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# $Ni^{58}(n,p)Co^{58}$ Cross Section for Neutrons of Energies between 2.2 and 3.6 Mev

L. GONZÁLEZ, J. RAPAPORT,* AND J. J. VAN LOEF
*Instituto de Física y Matemáticas, Universidad de Chile, Santiago, Chile*

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The relative cross section for $Ni^{58}(n,p)Co^{58}$ has been measured by an activation method for neutron energies of 2.2 to 3.6 Mev. The absolute cross section at 3.55-Mev neutron energy is found to be 195±30 mb by comparing the intensity of the 810-kev gamma ray of $Co^{58}$ with the amount of $Si^{31}$ formed in the $P^{31}(n,p)Si^{31}$ reaction, which has a previously known cross section of 96.2±9.0 mb. The cross section rises from 140 mb at 2.2 Mev to a maximum value of 214 mb at 3.0 Mev. Observed cross sections are compared with the predictions of the statistical theory of nuclear reactions by using a square well potential and a diffuse edge potential. In neither case could a satisfactory agreement with experimental data be obtained.

## INTRODUCTION

IN this paper we report on the cross section of the $Ni^{58}(n,p)Co^{58}$ reaction for neutrons of energies between 2.2 and 3.6 Mev. This work is part of a research project to investigate the $(n,p)$ cross sections of medium-weight isotopes at this range of neutron energies.[1] Besides nuclear theory, these cross sections are of interest for fast neutron detection, threshold detectors, and reactor design.

Previously, a reaction cross section of 30±3 mb has been measured by Robinson and Fink[2] for pile neutrons, but no other data are reported at neutron energies below 14 Mev. A few authors[3] determined the reaction cross section at 14-Mev incident neutron energy.

The reaction $Ni^{58}(n,p)Co^{58}$ has a positive $Q$ value of 0.39 Mev [4] and the product $Co^{58}$ decays with a half-life of 71.3 days.[5] The decay of the $Co^{58}$ ground state consists of 15% positron emission and 83% of $K$ capture to the 0.81-Mev first excited state of $Fe^{58}$. The remaining 2% electron capture leads to the 1.66-Mev second excited state which for 25% decays directly to the ground state.

We have measured the relative yield of the reaction $Ni^{58}(n,p)Co^{58}$ through the 810-kev gamma ray of $Fe^{58}$. The absolute cross sections are obtained by comparing the $Co^{58}$ activity with the amount of $Si^{31}$ formed in the $P^{31}(n,p)Si^{31}$ reaction which has a cross section of 96.2±9.0 mb at 3.56-Mev neutron energy.[6]

## EXPERIMENTAL PROCEDURE

The experimental equipment and procedure was the same as described by Rapaport and van Loef.[1] The excitation function was obtained by placing six nickel samples at various angles around the $d$-$D$ neutron source, and irradiating them simultaneously for twenty-four hours in order to get sufficient $Co^{58}$ activity in each sample. The neutron energy range from 2.2 to 3.6 Mev was covered in steps of about 200 kev by irradiations at 400- and 600-kev incident deuteron energy. The neutron yield during the irradiation, monitored by both a long counter and a Hornyak type scintillator, was kept constant within 5%.

The integrated neutron flux at each deuteron energy was obtained by the simultaneous irradiation of the nickel samples, and a red phosphorus sample of about 80 mg/cm² thickness placed on top of the Ni at the zero-degree position. After each period of eight hours, the irradiation was interrupted for a few minutes in order to replace the irradiated phosphorus sample by a new one. The 2.65-hour activity, $Si^{31}$, formed by the $P^{31}(n,p)Si^{31}$ reaction, was measured with a calibrated $2\pi$ proportional flow counter. The variation in absolute activity of the three phosphorus samples belonging to the same irradiation was 5% or less, in agreement with the monitor data.

