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Cross Sections for Nonelastic Interactions of 14-Mev Neutrons with Various Elements*

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The multiplication of neutrons by thin spherical shells of various materials surrounding a point source of 14-Mev neutrons has been measured. A special long counter was used whose energy response is independent of neutron energy over a range of energies from about 1 Mev to 14 Mev. The transmission of primary energy neutrons through the shells has been measured with a trans-stilbene detector and values of the inelastic collision cross sections have been derived. The quantity $\sigma_{n,2n}+2\sigma_{n,3n}-\sigma_c$ is calculated, where $\sigma_{n,2n}$ and $\sigma_{n,3n}$ are the cross sections for $(n,2n)$ and $(n,3n)$ reactions and σ_c is the sum of the cross sections of all processes which destroy a neutron. Upper and lower limits are derived for $\sigma_{n,2n}$, σ_c, and σ_{is} (inelastic scattering) for all materials investigated. For a number of materials specific values for the cross sections are obtained.

INTRODUCTION

USUALLY the cross sections for $(n,2n)$, (n,p), (n,α), etc., reactions are measured by utilizing induced activities.[1,2] However, where stable isotopes result, this method is not applicable and in many other cases it is impractical. However, the existence of $(n,2n)$ reactions is manifest in a material under neutron bombardment by an increase in the number of neutrons, while the effect of capture, (n,p), (n,d), (n,α) reactions etc., is to reduce the number of neutrons. The concept of neutron multiplication is thus introduced which is not dependent upon the characteristics of the end products of the reactions but only upon the balance between those processes which increase, those which leave unchanged, and those which decrease the number of neutrons, and upon the number of events of the three kinds which occur in the material. The neutron multiplication of a layer of material is then defined as the total number of neutrons emerging divided by the number of primary neutrons incident upon the layer.

It is clear that a primary neutron incident upon the layer either will suffer a collision while traversing the layer or will be transmitted without suffering a collision. The concept of the transmission of primary neutrons is thereby established, namely that fraction of the primaries which is transmitted without collision. For further ease in handling the problem this concept is in the present analysis extended to mean the transmission of *primary energy* neutrons, since collisions of the kind in which we are interested result in secondary neutrons of energy much lower than the primary energy. For intermediate and heavy nuclei, and to a lesser extent for light nuclei, the energy change of a neutron upon elastic scattering is so small that elastically scattered neutrons are classed as primary energy neutrons. The transmission of primary energy neutrons is thus defined as that fraction of the primary neutrons which, during traversal through the material, do not suffer a collision at all or suffer only elastic collisions. Hence, one minus the transmission represents that fraction of the source or primary neutrons which, during traversal of the material, suffer collisions wherein (1) the neutron is lost, (2) the neutron merely suffers appreciable energy loss, or (3) more than one neutron results from the interaction. These collisions are called inelastic collisions and are associated with the cross section for inelastic collision, σ_i. For brevity, neutrons resulting from such collisions, as distinguished from elastic scattering collisions, will be called inelastic-collision neutrons.

Having established the concepts of neutron multiplication and transmission, it is proposed firstly to establish the relationship between these quantities and certain cross sections; secondly to describe the measurement of these quantities for 14-Mev primary neutrons; and thirdly to derive, from these measurements, values of inelastic collision cross section, and limits of permissible values for, and in many cases specific values for, cross sections for the three kinds of inelastic events (1), (2), and (3) as described above.

OUTLINE OF METHOD

As has been stated by a number of investigators,[3] if a thin shell of material surrounds an isotropic point source of neutrons and all cross sections for neutron interaction in the material are zero except for elastic scattering, a neutron detector placed at sufficient distance from the shell will not detect the presence of the shell of material. That is, the neutrons per cm² per second passing through any imaginary surface for a fixed source strength will be unchanged by introducing the shell around the source. It follows that even if the cross sections for processes other than elastic scattering are not zero, the elastic scattering may still be ignored except insofar as it increases the average path length of neutrons emerging through the sphere. It is generally accepted that for 14-Mev neutrons the elastic scattering should be diffraction type scattering, and, except perhaps for very light elements, will be confined primarily to small angles. Consequently the path length of an elastically scattered neutron emerging through the shell

* Work done under the auspices of the U. S. Atomic Energy Commission.
[1] Stuart G. Forbes, Phys. Rev. 88, 1309 (1952).
[2] E. B. Paul and R. L. Clarke, Can. J. Phys. 31, 267 (1953).
[3] H. H. Barschall, Revs. Modern Phys. 24, 120 (1952), see p. 128.

differs only very slightly from an unscattered neutron and the effect may be neglected.

Let a thin spherical shell of material surround an isotropic source of 14-Mev neutrons. Then the following equation relating multiplication and transmission may be stated for nonfissioning materials:

$$M=T+(1-T)\left\{\frac{\sigma_{is}}{\sigma_i}+\frac{2\sigma_{n,2n}}{\sigma_i}+\frac{3\sigma_{n,3n}}{\sigma_i}\right\}, \quad (1)$$

where M, the multiplication, is the total number of neutrons emerging per source neutron, T, the transmission of primary energy neutrons is that fraction of the source neutrons which emerges from the shell having suffered no inelastic collisions, and σ_i is the inelastic collision cross section defined by

$$\sigma_i\equiv\sigma_{\text{total}}-\sigma_{\text{elastic}}=\sigma_{is}+\sigma_{n,2n}+\sigma_{n,3n}+\sigma_c, \quad (1a)$$

