$(n,2n)$ Reaction Cross Sections from 12 to 19.6 MeV*

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Cross sections for the $Cu^{63}(n,2n)Cu^{62}$, $Zn^{64}(n,2n)Zn^{63}$, $Ag^{107}(n,2n)Ag^{106}$ ($T_{1/2}=24$ min), and $Sb^{121}(n,2n)Sb^{120}$ ($T_{1/2}=16$ min) reactions have been measured at incident-neutron energies between 12 and 19.6 MeV. These cross sections were determined relative to the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction at an incident-neutron energy of 14.4 MeV. The measurements of Bame and Perry were used to determine the angular distribution of the neutrons from the $H^3(d,n)He^4$ reaction, which was needed in order to compute values of the relative cross sections. These relative cross sections were then expressed as absolute cross sections by using a value of 503 mb $\pm 7.3\%$ (the weighted mean of the measurements of several other investigators) for the cross section of the $Cu^{63}(n,2n)Cu^{62}$ reaction at 14.4 MeV. Some of these data are compared with the predictions of the compound-nucleus model

INTRODUCTION

MANY $(n,2n)$ reaction cross sections have been measured at incident-neutron energies near 14 MeV, the work of Paul and Clarke[1] representing the first extensive study of these reaction cross sections. Several investigators[2–6] have measured the variation of selected $(n,2n)$ reaction cross sections as a function of neutron energy from near threshold to 18–20 MeV. (Additional references to these cross-section measurements are listed in a previous paper.[7]) Many of these earlier measurements were characterized by rather large standard deviations for the measured cross sections as well as considerable disagreement in measured values at some neutron energies. The present work was undertaken in an effort to resolve some of the disagreements as well as to extend some earlier $(n,2n)$ reaction cross-section measurements[7] made at an incident-neutron energy of 14.4 MeV. The measurements reported here have standard deviations of approximately 9%.

EXPERIMENTAL DETAILS

Samples were irradiated with neutrons produced by the $H^3(d,n)He^4$ reaction. Approximately 3 μA of 3.6-MeV deuterons, accelerated by the Argonne 4.5-MeV Van de Graaff accelerator, were incident on a tritium gas target. The gas target was of the conventional double-foil type. The gas cell was 1 cm in diameter by 3 cm long and was filled with tritium gas to a pressure of about 72 cm Hg. Hydrogen was used as the cooling gas. It was circulated in the region between the foils (Fig. 1) in order to help prevent rupture of the foils. The sample being irradiated was placed either 4 in. or 6 in. from the center of the gas cell and at different angular positions around the cell. The arrangement used for sample irradiation is shown in Fig. 1.

For a given incident-deuteron energy, the neutron energy is a function of the angular position around the gas cell (measured relative to the direction of motion of the incident deuteron). One can then select various neutron energies by irradiating samples at different angular positions. One of the irradiation positions was chosen to correspond to that position for which the neutron energy was 14.4 MeV. The $(n,2n)$ reaction cross sections at this energy were known from previous measurements.[7] Those measurements[7] were expressed as absolute cross sections by making the measurements relative to the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction and using 503 mb$\pm 7.3\%$ as the value of the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction at 14.4 MeV. This value of the $Cu^{63}(n,2n)Cu^{62}$ reaction cross section is the weighted mean of the measurements of several other investigators.[1,3,4] The present measurements can then be expressed as absolute cross sections by using the above value of the $Cu^{63}(n,2n)Cu^{62}$ reaction cross section at 14.4 MeV if, in addition, the angular distribution of the neutrons from the neutron source is

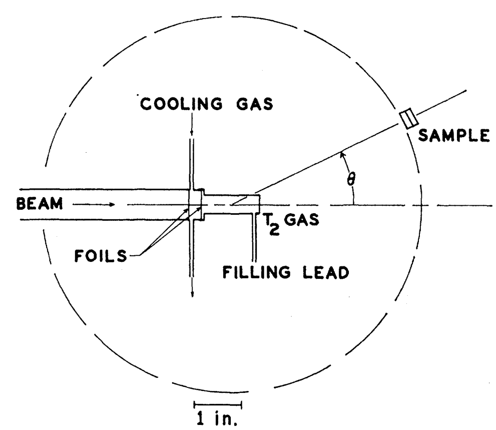

FIG. 1. Experimental arrangement for the irradiation of samples.

