model, as applied here, is not sufficient to completely describe the ^{57}Co nucleus.

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Neutron Activation Cross Sections for As, Br, Rb, and Sr Isotopes at 14.4 MeV*

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Activation cross sections at an incident neutron energy of 14.4 ± 0.3 MeV are measured for the $(n, 2n)$, (n, p), and (n, α) reactions on isotopes of As, Br, Rb, and Sr, by using the mixed-powder method and γ detection by Ge(Li) spectrometer. The use of a stoichiometric chemical compound as an alternative to the mixed-powder technique, where one of the constituents serves as the neutron flux monitor, is investigated and is recommended, whenever applicable, over all other methods for measurement of relative activation cross sections.

INTRODUCTION

Activation cross sections for $(n, 2n)$, (n, α), and (n, p) reactions for arsenic, bromine, rubidium, and strontium at 14.4 ± 0.3-MeV incident neutron energy are measured as part of a general program to determine accurate cross sections over a large range of mass numbers at a single neutron energy by means of the mixed-powder technique with Ge(Li) γ detection. A complete survey of the existing cross-section measurements on $(n, 2n)$ reactions relevant to the present work in the energy range 13 to 15 MeV is also presented for comparison and discussion of the need for more precise measurements.

In many of the activation measurements, the measured quantity is the ratio of two cross sections, one of which serves as the standard or monitor. The absolute value of the monitor cross section is usually assumed from the best-known precision values available in the literature. The important detail to be taken care of in such measurements is the assurance that the monitor sees the same incident neutron flux as the unknown sample. The mixed-powder method of Rao and Fink[1] is designed to guarantee such assurance and has been employed successfully for several elements at thermal energies[2,3] as well as at 14.4 MeV.[3-8] By including two standards in the mixture of powders along with the sample, the reliability of the method is checked in each individual measurement. To investigate the reliability and accuracy of the mixed-powder method, we have collected the results of measurements of cross sections for the reaction $^{27}Al(n, \alpha)^{24}Na$(15 h) relative to an adopted value of $\sigma = 100$ mb for the $^{56}Fe(n, p)^{56}Mn$(2.6 h) reaction from measurements by Liskien and Paulsen.[9] These measurements, presented in Table I, were spread over a period of 4 years and were made by bombarding uniform mixtures of samples containing iron and aluminum metal powders of the same grain size. These results are all at the same neutron energy, but were obtained by several different investigators. It is seen from Table I that the standard deviation from the average value of $\sigma = 114$ mb is 6.1%; the adopted average value from the literature for the $^{27}Al(n, \alpha)^{24}Na$ reaction is 114 ± 6 mb.

TABLE I. Measured cross-section values (error limits on these values are all within 6 to 10%) for the $^{27}Al(n,\alpha)^{24}Na$(15 h) reaction at 14.4 ± 0.3 MeV relative to that (100 ± 6 mb) of the $^{56}Fe(n,p)^{56}Mn$(2.6 h) reaction, as a check on the consistency of the mixed-powder method with Ge(Li) detection.

$^{27}Al(n,\alpha)^{24}Na$ σ (mb)					Reference
105	114				8
112					
115					
112					
106					
93					4
123					
113					
107					1
120					
110	112	128	113	108	7
107	113	118	115		
107	116	118	113		
108	118	120	116		
121					3, 5, 6
108					
122					
118					
118					
118					
$114.2 \pm 6.1\%$ average					

Chemical-Compound Technique

The ideal conditions can also be met if one uses a chemical compound containing the standard and unknown elements as constituents. In this case the uncertain factors present in the preparation of a *uniform* mixture of powers *of the same grain size*[1] are completely eliminated, and the equal exposure of all target nuclei to the same incident neutron flux is guaranteed. In order to exploit and test this method, a chemical compound was also irradiated. The compound chosen was $CdBr_2$, where cross sections of both bromine and cadmium were also determined independently by the mixed-powder method.

