Cross Sections for the $S^{32}(n,p)P^{32}$ and the $S^{34}(n,\alpha)Si^{31}$ Reactions*

L. ALLEN, JR., W. A. BIGGERS, R. J. PRESTWOOD, AND R. K. SMITH
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received May 17, 1957)

The cross section for $S^{32}(n,p)P^{32}$ has been measured for incident neutron energies up to 15 Mev. The data at high energies differ from previously published measurements. The cross section for $S^{34}(n,\alpha)Si^{31}$ also has been measured for incident neutron energies up to 14.1 Mev.

1. INTRODUCTION

In many instances sulfur has proved to be a valuable "threshold detector" for the measurement of continuous neutron spectra. The production of P^{32} by neutrons incident on elemental sulfur is relatively efficient for neutrons of energies greater than 3 Mev and the resultant activity is convenient to measure. P^{32} decays with a beta of end-point energy equal to 1.712 Mev[1] and a half-life of 14.3 days.[2] No appreciable number of γ rays has been observed to accompany the beta emission.[3] The $S^{32}(n,p)P^{32}$ cross section has been measured for neutron energies up to about 6 Mev[4,5] and at 14.3 Mev.[6] The shape of the cross section is primarily determined by the proton Coulomb barrier penetration factor, although recent measurements[7] have shown the existence of pronounced resonance structure for neutron energies between 2.0 and 4.0 Mev. When using sulfur as a threshold detector it has usually been the practice to calibrate the counting system by irradiating a sulfur sample with a known flux of 14.1-Mev neutrons produced by the $T(d,n)He^4$ reaction. Recently it has been noticed at this laboratory that the results of sulfur activation measurements of a degraded fission-neutron spectrum did not agree with measurements of the same neutron spectrum made by nuclear emulsion techniques. The experiment described herein was undertaken in order to discover the source of the discrepancy and to extend the earlier measurements somewhat.

2. EXPERIMENTAL METHOD

A. Neutron Sources

Neutrons with energies from 1.59 to 9.56 Mev were obtained from the large Los Alamos Van de Graaff accelerator. The reaction $T(p,n)He^3$ was used to produce neutrons with energies less than 6.0 Mev, while the $D(d,n)He^3$ reaction was used to produce neutrons with energies from 6.0 to 9.56 Mev. The bombarding beam was magnetically analyzed, collimated, and traversed a 0.0001-in. Ni foil before striking a cylindrical gas target, 3 cm in length. The spread in neutron energy was determined by losses in the Ni foil and the target gas. The sulfur sample was placed 5 cm from the end of the gas target and was fastened to the face of the neutron monitor. The neutron monitor consisted of an ionization chamber whose inside face was painted with an even, weighed, film of U^{238} in the form of U_3O_8. The output of the ionization chamber was amplified and fed to a scaler and a 100-channel pulse analyzer and thus measured the number of fissions occurring during a run. From the measured U^{238} fission cross section[8] and the measured number of fissions occurring it was thus possible to determine the flux of neutrons which passed through the U^{238} film. This flux monitor was a modification of the chamber used in the measurements[8] of $\sigma_f(U^{238})$ and contained the same U^{238} film, thus eliminating uncertainties in the knowledge of the U^{238} film. For determination of the flux at the sulfur sample, certain corrections were necessary. These corrections took into account (1) the difference in the distance from the neutron source to the sulfur and to the U^{238}, (2) counting losses of the neutron monitor due to absorption of fission fragments in the finite thickness of U_3O_8 where the forward momentum imparted to the fission fragments by the incident neutron was considered, (3) scattering losses in the sulfur and the wall of the ionization chamber, (4) background neutrons produced by the bombarding beam, as measured by a run with the gas target evacuated, and (5) neutrons produced[9] by the reaction of $D(d,np)D$. After all corrections have been made, the value of the neutron flux through the sulfur is believed to be accurate in absolute value to $\pm 7\%$, and internally consistent to $\pm 5\%$.

