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Absolute Measurement of $(n,2n)$ Cross Sections at 14.1 Mev*

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Absolute $(n,2n)$ cross sections have been obtained by counting double-pulse events in a 240-gal cadmium-loaded liquid scintillator. The detection efficiency was determined experimentally using a spontaneous fission source and known values of $\bar{\nu}$. Conventional methods were used to measure the absolute neutron flux. Cross sections were measured for C, N, F, V, Fe, Cu, Ag, Ta, Cd, Au, Pb, Bi, D, and Be. The values in barns are: C, 0.006±0.006; N, 0.019±0.010; F, 0.062±0.009; V, 0.66±0.05; Fe, 0.50±0.04; Cu, 0.76±0.06; Ag, 1.73±0.13; Ta, 2.64±0.20; Cd, 1.92±0.14; Au, 2.60±0.20; Pb, 2.74±0.20; Bi, 2.60±0.19; D, 0.20±0.02; Be, 0.54±0.04. The $(n,2n)$ cross sections for the last six elements are, within error, equal to the nonelastic cross sections. Nuclear temperatures were calculated.

INTRODUCTION

THE development by Reines *et al.*[1] of a large liquid scintillator having a high efficiency for the detection of neutrons suggested the present method for measuring $(n,2n)$ cross sections. Previous measurements[2] depended on a determination, after neutron bombardment, of the activity produced in a sample of material, and required that the final nucleus decay with the emission of measurable radiation and in a known manner. The present method depends on the detection of the emitted neutrons and permits the measurement of $(n,2n)$ cross sections whether or not the reaction products are unstable. Recently, other methods have been employed to determine $(n,2n)$ cross sections by detection of the neutrons.[3]

The work reported here is part of a continuing program of $(n,2n)$ cross-section measurements over the neutron energy range from threshold energy to 30 Mev.

METHOD OF DETECTION

Short bursts of 14.1-Mev neutrons were produced and collimated on a target at the center of the neutron detector. The counting equipment was then gated on for a 25-μsec period after each burst in order to detect double-pulse events resulting from the emission of two neutrons produced by $(n,2n)$ reactions in the target. The neutron detector used in the experiment was a large, cadmium-loaded, liquid scintillator. Neutrons which entered the scintillator were slowed down by collisions in the liquid and captured by the cadmium. More than 90% of the neutrons were captured in 25 μsec. (See Fig. 1.) The resulting capture gamma rays were than detected by the scintillator.

NEUTRON SOURCE

The neutron bursts were produced by the periodic deflection of the 500-kev deuteron beam of a Cockcroft-Walton accelerator on a tritium-loaded target. The neutron flux was measured by counting the alpha particles from the $T(d,n)He^4$ reaction with a proportional counter, in a known geometry, at 90 degrees with respect to the incident deuteron beam. The neutron bursts had a width of 0.5 μsec and a repetition rate of 2 kc/sec. The neutrons passed through a minimum of material in leaving the target assembly, then through approximately 32 ft of air to the collimator and the detector. The collimated neutron beam made an angle of slightly more than 90 degrees to the incident deuteron beam. The collimator consisted of a tapered hole in a concrete wall 5 ft thick. The detector was placed behind the wall in line with the collimator hole, covered with a $\frac{1}{2}$-in. layer of borated polystyrene, and enclosed in a concrete block structure whose walls were two ft thick.

A transit was used to align the source, collimator, and scintillator to within $\pm\frac{1}{16}$ in. The effectiveness of the collimator and the proper alignment of its axis were verified by mapping the profile of the collimated neutron beam. For this purpose, a small plastic scintillator was

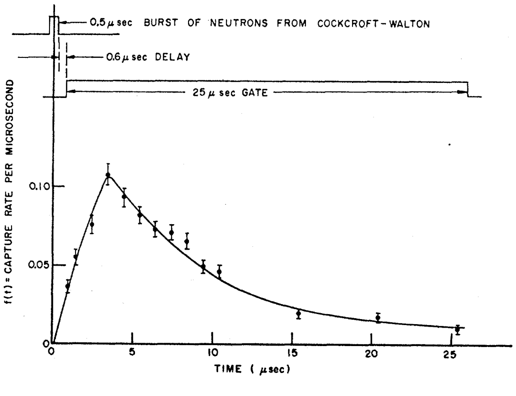

FIG. 1. Neutron capture rate *versus* time. The curve drawn through the experimental points was used to determine the time resolution correction. The positions in time of the neutron burst and the 25-μsec detection interval are shown on the same time scale as the capture rate curve.

