impart to electrons energies corresponding to 10^{10} volts in a time interval of the order of one second without great magnetic field intensities, and that the rate of acquiring energy may reasonably be expected to be greater than the rate of loss by collision. He appears to have considered that 10^9 ev might approximate the upper limit in the case of the sun.

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The Radioactivities of Some High Mass Isotopes of Cobalt

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By neutron bombardments of samples of Ni enriched in isotopes 61, 62, and 64, respectively, the following radioactivities have been identified:

Co^{61}, β^- 1.3 Mev, no γ, half-life 1.75 hours,
Co^{62}, β^- 2.3 Mev, γ1.3 Mev, half-life 13.9 min.

Evidence is also presented for a 1.6-minute β- and γ-activity associated with Co^{62}, and for a 4- to 5-minute activity possibly of Co^{64}.

I. INTRODUCTION

THE availability of isotopically enriched nickel samples in milligram amounts has made possible the study of radiations from cobalt nuclei in the region of a few mass units above the well-known Co^{60}.

The nickel samples employed in this investigation were prepared by the calutron process here at the Radiation Laboratory. Only the sample enriched in Ni^{64} has been isotopically analyzed. The relative abundances for this sample were found to be:

Ni^{64}	Ni^{62}	Ni^{61}	Ni^{60}	Ni^{58}
61.6%	2.8%	1.0%	13.6%	21.0%

This article presents data on activities assigned to Co^{61} and Co^{62}, and also on an activity which is tentatively assigned to Co^{64}.

II. RADIOACTIVITY OF COBALT 61

In a letter to the editor of the Physical Review[1] a 1.75 ± 0.05-hour half-life, β-activity was reported as a result of Co^{61}. Here we wish to present more complete evidence of this assignment, and data on the energy of the β-particle.

To help determine the isotope responsible for this activity, samples of nickel 61, 62, and 64 were placed one in front of the other, separated by paper, within a 0.035-in. cadmium shield in the neutron beam produced by 22-Mev deuteron bombardment of beryllium in the Crocker Laboratory 60-inch cyclotron. In all neutron bombardments of the nickel isotopes, the cadmium covering was used to minimize the $Ni^{64}(n,\gamma)Ni^{65}$ reaction yielding the 2.64-hour activity. The 1.75-hour activity appeared in each sample but much more strongly in connection with the Ni^{61} isotope than in the others.

Chemical identification was made as follows: A small sample of approximately 2-mg weight enriched in the isotope 61 was bombarded with neutrons as described above. The activated metal was dissolved in HNO_3, the nitrates were converted to chlorides, and 2 mg of cobalt and 2 mg of iron as chlorides were added. An iron fraction was separated by precipitation with NH_4OH and purified by solution in HCl and additional NH_4OH precipitations. The filtrate was acidified slightly with HCl, saturated with NH_4SCN, and cobalt was extracted with an

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[1] T. J. Parmley and B. J. Moyer, Phys. Rev. **72**, 82 (1947).

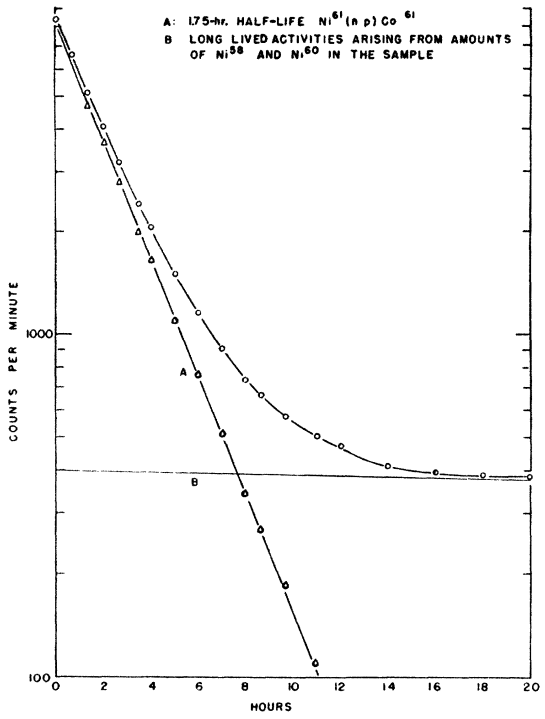

FIG. 1. Decay curve for neutron activated Ni^{61}.