The irradiated samples were disks of 99.9% pure nickel, 2.5 cm in diameter and 1 cm thick. They were held at 6.0 cm from the target in an arrangement similar to that described previously.[1]

The $Co^{58}$ activities were determined through the photopeak intensity of the 810-kev gamma ray in a

TABLE I. Cross sections for $Ni^{58}(n,p)Co^{58}$.

| Source reaction $D(d,n)He^3$ | $\theta_{\text{lab}}$ from neutron source | Relative angular distribution of source (measured) | Neutron energy (Mev)[a] | Initial counting rate (counts/min)[b] | $Ni^{58}(n,p)Co^{58}$ cross section (mb)[c] |
|---|---|---|---|---|---|
| $E_d=600$ kev | 0° | 1.00 | 3.55±0.10 | 1373 | 195±12 |
| | 30° | 0.72 | 3.40±0.13 | 1145 | 212±15 |
| | 60° | 0.41 | 3.04±0.20 | 690 | 214±15 |
| | 90° | 0.27 | 2.58±0.19 | 409 | 175±13 |
| | 120° | 0.28 | 2.22±0.16 | 296 | 142±10 |
| $E_d=400$ kev | 0° | 1.00 | 3.27±0.09 | 684 | 172±21 |
| | 30° | 0.71 | 3.15±0.12 | 555 | 188±23 |
| | 60° | 0.43 | 2.88±0.14 | 361 | 200±24 |
| | 90° | 0.29 | 2.53±0.14 | 228 | 178±21 |
| | 120° | 0.31 | 2.23±0.13 | 182 | 138±17 |

[a] The neutron energy spread at the sample due to target thickness and angular spread.
[b] Counting rate at the photopeak corrected for background. The time of counting was chosen such as to get a statistical error less than 2%.
[c] Standard deviations are relative. See text.

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* Now at Massachusetts Institute of Technology, Cambridge, Massachusetts.

[1] J. Rapaport and J. J. van Loef, Phys. Rev. **114**, 565 (1959).

[2] B. L. Robinson and R. W. Fink, Bull. Am. Phys. Soc. **1**, 40 (1956).

[3] D. L. Allan, Proc. Phys. Soc. (London) **A70**, 195 (1957); K. H. Purser and E. W. Titterton, Australian J. Phys. **12**, 103 (1959).

[4] *Nuclear Data Sheets* (National Academy of Sciences, National Research Council, Washington, D. C.)

[5] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

[6] J. A. Grundl, R. L. Henkel, and B. L. Perkins, Phys. Rev. **109**, 425 (1958).

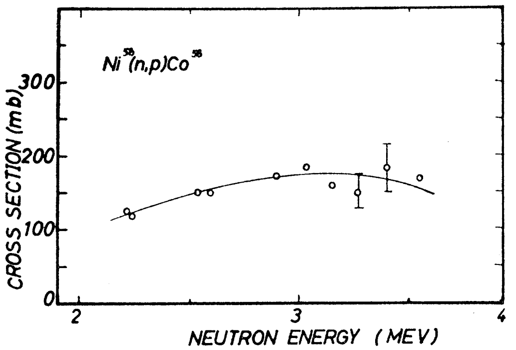

FIG. 1. Experimental cross sections of the $Ni^{58}(n,p)Co^{58}$ reaction in mb as function of neutron energy in Mev. Relative standard deviations are indicated.

calibrated 4.4 cm in diameter and 5-cm long NaI(Tl) scintillation spectrometer. A typical gamma-ray spectrum consists of photopeaks of the 0.51-Mev annihilation radiation and the 810-kev gamma ray, respectively, and a backscattering peak at about 200 kev.

## RESULTS

The results of the irradiations are given in Table I. The $Ni^{58}(n,p)Co^{58}$ absolute cross section of 1.95±30 mb at $E_n = 3.55$ Mev has been based on the absolute cross section for the $P^{31}(n,p)Si^{31}$ reaction at 3.56-Mev neutron energy measured at Los Alamos.[6] The normalization of the neutron flux in the forward direction at $E_d = 400$ kev with that at $E_d = 600$ kev was based on comparing the activities of the phosphorus samples, and interpolating the $P^{31}(n,p)Si^{31}$ reaction cross section from the data of Grundl *et al.*

In Table I the energy spread is indicated for each neutron energy; this spread arises from the target thickness and from the angular spread caused by the sample diameter. Also tabulated are the measured relative angular distributions used at each deuteron energy.

