PHYSICAL REVIEW VOLUME 73, NUMBER 2 JANUARY 15, 1948

A Determination of the $S^{32}(n,p)P^{32}$ Cross Section for Neutrons Having Energies of 1.6 to 5.8 Mev*

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(Received October 6, 1947)

Sulfur was irradiated with known fluxes of monoenergetic neutrons having energies of 1.6 to 5.8 Mev. The formation of P^{32} by the $S^{32}(n,p)P^{32}$ reaction was detected by means of the P^{32} beta-activity. The cross section for the reaction at the lower neutron energies has the same form as the penetrability of the protons from the reaction through the Coulomb barrier. At the higher energies the cross section for the reaction reaches an approximately constant value of 0.3×10^{-24} cm².

1. INTRODUCTION

THE production of radioactive phosphorus by the bombardment of fast neutrons on sulfur was reported by Fermi and his collaborators in 1934.[1] They reported a moderately strong activity having a half-life of about 13 days which was produced by neutrons from a radon-beryllium source.

Since that time a number of other workers have studied the production of P^{32} by other means[2] and also have measured the half-life and beta-spectrum with considerable accuracy. These studies indicate that the half-life is 14.295 days,[3] that the beta-spectrum has an upper limit of about 1.72 Mev,[4] and that there is no appreciable number of γ-rays accompanying the beta-decay.[5]

It should be pointed out that there are at least two reactions which occur on bombardment by neutrons of energies considered here. These are

$$(1)\qquad {}_{16}S^{32}+{}_{0}n^{1}\rightarrow {}_{15}P^{32}+{}_{1}H^{1}+Q_1;$$
$$ {}_{15}P^{32}\rightarrow {}_{16}S^{32}+\beta^{-}+1.72\text{ Mev}$$
$$(2)\qquad {}_{16}S^{32}+{}_{0}n^{1}\rightarrow {}_{14}Si^{29}+{}_{2}He^{4}+Q_2.$$

These reactions were studied by Huber,[6] using 2.76-Mev neutrons incident upon an ionization chamber filled with SO_2. From the heights of the pulses in the chamber he deduced values of $Q_1=-0.93\pm 0.1$ Mev and $Q_2=1.2\pm 0.1$ Mev.

The end-point energy of the β-spectrum (1.72 Mev) leads to a value of $Q_1=-0.97$ Mev or a threshold energy for the neutrons of 1.00 Mev.

The present work is concerned with the determination of the yield of reaction (1) when sulfur is bombarded by known fluxes of monoenergetic neutrons having energies of 1.6 to 5.8 Mev.

2. EXPERIMENTAL METHOD

A. General Arrangement

Although different sources of neutrons were used in the present work, the arrangement of the sulfur samples and neutron monitor with respect to the sources remained about the same and is shown in Fig. 1.

The sublimed elemental sulfur was melted and cast into disks 2-in. in diameter and $\frac{1}{4}$-in. thick. Two such disks (S), enclosed in spun cadmium covers, were placed on the two electrodes of an ionization chamber, as shown in the figure. A metal foil containing a thin deposit of uranium, also 2 in. in diameter, was placed inside the ionization chamber on the high voltage electrode.

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* This document is based on work performed at Los Alamos Scientific Laboratory of the University of California under Government Contract No. W-7405-eng-36, and the information contained therein will appear in Division V of the National Nuclear Energy Series (Manhattan Project Technical Section) as part of the contribution of the Los Alamos Laboratory.

** Now at the University of Illinois.

[1] E. Fermi, E. Amaldi, O. D'Agostino, F. Rasetti, and E. Segrè, Proc. Roy. Soc. **A146**, 483 (1934); E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti, and E. Segrè, Proc. Roy. Soc. **A149**, 522 (1935).

[2] H. W. Newson, Phys. Rev. **51**, 624 (1937); H. Fahlenbrach, Zeits. f. Physik **96**, 503 (1935).

[3] N. B. Cacciapuoti, Nuovo Cimento **15**, 213 (1938).