equal volume of amyl alcohol-ethyl ether (1:1). Cobalt was recovered from the organic layer with $6N$ NH_4OH, and after separation of this ammoniacal fraction and acidification with HCl, the above extraction procedure was repeated. Cobalt was precipitated with NH_4HS and mounted for counting as dried CoS or as CoO. The nickel fraction contained in the aqueous layer from the first extraction was further purified by again saturating it with NH_4SCN and reextracting with amyl alcohol-ethyl ether (1:1). The solution was boiled to expel ether, made ammoniacal; and nickel was precipitated with a 1 percent solution of dimethyl-glyoxime in alcohol. The 1.75-hour activity appeared in the cobalt fraction.

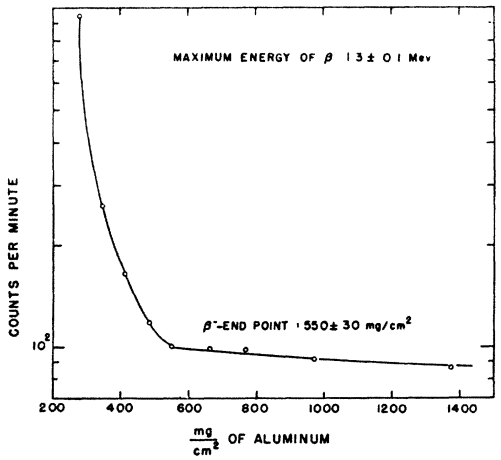

FIG. 2. Aluminum absorption curve for 1.75-hour half-life Co^{61}.

The mass assignment for this cobalt activity was made in the following way. A two-gram sample of isotopically normal nickel was given a 30-minute bombardment with approximately 22-Mev deuterons in the Crocker cyclotron. The activated metal was dissolved in HNO_3, the nitrates converted to chlorides, and 75 mg of copper and 50 mg of cobalt as chlorides were added. The copper was separated by reduction with SO_2 and precipitation with NH_4SCN. The filtrate was acidified with HCl and cobalt was precipitated with α-nitroso-β-naphthol in acetic acid. After being washed well with warm HCl (1:1) followed by H_2O, this precipitate was ignited to CoO. The CoO was converted to $CoCl_2$ by treating it with anhydrous Cl_2 at 650°C for 30 minutes. Calutron analysis of the $CoCl_2$ placed the 1.75-hour half-life in mass 61 position. We thus have both positive chemical and mass assignments for this activity.

As stated in reference 1, confirmatory evidence was obtained by neutron bombardment of electrolytic copper at the Crocker Laboratory 60-inch cyclotron, followed by calutron analysis, and by chemical analysis.

The chemical procedure was as follows: the copper metal, weighing 10 g, was dissolved in $6N$ HCl containing several milliliters of 30 percent H_2O_2. Excess H_2O_2 was boiled off, and 50 mg of cobalt as $CoCl_2$ were added. The copper was removed, and the cobalt separated and ignited to CoO as described in the previous chemical analysis.

The CoO was dissolved in HCl and 100 mg of copper and 25 mg of nickel as chlorides were added. Copper was removed a second time following the indicated procedure. A small part of the CoO was dissolved in HCl and mounted for counting on a platinum disk as CoO and the remainder was chlorinated as described above and used for the calutron analysis.

All beta-counting was done in the conven-

tional manner of placing the active sample at the proper distance from a thin mica window Geiger counter mounted within a thick-walled lead house. Corrections for coincidence count loss and for background were made in the usual way. Figure 1 displays a typical decay of the Co^{61} activity.

Measurement of the β-particle energy was done with Al absorbers. Figure 2 shows the curve of activity *vs.* absorber thickness, corrected of course for decay of the activity. The end point of the curve is taken to be 550 ± 30 mg/cm^2 of Al, yielding a maximum energy for the β-particles of 1.3 ± 0.1 Mev.

