Cross Section for the $Si^{28}(n,p)Al^{28}$ Reaction*

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By observing the radioactivity induced in glass samples bombarded by monoenergetic neutrons from the *d-d* reaction, the excitation function and the absolute cross section for the $Si^{28}(n,p)Al^{28}$ reaction have been measured for neutron energies from 4.4 to 8.0 Mev. In this energy region several resonances were found and the maximum cross section was measured to be 0.37 barn.

INTRODUCTION

THE measurement of the radioactivity induced in a sample by neutron bombardment may be used to determine the cross section for the nuclear reaction that leaves the active residual nucleus. This procedure has been used[1–4] in the investigation of neutron-induced reactions in the light- and medium-weight elements. If more than one reaction that produces radioactivity takes place, the activities must be separated in order to measure the individual cross sections. The (n,α) and (n,p) reactions in fluorine have been investigated in this manner.[4] The measurement of the induced activity as a function of neutron energy provides a convenient means of determining the excitation function for the reaction.

When silicon is bombarded by neutrons of several Mev, the following reactions may take place:

$$Si^{28}+n\rightarrow Al^{28}+p-3.87\text{ Mev}, \quad (1)$$

$$\rightarrow Mg^{25}+\alpha-2.60\text{ Mev}, \quad (2)$$

$$Si^{29}+n\rightarrow Al^{29}+p-3.0\text{ Mev}, \quad (3)$$

$$\rightarrow Mg^{26}+\alpha-0.04\text{ Mev}, \quad (4)$$

$$Si^{30}+n\rightarrow Mg^{27}+\alpha-4.22\text{ Mev}. \quad (5)$$

The $(n,2n)$ reactions are not energetically possible below 8.8 Mev [which is the threshold for the $Si^{29}(n,2n)$ reaction], and the cross sections for the (n,γ) reactions are quite small for neutrons in the Mev energy range. Since Si^{29} and Si^{30} are respectively only 4.70 and 3.09% abundant in natural silicon, the effects of reactions (3), (4), and (5) will be small in comparison with those of reactions (1) and (2). Reaction (1) leaves the radioactive nucleus Al^{28}, while reaction (2) leaves Mg^{25} which is stable. Therefore, radioactivity observed in the neutron bombardment of silicon will be predominantly from the $Si^{28}(n,p)Al^{28}$ reaction.

Early measurements[5] indicated the formation of Al^{28} in the bombarbment of silicon by neutrons from Ra-Be and similar sources. The $Si^{28}(n,p)Al^{28}$ cross section at a neutron energy of 14.5 Mev was found to be 220 ± 50 mb by Paul and Clarke.[6]

EXPERIMENTAL PROCEDURE

Silicon samples in the form of soft glass of dimensions 1 in.$\times$1 in.$\times\frac{1}{8}$ in. were used in the investigation of the excitation function for the $Si^{28}(n,p)Al^{28}$ reaction. These samples were bombarded by neutrons from the *d-d* reaction. The gas deuterium target that was used has been described previously.[4] The glass samples were placed at a distance of 2 inches from the center of the target chamber at which position the energy spread of the neutrons was approximately 100 kev.[4]

The samples were bombarded for 300 sec and then transferred to a counter some distance from the neutron source and shielded from it by about 6 feet of concrete. Allowing 30 sec for the transferring procedure, the activity was then counted for 250 sec while the next sample was being bombarded. In order to allow the 2.30-min Al^{28} activity to decay before the sample was used again, twelve pieces of glass, cut from the same piece of stock, were used. The detector was a plastic scintillator, 1.5 in. in diameter and $\frac{3}{16}$ in. thick, covered with a 0.0005 in. Al foil. A DuMont photomultiplier and the conventional electronics were used.

For the neutron energies used, no radioactivity could be produced in the oxygen content of the glass. Short-lived activities of 40 sec and 12 sec, arising from the (n,p) and (n,α) reactions in the sodium content of soft glass, although energetically possible, were not observed. The decay curve of the activity induced in the glass samples by 7.0-Mev neutrons is linear up to about 500 sec. The activity is predominantly that of Al^{28} with a 2.30-min half-life. It is possible that 6.6-min and 9.6-min activities arising from the reactions $Si^{29}(n,p)Al^{29}$ and $Si^{30}(n,\alpha)Mg^{27}$ may contribute to the deviation from linearity beginning near 500 sec.

Since the yield of neutrons from the gas target into the solid angle subtended by the samples was known,[4]

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[1] H. C. Martin, Phys. Rev. **93**, 498 (1954).
[2] R. L. Henkel, in *Neutron Cross Sections*, Atomic Energy Commission Report AECU-2040 (Technical Information Division, Department of Commerce, Washington, D. C., 1952), Supplement 3, April 1, 1954.
[3] R. Riacmo, Nuovo cimento **8**, 383 (1951).
[4] J. B. Marion and R. M. Brugger, Phys. Rev. **100**, 69 (1955).
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[6] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).

