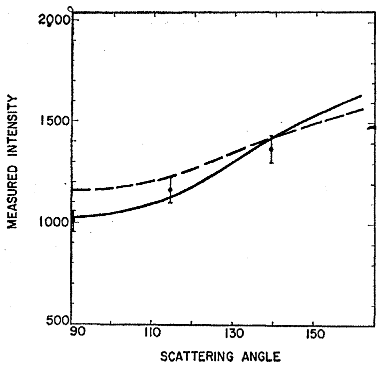

FIG. 6. The angular distribution for resonant scattering of 2.21-MeV radiation at $E_p=5.00$ MeV. The solid curve is the function $W(\theta)=1+0.37\ P_2(\cos\theta)$, the least-squares fit to the experimental points. This is indistinguishable from $W(\theta)=1+0.23\ P_2(\cos\theta)-0.053P_2{}^2(\cos\theta)$, which includes a polarization term. The broken curve is the distribution $W(\theta)=1+0.23P_2(\cos\theta)$ obtained at $E_p=4.115$ MeV by Metzger *et al.* (Ref. 8) and in the present work. The normalization of the two curves at 140° is arbitrary.

The reasons for the discrepancy at higher energy are not clear. One would prefer, of course, to work without the higher energy γ rays, but we are unable to discover how they could have this much effect. One suggestion that is plausible is that we are seeing an effect of partial linear polarization of the γ-ray source, as mentioned in Ref. 9, where it is also noted that a test for such polarization at 4.155 MeV gave a null result. The lower energy angular distribution allows two values of the mixing ratio, $\delta=+0.47$ or -0.083.[10] For a completely linearly polarized γ-ray source the angular distribution of the resonance scattering can be written[13] $W(\theta,\gamma)=1+0.23\times P_2(\cos\theta)+\cos2\gamma A_2P_2(\cos\theta)$, where γ is the angle between the plane of polarization and the scattering plane, and $A_2=-0.12$ or $+0.065$ for $\delta=0.47$ or -0.083. Figure 6 gives our 3 measured points for the angular distribution at $E_p=5.00$ MeV and the $1+0.37P_2$ fit. This fit is indistinguishable from $W(\theta)=1+0.23P_2(\cos\theta)-0.053P_2{}^2(\cos\theta)$, a possible result for a partially polarized source. Clearly our results can be explained this way, but much further investigation is required.

[13] L. W. Fagg and S. S. Hanna, Rev. Mod. Phys. **31**, 711 (1959); or S. Devons and L. J. B. Goldfarb, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, Sec. III, p. 434.

PHYSICAL REVIEW VOLUME 138, NUMBER 6B 21 JUNE 1965

New Isotope Ni^{67}†

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(Received 4 February 1965)

Irradiation of enriched Zn^{70} samples with 14–15-MeV neutrons was found to produce a new radioactive nuclide which was assigned to Ni^{67}. The following radiation characteristics have been observed to belong to the decay of Ni^{67}: half-life, 50 ± 3 sec; beta end-point energy, 4.1 ± 0.3 MeV; gamma-ray energies 0.90 ±0.04, 0.89 ± 0.04, and 1.26 ± 0.04 MeV, and relative intensities 100, 48 ± 6, and 44 ± 5, respectively. A partial decay scheme for Ni^{67} is proposed.

I. INTRODUCTION

THERE are a number of nuclides which have not yet been identified in the region of the 28-proton shell closure. The present study on Ni^{67} is part of a systematic investigation on the nuclides in this region, which can be produced by fast-neutron reactions using the University of Arkansas 400-kV Cockcroft-Walton accelerator. According to Yamada and Matumoto,[1] the β^--decay Q value for Ni^{67} is 4.0 MeV, and the half-life of this nuclide is probably 1 to 10 min.