Corrections for gamma-ray attenuation, neutron self-absorption, and multiple scattering in the nickel sample have to be considered. The gamma-ray attenuation was experimentally determined by using thin sources of $Cs^{137}$ and $Zn^{65}$, respectively, each 2.5 cm in diameter, on top of the NaI(Tl) crystal with nickel absorbers of different thickness in between. The variation of the counting efficiency of the crystal with distance of the source was taken into consideration. Interpolation between the results obtained for the 0.67- and 1.12-Mev gamma rays gave us the attenuation of the 0.81-Mev gamma ray of $Co^{58}$. The neutron self-absorption was calculated based on the total neutron cross section for nickel. The correction factor, defined as the ratio of the observed yield to the true yield, was 0.47 for nickel of 10 mm thickness. The multiple scattering correction for this sample thickness was estimated to be less than 4% at 2-Mev incident neutron energy and less than 9% at 3.5 Mev.

Small corrections have been applied to all data for counter background and effects due to a slight displacement of the beam. No corrections were considered necessary for backscattering from the sample-holding ring, or for the effect of degraded neutrons from wall scattering.

Counting statistics (2% or better), uncertainties in the angular distributions, absolute flux determinations, and geometry have all been taken into account in assigning relative standard deviations to the $Ni^{58}(n,p)Co^{58}$ reaction cross section. The results are shown in Fig. 1 where the experimental cross sections with their relative standard deviations are given as function of neutron energy. The standard deviation in the absolute cross section includes the efficiencies of the counters, and the absolute error in the cross section of the $P^{31}(n,p)Si^{31}$ reaction at 3.56-Mev neutron energy.

No half-lives other than that of $Co^{58}$ were observed. The measured half-life is 68±3 days (probable error) which is in agreement with the value given by Seaborg *et al.*[5]

## DISCUSSION

In Fig. 2 the cross sections reported in this paper are shown together with those measured by Robinson and Fink[2] for pile neutrons with an average energy of 1 Mev, and by Allan, and by Purser and Titterton[3] at 14 Mev.

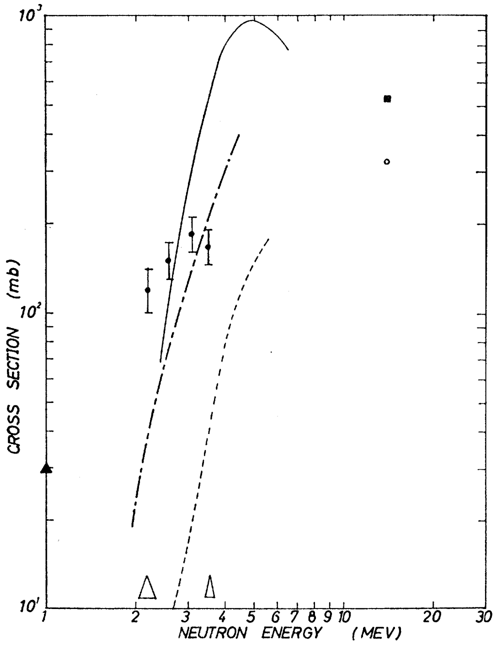

FIG. 2. Observed and calculated cross sections of the $Ni^{58}(n,p)Co^{58}$ reaction. Experimental data: ▲ Robinson and Fink, ● this work, ○ Allan, ■ Purser and Titterton. Excitation functions calculated with the following assumptions: ----- square-well potential with $r_0 = 1.50$ fermi (experimental level densities used), —·— diffuse-edge potential (experimental level densities used), ——— square-well potential with $r_0 = 1.50$ fermi, with the Weinberg and Blatt expression[9] applied for level densities.

Our reported $Ni^{58}(n,p)Co^{58}$ cross sections are consistent with a continuously varying excitation function.