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[1] Reines, Cowan, Harrison, and Carter, Rev. Sci. Instr. **25**, 1061 (1954).

[2] J. L. Fowler and J. M. Slye, Jr., Phys. Rev. **77**, 787 (1950); S. G. Forbes, Phys. Rev. **88**, 1309 (1952); E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953); J. J. Dudley and C. M. Class, Phys. Rev. **94**, 807 (1954); R. J. Prestwood, Phys. Rev. **98**, 47 (1955).

[3] Fowler, Owen, and Hanna, Atomic Energy Commission Report NYO-3864 (unpublished); E. R. Graves and R. W. Davis, Phys. Rev. **97**, 1205 (1955); L. Rosen and L. Stewart, Phys. Rev. **107**, 824 (1957).

used as a detector. The profiles were made at high and low detector biases, and agreed with a geometrical interpretation of the collimation system.

DESCRIPTION OF DETECTOR

The tank which contains the scintillator solution is a 240-gal cylinder about 40 in. in length and diameter and made of $\frac{1}{2}$-in. thick aluminum. The filling consists of toluene, terphenyl, α-NPO, and cadmium propionate dissolved in methyl alcohol to give a ratio of 0.003 cadmium atoms per hydrogen atom for the solution.[4] An axial tube, 6 in. in diameter and made of $\frac{9}{32}$-in. thick aluminum, allows the neutron beam to pass through the detector. The $(n,2n)$ targets were placed at the center of the detector. The inside of the tank has a reflective coating of aluminum oxide.[5] Twenty-four 5-in. photomultiplier tubes (Du Mont 6364) are spaced uniformly on the cylindrical wall of the tank. The tubes are operated in two banks in coincidence with each other to reduce counts due to tube noise.

$(n,2n)$ TARGET DESCRIPTION

The cadmium and iron targets were borrowed from another experiment and were each in the form of a spherical shell. All other targets consisted of several thin disks, spaced $\frac{1}{2}$ in. apart, having a total thickness of approximately $\frac{1}{3}$ of a total mean free path for 14-Mev neutrons. Except for bismuth, deuterium, fluorine, and nitrogen, these disks had diameters smaller than the collimated neutron beam. The nitrogen target was made of melamine contained in several 10-mil-thick aluminum cans. The deuterium was in the form of CD_2, and the fluorine in the form of CF_2.

ELECTRONICS

A simplified block diagram of the electronics is shown in Fig. 2. A pulse generator supplies the sweeper plates with the required voltage to produce a pulsed deuteron beam. It also initiates a 25-μsec gate which determines the detection time interval of the neutron signals.

The high voltages on the individual photomultiplier tubes are trimmed to the values required to equalize the individual tube gains. The signals from the two banks of tubes are amplified by fast distributed amplifiers. A triple coincidence, made with the two scintillator signals and the 25-μsec gate, serves to reduce the effects of photomultiplier and amplifier noise pulses. As shown in Fig. 1, the 25-μsec gate is sufficiently long to detect a large majority of the signals arising from the capture of a neutron by cadmium. The gate is delayed with respect to the burst of source neutrons by an amount which prevents the detection of signals occurring at essentially the same time as the source neutrons. Such prompt signals can be produced by recoil protons from the slowing down collisions of neutrons in the detector, and by nonelastic processes in the $(n,2n)$ target or the or the scintillator solution.

The triple coincidence output is applied to a fast discriminator and differential window which excludes small background pulses and large and small pulses from cosmic rays, but permits the detection of the majority of the cadmium capture pulses. When n pulses occur during any 25-μsec detection interval, this event is defined as having a multiplicity n. A circuit[6] containing a beam switching tube determines the multiplicity of each event, for values of n from one through six. The number of events of each multiplicity is recorded by a scaler. For the $(n,2n)$ data, only $n=2$ information is of primary interest; for fission data, yielding detector efficiency, all six multiplicities are used.

The signals from the photomultiplier banks have a rise time of less than 0.1 μsec and are made to have a fall time of less than 0.2 μsec. The pulse shape is maintained through the wide-band amplifiers and into the multiplicity sorter. The time resolution for the entire system has been measured to be 0.2 μsec for pulses having heights accepted by the differential window. The resolution was measured using a pulse generator built especially for this purpose. It produces from one to six pulses individually variable in delay and amplitude and having the same shape as those from the detector.