No successful attempt has been made in the past to irradiate zinc with fast neutrons and to observe the Ni^{67} activity in the nickel fraction isolated from the target by a rapid chemical method. We have performed numerous experiments in which several gram samples of natural zinc oxide were irradiated and the nickel fractions isolated, purified, and counted within a matter of several minutes, but we have found no new nickel activity. These experiments indicated that the half-life of Ni^{67} is more likely to be about one minute. In the work reported here, the radiation characteristics of Ni^{67} are recorded without chemically isolating the nickel fraction from the irradiated enriched Zn^{70} oxide.

† Work supported by the U. S. Atomic Energy Commission Contract AT-(40-1)-3235.
[1] M. Yamada and Z. Matumoto, J. Phys. Soc. Japan **16**, 1497 (1961).

II. EXPERIMENTAL PROCEDURE

The Ni^{67} activity was produced by irradiating the oxide of enriched Zn^{70} weighing 20 mg with 14.8-MeV neutrons. The isotopic composition of the enriched zinc sample used was as follows: Zn^{70}, 78.3 ± 0.2;

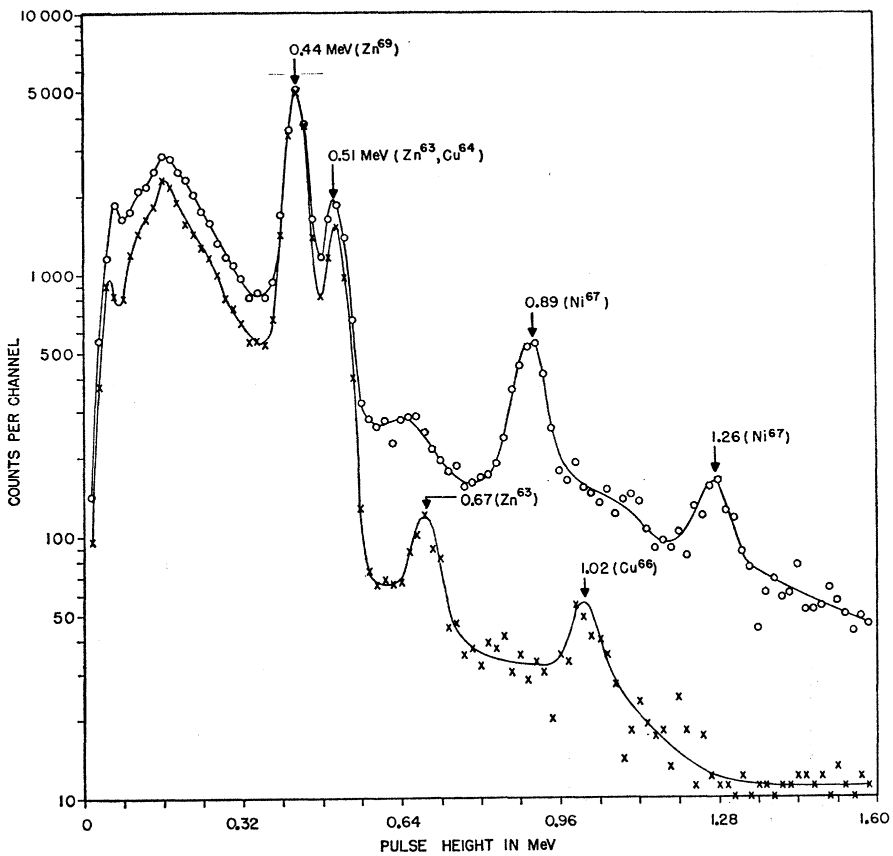

FIG. 1. Singles gamma-ray spectrum of Ni^{67}. The upper gamma-ray spectrum of Ni^{67} was taken 1 min after the end of a 2 min irradiation. The counting time was 4 min at a source-to-crystal distance of 0.8 cm. The lower gamma-ray spectrum was taken 9 min after the end of the irradiation at the identical geometry of the first spectrum. The counting time was 4 min.

Zn^{68}, 9.4±0.1; Zn^{67}, 0.7±0.05; Zn^{66}, 3.9±0.1; Zn^{64}, 7.7±0.1%.