where σ_{is} = cross section for inelastic scattering, i.e., any $(n,1n)$ inelastic reaction, $\sigma_{n,2n}$ and $\sigma_{n,3n}$ = cross section for $(n,2n)$ and $(n,3n)$ reactions [for higher-energy primary neutrons similar terms for $(n,4n)$, etc. should be included], and

$$\sigma_c=\sigma_{n,p}+\sigma_{n,\alpha}+\sigma_{n,\gamma}, \text{ etc.}, \quad (1b)$$

is the sum of the cross sections for all processes which destroy a neutron. Substitution for σ_{is} and collection of terms leads to

$$\frac{M-T}{1-T}=\left\{1+\frac{\sigma_{n,2n}}{\sigma_i}+2\frac{\sigma_{n,3n}}{\sigma_i}-\frac{\sigma_c}{\sigma_i}\right\}\equiv 1+k. \quad (2)$$

The left side of this equation combines the observable quantities M and T, each of which is a function of the thickness of the material while the right side involves only nuclear constants. The quantity in brackets in Eq. (2) is the number of neutrons per inelastic collision, and defines the quantity k as shown.

If a neutron detector whose sensitivity is entirely independent of neutron energy is placed at a sufficiently large distance from the shell surrounding the source, the counting rate of this detector per source neutron for the source surrounded by a shell divided by the counting rate per source neutron for the bare source is equal to the neutron multiplication M. However, if the detector sensitivity is not independent of neutron energy, the measured multiplication M', that is, the ratio of the counting rates just described, will be related to the true multiplication, M, in some manner which must be determined. It has been found by the photographic plate method[4-6] that the neutrons resulting from inelastic interaction of 14-Mev neutrons with intermediate and heavy nuclei are almost entirely of low energy, that is, below about 3 or 4 Mev. Hence neutrons emerging from the shell are in one of two energy groups, either 14 Mev or degraded to less than 3 or 4 Mev. If a detector such as the Hanson-McKibben[7] type long counter whose sensitivity is independent of neutron energy from approximately zero to 5 Mev be used, the equation for M', the measured multiplication, may be written

$$M'=T+(1-T)(1+k)(\epsilon'/\epsilon_0), \quad (3)$$

where ϵ'/ϵ_0 = efficiency for detecting the inelastic neutrons divided by the efficiency for detecting the primary neutrons.

The equation as derived so far assumes thin shells and ignores second-order effects, i.e., multiplication or capture of the inelastic-collision neutrons from the primary interaction before escape from the material. This effect may be introduced by defining M'', the apparent multiplication including this effect as well as detector sensitivity, as

$$M''=T+(1-T)(1+k)(\epsilon'/\epsilon_0)(1+\delta), \quad (4)$$

where δ may be either positive or negative and will be a function of the shell thickness for any given material. For the majority of materials, δ will be negative (if not zero) because of capture before escape. Experimentally, δ is shown to be either zero or negligible by establishing the invariance of $(M''-T)/(1-T)(\epsilon'/\epsilon_0)$ with respect to change of shell thickness.

NEUTRON DETECTORS

1. For the Measurement of M

A shielded Hanson-McKibben type long counter built as described by the originators[7] has a sensitivity to 14-Mev neutrons which is approximately 60 percent of the sensitivity to Ra-α-Be neutrons. The sensitivity of such a long counter was modified by changing the proportional counter in the central tube. A shorter counter (5-in. active length) was substituted which was located farther back in the paraffin such that its active volume began approximately at the base of the 1-in. holes which are drilled in the paraffin face, although the exact boundaries of the active volume within the counter tube were not determined. This served to reduce the absolute sensitivity to neutrons of all energies but reduced the sensitivity to faster ones less than to slower ones. The relative sensitivity depended strongly on the counter location.

A calibration of the sensitivity of the counter as a function of neutron energy was made with the 14-Mev neutron source whose strength was accurately determined by counting alpha particles from the reaction, with a standard Ra-α-Be source, and with mock fission,[8] Na-γ-D, and Sb-γ-Be sources whose strengths were determined by comparison of the flux produced in a

[4] E. R. Graves and Louis Rosen, Phys. Rev. **89**, 343 (1953).
[5] P. H. Stelson and C. Goodman, Phys. Rev. **82**, 69 (1951).
[6] B. G. Whitmore and G. E. Dennis, Phys. Rev. **84**, 296 (1951).
[7] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[8] D. S. Martin, Atomic Energy Commission Document No. 3077 (unpublished).

graphite pile[9] with that produced by the standard RaBe source. The thermal fluxes were compared and the source strengths calculated making use of the age theory with refinements indicated by Marshak.[10] It was assumed that because of the growing in of RaD+E+F the standard neutron source strength had increased by 2.0 percent between the standardization by Walker[11] in 1944 and this calibration which was made in February 1952.

The relative sensitivity values of the long counter are given in Table I for two locations of the counter such that position B was 0.75 in. farther back from the front face of the paraffin than position A. Position A was used for the multiplication measurements. The accuracy of the relative sensitivity is about 2 percent for the energy range up to Ra-α-Be neutrons. The accuracy of the comparison of this range with 14-Mev is limited by the uncertainty of 5 percent in the primary Ra-α-Be source standardization. It may be seen that the sensitivity drops off for neutron energies of a few hundred kilovolts. This means that the measured multiplications may fall slightly below the true values depending on the fraction of the neutrons which fall in this energy region. It is felt that the error is not large, however, and that the advantage of energy independence at the higher energies outweighs this disadvantage. (ϵ'/ϵ_0) as defined in Eq. (3) is taken to be equal to 1.00. It may be seen that an error in ϵ'/ϵ_0 will reflect in a systematic error of the same magnitude in $(M-T)/(1-T)$. This has not been included in the errors given for the measurements. The change in k and hence in $k\sigma_i$ induced by a 5 percent change in ϵ'/ϵ_0 is about equal to the experimental errors quoted for the light and intermediate elements and up to 4 or 5 times the quoted errors for the heavy elements.