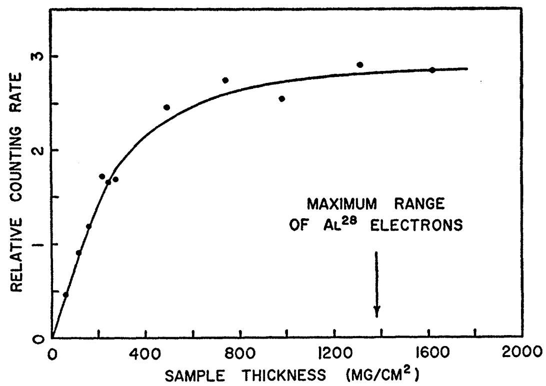

FIG. 1. Relative counting rate of the Al^{28} activity as a function of sample thickness.

and since the approximate composition of the glass was known,[7] the calculation of the absolute cross section required only a determination of the counting rate at a particular energy and a measure of the effects of self-absorption in the samples. The latter was accomplished by measuring the counting rates from samples of different thicknesses. The results of this determination are shown in Fig. 1. For sample thicknesses of less than 200 mg/cm^2, the counting rate is approximately a linear function of the thickness. Electrons of energy greater than about 0.58 Mev can penetrate this thickness.[8] For greater thicknesses, absorption is important, and the counting rate becomes approximately constant for thicknesses near the maximum range of the 2.87-Mev electrons. The point at 55 mg/cm^2 was used in the calculation of the absolute cross section. For this thickness, only about 15% of the decay electrons originating at the outer surface are absorbed and fail to reach the detector. The absorption in the thin Al foil covering the detector is about 2%.

The pulse-height distribution of the observed activity is shown in Fig. 2. An energy calibration made with the

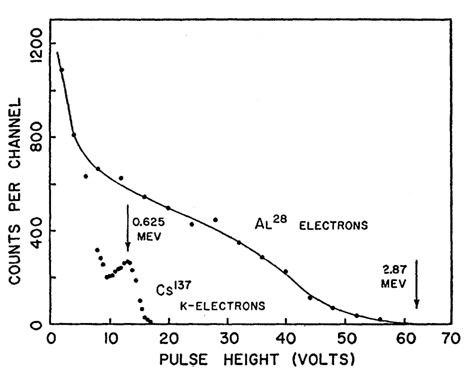

FIG. 2. Pulse-height distribution of the electrons from the Al^{28} decay in a glass sample.

[7] W. M. Latimer and J. H. Hildebrand, *Reference Book of Inorganic Chemistry* (The Macmillan Company, New York, 1946), p. 308.
[8] L. Katz and A. S. Penfold, Revs. Modern Phys. **24**, 28 (1952).

K-conversion electrons from Cs^{137} indicated that the electrons from the activity induced in the glass had a maximum energy of about 2.9 Mev, in good agreement with the measured value of 2.87 Mev for the Al^{28} decay electrons.[9] For the measurement of the absolute cross section, a bias setting of 2 volts was used, which allowed approximately 89% of the electrons reaching the detector to be counted. The excitation function was normalized to the absolute measurement which was carried out at a neutron energy of 7.0 Mev. Uncertainties in the absorption of electrons in the sample, the number of counts below the bias setting, the composition of the glass samples, and the neutron flux, limit the accuracy of the absolute cross section to about 50%.

RESULTS

The excitation function and the absolute cross section for the $Si^{28}(n,p)Al^{28}$ reaction, obtained by the above methods, are shown in Fig. 3 for neutron energies from 4.4 to 8.0 Mev. The resonance energies, peak cross sec-

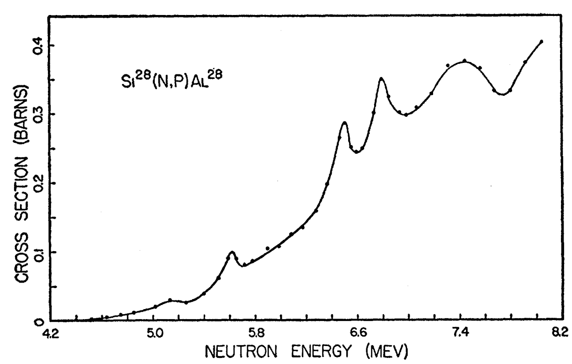

FIG. 3. Excitation function and absolute cross section for the $Si^{28}(n,p)Al^{28}$ reaction.

tions, and estimated widths of the maxima that were observed are summarized in Table I. The resonances at 5.62, 6.51, and 6.81 Mev all have widths of approximately 0.1 Mev, which was the energy resolution of the neutron beam. Therefore, it is possible that the corresponding states in Si^{29} are actually narrow and that the peak cross sections are very large. The peak at 7.45 Mev, however, may have a real width of about 0.3 Mev, unless it is a superposition of several narrow resonances.