There was no indication of γ-radiation with this half-life.

In summary it may be stated that a 1.75-hour β-activity, with disintegration energy of 1.3 Mev, has been assigned through chemistry and mass analysis to Co^{61}. In all, this activity has been produced by each of the following reactions:

$Ni^{61}(n,p)Co^{61}$,
$Cu^{65}(n,\alpha n)Co^{61}$,
$Ni^{64}(p,\alpha)Co^{61}$(14-Mev protons),
$Ni^{64}(d,\alpha n)Co^{61}$ (22-Mev deuterons).

III. RADIOACTIVITY OF COBALT 62

Neutron bombardment of the nickel sample enriched in isotope 62 yielded activities with half-lives of 13.9 ± 0.2 min. and 1.6 ± 0.2 min. These activities did not appear in the neutron bombardment of Ni^{61} and only slightly in the sample enriched in Ni^{64}.

In isolating the 13.9-minute activity it would have been most desirable to have performed both mass and chemical analyses as in the case of Co^{61}. Because of the short half-life, the mass separation has not been successfully performed. Chemical identification was made by preparing counting samples of nickel and cobalt within a time of twelve minutes from the end of bombardment. The cobalt fraction was extracted by the process previously described, and the nickel was precipitated with NH_4HS in the aqueous layer after the cobalt extraction. It was mounted for counting as NiS.

This experiment was tried, using both nickel 62 and nickel 61 with the activity appearing in the cobalt fraction from the nickel 62, but not in

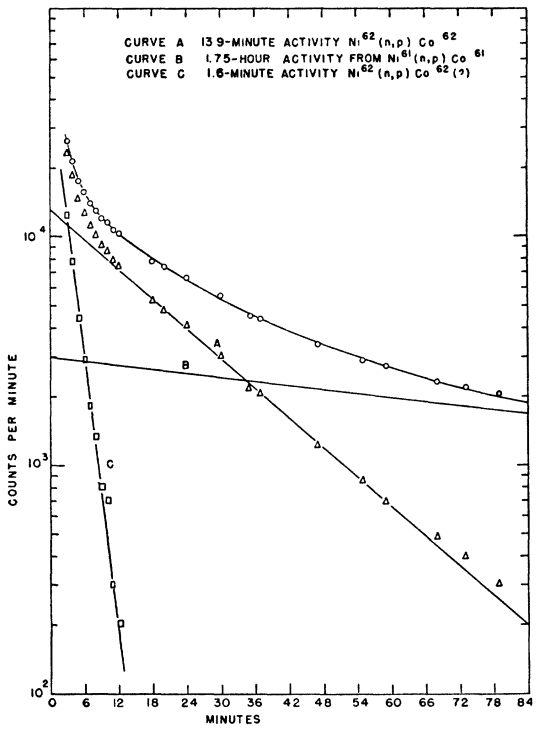

FIG. 3. Radioactive decay curve for 13.9-min. and 1.6-min. Co^{62}.

that from nickel 61. The activity did not appear in the residue in either case. The fact that nothing shorter than the 1.75-hour half-life appeared in the cobalt from nickel 61 is significant, since an (n,pn) reaction should yield cobalt 60 which has a 10.7-min. half-life activity. Inasmuch as this activity does not appear in the nickel 61 sample, it implies that the yield of (n,pn) reactions here is probably negligible. These facts make it apparent that the 13.9-minute decay is associated with an (n,p) reaction in Ni^{62} yielding radioactive Co^{62}. The decay curve in Fig. 3 shows the 13.9-minute and 1.6-minute lives in the Ni^{62} bombardment.

The 13.9-minute activity exhibits both β- and γ-radiation, the energies of which were measured by absorption in aluminum and lead in repeated runs with the Ni^{62} sample. The first 550 mg/cm^2 of aluminum eliminated the 1.75-hour β-particles, and the end point for β's with the 13.9-minute half-life came at 1100 ± 50 mg/cm^2. This denotes an energy of 2.3 ± 0.1 Mev.

Both β- and γ-absorption data are plotted in Fig. 4. The lead absorption half-value thickness

of 1.07 cm shows a gamma-quantum energy of 1.3 Mev. The system was checked by observing the absorption of Co^{60} gamma-rays whose energies are known to be 1.1 and 1.3 Mev.