The long-counter detector was placed at a distance of 180 cm from the neutron source. The background counting rate measured with a thick iron shadow cone between the source and long counter was about 14 percent for both 14-Mev neutrons and Ra-α-Be neutrons. Since the multiplications are close to unity and the background appeared not to vary appreciably with neutron energy, no correction was made for background in the measurement of M.

TABLE I. Sensitivity of the modified long counter as a function of neutron energy for two positions of the proportional counter in the center tube.

Neutron source	Neutron energy	Sensitivity = counts per neutron (arbitrary units) Position A	Position B
Sb-γ-Be	25 kev	0.57	0.45
Na-γ-Be	220 kev	0.63	0.56
M.F.	fission spectrum	1.01	...
Ra-α-Be	Average 5 Mev	1.00	1.00
$d-T$	14 Mev	1.00	1.00

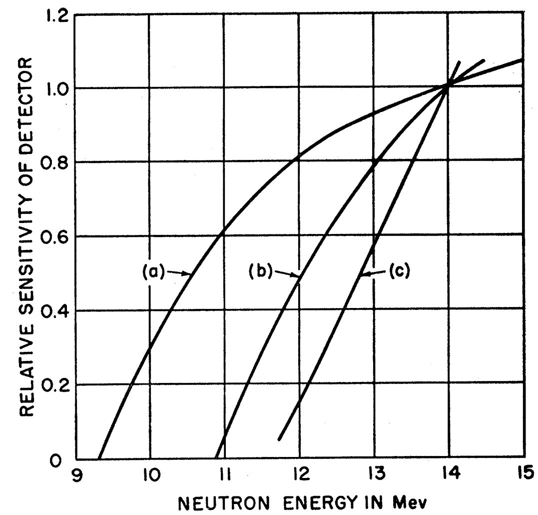

FIG. 1. Sensitivity of detectors. (a) Ideal hydrogen recoil detector biased such that all protons of energy greater than two-thirds of 14 Mev are counted. (b) Stilbene scintillator used in this experiment biased such that all pulses greater than two-thirds of the pulse height produced by a 14-Mev proton are counted. (c) $Cu^{63}(n,2n)$ detector from references 16 and 17.

2. For the Measurement of T

A trans-stilbene crystal mounted on a photomultiplier tube served to detect high-energy neutrons. The detector was biased so that all pulses larger than $\frac{2}{3}$ of the maximum pulse height were counted. The background counting rate determined with a shadow bar was approximately 1 percent. Curve (a) of Fig. 1 shows the calculated sensitivity of an ideal hydrogen recoil detector biased at $\frac{2}{3}$ of incident neutron energy. The curve of pulse height *vs* proton energy measured for another trans-stilbene detector was used to convert the ideal sensitivity curve to that of the actual detector used. Curve (b) portrays the result of this calculation. Since, for all but the lightest elements, degradation of neutron energy by elastic scattering is negligible, the counting rate of this detector with and without the sphere of scattering material surrounding the source gave the transmission, T, desired. Small deviations introduced by the detector sensitivity will be discussed later.

The assumption must be justified that the detector as used is sufficiently insensitive to γ rays. Inelastic scattering in the sphere material and in the target material both produce γ rays. Hence if the detector responds to γ rays, the observed transmission may be either too large or too small, depending on the properties of the sphere material. Calibration of the detector showed the pulse height of a 14-Mev proton to be 6.5 times the maximum height of the pulse from a 1.28-Mev γ ray. Hence the bias of two-thirds of the 14-Mev proton pulse height was still about $4\frac{1}{2}$ times the γ-ray

[9] A. C. Graves *et al.*, *Neutron Sources* (McGraw-Hill Book Company, Inc., New York, 1952); National Nuclear Energy Series, Plutonium Project Record, Vol. 3, Div. V, Chap. 2, Sec. 5.

[10] R. E. Marshak, Revs. Modern Phys. **19**, 185 (1947).

[11] R. L. Walker, Atomic Energy Commission Document MDDC-414 (unpublished).

TABLE II. Summary of measurements of transmissions and multiplication of spherical shells of various materials. Symbols are defined in Eqs. (1) through (4) and text.

Element	N (atoms/cm²) $\times 10^{-24}$	M''	T	$\left(\frac{M-T}{1-T}\right)$	$\left(\frac{M-T}{1-T}\right)-1 = k$	σ_i (barns) from $T=e^{-N\sigma_i}$	$k\sigma_i$ (barns)
C	0.299	0.9831	0.8364	0.897	−0.103	0.597	−0.062
	0.597	0.9507	0.695	0.839	−0.161	0.609	−0.098
Al	0.218	0.9590	0.7962	0.799	−0.201	1.01[a]	−0.20
	0.435	0.9194	0.6409	0.776	−0.224	0.994[a]	−0.22
Fe	0.174	1.012	0.8052	1.062	0.062	1.24	0.077
	0.349	1.009	0.6325	1.026	0.026	1.31	0.034
Cu	0.175	1.040	0.7851	1.187	0.187	1.38	0.266
	0.349	1.056	0.5997	1.139	0.139	1.47	0.197
Zn	0.169	1.021	0.7851	1.098	0.098	1.43	0.143
	0.340	1.014	0.6014	1.036	0.036	1.50	0.053
Ag	0.151	1.095	0.7596	1.394	0.394	1.82	0.717
Cd	0.139	1.113	0.7573	1.467	0.467	2.00	0.911
	0.279	1.175	0.5914	1.429	0.429	1.88	0.837
Sn	0.130	1.123	0.7669	1.527	0.527	2.04	1.03
	0.259	1.208	0.6142	1.539	0.539	1.88	1.06
Au	0.130	1.136	0.7282	1.501	0.501	2.44	1.22
Pb	0.105	1.166	0.7699	1.721	0.721	2.49	1.80
	0.210	1.280	0.5929	1.688	0.688	2.49	1.71
Bi	0.0985	1.165	0.7789	1.746	0.746	2.54	1.88
	0.1970	1.285	0.6099	1.730	0.730	2.51	1.84