Neutrons with energies near 14 Mev were obtained from the Los Alamos Cockcroft-Walton accelerator, using the $T(d,n)He^4$ reaction. The beam of 350-kev deuterons was magnetically analyzed and collimated before striking a thick Zr-T target. The neutron flux was monitored by counting a known fraction of the alpha particles generated from the $T(d,n)He^4$ reaction. Data were obtained for the various energies in a single

* This document is based on research performed under the auspices of the U. S. Atomic Energy Commission.
[1] Pohm, Waddell, and Jensen, Phys. Rev. **101**, 1315 (1956).
[2] N. B. Cacciapuoti, Nuovo cimento **15**, 213 (1938).
[3] Kurie, Richardson, and Paxton, Phys. Rev. **49**, 368 (1936).
[4] E. D. Klema and A. O. Hanson, Phys. Rev. **73**, 106 (1948).
[5] Lüscher, Ricamo, Scherrer, and Zünti, Helv. Phys. Acta **23**, 561 (1950).
[6] E. B. Paul and R. L. Clark, Can. J. Phys. **31**, 267 (1953).
[7] P. Huber and T. Hürlman, Helv. Phys. Acta **28**, 33 (1955).
[8] Smith, Henkel, and Nobles, Bull. Am. Phys. Soc. Ser. II, **2**, 196 (1957).
[9] Cranberg, Armstrong, and Henkel, Phys. Rev. **104**, 1639 (1956).

run with sulfur samples exposed at the appropriate angles with respect to the incident beam and at a distance of 21.1 cm from the target. In addition to the run to determine energy dependence, several runs were made at the 90° position, where the neutron energy is 14.1 Mev, and at various source to sample distances. The absolute value of the neutron flux at the sulfur is believed accurate to ±5% and internally consistent to ±4%.

B. Relative Cross-Section Measurements

The sulfur samples were prepared by pressing 2.00±0.01 grams of sublimed, elemental sulfur (at 12 000 psi) into a disk 1 inch in diameter and $\frac{3}{32}$ inch thick. After irradiation, the samples were counted in an insertion-type methane-flow proportional counter. The P^{32} activity was followed for about one half-life, and selected samples were followed for several half-lives. Each counting rate determination was corrected for background and converted to initial counting rate A_0 by using the known half-life; the deviation of the individual A_0's from the average for a given sample served as a measure of the reproducibility of the counting system. When counting rates were sufficiently high to obtain 1% statistical error, A_0 was observed to remain constant to within ±3% over a period of several half-lives. The average A_0's were corrected for variations in the weights of the samples; since the samples were thick for the beta being counted, this weight correction was less than 0.5%. Samples were counted on both front and back surfaces (the difference was ~3%) and the average of the two was correlated with the neutron flux at the center of the sample. The relative cross sections were then obtained by dividing the corrected A_0 by the corrected value of the neutron flux.

TABLE I. Summary of $S^{32}(n,p)P^{32}$ cross-section data.

Neutron source	E_n Average neutron energy (Mev)	ΔE_n Energy spread[a] (Mev)	$\sigma_{n,p}$ (normalized) (10^{-27} cm^2)	$\sigma_{n,p}$ (absolute) (10^{-27} cm^2)
$T(p,n)He^3$	1.59	0.11	$0_{-0.0}^{+1.0}$	...
	1.98	0.10	5.2± 0.5	...
	2.08	0.10	7.2± 0.7	...
	2.18	0.10	22 ± 1.5	...
	2.57	0.09	73 ± 6.0	...
	2.92	0.08	117 ± 8	115
	3.56	0.07	221 ±15	...
	4.04	0.06	302 ±20	304
	4.54	0.06	263 ±18	...
	4.82	0.06	250 ±17	...
	5.33	0.05	248 ±17	...
	5.69	0.05	304 ±20	...
$D(d,n)He^3$	6.11	0.16	331 ±21	330
	6.61	0.15	336 ±21	...
	7.11	0.13	322 ±20	...
	7.61	0.11	346 ±22	...
	8.09	0.11	324 ±20[b]	311
	8.58	0.10	351 ±22	...
	9.07	0.09	351 ±25	...
	9.56	0.09	376 ±40	...
$T(d,n)He^4$	13.38	0.28	285 ±15	...
	13.41	0.25	291 ±15	...
	13.59	0.13	274 ±14	...
	13.70	0.12	266 ±14	...
	13.89	0.025	257 ±13	...
	14.10	0.04	248 ±13	254±10
	14.32	0.16	231 ±12	...
	14.53	0.26	225 ±12	...
	14.70	0.29	220 ±11	...
	14.83	0.40	214 ±11	...
	14.93	0.45	213 ±11	...
	14.95	0.47	214 ±11	...