[4] E. M. Lyman, Phys. Rev. **51**, 1 (1937); J. L. Lawson, Phys. Rev. **56**, 131 (1939); C. M. Witcher, Phys. Rev. **60**, 32 (1941); Kai Siegbahn, Phys. Rev. **70**, 127 (1946).

[5] F. N. D. Kurie, J. R. Richardson, and H. C. Paxton, Phys. Rev. **49**, 368 (1936); H. W. Newson, see reference 2.

[6] P. Huber, Helv. Phys. Acta **14**, 163 (1941).

The ionization chamber was connected to an amplifier and recorder system which served to measure the total number of fissions which occurred in the uranium foil during a given irradiation period. This number of fissions occurring in the uranium foil of known mass was then used to determine the flux of neutrons which passed through the ionization chamber.

B. Neutron Sources

Neutrons of 1.63- and 1.83-Mev energy were obtained from the $Li^7(p,n)Be^7$ reaction using protons accelerated by the Wisconsin electrostatic generator.[7] The protons were incident upon a thin film of lithium metal evaporated on a tantalum backing plate. The spread in energy of the neutrons was due primarily to the thickness of the lithium target, which was sufficient to reduce the energy of the protons by about 0.100 Mev. The uncertainty in the neutron energy was therefore estimated as ±0.050 Mev.

The points at 2.5 and 2.9 Mev were obtained with neutrons from the $d-d$ reaction, using deuterons accelerated by the Illinois Cockcroft-Walton set.[8] The deuterons were incident upon a thick heavy-ice target with an energy of 200 kev. The point at 2.5 Mev was obtained with the samples at right angles to the direction of the deuteron beam, while the point at 2.9 Mev was obtained in the forward direction. The effective spread in energy for these points was estimated to be approximately ±0.3 Mev.

The neutrons of 3.4, 4.3, 4.6, and 5.8 Mev energy were obtained from the $d-d$ reaction using the Wisconsin machine for accelerating the deuterons. The deuterons in this case were made to pass through a thin nickel foil into a gas cell containing deuterium. The spread in energy caused by target thickness and other causes was estimated to be approximately ±0.15 Mev.

C. Relative Cross Sections

After irradiation, the sulfur was remelted and cast into cylinders 4.5 in. long with a wall thickness of 2.5 mm and an inner diameter of $\frac{7}{8}$ in. These cylinders, protected by being cast inside of brass sleeves, fitted snugly around a thin-walled aluminum Geiger counter which had a length of 7 in. and a uniform wall thickness of 0.007 in. The counting rate caused by a small beta-active sample moved along the length of the counter was independent of the position of the sample for the 4.5-in. length covered by the sulfur cylinders.

The irradiated sulfur samples were counted in this geometry, and the initial activity of the sulfur in counts/min./g was determined from the observed counting rates and the known time after the neutron irradiation. These initial activities, divided by the known flux of neutrons through the various samples, are proportional to the cross section of the $S^{32}(n,p)P^{32}$ reaction. The initial activities, after subtraction of natural background counts, are listed in Table I.

Since the measurements extended over a period of several months, the sensitivity of the Geiger counter was checked frequently by means of a short cylinder of uranium glass which fitted snugly over the counter in a standard position. The counting rate attributable to the uranium glass was found to remain constant to within 1 percent during these measurements, although the threshold voltage rose slightly and the length of the plateau decreased as the counter aged.

The initial activity of the sample irradiated with 4.3-Mev neutrons was quite high, and it was followed for about 30 days. The activity was found to decay with a half-life of 14.35±0.05 days, which is to be compared with the value of 14.295 days obtained by Cacciapuoti.[9]

D. Efficiency of Counting

In order to obtain an absolute value for the magnitude of the $S^{32}(n,p)P^{32}$ cross section, it is

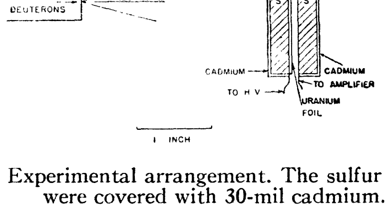

FIG. 1. Experimental arrangement. The sulfur disks, S, were covered with 30-mil cadmium.