[a] Correction has been made for copper content of alloy used.

pulse quoted. For most materials the γ-ray energy emitted is predominately lower than 6 or 7 Mev,[12] and hence would not be detected with appreciable efficiency. However, iron emits some γ rays of ≈ 7 Mev and 9 Mev with a cross section of ≈ 0.1 barn.[13,14] The neutrons emitted from the target in the present experiment pass through a thin stainless steel shell and it may be calculated that about 0.03 percent of them produce these γ rays. The number of γ rays per source neutron produced in the tungsten target backing is estimated to be 0.5 percent per barn of cross section for their production. Since it may be shown that the stilbene detector is somewhat less sensitive to γ rays of this energy than it is to 14-Mev neutrons, the effect of γ rays from the target is considered negligible.

Of the materials investigated, the only one for which γ rays from the sphere itself might be detected is iron. It has been calculated that, if they all emerged from the sphere and the pulses generated in the detector were recorded with the same efficiency as the 14-Mev neutron pulses, the measured transmission of the $\frac{1}{2}\lambda$ sphere should be multiplied by a factor 0.96 and of that of the $\frac{1}{4}\lambda$ sphere by a factor 0.98. Since the bias of the detector is relatively higher for the γ rays than for the neutrons, and since there is considerable attenuation of the γ rays by the sphere, it is felt that this correction should not be made and it has therefore been omitted.

[12] M. E. Battat (private communication).
[13] Sherrer, Theus, and Faust, Phys. Rev. **89**, 1268 (1953).
[14] Sherrer, Theus, and Faust, Phys. Rev. **91**, 1476 (1953).

NEUTRON SOURCE AND SCATTERERS

A thick Zr-T target was bombarded by a collimated $\frac{3}{16}$-inch diameter beam of 220-kev diatomic deuterium ions to produce neutrons. The strength of the source was measured by counting alpha particles in a proportional counter in a known geometry. The emission of neutrons was only slightly different from isotropic. The forward yield was calculated to be four percent greater and the backward yield four percent lower than the yield at 90°. Both neutron detectors were very nearly at 90°. It is felt that the yield variation is not important for the spherical shell experiments reported here. The neutron energy varied somewhat with angle of emission. Neutrons emitted at 90° to the incident beam had an average energy of 14.1 Mev while at 0° and 180° the averages were, respectively, 0.6 Mev higher and 0.6 Mev lower than the 90° value.

The scatterers were interlocking hemispherical shells through which two holes three-quarters of an inch in diameter and one hole one-half inch in diameter passed to accomodate the beam tube, target tube, and alpha monitor tube. The shells were hung by means of screw eyes which threaded into them. The outer diameter of all the shells was 8.00 inches, and the wall thickness of any shell was uniform to within ± 0.001 inch. Thick-

TABLE III. Summary of cross sections in barns derived from transmission and multiplication measurements. Columns 2 and 3 give values of σ_i and $k\sigma_i$ as measured in the present experiment. For comparison, σ_i from Phillips, Davis, and Graves[a] is given in parenthesis under σ_i from this experiment in Column 2. Columns 4, 5, and 6 give limits of σ_c, $\sigma_{n,2n}$, and σ_{is} as defined in Eqs. (1a) and (1b). For elements Al through Ag values for one of the three cross sections are taken from Forbes[b] or Paul and Clarke[c] and the other two calculated from Eqs. (5a) and (6).