The gamma spectrometry was carried out with 3-×3-in. NaI(Tl) crystals, which were used to obtain singles, ordinary coincidence, and sum-peak coincidence spectra.[2] For beta spectrometry, a $1\frac{1}{2}$-in.-diam by $\frac{13}{16}$-in.-high cylindrical plastic crystal was used. These crystals were also used to obtain gamma-beta and beta-gamma coincidence spectra.

A fast pneumatic transport system was available to bring samples to the detection room. For details of irradiation and detection techniques used, see Ref. 2.

III. GAMMA-RAY MEASUREMENTS

The gamma-ray spectra were obtained with the 3-×3-in. NaI(Tl) crystals shielded by a lead collimator. Figure 1 shows a typical spectrum in the energy range zero to 1.6 MeV. The upper curve is a plot of the spectrum which was obtained by starting the observation 1 min after exposure and counting for 4 min. Gamma rays of 0.44 MeV are due to Zn^{69}, which is the product of $(n,2n)$ reaction on Zn^{70}, and gamma rays of 0.51 MeV are due to Zn^{63}, from the $(n,2n)$ reaction on Zn^{64}.

[2] J. Kantele and R. W. Fink, Nucl. Instr. Methods **13**, 141 (1961); **15**, 69 (1962); **17**, 33 (1962).

The lower curve of Fig. 1 was obtained using the same sample and the same geometry, the count beginning 9 min after irradiation.

Gamma rays of 0.89- and 1.26-MeV decay with a half-life of somewhat less than one min.

IV. GAMMA-GAMMA COINCIDENCE MEASUREMENTS

In order to determine the relationship between the 0.89- and 1.26-MeV gamma rays and to search for others, gamma-gamma coincidence measurements were performed. Two 3-×3-in. NaI(Tl) crystals were used as detectors. One detector was calibrated so that it observes pulses corresponding to an energy of 890±50 keV, and the other was calibrated to observe the gamma spectrum in the energy range of zero to 2 MeV. The pulses formed in each detector go to a coincidence unit with a resolving time of one μsec. These experiments revealed the presence of gamma rays of 0.90±0.04 and 1.26±0.04 MeV.

A sum-coincidence spectrum was also taken, the results of which indicate two distinct peaks at 1.80±0.10 and 2.16±0.10 MeV. These peaks are the sums of 0.89- plus 0.90-MeV and 0.89- plus 1.26-MeV gamma rays, respectively.