In order to determine the decay pattern for this activity a β–γ-coincidence counting experiment was performed. We are indebted to Dr. Cornelius Tobias and Mr. Hal Anger of the Donner Laboratory for use of their calibrated counting equipment for this test. Figure 5 gives the decay of the β-, γ-, and coincidence counting rates. The known efficiencies of the β- and γ-counters, together with the three counting rates, allow the statement that there is one γ-ray with each β-particle.

Because of its short life, the 1.6-minute activity has not been positively identified, but the following evidence leads to its tentative assignment to Co^{62}.

(1) It arises from fast neutron bombardment of the sample enriched in Ni^{62}. It is not due to an (n,α) reaction, since this yields the known 47-day Fe^{59}.

(2) It is not Ni^{63}, for it does not arise from an (n,p) reaction on Cu^{63}, nor from a (d,α) reaction on Cu^{65} which was tried with 30-Mev deuterons at reduced radius on the 184-in. cyclotron. Also exposure of the Ni^{62} sample without Cd covering to slow neutrons by use of paraffin with neutrons from the 60-in. cyclotron did not augment the activity.

(3) It arises also from deuteron bombardment (30 Mev) of the sample enriched in Ni^{64}, presumably by the (d,α) reaction. It was not noted in bombardment of Ni^{64} with 14-Mev protons from the 37-in. frequency-modulated cyclotron though the Co^{61} 1.75-hour activity was produced by the (p,α) reaction.

Crude absorption experiments suggest the existence of γ-radiation since the activity has been observed through as much as 4 g/cm² of lead. Also the β–γ-coincidence data of Fig. 5 show both β- and γ-radiation with a short life of 1–2 minutes.

The best determination of the half-life of this activity was obtained from the $Ni^{64}(d,\alpha)Co^{62}$ bombardment. This is not displayed here, but leads to a value of 1.6 ± 0.2 minutes. Both the 13.9-minute and the 1.6-minute lives appear with good yield in this bombardment.

IV. RESULT OF NEUTRON BOMARDMENT OF Ni^{64}

A 4- to 5-minute half-life activity was observed in a neutron bombardment of nickel 64 which did not appear in similar bombardments

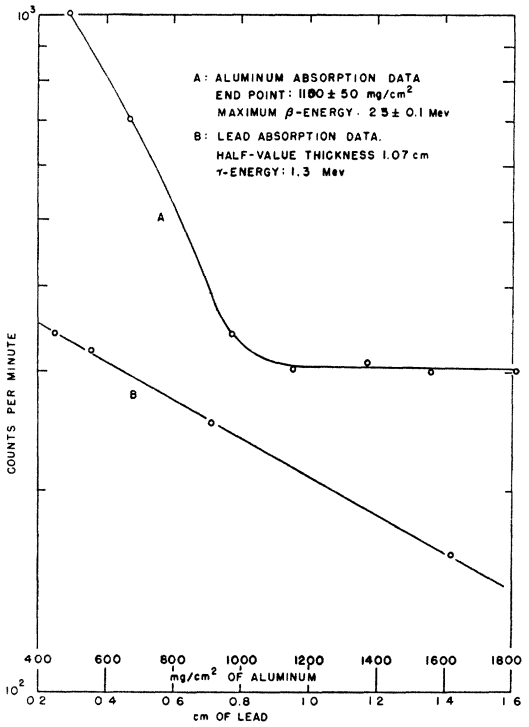

FIG. 4. Absorption data for 13.9-min. Co^{62} radiations.