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[7] R. G. Herb, C. M. Turner, C. M. Hudson, and R. E. Warren, Phys. Rev. **58**, 579 (1940).

[8] L. J. Haworth, J. H. Manley, and E. A. Luebke, Rev. Sci. Inst. **12**, 591 (1941).

[9] N. B. Cacciapuoti, see reference 3.

Table I. Summary of results of measurement.

Source	Bombarding energy in Mev	E_n average neutron energy in Mev	ΔE_n in Mev	Approx. time of bombardment in hours	ϕ neutrons/ cm$^2\times10^9$	C counts/* minute/ gram of sulfur	$\sigma_{n,p}$ $\times10^{-25}$ cm^2
Li(p,n)	3.36	1.63	±0.05	9	32.2	1.56	0.0131
	3.56 (0°)	1.83	±0.05	7	8.48	1.61	0.0509
$d-d$	0.2 0.2 (90°)	2.5	±0.3	8	4.42	12.9	0.784
	0.2 (0°)	2.9	±0.3	8	9.42	54.4	1.55
$d-d$	1.24	3.4	±0.07	2	0.732	5.56	2.04
	1.86	4.3	±0.11	8.1	9.66	125.0	3.49
	2.13	4.6	±0.15	2	2.16	23.1	2.88
	3.09 (0°)	5.8	±0.17	2	2.42	27.0	3.00

* Average thick sample contained 44±2 grams of sulfur. Average background count on counter about 65 counts/minute.

necessary to know the efficiency of counting the beta-rays from the P^{32} in the counting geometry used. This counting efficiency was determined in the following way. A small cylindrical sample of finely powdered sulfur was given an intense neutron irradiation by placing it in the center of the small reactor (waterboiler) at Los Alamos for a fraction of a minute. The sample was then thoroughly mixed and part of it was weighed accurately and mixed with a known amount of unirradiated sulfur. This mixture was then melted and cast into a cylindrical sample of the same dimensions as those used in the previous work.

Another part of the sulfur irradiated in the small reactor was made up into a thin sample by dusting a small amount of the powder on a cylinder made of a single layer of Scotch Tape with its sticky side out. Another layer of Scotch Tape was put over the cylinder and served to protect the sulfur. The sample was about 2 in. long, and it fitted snugly around the counter tube. The Scotch Tape used had a mass of about 9 mg/cm^2. The weight of sulfur in the sample was obtained by weighing the cylinder of Scotch Tape before and after the sulfur had been deposited. Blank checks with similar Scotch Tape cylinders showed that the Scotch Tape lost a small amount of weight because of drying, but this effect amounted to only 1 percent of the weight of the sulfur and was easily taken into account.

The ratio of the counting rates/g of activated sulfur was determined for a number of sets of thin and thick diluted samples. The average of these results gave a value of 0.214±0.03 for the ratio of the counting rate/g of a thick sample to that of a thin one. To make certain that the activity induced in the sulfur by the fission neutrons from the small reactor was the same as that produced by the other neutron sources, the activity of one of the samples was followed for a period of two weeks and was found to have the correct half-life.

In order to obtain the efficiency for counting the thin irradiated sulfur samples in the geometry used, an attempt was made to estimate the total number of beta-particles emitted by a very active thin sample of P^{32}. This sample was deposited on a 1-mil aluminum foil in an area about 2 mm in diameter. It was then counted by placing it at a distance of 2 cm from a circular aperture 1 cm in diameter in a 0.16-cm lead sheet, obtaining the counting rate in a cylindrical Geiger counter with aluminum walls having a thickness of 4.5 mil (31 mg/cm^2).