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[1] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).
[2] J. M. Ferguson and W. E. Thompson, Phys. Rev. **118**, 228 (1960).
[3] A. V. Cohen and P. H. White, Nucl. Phys. **1**, 73 (1956).
[4] J. E. Brolley, Jr., J. L. Fowler, and L. K. Schlacks, Phys. Rev. **88**, 618 (1952).
[5] D. R. Koehler and W. L. Alford, Phys. Rev. **119**, 311 (1960).
[6] R. J. Prestwood and B. P. Bayhurst, Phys. Rev. **121**, 1438 (1961).
[7] L. A. Rayburn, Phys. Rev. **122**, 168 (1961).

TABLE I. $(n,2n)$ reaction cross sections.

Incident-neutron energy (MeV)	Measured reaction cross sections (mb) $Cu^{63}(n,2n)Cu^{62}$ ($T_{1/2}=9.9$ min)	$Zn^{64}(n,2n)Zn^{63}$ ($T_{1/2}=39.9$ min)	$Ag^{107}(n,2n)Ag^{106}$ ($T_{1/2}=24.4$ min)	$Sb^{121}(n,2n)Sb^{120}$ ($T_{1/2}=15.7$ min)
12.05±0.12	62.7	...	610	695
12.28±0.20	...	...	593	...
12.61±0.31	170	...	782	813
13.00±0.42	248	...	855	893
13.47±0.42	{310 317	74.4	927	929
14.05±0.62	422	...	852	979
14.4 ±0.3	...	167[a]	889[a]	1056[a]
15.24±0.66	525	...	966	1053
15.88±0.67	{531 600	262	924	...
16.56±0.67	631	...	785	928
17.24±0.63	602	325	842	975
17.86±0.53	639	...	846	974
18.41±0.45	658	388	722	932
18.88±0.36	683	...	774	810
19.23±0.30	645	...	715	783
19.48±0.18	{658 689	379	690	803
19.57±0.13	653	...	689	...

[a] Reference 7.

known. A value of 0.982 was used[8] for the number of positrons per disintegration in the decay of Cu^{62}.

The reaction cross sections at 14.4 MeV and the neutron angular-distribution measurements of Bame and Perry[9] were used in order to calculate the neutron flux at each irradiation position. In each of the reactions considered in this paper, the residual nucleus decayed at least in part by positron emission. A knowledge of this induced positron activity and the neutron flux enables one to compute the reaction cross section for each irradiation position (and hence for the neutron energy corresponding to each irradiation position) for each sample. (The positron activity was determined by counting coincidences between the two 511-keV gamma rays resulting from positron annihilation in the irradiated samples. See reference 7 for details of the counting arrangement.)

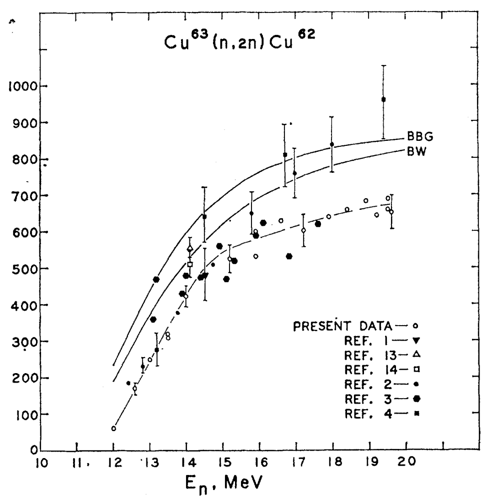

FIG. 2. Cross sections for the $Cu^{63}(n,2n)Cu^{62}$ reaction as a function of incident-neutron energy. The dashed line is a smooth curve drawn through the data reported in this paper. The curves labeled BW and BBG are theoretical curves obtained by the use of equations derived by Blatt and Weisskopf (reference 10) and Barr, Browne, and Gilmore (reference 11), respectively. Typical standard deviations are shown for some of the present data.

A suitable correction was applied to take account of the different solid angles which the gas cell subtended at the sample when the latter was at different angular positions. This correction was always less than 4%. The rate of neutron production was monitored by a plastic scintillator [biased above the maximum neutron energy obtainable from the $H^2(d,n)He^3$ reaction] which was positioned about 30 cm from the gas target. The rate of neutron production varied less than 3% during any one of the time intervals when samples were being irradiated.