[a] Energy spread is given as the half-width at half-area height of the yield *vs* energy curve.
[b] For illustration this sample was irradiated with 1.26×10^{10} neutrons/cm^2 and had $A_0=850\pm10$ counts/min from which a background of 60±2 counts/min has been subtracted.

C. Absolute Cross-Section Measurements

Four of the samples which had been irradiated at the Van de Graaff accelerator were counted as described above for about two weeks and then were radiochemically analyzed to determine the absolute amount of P^{32} contained in the sample immediately after irradiation. The absolute cross section was then computed using the value of neutron flux determined as described above. Similar determinations were made for several sulfur samples which had been irradiated in separate runs by 14.1-Mev neutrons. The radiochemical procedure was as follows:

The irradiated sulfur samples were dissolved in fuming HNO_3 in the presence of standardized $(NH_4)_2HPO_4$ carrier solution. The sulfur and radioactive phosphorus were oxidized to sulfate and phosphate, respectively. The phosphorus was precipitated as $MgNH_4PO_4\cdot6H_2O$. The precipitate was dissolved and reprecipitated and mounted in a standard manner for counting.[10] The geometry was obtained by 4π-counting "weightless" samples of high specific activity P^{32} and then mounting various macro samples made up from the calibrated active P^{32} and the standardized phosphate carrier solution.

3. RESULTS

The relative cross sections for $S^{32}(n,p)P^{32}$ were normalized to the absolute cross sections as determined for five values of the neutron energy. The values at 14.1 Mev are based on six relative determinations obtained from four separate runs and on eight absolute determinations based on two separate runs; the resulting increase in reliability was considered in the normalization. The normalized values and the absolute determinations are tabulated in Table I and displayed in Fig. 1 along with results of previous measurements. The errors shown represent the probable absolute error in the cross section. A measure of internal consistency is

[10] "Collected radiochemical procedures," compiled by J. Kleinberg, Los Alamos Scientific Laboratory Report LA-1721 (unpublished).