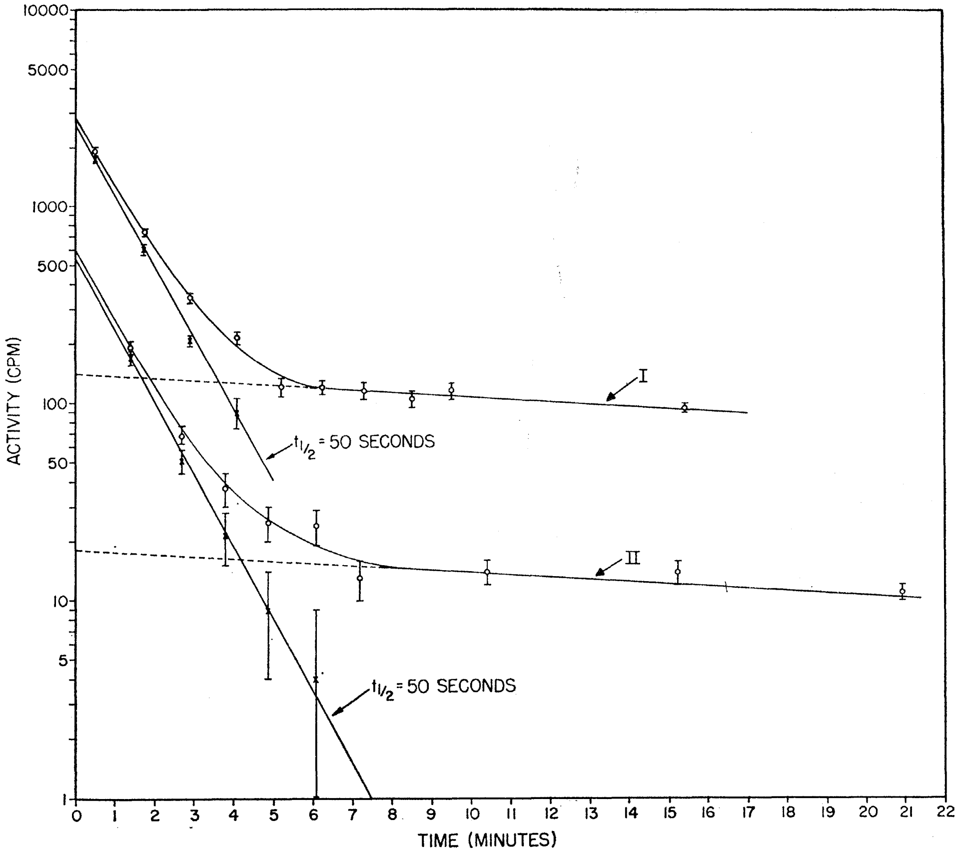

FIG. 2. Decay curves of Ni^{67} taken by gamma-gamma coincidence techniques and gross beta above 3 MeV. CPM = counts per minute. (I) is a decay curve of Ni^{67} taken by measuring the coincidence counting rate of the 890±50-keV gamma ray with gamma rays in the energy region 0 to 2 MeV. (II) is a decay curve of Ni^{67} taken by observing the counting rate of beta rays with an energy of 3 MeV or greater.

The relative intensities of the gamma rays of 0.90, 0.89, and 1.26 MeV were 100±10, 48±6, and 44±5, respectively.

V. THE BETA-RAY SPECTRUM

The maximum beta energy was found to be 4.1±0.3 MeV, and a beta spectrum taken in coincidence with the 0.89-MeV gamma ray revealed an end-point energy of 3.2±0.2 MeV. A beta spectrum was also taken in coincidence with the 1.26-MeV gamma rays, but only a rough estimate of about 2 MeV could be made for the beta end point, owing to the extremely low counting rate.

A gamma spectrum taken in coincidence with beta rays when the beta detector was biased at 2 MeV revealed a strong peak at 0.89±0.04 MeV and a less intense peak at 1.26±0.04 MeV.

The relative intensities of the beta rays of 4.1, 3.2, and 2 MeV were found to be 50, 20, and 30%, respectively.

VI. THE HALF-LIFE MEASUREMENTS

The half-life of the new activity was measured by observing (a) the decay of the 0.89- and 1.26-MeV gamma-ray peaks in the singles spectra, (b) the gross beta decay with the detector biased at 3 MeV, and (c) the gamma-beta and gamma-gamma coincidence counting rates. Figure 2 shows the experimental results. The average value obtained was 50±3 sec.

VII. MASS ASSIGNMENT

It appears to be highly unlikely that the new activity is attributable to the (n,p) reaction product Cu^{70}. According to Yamada and Matumoto,[1] the β^--decay Q value for Cu^{70} is 6.5 MeV, and a half-life of a few seconds is anticipated for the decay of this nuclide. The above investigators gave a value of 2.75 MeV for the β^--decay Q value for Cu^{69}, which is the (n,np) reaction product on Zn^{70}. This Q value most likely corresponds to a half-life of 5 to 50 min for Cu^{69}. The (n,np) reaction cross sections are, in general, much smaller than the (n,p) and (n,α) reaction cross sections. The possibility of observing the Cu^{69} activity under the experimental setups employed in this work, without observing a much stronger Ni^{67} activity, seems to be extremely remote.

Since it was difficult to show radiochemically that the new activity is attributable to Ni^{67}, we have performed the following experiment, in which a 4.19 mg, sample of $Zn^{70}O$ was irradiated with 14.8-MeV neutrons simultaneously with a 0.80 mg sample of natural ZnO for 30 min. The sample sizes were so chosen so that the weight of Zn^{67} was identical in both.