RESULTS

The experimental measurements are tabulated in Table I. The standard deviations of the measured cross sections are approximately 9%. The contributions to these estimated total standard deviations consisted of the following: (a) uncertainty in the $Cu^{63}(n,2n)Cu^{62}$ reaction cross section at 14.4 MeV, ±7.3%; (b) uncertainty in the angular distributions,[9] ±3.5%; and (c) all other contributions, ±4%.

$Cu^{63}(n,2n)Cu^{62}$

The results for this reaction are shown in Fig. 2. The dashed line is a smooth curve drawn through the data

[8] *Nuclear Data Cards* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C., 1959).

[9] S. J. Bame, Jr., and J. E. Perry, Jr., Phys. Rev. **107**, 1616 (1957).

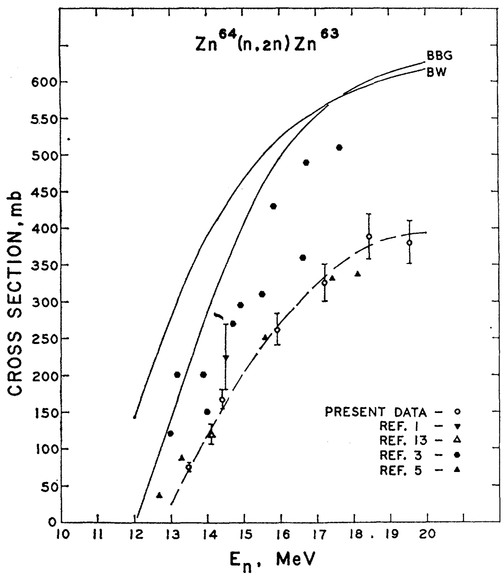

FIG. 3. Cross sections for the $Zn^{64}(n,2n)Zn^{63}$ reaction as a function of incident-neutron energy. The dashed line is a smooth curve drawn through the data reported in this paper. The curves labeled BW and BBG are theoretical curves obtained by the use of equations derived by Blatt and Weisskopf (reference 10) and Barr, Browne, and Gilmore (reference 11), respectively. Standard deviations are shown for the present data.

reported in this paper. The measurements of the various workers agree very well except for two series of measurements in the neutron energy region above about 16 MeV. Also shown in Fig. 2 are theoretical curves obtained by the use of equations found in Blatt and Weisskopf[10] (indicated by BW) and in Barr, Browne, and Gilmore[11] (indicated by BBG). The statistical concepts employed in the derivation of these equations were based on the compound-nucleus model. In the present calculations the cross sections for compound-nucleus formation and the level-density parameters were obtained from empirically determined equations given by Barr, Browne, and Gilmore.[11] Both of these theoretical curves reproduce the shape of the experimental excitation function very well although the reaction cross sections predicted by each appear to be too large over the entire energy region.

$Zn^{64}(n,2n)Zn^{63}$

The results for this reaction are shown in Fig. 3. The dashed line is a smooth curve drawn through the data reported in this paper. The measurements of the various experimenters agree very well except for some of the measurements reported by Cohen and White.[3] The values obtained by these latter authors are consistently larger than the other reported values. The curves labeled BW and BBG in Fig. 3 are theoretical curves obtained in the same way as described in the preceding section. One important factor which makes the agreement between theory and experiment appear so bad is the occurrence of the competing $Zn^{64}(n,p)Cu^{64}$ reaction. The theoretical calculations are made under the assumption that reactions competing with the $(n,2n)$ reaction can be neglected. However, in the present case the cross section[12] for the $Zn^{64}(n,p)Cu^{64}$ reaction is of the order of 100 to 200 mb in the energy region considered here.