The electronic system associated with the alpha counter neutron monitor consists of a preamplifier, amplifier, discriminator, and scaler. Several precautions were taken to insure accuracy of the neutron monitor. Provision was made for the insertion of a shutter in front of the entrance window of the alpha counter for the measurement of background. A detailed study of the monitoring problem was made by recording the alpha counter pulse-height distributions on a 256-channel analyzer with the shutter both open and closed. It was concluded that the principle background arises from neutron-induced reactions in the walls and gas of the counter, amounting to a few percent of the alpha counts. A few percent of the alpha pulses occurred below the discriminator setting used in the experiment and

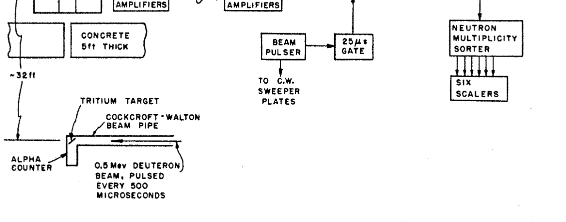

FIG. 2. Experimental arrangement and simplified block diagram.

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[4] This recipe and much other valuable information were obtained from F. Reines and C. L. Cowan at Los Alamos.

[5] The recipe and instructions for the application of the coating were furnished by P. R. Bell, Oak Ridge National Laboratory.

[6] Obtained from B. C. Diven, Los Alamos Scientific Laboratory.

tended to compensate for the background correction.

For the $(n,2n)$ experiment, it is particularly important that neutrons be produced only during the pulsed period, and not during the 25-μsec detection interval following each burst. To insure that this requirement was met, two additional scalers were employed in the alpha counter monitor. One was sensitive only during a time corresponding to each neutron burst, and was used to determine the neutron flux. The other was sensitive only during a time corresponding to the 25-μsec detection interval.

To pulse the deuteron beam a dc bias was applied to the sweeper plates, on which was superimposed a 0.5-μsec-wide square-wave voltage having the same amplitude but opposite sign of the bias voltage. This method has several advantages over the conventional use of a sine-wave voltage applied to the sweeper plates, the main one being that fewer neutrons are produced during the intervals between the main bursts. Such unwanted neutrons can be produced both before and after the main bursts with a sine-wave sweeping system if the accelerator conditions happen to produce a deuteron beam having a well-focused core surrounded by a "halo" of not-so-well-focused deuterons. The square-wave sweeping system allows this halo of current to pass only during a part of the comparatively short rise-and-fall time of the applied voltage. Other advantages of the latter system are optimum neutron yield during the effective burst width, and easily variable neutron intensity (by varying the pulse width) without disturbing other accelerator parameters.

DETERMINATION OF DETECTOR EFFICIENCY

The neutron detection efficiency of the scintillator was determined by the following method. The number of events of multiplicity one through six was observed when a spontaneous fission counter containing Cm^{244} or Cf^{252} was placed in the center of the detector. The signals from the fission counter, after discrimination against alpha pulses, were used to start the 25-μsec gate. The time interval between the fission pulse and the beginning of this gate was made the same as the time between the center of the neutron burst and the beginning of the gate in the $(n,2n)$ arrangement. The efficiency was then determined by dividing the observed average number of neutrons per fission by the values of $\bar{\nu}$ for Cm^{244} and Cf^{252} determined by Diven *et al.*[7]

DATA TAKING

The $(n,2n)$ cross sections were obtained by the accumulation of three kinds of data: target in and beam on, target out and beam on, and beam off. Each run was of ten- to twenty-minute duration. Most targets were run more than once and on different days and months. Efficiency determinations were made at frequent intervals and appropriate average values taken.

The stability of photomultiplier high voltages, amplifier gains, discriminator levels, timing relationships, and background rates was checked periodically. Careful attention was given to the data of the alpha counter scalers with regard to the proper pulsing of the neutron source. The dectector background was sensitive to the over-all gain of the system and the lower discriminator level of the differential window. The detector efficiency measurements gave a further check on stability.