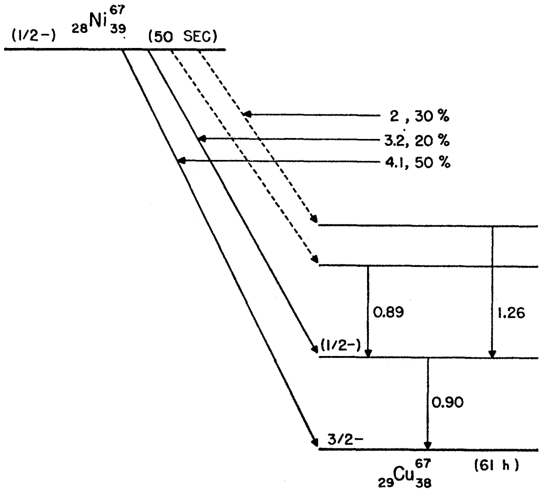

FIG. 3. Proposed partial decay scheme for Ni^{67}.

The gamma-ray spectra of the enriched zinc sample was followed for about 2 weeks. Strong gamma rays corresponding to energies of 440 and 511 keV were noted shortly after the irradiation. The 511 keV, due to Zn^{63}, disappeared in a matter of hours, leaving only the 440-keV gamma ray from 14-h Zn^{69m}. Since backscattering from the 440-keV gamma ray obscured any weak lines in the 180- and 90-keV region, several days were allowed for the enriched sample to "cool." After about 5 days the 440-keV gamma ray had completely disappeared revealing the presence of the 90- and 180-keV lines from Cu^{67}.

The gamma-ray spectra of natural zinc was followed, utilizing the exact conditions under which the enriched zinc sample was counted. Initially a strong line at 511 keV from Zn^{63} was present. After several days of "cooling" the natural zinc sample was counted again and revealed the presence of nothing except background.

The results of this experiment show clearly that the Cu^{67} activity is being produced via Zn$^{70}(n,\alpha)$Ni $\xrightarrow{\beta^-}$ Cu^{67} and not by Zn$^{67}(n,p)$Cu^{67}. Using the ratio of activities of Zn^{63} produced by the $(n,2n)$ reaction on Zn^{64} and Cu^{67} produced through the process Zn$^{70}(n,\alpha)$Ni^{67} $\xrightarrow{\beta^-}$ Cu^{67} $(=6.1\times10^{-3})$ and the cross-section value for the $(n,2n)$ reaction [$=167$ mb, according to Koehler and Alford[3]], the (n,α) cross-section value was calculated to be 11.4 ± 3.2 mb. The cross-section value thus obtained was somewhat higher than the value of 7.8 ± 2.2 mb obtained for the production of the 50-sec activity from the irradiation of the enriched zinc sample, but the experimental data accumulated so far seem to be sufficient to rule out the possiblity that the new activity is attributable to a nuclide other than Ni^{67}.

VIII. PROPOSED DECAY SCHEME

The radiation characteristics of the new activity found in this investigation seem to be consistent with the partial decay scheme such as shown in Fig. 3.

Since the 39th neutron falls into the $3p_{1/2}$ level, the ground-state spin of Ni^{67} is most likely $\frac{1}{2}-$, and the ground-state spin of Cu^{67} is $\frac{3}{2}-$.[4] A ground-state beta-transition energy of 4.0 MeV has been calculated by Yamada and Matumoto,[1] and this value is in excellent agreement with the experimentally obtained value of 4.1 ± 0.3 MeV. The ground-state to ground-state transition is allowed ($\Delta I=1$, no) and the $\log ft$ value is 5.4.

The first excited state in Cu^{67} is most likely $\frac{1}{2}-$,[4] and the transition to the first excited state is allowed ($\Delta I=0$, no) and the $\log ft$ value is calculated to be 5.0.

No definite spin and parity assignments can be given for the higher levels at the present time.

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[3] D. R. Koehler and W. L. Alford, Phys. Rev. **119**, 311 (1960).
[4] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1959), NRC 59-1-10.