creasing energy, a minimum at about 100°, and a back-angle rise. Figure 8 indicates that the absolute cross sections are also the same. This coincidence of the two cross sections for these companion reactions may be considered as a demonstration of the charge symmetry of nuclear forces.[5]

The analysis by Butler and Symonds[6] of the older 10-Mev data on these reactions[4,7] indicates that a simple stripping model can account for the shape of the distributions from the forward peak through the second minimum. Their calculation, however, cannot account for the back-angle rise. An attempt to account for this rise by considering stripping of the triton, using the exchange stripping model of Owen and Madansky,[9,8] led to the conclusion that a triton stripping amplitude that would account for the back-angle rise was inadequate to account for the magnitude of the second maximum. A triton amplitude sufficiently large to give rise to an interference term sufficiently large to account for the second maximum would indicate a cross section at 180° an order of magnitude or more higher than that observed experimentally. This would indicate that distorting effects not considered in a simple stripping model must be accounted for. Therefore, a distorted-wave stripping calculation, using an exchange wave function for the final-state neutrons, would seem to be required to fully describe the observed angular distributions for these reactions.

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14.4-Mev $(n,2n)$ Cross Sections*

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Cross sections for the $(n,2n)$ reaction have been measured at an incident neutron energy of 14.4±0.3 Mev for 27 nuclides. These measurements were made relative to the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction. The relative cross sections were then converted to absolute cross sections by using the weighted mean of several $Cu^{63}(n,2n)Cu^{62}$ reaction-cross-section measurements made by other investigators.

INTRODUCTION

MANY $(n,2n)$ cross sections have been measured at incident neutron energies near 14 Mev,[1–12] because of the ease with which neutrons having this energy can be produced by use of low-voltage accelerators and the $H^3(d,n)He^4$ reaction. Other investigators[13–17] have measured the variation of the cross section for the $(n,2n)$ reaction as a function of neutron energy from near threshold to 18 to 20 Mev. Most of these measurements have been characterized by rather large standard deviations for the measured cross sections because of the experimental difficulties encountered. The present method eliminates some of these difficulties so that in general the standard deviations of the measured cross sections are somewhat less than those of most previously reported $(n,2n)$ cross-section measurements.

The compound nucleus model[18] has frequently been used in the theoretical evaluation of $(n,2n)$ cross

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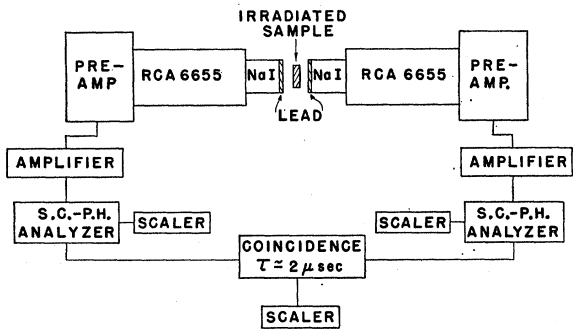

FIG. 1. Electronic circuitry. The windows on the single-channel pulse-height analyzers were set so that only those pulses falling under the 511-kev photoelectric peak were fed to the coincidence circuit.

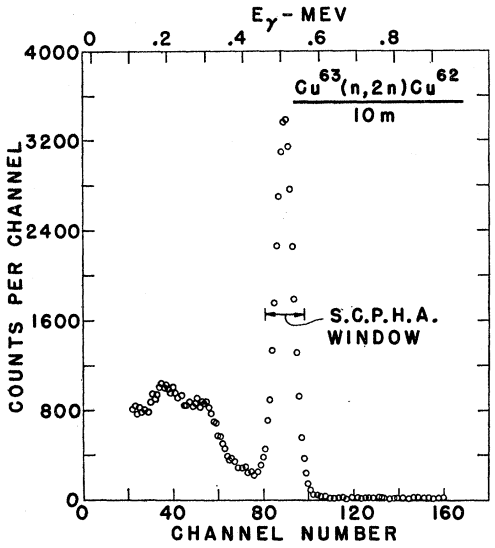

FIG. 2. Gamma-ray spectrum from a Cu sample irradiated with 14.4-Mev neutrons for 25 min. The count was taken during the third, fourth, and fifth minute after the end of the irradiation.

sections in order to compare experimental measurements[3,11,17] with the theoretical predictions. Computation of theoretical values of the $(n,2n)$ cross sections by use of this model requires knowledge of two parameters (the nuclear temperature and the cross section for the emission of the first neutron from the compound nucleus), which are generally not known. This makes it difficult to compare the theory with experimental data at only one incident neutron energy. If one compares theoretical and experimental curves,[3,11] it is evident that there is, at best, only order of magnitude agreement between the theoretical and experimental values of the cross sections. Yet the predictions from this model are more accurate than those from any other theoretical model. For these reasons no attempt has been made to compare the present measurements with theoretical predictions.