ANALYSIS OF DATA

Fission Analysis

The efficiency of the detector was calculated from the observed fission data, essentially as described by Diven *et al.*,[7] in the following manner. F_n, the probability of observing n pulses per fission gate, corrected for time resolution, was obtained from F_n', the experimentally observed probability, uncorrected for time resolution, by use of the n equations

$$F_n' = F_nP_n(n) + F_{n+1}P_{n+1}(n),$$

where in general $P_m(n)$ is the probability that n pulses are observed when m pulses are present. Terms involving $F_{n+2}P_{n+2}(n)$ and higher were found to be negligible. For $n=2$, $P_2(1)=2\tau\int f^2(t)dt$ and $P_2(2)=1-P_2(1)$, where $f(t)$ is the normalized time distribution of fission neutron pulses (see Fig. 1). If $n>2$, there are time resolution losses due to the accidental coincidence of more than two pulses. Then the inclusion of 3 pulses in accidental coincidence in the calculation of $P_n(n)=1-[P_n(n-1)+P_n(n-2)]$ resulted in small corrections. These corrected values were used in making the time resolution correction. A similar correction was used to obtain β_n, the probability of observing n background pulses per gate, corrected for time resolution. Then C_n, the probability of observing n fission neutron pulses per gate, is given by the n equations

$$F_n = C_0\beta_n + C_1\beta_{n-1} + \cdots + C_n\beta_0,$$

and the scintillator efficiency, ϵ, by

$$\epsilon = (C_1 + 2C_2 + \cdots + nC_n)/\bar{\nu}.$$

Values of ϵ obtained from Cf^{252} and Cm^{244} agreed within experimental error.

CROSS-SECTION CALCULATION

The absolute determination of $(n,2n)$ cross sections required the measurement of the number of neutrons incident on a known amount of target material, the detector efficiency for $(n,2n)$ neutrons, and the number of double-pulse events caused by the $(n,2n)$ reaction. $\sigma_{n,\,2n}$ was calculated from the expression

$$K_2 = Q\Omega N\epsilon^2\sigma_{n,\,2n},$$

where K_2 = number of double-pulse events attributed to the $(n,2n)$ reaction, Q = number of 14-Mev neutrons

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[7] Diven, Martin, Taschek, and Terrell, Phys. Rev. **101**, 1012 (1956).

per steradian made by the Cockcroft-Walton accelerator, Ω = solid angle (in steradians) subtended by the $(n,2n)$ target, and N = number of atoms per square centimeter in the $(n,2n)$ target.

The doubles per alpha count attributed to the $(n,2n)$ reaction, K_2/α_c, were obtained from the following equation:

$$\frac{K_2}{\alpha_c}=\frac{\bar{C}_2-(\bar{\beta}_2)_{\text{Av}}}{\alpha_c/G_c}-\left\{\frac{1}{\alpha_B/G_B}\left[\bar{B}_2-(\bar{\beta}_2)_{\text{Av}}\right]\right\}_{\text{Av}}.$$

$\bar{C}_2$, $\bar{B}_2$, and $\bar{\beta}_2$ represent the doubles counts per gate, corrected for time resolution losses and accidental coincidences within the 25-μsec gate, for the three experimental conditions: target in and beam on, target out and beam on, and beam off. α_c/G_c and α_B/G_B are the observed alpha counts divided by the number of 25-μsec gates used in a particular "C" or "B" run. Av indicates an average of a number of "B" or "β" runs.

It was necessary to subtract the beam-independent background, $\bar{\beta}_2$, from the "C" and "B" data in the above manner since the beam intensity was not always the same in the "C" and "B" runs.

For cross sections larger than 0.5 barn (all elements except D, C, N, and F) the ratio of double events attributed to the $(n,2n)$ reaction to the background was between 10 and 30. For D, C, N, and F, the corresponding ratios were 0.7, 0.3, 1.1, and 5.0.

The true rate of double events, $\bar{C}_2$, was obtained from C_1 and C_2, the observed number of single and double events per gate corrected for time resolution, by use of the following expressions:

$$\begin{aligned} C_2&=P_1(\bar{C}_2)P_0(\bar{C}_1)+P_2(\bar{C}_1)P_0(\bar{C}_2)\\ &=[\bar{C}_2-\tfrac{1}{2}(\bar{C}_1)^2]\exp[-(\bar{C}_1+\bar{C}_2)],\\ C_1&=P_1(\bar{C}_1)P_0(\bar{C}_2)=\bar{C}_1\exp[-(\bar{C}_1+\bar{C}_2)],\end{aligned}$$

where $\bar{C}_1$ is the true rate of single events, and $P_i(\bar{C}_1)$ and $P_i(\bar{C}_2)$ are the Poisson expressions for the probability of detecting i single or double events in one 25-μsec period. The time resolution correction was similar to that applied to the fission data and amounted to 2% for double events. $\bar{C}_2$ differed from C_2 by less than 3% for all elements except D, C, N, and F. For these four elements this correction was 6, 26, 34, and 20%. A similar correction was used to obtain the true rates $\bar{B}_2$ and $\bar{\beta}_2$.