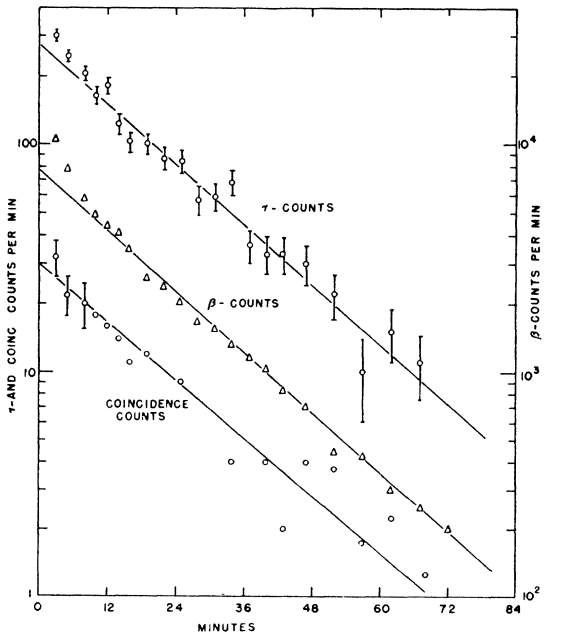

FIG. 5. Decay of β-, γ-, and coincidence counting rates for 13.9-minute Co^{62} (note evidence of the 1.6-minute decay in both β- and γ-radiation).

of nickel 61 or 62. Inasmuch as copper 66 exhibits an activity of 5 minutes, it was deemed advisable to free the nickel 64 isotope of any copper and zinc which might accidently be present. This chemical procedure was carefully done with the isotope appearing for bombardment as an oxide. In a subsequent neutron bombardment of the sample, the 4- to 5-minute activity persisted, suggesting that the activity is produced from a neutron bombardment of nickel 64. As an aid to the determination of this half-life, it was found useful to count the activity through sufficient absorber to eliminate the 1.75-hour half-life produced from the fraction of Ni^{61} existing in this sample. This left the 2.6-hour half-life as a good base line from which to proceed in the analysis of the decay curve. The activities remaining were the 13.9-minute Co^{62} from Ni^{62} in this sample, and the 4- to 5-minute period. The latter has been detected through as much as 1250 mg/cm^2 of aluminum.

Because of the shortness of the half-life involved and to the very small size of the sample of Ni^{64}, it has been difficult to establish certainly whether the source of the activity is in the cobalt or nickel group. Present chemical evidence points to cobalt with the suggestion that we are dealing with an n,p reaction on nickel 64 producing cobalt 64.

V. ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of Messrs. Duane Sewell and James Vale of the 184-in. cyclotron staff, and Thomas Putnam and B. Rossi of the Crocker Laboratory 60-in. cyclotron group. Mr. Putnam contributed the use of special counting equipment for the study of short half-lives in the measurements of the 1.6-minute activity.

The metallic samples of isotopic nickel were prepared by J. Beaufait by an electroplating and stripping process.

The calutron analyses were carried out under the direction of Dr. Keith Pierce.

This problem was carried out under the auspices of the Atomic Energy Commission.

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Quantitative Measurements with Scintillation Counters

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The efficiency of a number of fluorescent materials used as scintillation counters for various materials has been measured. Two characteristics have been distinguished: (a) The physical light yield, i.e., the fraction of the absorbed energy transformed into light, and (b) the practical light yield, i.e., the amount of light obtained from a given intensity of radiation of a particular type, with the thickness of the phosphor adjusted for optimum results. Although the sulfide phosphors are high in physical yield, their practical yield is relatively lower because they are quite opaque to their fluorescent radiations. The organic phosphors, such as naphthalene and phenanthrene, and the potassium bromide phosphors are very much better in this respect.

THE counting of radioactive radiations by means of scintillations detected by photomultiplier tubes has recently received much interest.[1] We have performed a series of experiments with various fluorescent materials to investigate the applicability of this method to the determination of the intensity and energy of various radiations.[2] We characterize various phosphors by two main characteristics: (a) The physical light yield which is the fraction of the absorbed radiation energy transformed into

[1] See, e.g., F. Marshall and J. W. Coltman, Phys. Rev. **72**, 528A (1947); R. J. Moon, Phys. Rev. **73**, 1210 (1948); P. R. Bell, Phys. Rev. **73**, 1405 (1948); G. B. Collins and R. C. Hoyt, Phys. Rev. **73**, 1259 (1948).

[2] See also I. Broser and H. Kallmann, Zeits. f. Naturf. **2a**, 439 (1947), Natur and Technik (July, 1947).