From the activation of the $CdBr_2$ sample, the ratio of the cross section of the $^{81}Br(n, 2n)^{80m}Br$(4.2 h) reaction to that of the $[^{112}Cd(n, 2n) + ^{111}Cd(n, n')]\ ^{111m}Cd$(48.6 min) reaction was found in the present work to be 1.04 ± 0.08. The cross section for the production of ^{111m}Cd from a natural Cd target was measured by Lu, Ranakumar, and Fink by the mixed-powder method to be 725 ± 50 mb, and in the present work the cross section for production of ^{80m}Br is found to be 735 ± 75 mb, thus giving a ratio of 1.02 ± 0.12 which compares very well with the above ratio. Consequently, the use of stoichiometric chemical compounds as targets with one of the constituents as a monitor is highly recommended whenever feasible.

EXPERIMENTAL PROCEDURE

The $^3H(d, n)^4He$ reaction was employed to produce neutrons of average energy 14.4 ± 0.3 MeV from the Georgia Institute of Technology 200-kV accelerator. The energy spread is calculated by the procedure outlined by Ricci,[10] taking into consideration the geometry of the sample and target assembly. A histogram of neutron energies reaching the sample is shown in Fig. 1. The neutron flux was monitored by an α-particle Si(Au) detector to follow the decay of the flux due to deterioration of the Ti-T target during irradiation. The flux decayed exponentially in many of the runs.

The γ activities were observed with a 16-cm^3 coaxial Ge(Li) detector, the relative photopeak efficiency of which was calibrated with standard sources supplied by the International Atomic Energy Agency, Vienna. The standard sources ef-

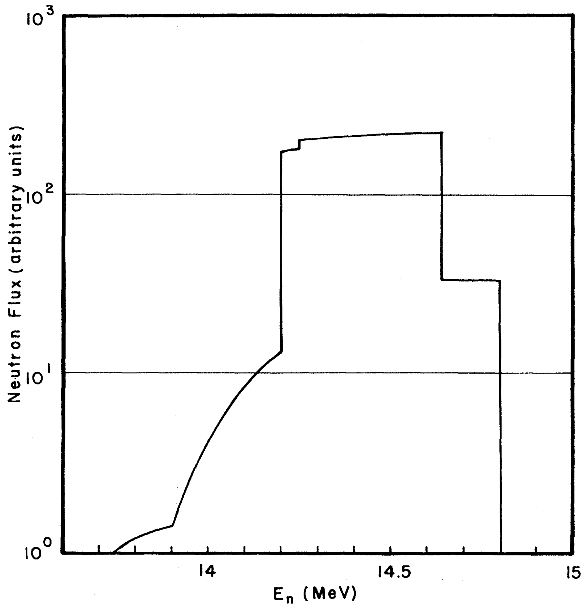


FIG. 1. Energy profile of the neutron flux from the Georgia Institute of Technology 200-kV accelerator, based on the $^3H(d,n)^4He$ reaction. The average energy is estimated to be 14.4 ± 0.3 MeV.

fectively are point sources, while almost all of the irradiated samples were disks with an area of about 2 cm^2. At close geometries the detector sees γ activities which are not at normal incidence, whereas the efficiency calibration was made for normal incidence. A careful determination of the slope of the relative photopeak efficiency curve off the central axis at various distances away from the detector surface revealed no serious departures from the efficiency at normal incidence, except at energies below 60 keV. However, at such low energies the source self-absorption becomes a greater problem than these deviations in the efficiency calibration.

In the present work, powders of arsenic metal, NaBr, Rb_2SO_4, and $SrCO_3$ were used as targets. Several independent bombardments were made with different ratios of mixtures and various periods of irradiation.

RESULTS AND DISCUSSION

The calculation of the cross sections from the γ activities is described in detail previously.[1] The results of the present work are summarized in Table II, which also includes the energies (E_γ)

TABLE II. Neutron activation cross sections at 14.4 ± 0.3 MeV measured relative to σ = 100 ± 6 mb of the $^{56}Fe(n,p)$-^{56}Mn(2.6 h) reaction in the present work. The limits quoted are standard errors.