EXPERIMENTAL DETAILS

Samples were irradiated with neutrons produced by the $H^3(d,n)He^4$ reaction. The deuterons were accelerated to approximately 120 kev in a Cockcroft-Walton accelerator and allowed to strike a thick Zr-T target. The alpha particles going off at 90° to the direction of the incoming deuterons were collimated by apertures and then detected with a plastic scintillator mounted on an RCA-6342 photomultiplier tube. The neutron yield was monitored by counting these alpha particles. The total neutron yield was usually about 5×10^8 neutrons per second and did not vary more than a few percent during the course of any one irradiation.

All of the samples were irradiated in cylindrical Lucite sample holders having an inside diameter of 1 in. These sample holders had different thicknesses so that variable amounts of the solid or powdered samples could be irradiated. Two irradiation positions were used, one approximately 3 cm from the target and the other 10 cm from the target. In each of these positions, the axis of the cylindrical sample holder made an angle of 45° with the direction of the incoming deuteron beam. The incident neutron energy was 14.4 ± 0.3 Mev at each of the irradiation positions. The irradiation times used were about three times the half-life of the expected activity. The maximum irradiation time for any sample was 7 hr.

After irradiation the sample was placed between two NaI(Tl) scintillation spectrometers positioned 180° from each other. Interest was confined to those residual nuclei which decayed at least in part by positron emission. Coincidences between the two 511-kev gamma rays from positron annihilation were counted by use of the electronic circuitry shown in Fig. 1. The usual setting of the windows on each single-channel pulse-height analyzer is shown in Fig. 2. The end of each NaI crystal holder, $1\frac{1}{2}$ in. in diameter by $1\frac{1}{2}$ in. long, was covered with a sheet of lead in order to insure that annihilation of the positrons took place between the crystals. The proper operation of the circuitry was checked during the experiment by using a Na^{22} source.

The radioactive decay was followed for several half-lives. A least-squares analysis of the coincidence counting rate taken at periodic time intervals allowed the positron activity present at the end of the irradiation period to be determined. In some cases it was necessary to correct the data for "spurious" coincidences due to (1) gamma rays which were coincident with the positron emission, and (2) cascade gamma rays from the $(n,2n)$ or other reactions with the target nuclide or other isotopes of the element. These corrections were usually not more than a few percent. In two or three cases the corrections amounted to as much as 10%. Each irradiated sample was checked to determine the extent of these "spurious" coincidences and corrections were applied to the data where necessary.

Several different thicknesses of each sample were irradiated and the positron activity at the end of the

irradiation period in each case was determined as described above. These data were used in order to determine a correction to be applied for the absorption of the 511-kev gamma rays in the sample. (See Appendix.)

Cross sections for the $(n,2n)$ reaction were computed from the equation

$$\sigma_{n,2n}=\frac{K_{00}MT}{K_N\beta_1\beta_2(1-e^{-\lambda T})}\frac{2b}{(e^b-e^{-b})},$$

where K_{00} is the coincidence counting rate at the end of the irradiation period per gram of sample per unit incident neutron (extrapolated to zero sample thickness), M is the atomic weight of the target isotope, T is the irradiation time, K_N is a constant of the experimental arrangement which includes contributions from the irradiation geometry, the efficiency of the alpha counter (neutron production rate), and the efficiency for the coincident counting of positron annihilation radiation, β_1 is the relative isotopic abundance of the

