large spin change between the parent and daughter. For instance, if the one-particle nuclear shell model and simple addition of the odd neutron and proton spins in Co^{56} are assumed valid here, the spin difference between Ni^{56} and Co^{56} is 6. Such a large spin difference would allow the existence of several states of intermediate spin. Unfortunately since the total decay energy is not known, a comparison of the observed decay energy with that determined from the equation for the electron capture decay energy containing the Weizsäcker-Bohr-Wheeler terms,

$$E_d^k = B_A(Z - Z_A - 0.5) - \delta_A,$$

with suitably chosen values of B_A, Z_A, and δ_A, cannot be made. Such comparisons have been made by C. D. Coryell *et al.* for a wide variety of nuclides, especially those of odd atomic mass where the δ effects cancel to a first approximation, and a discrepancy of about 1 Mev has been found on crossing above either the 28-neutron or the 28-proton shell.[8]

From the semi-empirical mass difference between Ni^{56} and Co^{56} given in the tables of Metropolis and Reitwiesner,[9] an energy difference of 3.0 Mev is obtained. On the assumption that the 6.4-day activity represents decay of the ground state of Ni^{56}, the observed energy difference is greater than or equal to 1.75 Mev since this is the energy of the most energetic observed gamma. Then if a discrepancy of about 1 Mev is to be expected, it may be concluded that the total decay energy should not be greater than about 2 Mev.

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[8] Coryell, Brightsen, and Pappas, Phys. Rev. **85**, 732 (A) (1952); also C. D. Coryell (private communication) has pointed out that in the case of Ni^{56} decay only the effect of exceeding a closed shell should be observed, i.e., only the effect of going from 28 to 29 neutrons should be noticed and not any additional effect due to going from 28 to 27 protons.

[9] N. Metropolis and G. Reitwiesner, AEC Report No. NP-1980 (1950).