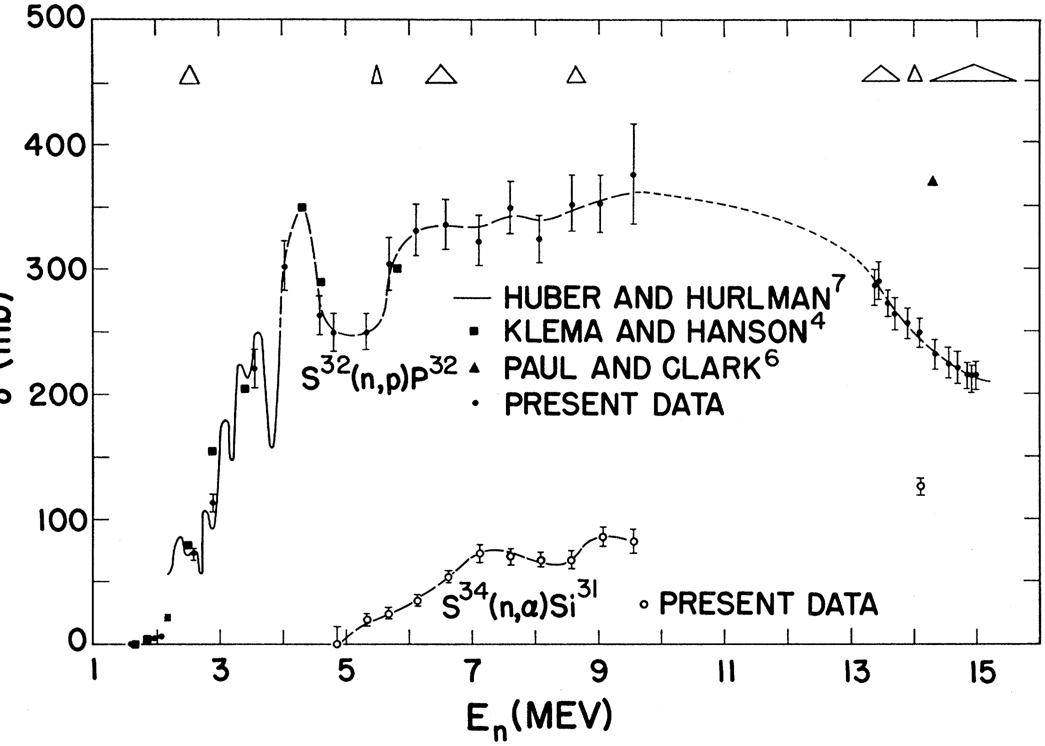

FIG. 1. Cross sections for the reactions, $S^{32}(n,p)P^{32}$ and $S^{34}(n,\alpha)Si^{31}$, *versus* neutron energy. Total probable errors are displayed. The open triangles are approximations to the neutron energy resolution curve such that the full width at half-maximum corresponds to that same quantity on the actual resolution curve. The solid curve has been drawn through the high-resolution points of reference 7. The broken lines merely connect the experimental points in a reasonable manner.

is obtained from the probable error of the normalization constant based on eight comparisons of relative and absolute values; this error is $\pm 2\%$.

4. DISCUSSION

The $S^{32}(n,p)P^{32}$ cross section as measured here is seen to be in general agreement with previous work, except that the value near 14 Mev is considerably lower than that measured before.[6] When the value measured here is applied to the calibration of sulfur threshold detectors, then the sulfur activation measurements of continuous spectra are brought into agreement with other methods of measurement. There is some evidence for resonance structure above 4.0 Mev although the present measurements do not resolve the details. The decreasing value of the cross section near 14 Mev is attributed to competition with the (n,d) and (n,np) processes.

5. CROSS SECTION FOR $S^{34}(n,\alpha)Si^{31}$

In the course of the above measurements, early counting data revealed the presence of a shorter period activity which was attributed to Si^{31}. The half-life of this activity was observed to be 2.5 ± 0.2 hours, in agreement with the more accurate observation of 2.59 hours.[5] Since the energy of the beta (1.5 Mev)[11] is only slightly lower than that from P^{32}, the absolute P^{32} measurements were used to calibrate the counter and a determination was made of the (n,α) cross section for the less abundant isotope S^{34}. The isotopic abundances were taken to be: S^{32}, 95%; S^{34}, 4.18%. The quantity, A_0, for the Si^{31} activity was determined by analyzing the composite decay curve. The appropriate correction for decay during irradiation was made.

TABLE II. Summary of $S^{34}(n,\alpha)Si^{31}$ cross-section data. Energy Spreads are as given in Table I.

E_n (Mev)	$\sigma_{n,\alpha}(S^{34})$ $(10^{-27}\ cm^2)$
(for $E_n<4.8$)	0
4.82	$0_{-0.0}^{+15}$
5.33	21 ± 4
5.69	24 ± 3
6.11	36 ± 3
6.61	53 ± 5
7.11	73 ± 7
7.61	70 ± 7
8.09	68 ± 6
8.58	68 ± 7
9.07	86 ± 8
9.56	82 ± 9
14.10	126 ± 7

[11] H. W. Newson, Phys. Rev. **51**, 623 (1937).

These data are shown in Table II and Fig. 1. Evidence of partially resolved resonance structure is seen. The value at 14.1 Mev agrees well with an earlier measurement[6] where the cross section for $S^{34}(n,\alpha)Si^{31}$ was determined to be 140±30 mb at 14.3 Mev.

6. ACKNOWLEDGMENTS

We wish to express our appreciation to R. W. Davis, who provided the Cockcroft-Walton irradiation; to T. T. Shull, who assisted with the radiochemistry; and to F. Waddell, who assisted with the counting.