A 7.7% correction was applied to all data for the air attenuation of the incident neutrons. Since the collimation system provided essentially good geometry, the total cross section for 14.1-Mev neutrons in air was used for this correction.

The cross-section expression, as it has been described, applies only to thin $(n,2n)$ targets. Accordingly, a correction was made for the attenuation of the incident neutrons in traversing a thick target. In the thin target expression, $\sigma_{n,2n}$ was replaced by

$$\frac{\sigma_{n,2n}}{N\sigma_T}(1-e^{-N\sigma_T})(1+R),$$

where N is the number of atoms per square cm of target material, as before, and σ_T is the total cross section for 14-Mev neutrons. R is the ratio of $(n,2n)$ events produced by neutrons which are elastically scattered in their first collision, but subsequently undergo an $(n,2n)$ collision, to the $(n,2n)$ events resulting directly from first collisions of incident neutrons.

The values of R were calculated by a Monte Carlo procedure using the known angular distributions for elastic scattering. The exponential part of the expression overcorrects for the thickness of the target, since it treats elastically scattered neutrons as being removed from the incident beam; the Monte Carlo procedure determines how many $(n,2n)$ events result from these elastically scattered neutrons as they traverse their various paths in escaping from the target.

It would also be appropriate to make a similar correction for those inelastic neutrons which have energies exceeding the $(n,2n)$ threshold, but sufficient energy and angular distribution data for inelastic scattering are not available. Such a correction would be considerably smaller than that which has been made for the elastic contribution.

The thick target correction increased the cross sections by the following amounts: 5 to 16% for the elemental targets in the form of disks; 20% for the Fe and Cd spheres; 15, 65, and 30% for D, N, and F.

With the exception of D and Be, no correction has has been made for the attenuation in the target of the neutrons emitted in the $(n,2n)$ reaction. For the heavy elements, at least, such a correction would be very small, since the only effective attenuation process would be the $(n,2n)$ reaction itself, resulting in neutron multiplication. Only in the case of D and Be were a significant number of events of multiplicity three observed. For these two elements, the cross sections were corrected for this effect by multiplying them by

$$\delta=1-\frac{K_3/\alpha_c}{K_2/\alpha_c}\left(\frac{2-3\epsilon}{\epsilon}\right),$$

where K_3/α_c is the number of events of multiplicity three per alpha count corrected for time resolution, accidental triplets, and background triple events. The average of eleven sets of Be data gave $\delta=0.95\pm0.01$. The one D run gave $\delta=0.98\pm0.01$.

ERRORS

The main contributions to inaccuracies in the cross sections are errors in the determination of the efficiency of the detector and statistical errors in the determination of the net doubles per alpha count.

TABLE I. Cross section in barns for 14-Mev neutrons.

	$\sigma_{n,2n}$						
	This experiment, 14.1 Mev	Paul and Clarke,[b] 14.5 Mev	Other experimenters, 14 Mev	σ_{nx},[d] 14.1 Mev	$\sigma_{n,2n}/\sigma_{nx}$	Threshold energy, Mev	T, Mev
D	0.20 ±0.02[a]			0.19±0.03[e]	1.05±0.20	3.34	
Be	0.54 ±0.04		0.42±0.07 (Rosen and Stewart)[c]	0.49±0.02[f]	1.10±0.09	1.85	
C	0.006±0.006					20.3	
N	0.019±0.010[a]	0.0057±0.0008	0.0034±0.0010 (Dudley and Class)[b]	0.82±0.02[g]	0.02±0.01	11.3	
F	0.062±0.009[a]	0.0606±0.0018		0.83±0.05	0.07±0.01	10.8	
V	0.66 ±0.05			1.33[h]	0.49	11.3	
Fe	0.50 ±0.04			1.36±0.03	0.36±0.03	11.3	2.0−2.2
Cu	0.76 ±0.06	0.67 ±0.17	0.65±0.08 (Forbes)[b]	1.49±0.02	0.51±0.04	11	1.9−2.2
Ag	1.73 ±0.13	0.42 ±0.31	0.77±0.11 (Forbes)[b]	1.90±0.04	0.91±0.07	10	0.8−1.4
Cd	1.92 ±0.14			1.91±0.03	1.01±0.08	9	<1.2
Ta	2.64 ±0.20	0.867 ±0.220	1.8 ±0.3 (Rosen and Stewart)[c]	2.38[h]	1.11	7.6	
Au	2.60 ±0.20	1.722 ±0.465		2.42±0.04	1.07±0.08	8.0	<0.9
Pb	2.74 ±0.20			2.56±0.03	1.07±0.08	7	<1.0
Bi	2.60 ±0.19		2.3 ±0.3 (Rosen and Stewart)[c]	2.56±0.03	1.02±0.08	7.4	<1.5