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

	This work. Incident neutron energy = 14.4±0.3 Mev						Work of other investigators			
Target nuclide	Sample	β_2 [a] (%)	Measured cross section (millibarns)	Standard deviation (%)	Measured half-life	Standard deviation (%)	Measured cross section (millibarns)	Standard deviation (%)	Incident neutron energy (Mev)	Reference
$_{7}N^{14}$	NaN_3	100	7.41	7.9	12.3 min	5.4	5.67	15	14.5	k
$_{9}F^{19}$	CF_2	97	51.9	7.4	1.85 hr	2	60.6	30	14.5	k
							62	15	14.1	l
$_{15}P^{31}$	Element	100	10.9	7.8	2.53 min	4.9	...	...	...	...
$_{17}Cl^{35}$	NaCl	100	5.42[b]	7.5	31.2 min	2	3.47[b]	45	14.5	k
$_{19}K^{39}$	K_2CO_3	100	3.37	7.9	7.7 min	6.5	10.0	55	14.5	k
$_{21}Sc^{45}$	Sc_2O_3	93	198[c]	7.4	4.04 hr	2	...	...	...	...
$_{21}Sc^{45}$	Sc_2O_3	93	149[d]	7.5	59.1 hr	2	...	...	...	...
$_{22}Ti^{46}$	Element	84	31.8	7.6	2.91 hr	2	...	...	...	...
$_{24}Cr^{50}$	Element	92	26.4	8.3	38.5 min	3.9	...	...	...	...
$_{26}Fe^{54}$	Element	98.1	15.0	8.8	8.80 min	2.7	10	40	14.0	m
							no trace found		14.1	n
$_{28}Ni^{58}$	Element	46.9	34.2	7.5	43.7 hr	2	40.6	30	14.5	k
$_{29}Cu^{65}$	Element	19	959	8.3	13.6 hr	3.3	1085	16	14.5	k
							970	8	14.1	o
$_{30}Zn^{64}$	Element	90.4	167	7.6	39.9 min	2	224	20	14.5	k
							150	20	14.0±0.2	p
							119	12	14.1	n
$_{31}Ga^{69}$	Element	87.5	923	7.5	69.2 min	2	552	30	14.5	k
$_{32}Ge^{70}$	GeO_2	36.1	598	7.5	38.6 hr	2	666	35	14.5	k
$_{34}Se^{74}$	Element	70.6	383[e]	7.7	6.8 hr	2.5	...	...	...	...
$_{34}Se^{74}$	Element	100	48.7[f]	16.4	39 min	12	...	...	...	...
$_{35}Br^{79}$	NaBr	93.2	835	7.5	6.33 min	2	1141	25	14.5	k
$_{35}Br^{81}$	NaBr	2.6	752[g]	9.4	4.49 hr	2	828[g, j]	20	14.5	k
$_{40}Zr^{90}$	Element	25	677[h]	7.6	79.4 hr	2	...	...	...	...
$_{42}Mo^{92}$	Element	94.7	211[i]	7.4	15.2 min	2	190	15	14.5	k
							132	16	14.1	n
							320	28	14.5±0.5	q
$_{44}Ru^{96}$	Element	19.5	634	7.5	1.63 hr	2	478	19	14.5	k
$_{47}Ag^{107}$	Element	61	889	7.4	24.4 min	2	519[j]	50	14.5	k
							458	11	14.1	n
							560	10	14.1	o
$_{48}Cd^{106}$	Element	55	827	7.6	50.7 min	2	...	...	...	...
$_{50}Sn^{112}$	Element	29	1508	7.7	32.1 min	2	...	...	...	...
$_{51}Sb^{121}$	Element	43.6	1056	7.5	15.7 min	2	750[j]	25	14.5	k
$_{59}Pr^{141}$	Pr_6O_{11}	47	1801	7.5	3.13 min	3.1	2060	35	14.5	k
$_{60}Nd^{142}$	Nd_2O_3	2	2411	8.3	2.54 hr	2	...	...	...	...
$_{62}Sm^{144}$	Sm_2O_3	43	1484	8.0	9.4 min	6.0	...	...	...	...

[a] The fraction of the radioactive residual nuclei that decay by positron emission. In those cases in which the decay is from a metastable state through the ground state, the percent shown includes contributions from both states. These values were obtained from the compilation of D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958) or from Nuclear Data Cards [reference 19], or were computed from tables given by P. F. Zweifel, Phys. Rev. **107**, 329 (1957).

[b] This is the value of the cross section for the reaction $Cl^{35}(n,2n)Cl^{34m}$ only.

[c] This is the value of the cross section for the reaction $Sc^{45}(n,2n)Sc^{44}$ only.

[d] This is the value of the cross section for the reaction $Sc^{45}(n,2n)Sc^{44m}$ only.

[e] This is the value of the cross section for the reaction $Se^{74}(n,2n)Se^{73}$ only.