Reaction	Half-life	E_γ (keV)	f_d	Measured cross section σ (mb)
		$(n,2n)$ cross sections		
$^{75}As(n,2n)^{74}As$	18 day	596	0.61	1016 ± 102
$^{79}Br(n,2n)^{78}Br$	6.4 min	614	0.13	741 ± 74
$^{81}Br(n,2n)^{80m}Br$	4.2 h	618 [a]	0.066 [a]	737 ± 74
$^{81}Br(n,2n)^{80g}Br$	18 min	618	0.066	391 ± 39
$^{85}Rb(n,2n)^{84m}Rb$	20 min	250	0.60	478 ± 48
$^{85}Rb(n,2n)^{84g}Rb$	33 day	880	0.74	414 ± 41
$^{87}Rb(n,2n)^{86}Rb$	18.7 day	1078	0.088	995 ± 99
$^{84}Sr(n,2n)^{83}Sr$	32.4 h	762	0.332	482 ± 80
$^{86}Sr(n,2n)^{85m}Sr$	70 min	231 + 237	0.83	247 ± 25
$^{87}Sr(n,n')^{87m}Sr$ + $^{88}Sr(n,2n)$	2.8 h	388	0.78	235 ± 24
		(n,p) cross sections		
$^{75}As(n,p)^{75}Ge$	80 min	265	0.11	19 ± 2
$^{81}Br(n,p)^{81m}Se$	57 min	103	0.12	13 ± 2
$^{85}Rb(n,p)^{85m}Kr$	4.4 h	150	0.78	4.1 ± 0.4
$^{87}Rb(n,p)^{87}Kr$	76 min	405	0.87	4.9 ± 0.5
$^{88}Sr(n,p)^{88}Rb$	17.8 min	898	0.15	13 ± 1
		(n,α) cross sections		
$^{75}As(n,\alpha)^{72}Ge$	14.1 h	832	0.75	13.5 ± 1.5
$^{79}Br(n,\alpha)^{76}As$	26.5 h	559	0.392	20 ± 2
$^{81}Br(n,\alpha)^{78}As$	90 min	614	0.42	19 ± 2
$^{85}Rb(n,\alpha)^{82}Br$	35 h	553	0.73	4.9 ± 0.5
$^{87}Rb(n,\alpha)^{84g}Rb$	32 min	880	0.42	18 ± 2

[a] Activity observed from ^{80g}Br.

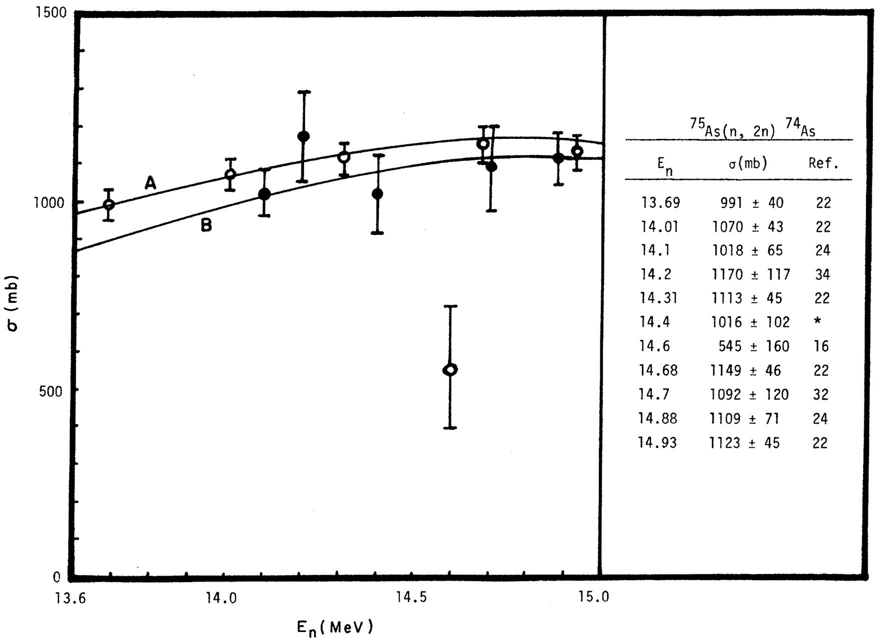


FIG. 2. Cross sections for the $^{75}As(n, 2n)^{74}As$ reaction. Curves A and B are excitation functions drawn through the results from Refs. 23 and 25, respectively. The activity was measured by detecting (o) β particles, and (•) γ rays. * indicates present work.

of the γ ray measured, the number (f_d) of photons per disintegration, and the half-life ($T_{1/2}$) of the decay observed. The cross sections were measured relative to that of $^{56}Fe(n,p)^{56}Mn$(2.576 h) (100 ± 6 mb).