Element	σ_i, this expt. (σ_i, reference a)	$k\sigma_i$	σ_c	$\sigma_{n,2n}$	σ_{is}
C	0.601±0.006 (0.76±0.04)	−0.08±0.02	0.08±0.02 (=C(n,α)Be^9 grnd. state)	0.00 (below threshold)	0.52±0.02 (See text for components)
Al	1.00±0.01 (1.06±0.05)	−0.21±0.01	0.214±0.015[b] [0.13±0.03][c]	0.00±0.02 [−0.08±0.03]	0.79±0.03
Fe	1.27±0.04 (1.45±0.02)	0.07±0.03	$0.114\leqq\sigma_c\leqq0.60$ ±0.01 ±0.03[b]	$0.18\leqq\sigma_{n,2n}\leqq0.67$ ±0.03 ±0.04	$0.97\geqq\sigma_{is}\geqq0.00$ ±0.06
Cu	1.42±0.04 (1.51±0.06)	0.24±0.02	0.41±0.06 (See text)	0.65±0.05[b]	0.36±0.09
Zn	1.46±0.03	0.11±0.04	$0.22\leqq\sigma_c\leqq0.68$[c] ±0.04 ±0.03	$0.33\leqq\sigma_{n,2n}\leqq0.79$ ±0.06 ±0.05 (See text)	$0.91\geqq\sigma_{is}\geqq0.00$ ±0.09
Ag	1.82±0.02	0.72±0.03	0.06±0.09	0.77±0.08[b]	1.0±0.2
Cd	1.95±0.05 (1.89±0.06)	0.89±0.02	$0.00\leqq\sigma_c\leqq0.53$ ±0.03	$0.89\leqq\sigma_{n,2n}\leqq1.42$ ±0.02 ±0.04	$1.06\geqq\sigma_{is}\geqq0.00$ ±0.06
Sn	1.96±0.05	1.04±0.02	$0.00\leqq\sigma_c\leqq0.46$ ±0.03	$1.04\leqq\sigma_{n,2n}\leqq1.50$ ±0.02 ±0.04	$0.92\geqq\sigma_{is}\geqq0.00$ ±0.06
Au	2.44±0.02 (2.51±0.04)	1.22±0.02	$0.00\leqq\sigma_c\leqq0.61$ ±0.02	$1.22\leqq\sigma_{n,2n}\leqq1.83$ ±0.02 ±0.03	$1.22\geqq\sigma_{is}\geqq0.00$ ±0.04
Pb	2.49±0.02 (2.56±0.05)	1.76±0.04	$0.00\leqq\sigma_c\leqq0.36$ ±0.03	$1.76\leqq\sigma_{n,2n}\leqq2.12$ ±0.04 ±0.05	$0.73\geqq\sigma_{is}\geqq0.00$ ±0.06
Bi	2.53±0.02 (2.56±0.05)	1.86±0.02	$0.00\leqq\sigma_c\leqq0.33$ ±0.02	$1.86\leqq\sigma_{n,2n}\leqq2.19$ ±0.02 ±0.03	$0.67\geqq\sigma_{is}\geqq0.00$ ±0.04

[a] See reference 15.
[b] See reference 1.
[c] See reference 2.

nesses in atoms per cm^2 were calculated from accurate weights and dimensions and are thought to be accurate to about ±1 percent. Two shells of approximately one-quarter and one-half mean free path thickness for inelastic collisions were measured for each element except gold and silver.

RESULTS

Table II summarizes the measurement of M and T and the resulting inelastic-collision cross sections and number of neutrons per inelastic collision. Column 5 lists measured values of $(M''-T)/(1-T)$ which should be equal to $(M-T)/(1-T)$, the number of neutrons per inelastic collision, if δ as defined in Eq. (4) is zero. It may be seen that $(M''-T)/(1-T)$ for the thinner shells tends to be around two to four percent higher than for the thicker shells. Not only true capture, i.e., $\delta<0$, could cause this effect but a degradation of neutron energy by multiple scattering into the few-hundred-kilovolt energy region where the sensitivity of the long counter is reduced. The effect, if real, is so small that the thin-shell values are interpreted as good values of the number of neutrons per inelastic collision. The statistical errors in the data are negligible.

The inelastic-collision cross sections, σ_i, given in Column 7 have been calculated from the formula $T=e^{-N\sigma_i}$, where N is the number of atoms per cm^2 in the shell. This method ignores elastic scattering effects which tend to increase the average path length of the emerging neutrons. However, for 14-Mev neutrons the elastic scattering is concentrated in a forward cone so that the increase of path length is not very large. It is estimated that for the 60 percent transmission shells the error in the calculated value of σ_i will be less than 3 percent. This correction has not been made. For the thinner shells the error is negligible.

A second source of possible error in the σ_i values is the variation of sensitivity of the scintillation detector with energy of elastically scattered neutrons. Only in the lightest elements will there be sufficient energy loss accompanying elastic scattering to cause any possibility of error. A neutron scattered from carbon at an angle of 40° has an energy of 0.96 times the primary energy. It may be seen from Fig. 1 that for this energy the detector sensitivity has dropped to 89 percent of its value for the primary energy, while for 70° scattered neutrons the detector sensitivity is reduced to 65 percent of the primary value. A rough estimate of the contribution of elastic scattering to the measured σ_i is 0.05 barn. The $Cu^{63}(n,2n)$ threshold detector was used to measure inelastic-collision cross sections by Phillips *et al.*[15] and their values appear in parenthesis in Table III Column 2 for comparison. Curve (c) of Fig. 1 gives the normalized sensitivity of the $Cu^{63}(n,2n)$ detector from measurements of Fowler and Slye,[16] and Brolley *et al.*[17] The same assumptions concerning elastic scattering as made above lead to the conclusion that as much as 0.1 barn of elastic scattering cross section might be included in the σ_i value measured with the copper detector. The difference between the values for carbon is thus fairly well accounted for by the estimate of the difference in detector sensitivity. Measurements of angular distribution of elastic scattering now being completed by J. H. Coon of this laboratory will allow more precise evaluation of this effect on σ_i as measured. Except for iron, the inelastic-collision cross section measurements are in reasonably good agreement for the various materials. No explanation is offered here for the discrepancy between the iron values.