[f] This is the value of the cross section for the reaction $Se^{74}(n,2n)Se^{73m}$ only.

[g] This is the value of the cross section for the reaction $Br^{81}(n,2n)Br^{80m}$ only.

[h] This is the value of the cross section for the reactions $Zr^{90}(n,2n)Zr^{89m}$(93%) and $Zr^{90}(n,2n)Zr^{89}$.

[i] This is the value of the cross section for the reactions $Mo^{92}(n,2n)Mo^{91m}$(57%) and $Mo^{92}(n,2n)Mo^{91}$.

[j] Lower limit since only one isomer was observed.

[k] Reference 3.

[l] V. J. Ashby, H. C. Catron, L. L. Newkirk, and C. J. Taylor, University of California Radiation Laboratory Report UCRL-5054 (unpublished).

[m] Reference 12 [n] Reference 7. [o] Reference 2. [p] Reference 16. [q] Reference 14.

target isotope, β_2 is the fraction of the radioactive residual nuclei that decay by positron emission, λ is the disintegration constant, and $b=\frac{1}{2}\lambda(t_2-t_1)$, where (t_2-t_1) is the length of time coincidence counts were collected for each point on the decay curve. The quantity $2b/(e^b-e^{-b})$ has a value different from unity only in those cases in which the counting time for each point approaches a value equal to the half-life of the radioactive decay.

The constant K_N was determined by irradiating copper samples, determining K_{00} from the induced positron activity from the $Cu^{63}(n,2n)Cu^{62}$ reaction, and using a value of 503 mb$\pm$7.3% for the cross section of this reaction. A value of 0.982 was used[19] for the number of positrons per disintegration for Cu^{62}. This value of the $Cu^{63}(n,2n)Cu^{62}$ reaction cross section is the weighted mean of the measurements of several other investigators.[3,14,16] One or more values of K_N were determined when cross-section measurements were made for each of the samples. The measured relative cross sections can then be expressed as absolute cross sections by using the above cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction.

RESULTS

The experimental measurements are tabulated in Table I. The standard deviations of the measured cross sections include all known contributions, including the uncertainty in the $Cu^{63}(n,2n)Cu^{62}$ measurement. In the same table the measurements of other investigators are listed where these measurements exist for incident neutron energies near 14.4 Mev. The agreement between the present measurements and those reported by other investigators is in general very good.

In some cases the decay scheme of the residual nucleus is such that it allows measurement of the cross section for the $(n,2n)$ reaction leading to a metastable state. Cross sections for this type of reaction are shown in Table I for the reactions $Cl^{35}(n,2n)Cl^{34m}$, $Sc^{45}(n,2n)Sc^{44m}$, $Se^{74}(n,2n)Se^{73m}$, and $Br^{81}(n,2n)Br^{80m}$. In other cases it was not possible to entirely separate the decay through the metastable state from the decay through the ground state of the residual nucleus. In the two cases of this type shown in Table I, Zn^{90} and Mo^{92}, it was possible to include only a fraction of the decay through the metastable state.

The measured half-lives are in generally good agreement with the values in the literature[19] except for the half-life of Ni^{57} which was found to be 43.7$\pm$0.9 hr.

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APPENDIX. ABSORPTION CORRECTION

The value of the linear absorption coefficient for 511-kev gammas was measured in the present experimental arrangement for samples of Cu, Mo, Ag, Cd, and Sb. Because of the experimental arrangement used, it was expected that the value of this measured linear absorption coefficient would be less than the value of the theoretical linear absorption coefficient computed on the assumption of good geometry. The ratio of the measured to the theoretical linear absorption coefficients was found to be 0.899$\pm$(5.8%) for the above mentioned samples. The theoretical values were computed from equations given by Heitler.[20] The experimental linear absorption coefficient was then obtained for all the other samples by multiplying the theoretical value by 0.899. A least-squares analysis of the activities found for different sample thicknesses by use of the experimental linear absorption coefficient as found above then enables one to determine K_{00} (the coincidence counting rate at the end of the irradiation period per gram of sample per unit incident neutron—extrapolated to zero sample thickness).

It should be pointed out that the value of the experimental linear absorption coefficient could be changed considerably without changing the value of K_{00} very much. In a typical case a 5% change in the value of the experimental linear absorption coefficient produced a change of $\frac{1}{2}$% in the value of K_{00}.

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