PHYSICAL REVIEW VOLUME 107, NUMBER 5 SEPTEMBER 1, 1957

Angular Distribution of Protons from the $Ca^{40}(d,p)Ca^{41}$ Reaction*

C. K. BOCKELMAN† AND W. W. BUECHNER
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received May 31, 1957)

Proton groups emitted from a thin CaO target under 7-Mev deuteron bombardment were studied with a magnetic spectrograph. Their angular distributions were analyzed in terms of stripping theory to determine the orbital angular momenta and relative reduced widths for neutrons captured to form levels in Ca^{41} up to 4.2-Mev excitation. Capture gamma rays measured elsewhere can be fitted to a scheme comprised of levels strongly excited in the (d,p) reaction. Evidence is found for single-particle $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ states, but the expected $f_{5/2}$ level does not appear. Relative cross sections and reduced widths for (d,p) reactions forming states in Ca^{43} and Ca^{45} are also tabulated.

THIS paper is the third of a series reporting measurements of the angular distributions of proton groups produced by (d,p) reactions on calcium isotopes. The previous two papers[1,2] have been concerned with the reactions $Ca^{42}(d,p)Ca^{43}$ and $Ca^{44}(d,p)Ca^{45}$. The present publication presents results on the $Ca^{40}(d,p)Ca^{41}$ reaction and summarizes the relative intensities of the groups observed in each of the three reactions.

The present experiment supplements the work of Holt and Marsham,[3] who used the 8-Mev deuteron beam of the Liverpool cyclotron to study the angular distribution of protons emitted from a calcium target. The energy resolution of the Liverpool work was considerably lower than that of the work done by Braams,[4] whose experiment showed that certain of the proton groups observed by Holt and Marsham were composite and that a large number of low-intensity groups had been missed. In view of the importance of understanding the level structure of Ca^{41}, it appeared worth while to repeat the angular-distribution measurements using the high-resolution equipment available at this laboratory. In addition, the presence of groups from Ca^{40} in the Ca^{42} target used earlier[1] required a run on Ca^{40} to separate the effects of superimposed groups, as well as to check on the assignment of weak groups to impurities. As in the earlier reports from this laboratory on the calcium isotopes, the experiment described herein uses the results of Braams for identification of the proton groups and accepts his measurement of the energies of the excited states.

The previous communications of this series have outlined the experimental arrangements, with particular reference to the use of the broad-range magnetic spectrograph in measuring an angular distribution. The spectrograph itself and its use as a momentum analyzer have been described in detail.[5] Momentum analyses were obtained by deflecting the charged particles in a uniform magnetic field. The particles were detected in nuclear emulsions placed in the focal surface of the spectrograph, and plots were made of the number of particles against position on the plate. Polonium alpha particles afford a calibration of plate position against radius of curvature. Two such momentum plots are shown in Fig. 1. To simplify the plate counting, the emulsions were covered with sufficient aluminum foil to stop all particles heavier than protons.

The targets were prepared by Braams by vacuum evaporation of calcium metal onto Formvar backed with gold foil. The incident deuteron energy was 7.010 Mev. The proton groups, identified by numbers in Fig. 1, correspond to calcium levels identified by Braams,[4] and their energies are consistent with the measured Q values. A very intense peak produced by protons forming the ground state of C^{13} blocks out a portion of the spectrum. The obscured regions are graphed as a function of angle in Fig. 2. The unmarked peak to the right of group 7 in Fig. 1 is produced by the formation of the 1.902-Mev Ca^{45} level in the

* This work was supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† Now at Yale University, New Haven, Connecticut.
[1] Bockelman, Braams, Browne, Buechner, Sharp, and Sperduto, Phys. Rev. **107**, 176 (1957).
[2] W. C. Cobb and D. B. Guthe, Phys. Rev. **107**, 181 (1957).
[3] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A46**, 565 (1953).
[4] C. M. Braams, Phys. Rev. **103**, 1310 (1956).
[5] Buechner, Mazari, and Sperduto, Phys. Rev. **101**, 188 (1956); and C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).