Most of the 14-MeV neutron cross-section measurements reported in the literature are spread over an energy range between 13.5 and 15.5 MeV. In Figs. 2 to 7 we present a summary of all the $(n, 2n)$ cross sections available[11-35] for the reac-

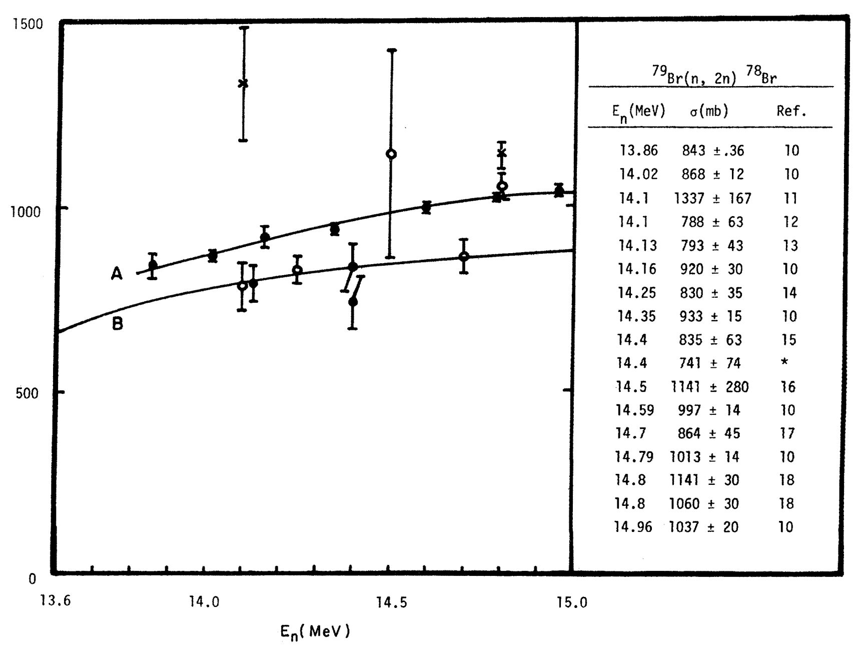
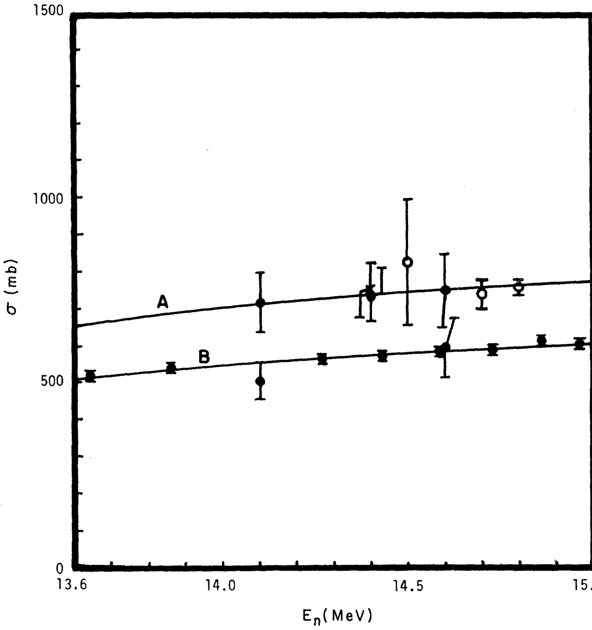


FIG. 3. Cross sections for the $^{79}Br(n, 2n)^{78}Br$ reaction. Curves A and B are excitation functions drawn through the results from Refs. 11 and 15, respectively. The activity was measured by detecting (o) β particles, and (•) γ rays, and × annihilation radiation. * indicates present work.