The maximum value of the measured cross section in the energy interval studied is 0.37 barn at the peak of the 7.45-Mev resonance. In general, the cross section is about the same as observed for other reactions of similar type.[1–4]

DISCUSSION

The *Q*-value for the $Si^{28}(n,p)Al^{28}$ reaction is -3.87 Mev, and the reaction is not energetically possible for neutron energies below 4.0 Mev. The cross section is quite small immediately above threshold due to the

[9] H. T. Motz and D. E. Alburger, Phys. Rev. **86**, 165 (1952).

Coulomb barrier, and no Al^{28} activity was observed until a neutron energy of 4.5 Mev was reached. Below this energy, the cross section is $\lesssim 2$ mb, the lower limit which could be detected by the method used.

The neutron total cross section of silicon has been measured from 3 to 12 Mev with a resolution of about 10% by Nereson and Darden,[10] who find two broad resonances at 4.8 and 6.0 Mev. Above these energies the value of the cross section is approximately constant at 1.7 barns. The $Si^{28}(n,p)Al^{28}$ cross section does not indicate resonances at either 4.8 or 6.0 Mev, but the low value of the (n,p) cross section near 4.8 Mev and the general rise due to penetrability would tend to obscure the effects of broad resonances in these regions. It is not difficult to understand why the total cross-section data failed to show the 0.1-Mev wide resonances, since the resolution was approximately 0.6 Mev in this energy region. Even the peak at 7.45 Mev would have been averaged over, despite its 0.3-Mev width.

[10] N. Nereson and S. Darden, Phys. Rev. **89**, 775 (1952).

TABLE I. Resonances in the $Si^{28}(n,p)Al^{28}$ reaction.

Neutron energy (Mev)	Peak cross section (barns) (±50%)	Γ (Mev)
5.14 (?)	(0.03)	
5.62±0.05	≥0.09	≲0.1
6.51±0.05	≥0.28	≲0.1
6.81±0.05	≥0.35	≲0.1
7.45±0.10	0.37	≈0.3

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Range and Range Dispersion of Specific Fission Fragments

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The range and dispersion in range of specific U^{233} and U^{235} fission fragments; namely, those associated with delayed-neutron emitters, have been determined in gases of different atomic number. These measurements give the Z-dependence of the range and range dispersion for fragments associated with a specific mode of fission. After corrections for foil thickness and geometry the Z-dependent part of the range dispersion which arises from the nuclear stopping process was determined and values were obtained for the residual component corresponding to the energy dispersion associated with the fission process itself. The values thus obtained for this energy dispersion are found to be in fair accord with recent theoretical results of Fong.

INTRODUCTION

MEASUREMENTS have been made of the range and dispersion in range of specific fission fragments in various stopping gases. From the range dispersion it has been possible to obtain information on the dispersion in the energy release accompanying fission and these results can now be compared with some recent theoretical work of Fong.[1] Experimentally, the dispersion in energy accompanying a given mode of fission has been given in the literature only indirectly. The fission-product energy spectra measurements of Brunton and Hannah,[2] Demmers,[3] and Leachman,[4,5] and others involve the gross fission process. The dispersion in energy observed in these experiments is therefore partly associated with the variation in energy release accompanying different modes of fission. Another class of experiments employs the measurements of range. Katcoff[6] has measured the dispersion in range corresponding to what might well be ranges of fragments of a unique mode of fission. These measurements, however, were made in air only and complete reliance must be placed upon the theory of the stopping of fission fragments to derive from the dispersion in range the dispersion in the energy of the given fragment. Boggild[7] has measured the fission fragment ranges and the dispersion in the range in gases of different atomic weights but the measurements were made upon gross fission fragments. It seems thus not untimely to present now some measurements made in 1948 which have a somewhat more direct bearing than the experiments just mentioned upon the question of the dispersion in the energy of a given fragment associated with a single mode of fission. For various reasons these results have not previously been presented in detail; some results have, however, appeared in abstract.[8]

The experiment here described consisted of measuring

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[2] D. C. Brunton and G. C. Hannah, Can. J. Research **A28**, 190 (1950).
[3] P. Demers, Can. J. Phys. **31**, 78 (1953).
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[5] R. B. Leachman and H. W. Schmitt, Phys. Rev. **96**, 1366 (1954).
[6] Katcoff, Miskel, and Stanley, Phys. Rev. **74**, 631 (1948).
[7] Boggild, Arroe, and Sigurgeirsson, Phys. Rev. **71**, 281 (1947).
[8] Good, Wollan, and Strauser, Phys. Rev. **74**, 1225 (1948); Good, Campbell, and Strauser, Phys. Rev. **75**, 1292 (1949).