From Eq. (2) it may be seen that

$$\left(\frac{M-T}{1-T}-1\right)\sigma_i=k\sigma_i\equiv\sigma_{n,2n}+2\sigma_{n,3n}-\sigma_c. \quad (5)$$

Rewriting Eq. (1a) in more convenient form, one has

$$\sigma_i=k\sigma_i+2\sigma_c+\sigma_{is}-\sigma_{n,3n}. \quad (6)$$

Provided that $\sigma_{n,3n}$ be zero, which must be true for 14-Mev neutrons on almost all elements, Eqs. (5) and (6) used with the measured values of $k\sigma_i$ and σ_i serve to establish upper and lower limits on the allowed values of $\sigma_{n,2n}$, σ_c, and σ_{is}. From Eq. (5) it is seen that lower limits for σ_c and $\sigma_{n,2n}$ are $\sigma_c\geqq 0$ and $\sigma_{n,2n}\geqq k\sigma_i$ corresponding to the upper limit $\sigma_{is}\leqq\sigma_i-k\sigma_i$ for σ_{is} from Eq. (6). The lower limit for σ_{is} is obviously zero and leads to upper limits of $\sigma_c\leqq\frac{1}{2}(\sigma_i-k\sigma_i)$ and $\sigma_{n,2n}\leqq[k\sigma_i+\frac{1}{2}(\sigma_i-k\sigma_i)]$. The limits derived thusly define the range of possible values for the cross sections $\sigma_{n,2n}$, σ_c, and σ_{is}. Selection of any particular allowed value for one of them fixes the values of the other two. Various information available in the literature allows determination for some elements of values of the cross sections. For elements where such is not the case, limits of possible cross section values are derived. Table III summarizes the values of σ_i and $k\sigma_i$ from this experiment, and the resulting limits of values for $\sigma_{n,2n}$, σ_c, and σ_{is} or the specific values for each in cases where one is available from the literature.

Carbon

Since $(n,2n)$ reaction is impossible for 14-Mev incident neutrons, $k\sigma_i$ is equal to $-\sigma_c$. An average cross section from the two shells for σ_c is 0.08 ± 0.02 barn. Since the reactions $C^{12}(n,p)B^{12}$ and $C^{12}(n,d)B^{11}$ with Q values of -12.6 Mev and -13.7 Mev are not likely to occur, this cross section is assigned, at least as an upper limit, to the reaction $C(n,\alpha)Be^9$ where the Be^9 is formed in the ground state. Formation of Be^{9*} in the 2.43-Mev level which decays mainly by neutron emission[18,19] would not be included in this cross section. The difference between $\sigma_i=0.601\pm0.006$ barn and 0.08 ± 0.02 barn must represent the cross section for all reactions which do not result in the disappearance of a neutron. Two different reactions may contribute to this cross section:

(1) $C+n\rightarrow C^{13*}\rightarrow C^{12*}+n$,

(2) $C+n\rightarrow C^{13*}\rightarrow Be^{9*}+\alpha\rightarrow Be^8+n+\alpha$.

The nucleus C^{12} in (1) may be left in a number of different states. Decay to the ground state of C^{12} by gamma emission has been measured by a number of observers.[14,20–22] Values range from 0.1 to 0.3 barn for the cross section for production for the 4.4-Mev line. Green and Gibson[23] have measured the cross section for $C^{12}(n,n)C^{12*}\rightarrow 3\alpha+n$ by the photographic emulsion technique to be 0.16 barn for 14.5-Mev neutrons. If 0.20 barn be taken for the decay by gamma-ray emission and 0.16 barn for decay by alpha emission there remains 0.15 barn of cross section for other processes in which a neutron does not disappear. Within the errors this value could be as low as 0.05 barn.

Reaction (2) leads to the same end products as those reached from C^{12*} levels decaying by alpha emission. The Q for reaction (2) going to the first excited state of Be^{9*} is -8.1 Mev and hence the alpha particles emitted should have about 4 Mev of energy. These should be easily observable as should the ground-state alphas.

Since the 7.5-Mev level of C^{12} cannot decay to the ground state by gamma emission ($J=0\rightarrow J=0$) it must decay by cascade gamma emission, by internal pair formation, or by alpha emission. The energy available for alpha emission is very small, only about 0.2 Mev and such disintegration would be most difficult to observe. Internal pair formation of this level has been observed by Harris and Davis[24] along with similar decay of the 4.4-Mev level. However, as expected theoretically, the probability was extremely small. Sherrer, Theus, and Faust[14] have reported a 2.8-Mev gamma-ray line which might be a cascade line with a production cross section approximately one-third of that for the 4.4-Mev line, but this was not observed by Battat and Graves.[21] One is forced to conclude that the 7.5-Mev level is not

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[22] L. C. Thompson and J. R. Risser, Phys. Rev. **94**, 941 (1954).
[23] L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **62**, 296 (1949).
[24] G. Harries and W. T. Davis, Proc. Phys. Soc. (London) **A65**, 564 (1952).

formed with any degree of abundance or that it decays by alpha emission of such low energy as to be unobservable. More precise determinations of the 4.4-Mev gamma-production cross section and of the $C^{12}(n,\alpha)Be^{9*}$ reaction cross section should be useful in this connection.† It is suggested then that the component parts of $\sigma_i = 0.60$ barn are as follows:

$C^{12}(n,\alpha)Be^9$, $\sigma = 0.08 \pm 0.02$ barn;

$C^{12}(n,n)C^{12*}$ levels 9.6 Mev to ≈ 13 Mev, $\sigma = 0.16$ barn, (these levels go to 3 alphas);

$C^{12}(n,n)C^{12*}$ levels 7.5 Mev and 4.4 Mev, $\sigma \approx 0.10$ to 0.30 barn;

$C^{12}(n,\alpha)Be^{9*}$, $\sigma = 0.31$ barn minus σ for $C^{12}(n,n)C^{12*}$ for 7.5-Mev and 4.4-Mev levels;

$C^{12}(n,n)C^{12}$ elastic scattering included in σ_i, $\sigma_{es} \approx 0.05$ barn.