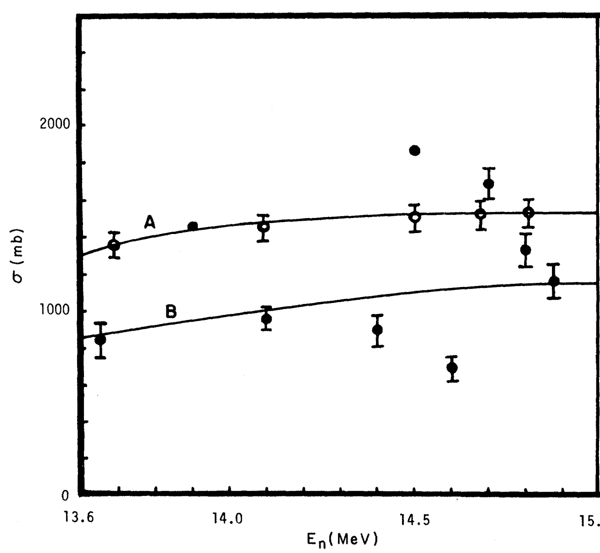


$^{81}Br(n, 2n)^{80m}Br$

E_n(MeV)	σ(mb)	Ref.
13.64	424 ± 14	10
13.86	447 ± 17	10
14.1	720 ± 80	19
14.1	510 ± 50	20
14.27	461 ± 18	10
14.4	737 ± 74	*
14.4	752 ± 75	15
14.5	828 ± 170	16
14.59	487 ± 15	10
14.6	600 ± 80	25
14.6	750 ± 90	19
14.7	740 ± 40	21
14.73	486 ± 13	10
14.8	760 ± 15	18
14.86	517 ± 14	10
14.96	505 ± 14	10

FIG. 4. Cross sections for the ^{81}Br, $(n, 2n)^{80m}$Br reaction. Curves A and B are excitation functions drawn through the results from Refs. 20 and 11, respectively. The activity was measured by detecting (o) β particles, (•) γ rays, and × annihilation radiation. * indicates present work.

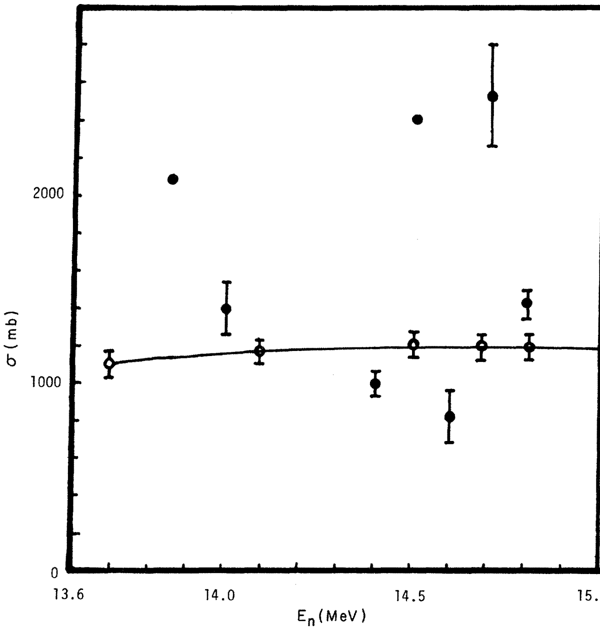
tions in the present study. These cross sections, which are in reality folded weighted averages of cross sections over energy distributions similar to that shown in Fig. 1, are plotted as functions of the quoted neutron energy. The numerical values of $\sigma_{n,2n}$ and the neutron energy E_n in each case are also listed alongside for quick reference. The values obtained by β-counting methods are distinguished from those obtained by γ-activity measurement. Wherever measurements are available at several energies by one group of authors, a line is drawn through them to indicate the trend of the excitation function. The wide scatter in the experimental points in almost all the cases is disturbing. It is likely that some of this scatter is due to the differing flux-energy distributions used



$^{85}Rb(n, 2n)^{84}Rb$

E_n	σ(mb)	Ref.
13.65	830 ± 125	32
13.69	1356 ± 68	22
13.9	1440	23
14.09	1447 ± 72	22
14.1	964 ± 58	24
14.4	892 ± 70	*
14.5	1870	23
14.5	1498 ± 75	22
14.6	687 ± 74	25
14.68	1520 ± 76	22
14.7	1682 ± 222	21
14.7	1430	23
14.8	1335 ± 90	26
14.81	1530 ± 77	22
14.88	1174 ± 94	24

FIG. 5. Cross sections for the ^{85}Rb$(n, 2n)^{84}$Rb reaction. Curves A and B are excitation functions drawn through the results from Refs. 23 and 25, respectively. The activity was measured by detecting (o) β particles, and (•) γ rays. * indicates present work.