This counting rate, after subtracting the appropriate background and correcting for the absorption in the counter wall (20 percent), was used as the total number of beta-particles emitted in the solid angle defined by the lead aperture. The same sample was then counted through the same amount of absorber and in the same geometry used for the thin irradiated sulfur samples. The net counting rate in this case, divided by the total number of beta-particles emitted by the sample as determined by the previous experiment, gave a value of 0.29 for the efficiency of counting the thin irradiated sulfur sample through 57 mg/cm² of absorber. This value for the efficiency is about 15 percent lower than that obtained simply by correcting for the exponential absorption obtained through various thicknesses of absorber in the same geometry and assuming that the counting rate extrapolated to zero absorber thickness corresponds to $\frac{1}{2}$ of all the beta-particles emitted.

By the use of the value of 0.29 for the efficiency of counting the thin sulfur samples, the efficiency of counting the thick samples is 0.214×0.29 or 0.062 count/disintegration. The uncertainty in this efficiency is difficult to estimate, but it may be of the order of 15 percent and is therefore the largest source of error in the determination of the absolute values obtained for the cross section of the (n,p) reaction in sulfur.

RESULTS

The data previously discussed are shown in Table I. The cross section for the reaction can be expressed by the following relation:

$$\sigma(n,\,p)=C/EN_s\lambda\phi=2.69\times 10^{-17}\;C/\phi,$$

where C is the initial counting rate of the thick sample in counts/min./g; ϕ is the number of neutrons/cm² which passed through the sulfur during the irradiation period; E is the efficiency of counting (0.062); N_s is the number of S^{32} atoms/g of sulfur (1.79×10^{22}); λ is the fraction of the P^{32} atoms decaying/min. (3.35×10^{-5}).

The values of the cross section are shown in Fig. 2. Although these values do not lie nicely on a smooth curve, it appears that the cross section at the higher energies remains at a fairly constant value of 0.3×10^{-24} cm².

3. DISCUSSION

It might be expected that the (n,p) cross section for S^{32} would show resonance effects as a function of neutron energy. Such resonances have been observed in the capture of fast neutrons by N^{14}.[10] However, an examination of the excitation function (Fig. 2) indicates that the curve is smooth within the limits of resolution obtained in this experiment; and it would appear that the penetration of the Coulomb barrier by the emitted proton is the predominant factor determining the cross section.

In order to obtain an estimate of the cross section expected for the reaction, it might be assumed that the cross section for the formation of the intermediate S^{33} nucleus can be represented by

$$\sigma_n{}^I=S\pi\lambda^2\xi,$$

where S is a statistical factor of the order of $2l_n+1$, l_n being the effective angular momenta of the incoming neutrons giving rise to the intermediate nucleus; λ is the wave-length of the neutron divided by 2π; ξ is the sticking probability, which in this case includes the penetrability (P_n) of the incoming neutrons, and which will be considered to be constant.

If the intermediate nucleus can disintegrate either by proton or neutron emission, the fraction of the intermediate nuclei which disintegrate by proton emission is given by P_p/P_n+P_p, where P_p is the penetrability of the Coulomb barrier for

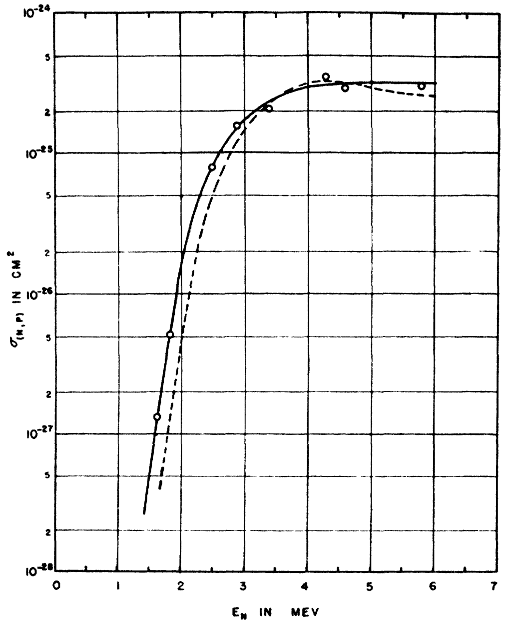

FIG. 2. Solid curve: observed cross section for the $S^{32}(n,p)P^{32}$ reaction as a function of the energy of the incident neutrons. Broken curve: cross section for the $S^{32}(n,p)P^{32}$ reaction calculated from Eq. (1).