Aluminum

The average value of $k\sigma_i$ from the two shells is -0.21 ± 0.01 barn. Forbes[1] has measured the cross sections for (n,p) and (n,α) reactions, the sum of which equals σ_c for aluminum. This sum is 0.214 barn and substituting in the equation $k\sigma_i = \sigma_{n,2n} - \sigma_c$ we find that $\sigma_{n,2n} = 0.00$ barn which checks expectation from measurements of the (γ,n) reaction,[25,26] and with measurements in this Laboratory. Paul and Clarke[2] find a value for the sum of (n,p) and (n,α) reactions equal to 0.13 barn which, combined with the present experiment would lead to an $(n,2n)$ cross section of -0.08 ± 0.01 barn. The more consistent results are hence obtained using the values of Forbes. The difference $(\sigma_i - \sigma_c) = 0.79 \pm 0.02$ barn hence represents inelastic scattering to be compared with 0.65 ± 0.17 barn from nuclear plate measurements.[4]

Iron

If a value of $\sigma_c \geqq 0.114$ barn is taken for the normal isotopic mixture derived from Forbes' cross-section value of 0.124 barn for the $Fe^{56}(n,p)Mn^{56}$ reaction, Eq. (5) leads to $\sigma_{n,2n} \geqq 0.18 \pm 0.02$ barn for the normal isotopic mixture. Because the Q-value for $Fe^{54}(n,2n)Fe^{53}$ is -13.8 Mev, all of this is probably due to $Fe^{56}(n,2n)$-Fe^{55} which would then have an isotopic cross section of $\geqq 0.36 \pm 0.04$ barn.

† *Note added in proof.*—Recently completed work by Frye, Rosen, and Stewart of this Laboratory [G. M. Frye, Jr., L. Rosen, and L. Stewart (to be published)] utilizes the nuclear emulsion technique to investigate three-alpha-decay processes following neutron bombardment of carbon. For 14-Mev primary neutron energy, only a small fraction of the observed events could be attributed to decay through Be^{9*}. The observed events are examined carefully according to momentum considerations and various modes of disintegration are assigned. A correction for "missed" events is applied leading to a cross section of 230 ± 50 mb for three-alpha decay through C^{12*} excited to 9.6 Mev and higher.

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[26] L. Katz and A. G. W. Cameron, Phys. Rev. **83**, 892 (1951).

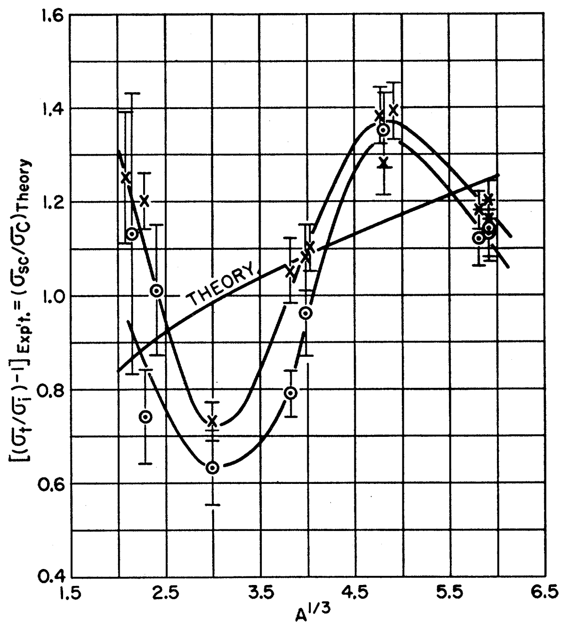

FIG. 2. Experimental values of $[(\sigma_t/\sigma_i)-1]$ are plotted as a function of the cube root of the mass. Values of σ_t are taken from reference 29. × points are from σ_i reported here (with the exception of beryllium for which a preliminary unreported value is included), whereas circles are from σ_i values from reference 15. The solid line marked "THEORY" shows the prediction of Weisskopf and his associates (see references 27 and 28) for σ_{sc}/σ_C which is identified with the experimental quantity plotted.

Copper

From Forbes,[1] $\sigma_{n,2n}$ for the normal mixture is 0.65 ± 0.05 barn. Solving Eq. (5) one finds $\sigma_c = 0.41 \pm 0.06$ barn. The contribution[1] to σ_c of $Cu^{65}(n,p)Ni^{65}$ is 0.006 barn, leaving 0.40 ± 0.06 barn for the normal isotopic mixture to be accounted for by some other reaction which destroys a neutron. The reaction $Cu(n,np)Ni$ does not result in the destruction of a neutron and hence, in this kind of measurement, is not included in σ_c but is included in σ_{is}. Substituting in Eq. (1a) one derives for the normal isotopic mixture $\sigma_{is} = 0.36 \pm 0.09$ barn.

Zinc

From Paul and Clarke's[2] measurements of $Zn^{64}(n,p)$-Cu^{64} and $Zn^{66}(n,p)Cu^{66}$ reaction cross sections, a value for σ_c is calculated of $\geqq 0.22 \pm 0.04$ barn for the normal isotopic mixture. The value for $\sigma_{n,2n}$ derived from Eq. (5) is then $\sigma_{n,2n} \geqq 0.33 \pm 0.06$ barn and for σ_{is} is $\leqq 0.91 \pm 0.09$ barn. Paul and Clarke also measured $\sigma_{n,2n}$ for Zn^{64}. Their value would give a contribution of 0.11 ± 0.02 barn to the normal isotopic mixture value leaving 0.22 ± 0.07 barn to be accounted for by the other isotopes. This would imply that the isotopic cross section for $Zn^{66}(n,2n)Zn^{65}$ must be from 0.4 to 0.5 barn.