$Ag^{107}(n,2n)Ag^{106}$ ($T_{1/2}$=24.4 min)

The results for this reaction are shown in Fig. 4. The residual Ag^{106} can decay in two ways,[8] one with a half-life of 24.4 min and the other with a half-life of 8.2 days. Values of the cross section for the formation of the 8.2-day isomer are not available. Because of this it would not be meaningful to compare theoretical values with the measurements shown in Fig. 4. It is evident that serious disagreement exists between these measurements and the work of the other experimenters. It would perhaps be instructive to examine the general trend of other common $(n,2n)$ measurements made by these same investigators. The measurements of Paul and Clarke[1] are in generally good agreement with those made by the present investigator[7] except in a few cases such as this reaction and the $Sb^{121}(n,2n)Sb^{120}$ ($T_{1/2}$=16 min) reaction. The measurements made by Yasumi[13] are usually much lower than those made by the present

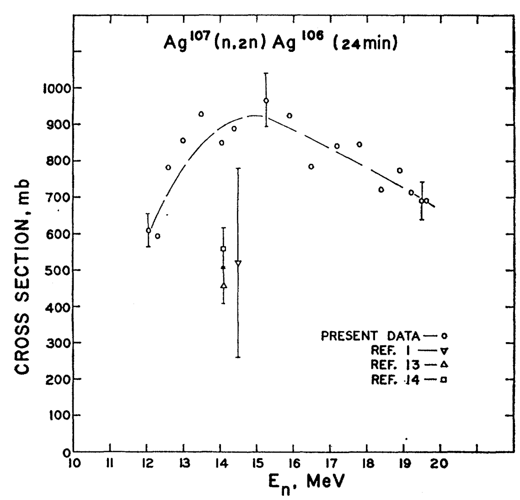

FIG. 4. Cross sections for the $Ag^{107}(n,2n)Ag^{106}$ ($T_{1/2}$=24.4 min) reaction as a function of incident-neutron energy. The dashed line is a smooth curve drawn through the data reported in this paper. Typical standard deviations are shown for some of the present data.

[10] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. VIII.
[11] D. W. Barr, C. I. Browne, and J. S. Gilmore, Phys. Rev. 123, 859 (1961).
[12] L. A. Rayburn (to be published).
[13] S. Yasumi, J. Phys. Soc. Japan 12, 443 (1957).

investigator[7] except in one or two cases. In the only other measurement common to both works, the value obtained by Forbes[14] is in excellent agreement with that obtained by the present investigator.[7] Consequently, one would expect better agreement in the present case on the basis of these other measurements. An auxiliary experiment was performed in order to ensure that the 513-keV gamma ray which appears in the decay of $Ag^{106} \rightarrow Pd^{106*}$ did not contribute to the measured positron activity of the irradiated Ag. It was determined that this contribution was much less than 1%. The present experimental procedure and calculations have been examined in great detail in an effort to eliminate all elements that might contribute to these disagreements.

The shape of the excitation function for this reaction suggests that the cross section for some competing reaction becomes large for neutron energies above about 15 MeV.

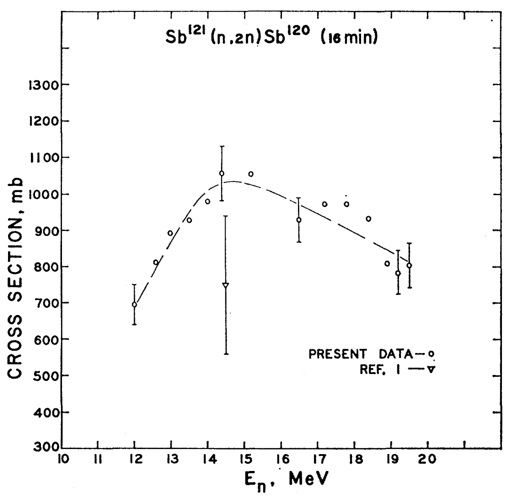

FIG. 5. Cross sections for the $Sb^{121}(n,2n)Sb^{120}$ ($T_{1/2}=15.7$ min) reaction as a function of incident-neutron energy. The dashed line is a smooth curve drawn through the data reported in this paper. Typical standard deviations are shown for some of the present data.

[14] S. G. Forbes, Phys. Rev. **88**, 1309 (1952).

$Sb^{121}(n,2n)Sb^{120}$ ($T_{1/2}=15.7$ min)

The results for this reaction are shown in Fig. 5. The residual nucleus Sb^{120} can decay in two ways,[8] one with a half-life of 15.7 min, the other with a half-life of 5.8 days. Values of the cross section for the formation of the 5.8-day isomer are not available. For this reason no attempt was made to compare theoretical values with the present measurements. The shape of the excitation function for this reaction indicates the occurrence of some competing reaction at neutron energies above 16 MeV.

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