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[10] H. H. Barschall and M. E. Battat, Phys. Rev. 70, 245 (1946).

the emitted protons.[11] P_n is the effective penetrability of the angular-momentum barrier for the emitted neutrons.

In the present discussion it is assumed that there is no distinction between the emission of a neutron or a proton except for the influence of the Coulomb barrier. P_n will be taken as unity, since it is not known which of the various angular momenta may contribute to the reaction. This approximation has very little effect on the shape of the cross-section curve, since P_n for $l_n \leq 2$ varies only slightly as compared to P_p in the energy range considered here. The expression for the (n,p) cross section then becomes

$$\sigma(n,p) = S\pi\lambda\!\!\!^{-2}\xi\cdot\frac{P_p}{1+P_p}. \tag{1}$$

The curve calculated on this basis is shown as the broken line of Fig. 2. It can be seen that the calculated curve represents the observed data quite well except for a shift of the curve toward higher energy by about 0.2 Mev. One could obtain better agreement between the observed and calculated curves by using a larger value for the nuclear radius or by increasing the energy available to the emitted proton by about 0.2 Mev, since both of these quantities enter directly into the calculation of P_p. It is difficult to explain so large a shift at the lower energies by the uncertainty in the nuclear radius, since a 10 percent change in the radius corresponds to a shift of only 0.05 Mev at these lower energies (i.e., $E_n \sim 1.5$ Mev, $E_p \sim 0.5$ Mev). It is just possible, however, that a shift of 0.2 Mev might be accounted for by errors in the absolute values of the proton accelerator voltage,[12] the effective target thickness, and the value of Q_1.

It might be of interest to examine the value of $S\xi$ needed to obtain numerical agreement with the cross section found experimentally. If we use the observed value of 0.3×10^{-24} cm^2 at 5 Mev, we find that $S\xi$ must be assigned a value of 4.6 which might seem to indicate that $S \geq 5$. On the simplified assumption that $S = 2ln+1$, this value would indicate that neutrons of angular momentum $l_n = 2$ would be necessary to explain this large cross section.

Although the above description gives a fairly good agreement with the data, it is not the only possible interpretation. Since the shape of the curve is primarily determined by the proton penetration factor, any other description giving the correct magnitude of the cross section at the high energy points would be equally permissible. Another simple method of getting a cross section of 0.3×10^{-24} cm^2 at the high energy points is to assume that the cross section for the formation of the compound S^{33} nucleus is just the geometrical cross section (πR^2) of the sulfur nucleus, which may be taken as 10^{-24} cm^2, and to assume that this intermediate nucleus may disintegrate by the emission of a neutron, a proton, or an alpha-particle with equal probability, since each of these particles has a penetrability close to unity at the higher energies. Previous measurements of the effective cross section for the (n,α) reaction seem to indicate a very high cross section for this process (0.065×10^{-24} cm^2 for 2.76-Mev neutrons).[13]

An unambiguous interpretation of these reactions must, therefore, await further studies giving more information about the relative yields and possibly the angular distributions of the particles emitted.

We wish to express our appreciation to Professors E. J. Konopinski and S. M. Dancoff for valuable discussions on the interpretation of these results.

The neutron irradiations and the preliminary determination of the cross section were made at Los Alamos. The work on the redetermination of the efficiency of counting the thin P^{32} samples, using the method described above, was done at the University of Illinois.

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[11] The proton penetrabilities were calculated by means of Eq. (600) of H. A. Bethe, Rev. Mod. Phys. **9**, 166 (1937) for protons having zero angular momentum. A nuclear radius of 5.6×10^{-13} cm was used, in accordance with the experiments of Sherr (R. Sherr, Phys. Rev. **68**, 240 (1945)).

[12] E_n from the Li(p,n) reaction was calculated on the basis that the threshold of the reaction is at 1.86 Mev (A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944)).

[13] P. Huber, see reference 6.