Cross-section calculations were made at this laboratory by applying the statistical theory of nuclear reactions.[7] Two different types of nuclear potential were used and the resultant excitation functions are given in Fig. 2 by dotted curves. The upper of the two refers to a diffuse-edge potential with the parameters proposed by Woods and Saxon,[8] and the lower to a square-well potential with $r_0=1.50$ fermi. Experimental level densities were used, which were slightly different from those described in an earlier paper.[1] In spite of the fact that diffuseness of the nuclear potential enhances the cross section considerably, the predicted cross sections are far too small at neutron energies below 3 Mev. In an attempt to obtain a better fit between observed and calculated cross sections, the exponential level density formula based on a degenerate Fermi gas model was applied to $Co^{58}$ and $Ni^{58}$ in a form suggested by Weinberg and Blatt.[9] Energy corrections were used to take account of both the pairing energy of the even number of protons and neutrons, and the proton shell closure in $Ni^{58}$. Recently, Kaufman[10] has successfully applied the formula to calculate $(p,\alpha)$, $(p,2p)$, and $(p,pn)$ cross sections for $Ni^{58}$ near threshold. The correction terms indicated by Kaufman were used to calculate $Ni^{58}(n,p)Co^{58}$ cross sections for a square-well potential and $r_0=1.50$ fermi, the result of which is given by the full curve in Fig. 2. Although the agreement with the experimental points is somewhat better, the calculated excitation function has a very different slope. In conclusion it can be stated that no satisfactory explanation can be given for the observed cross sections.

## ACKNOWLEDGMENT

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[7] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

[8] R. D. Woods and D. S. Saxon, Phys. Rev. **95**, 577 (1954).

[9] I. G. Weinberg and J. M. Blatt, Am. J. Phys. **21**, 124 (1953).

[10] S. Kaufman, Phys. Rev. **117**, 1532 (1960).

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# Decay of $Si^{26}$†

E. L. Robinson and O. E. Johnson
*Physics Department, Purdue University, Lafayette, Indiana*

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A (2.1±0.3)-sec activity was observed when vacuum distilled magnesium was bombarded with 8-Mev $He^3$ ions. Half-life studies using NaI(Tl) scintillation counters yielded evidence that this activity was due to the decay of a positron emitting isotope with a maximum kinetic energy greater than 3.5 Mev. The features of gamma-ray spectrum with the exception of a weak line at 824±15 kev could be understood in terms the decay characteristics of known radioisotopes. An internally consistent argument based on the known decay characteristics of reaction products that may be expected from energy considerations, the results of half-life studies, experimental gamma spectra, and nuclear systematics can be made to support the conclusion that the (2.1±0.3)-sec half-life is that of $Si^{26}$ produced in the reaction $Mg^{24}(He^3,n)Si^{26}$, and a consistent decay scheme can be proposed. The ground state of $Si^{26}(0+)$ decays by the emission of two positron groups to excited states of $Al^{26}$. The most intense transition, $E_0=3.76$ Mev, is to the 0.228-Mev state (0+) of $Al^{26}$. The second transition, $E_0=2.94$ Mev, is to the 1.05-Mev state (1+) of $Al^{26}$. The 1.05-Mev and 0.228-Mev states are then connected by a (824±15)-kev gamma transition. The energies of the positron transitions are derived from the known levels of $Al^{26}$ and the $Si^{26}$-$Al^{26}$ mass difference.

## I. INTRODUCTION

TYREN and Tove[1] observed an activity with a half-life of 1.7 sec after bombarding aluminum targets with protons. Bombardments were made at proton energies of 23, 50, 80 or 100, 130, and 180 Mev. Twenty-three Mev was reported to be "the lowest energy at which the activity appears in appreciable amounts." The activity was attributed to the decay of $Si^{26}$ produced in the reaction $Al^{27}(p,2n)Si^{26}$. Recently the ground-state $Q$ value for the reaction $Mg^{24}(He^3,n)Si^{26}$ has been measured.[2] The mass excess of $Si^{26}$ is given as 0.47±0.09 Mev. Using this value, the calculated $Q$ value for the reaction $Al^{27}(p,2n)Si^{28}$ is $-18.9$ Mev. This indicates that the 23-Mev protons used were above the threshold energy. The published information concerning the decay of $Si^{26}$ gives little information concerning the radiation detected and the characteristics of the spectra. In addition, there have to date been no reports of experimental results either in agreement of disagreement with results and interpretation of Tyren and Tove. Two recent compilations of nuclear data[3,4] cite the observation but present no additional experimental information that has any direct

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[1] H. Tyren and P. A. Tove, Phys. Rev. **96**, 773 (1954).

[2] F. Ajzenberg-Selove and K. L. Dunning, Bull. Am. Phys. Soc. **5**, 36 (1960).

[3] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

[4] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).