Silver

Combining $k\sigma_i = 0.72 \pm 0.03$ barn with $\sigma_{n,2n} = 0.774$ ± 0.08 barn for the normal isotopic mixture as derived from Forbes leads to $\sigma_c=0.06\pm0.09$ barn. σ_{is} becomes 1.0 ± 0.2 barns for the normal isotopic mixture.

Cadmium, Tin, Gold, Lead, and Bismuth

For these materials only permissible limits of the cross section are presented as shown in Table III.

Behavior of σ_i

The inelastic-collision cross sections reported here increase somewhat the precision with which a comparison may be made with the theory of nuclear interactions of Weisskopf and his associates.[27,28] Figure 2 portrays the behavior of the quantity $[(\sigma_t/\sigma_i)-1]$ where the values of σ_t, the total cross section for 14.1-Mev neutrons are taken from Coon, Graves, and Barschall.[29] The × points refer to values of σ_i reported here and the circles to values obtained by Phillips *et al.*[15] Although the measurements on beryllium are not reported here, a preliminary value is included in the curve. A curve through the × points and another through the circles are drawn to indicate a band which portrays the general behavior of the experimental quantity. The inelastic collision cross section σ_i experimentally determined is identified with σ_C for compound nucleus formation from the theory where

$$\sigma_t=\sigma_C+\sigma_{sc}.$$

Hence $[(\sigma_t/\sigma_i)-1]$ is equivalent to (σ_{sc}/σ_C) from the theory. The curve marked "THEORY" shows (σ_{sc}/σ_C) upon the assumption that the nuclear radius $=1.5\times10^{-13}A^{\frac{1}{3}}$ cm. Although this theory is undergoing revision, it is felt that the comparison as shown is a useful one since it deals with a fairly fundamental concept. It also shows clearly the regions of atomic mass which need further investigation to better establish the empirical curve.‡

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[28] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. VIII, Sec. 4.
[29] Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952).

‡ *Note added in proof.*—Further investigation of the region between carbon and iron has been made. Preliminary values of the inelastic collision cross section, σ_i, have been obtained for F, S, KCl, Ca, Sc, Ti, and V. These show a discontinuity in the curve of σ_i *vs* $A^{1/3}$ between Ca and Sc, preceded by a smooth rise of σ_i to 1.5 ± 0.1 barn for Ca. Beginning with Sc the values fall on a new smooth curve which extrapolated to lower masses would join the lower branch between F and Al. The preliminary value of σ_i for Ti is 1.23 ± 0.04 barns and for V is 1.32 ± 0.08 barns. These results in conjunction with total cross sections (see reference 29) give additional experimental points for $[(\sigma_t/\sigma_i)-1]$ as a function of $A^{1/3}$ as shown in Fig. 2. From $A^{1/3}=3.00$ the points continue to drop through 0.58 ± 0.07 for $A^{1/3}=3.3\pm0.1$ (KCl) to 0.43 ± 0.10 for $A^{1/3}=3.42$ (Ca). For the next higher $A^{1/3}$ values, Sc and Ti, the values are on a rising curve. For $A^{1/3}=3.63$ (Ti) the preliminary value is 0.85 ± 0.10. Further measurements are in progress.

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Alignment of Cerium-141 and Neodymium-147 Nuclei*†

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The radioactive nuclei Ce^{141} and Nd^{147} have been aligned by the magnetic hfs method (Bleaney) using single crystals of cerium magnesium nitrate. The cerium site is characterized by $B\gg A$, i.e., the "alignment" occurs in a plane. The anisotropies for the 142-kev gamma ray of Ce^{141}, and the 92-kev and 530-kev gamma rays of Nd^{147}, at the lowest temperature (0.00308°K) were found to be +0.12, 0, and −0.39, respectively. These values coupled with the rate of change of anisotropy with temperature identify the transitions as $M1$, $M1+E2$, and $E2$, respectively. The decay schemes supported by these experiments are as follows: Ce^{141} (142 kev), $7/2^- \xrightarrow{0} 7/2^+ \xrightarrow{1} 5/2^+$; Nd^{147} (92 kev), $9/2^- \xrightarrow{1} 7/2^+ \xrightarrow{1,2} 5/2^+$; Nd^{147} (530 kev), $9/2^- \xrightarrow{0} 9/2^+ \xrightarrow{2} 5/2^+$. From the temperature dependence of the anisotropies we can deduce values for the magnetic moments as follows: Ce^{141}, 0.16 ± 0.06 nm; Nd^{147}, 0.22 ± 0.05 nm. These rather small values for odd-neutron nuclei may not be meaningful because of possible internal magnetic field effects in the crystal which are not taken into account in the treatment of the hyperfine interaction.

1. INTRODUCTION

To date, two of the methods which have been proposed for producing oriented nuclear systems at low temperatures have been carried out successfully. Both methods rely on the fact that at the nucleus of certain paramagnetic ions there exists a very large magnetic field (10^5-10^6 oersteds, produced by the unpaired electrons in the unfilled shell) which couples together the electron and nuclear magnetic moments, and produces a considerable hyperfine splitting.

In one method, suggested independently by Gorter[1]

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† A preliminary account of the work on cerium-141 was given at the Spring Meeting of the American Physical Society, April 29–May 1, 1954 [Ambler, Hudson, and Temmer, Phys. Rev. **95**, 625 (1954)].

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