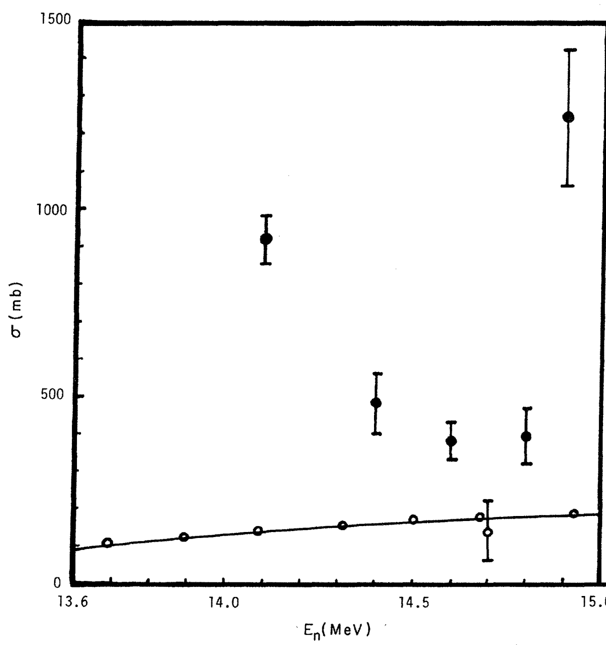
$^{87}Rb(n, 2n)^{86}Rb$

E_n(MeV)	σ(mb)	Ref.
13.69	1107 ± 55	22
13.85	2080	23
14.05	1390 ± 140	27
14.09	1170 ± 59	22
14.4	995 ± 99	*
14.5	1211 ± 61	22
14.5	2420	23
14.6	838 ± 136	25
14.68	1194 ± 60	22
14.7	1560 ± 160	27
14.7	2551 ± 300	21
14.8	1417 ± 72	26
14.81	1191 ± 60	22

FIG. 6. Cross sections for the $^{87}Rb(n, 2n)^{86}Rb$ reaction. The excitation function is drawn through the results from Ref. 23. The activity was measured by detecting (o) β particles, and (•) γ rays. *indicates present work.

by the various authors. It appears certain that the majority of the β-counting measurements yielded slightly higher values compared with those from γ counting.

The (n, p) cross sections, Table II, are small in this mass region and generally agree with previous work. The (n, α) cross sections, Table II, are of importance in order to examine the existence of a dip in the region around $Z_R = 32$, where Z_R is the atomic number of the residual nucleus, as proposed by Chatterjee.[36] The particular region of interest is the $2p_{3/2, 1/2}$ proton subshell closure in the Ga-Ge-As region. Total (n, α) cross sections for two of these residual nuclei (i.e., Ga and



$^{84}Sr(n, 2n)^{83}Sr$

E_n(MeV)	σ(mb)	Ref.
13.69	111.1 ± 5.6	22
13.88	115.9 ± 5.8	22
14.09	142.4 ± 7.1	22
14.1	917 ± 65	31
14.31	149.9 ± 7.5	22
14.4	482 ± 80	*
14.5	171.7 ± 8.6	22
14.6	380 ± 50	25
14.68	176.8 ± 8.8	22
14.7	140 ± 80	28
14.8	395 ± 75	26
14.8	1770 ± 180	29
14.9	1244 ± 114	31
14.93	180.6 ± 9.0	22

FIG. 7. Cross sections for the $^{84}Sr(n, 2n)^{83}Sr$ reaction. The excitation function is drawn through the results from Ref. 23. The activity was measured by detecting (o) β particles, and (•) γ rays. *indicates present work.

As) were measured in the present work. In addition, the cross sections for reactions leading to the residual nuclei ^{82}Br, ^{84g}Br, and ^{85m}Kr were measured. An examination of the (n, α) cross sections covering the residual nuclei $Z_R = 30$ to 36, measured at 14.4 MeV, does not indicate any systematic behavior that would reflect the effects of shell structure. The dips in σ vs Z_R pointed out by Chatterjee[36] in other regions may have two possible origins: (1) shell-structure effects; or (2) the absence of stable isotope targets to cover all possible values of Z_R.

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