[a] Preliminary—not more than two determinations made.
[b] See reference 2.
[c] See reference 3.
[d] All cross sections, unless otherwise noted, are from MacGregor, Ball, and Booth, Phys. Rev. **108**, 726 (1957).
[e] Total−elastic, J. D. Seagrave, Phys. Rev. **97**, 757 (1956).
[f] It should also be noted that the values 0.37 and 0.64 are reported by Taylor, Lönsjö, and Bonner, Phys. Rev. **100**, 174 (1955), and by reference g, respectively.
[g] N. N. Flerov and V. M. Talyzin, Soviet J. Atomic Energy **4**, 617 (1956).
[h] Optical model calculation, F. Bjorklund and S. Fernbach, University of California Radiation Laboratory Report UCRL-4932-T (unpublished).

The error in the efficiency consists of a quoted[7] 2.1% error in $\bar{\nu}$ and a 1.4% error from counting statistics, resulting in a 2.5% error in determination of the efficiency which contributes a 5.0% error to the cross section. All errors quoted are standard deviations.

The spread in observed values of the cross section for a particular element was in good agreement with the statistical error calculated from the observed number of counts, and was less than 8% for all elements with cross sections greater than 0.5 barn. The observed standard deviation of the mean was combined with the previously mentioned error in $\bar{\nu}$, an estimated 3.4% error in the neutron flux and a 4% error in the self-absorption of the incident neutrons. Errors in solid angle and mass of target material were much smaller and were neglected. The target purities were at least 99.5%. The energy spectrum of the collimated neutrons was examined by means of photographic plates. There was no significant number of neutrons degraded in energy.

RESULTS AND CONCLUSIONS

Table I lists in column 2 the $(n,2n)$ cross-section values obtained in this experiment, and in columns 3 and 4 those obtained by other investigators. The values attributed to Forbes and to Paul and Clarke for Cu and Ag were computed for the natural isotopic ratio from their experimentally determined isotopic cross sections.

The observed cross section for C is zero within experimental error, as it should be since the threshold energy is 20.3 Mev for C^{12}. The slight indication of a positive cross section could be due to the 1% abundant C^{13}, which has a calculated $(n,2n)$ threshold of 5 Mev.

The lack of agreement with the Ag and Ta cross sections determined by activation is probably due to the measurement, in the activation method, of only one isomer of Ag^{106} and Ta^{180}. Ag^{106} is known to have two levels with 25-min and 8.3-day half-lives. Using Forbes' $(n,2n)$ cross sections of 1.00 b±10% for Ag^{109} and 0.56 b±10% for Ag^{107} to the 25-min level in Ag^{106}, and our observed value for the natural isotopic ratio of Ag, a value of 1.87±0.28 barns was computed for the $(n,2n)$ cross section for Ag^{107} going to the 8.3-day level in Ag^{106}. It is known that Ta^{180} has two isomeric states with half-lives of 8 hours, and of greater than 10^7 years. Then, ignoring the difference in incident neutron energy of this experiment and that of Paul and Clarke, the difference in cross section of 1.77±0.30 barns can be attributed to the $Ta^{181}(n,2n)$ cross section leading to the Ta^{180} state with the 10^7-year half-life.

The nonelastic collision cross sections listed in column 5 were used to obtain the ratio $\sigma_{n,2n}$ (this experiment)/σ_{nx} (given in column 6). This ratio is unity within error for Cd, Au, Pb, Bi, D, and Be, where the threshold energy is well below 14 Mev. The tendency of this ratio to be consistently greater than unity for these elements could result from an error in the detector efficiency. It was assumed that the efficiency was the same for $(n,2n)$ and spontaneous fission neutrons. If the energy of the $(n,2n)$ neutrons is predominantly less than the energy of the fission neutrons, the detection efficiency for $(n,2n)$ neutrons will be greater than the value used, and the cross sections reduced. The data of Rosen and Stewart[3] show this to be true for Ta and Bi. A crude calculation indicates that inclusion of this effect would reduce the cross sections by not more than 3%. This correction has not been applied to the data, because of uncertainties in the energy dependence of the detector efficiency and in the energy distribution of the (n,2n) neutrons.

Recently Nicodemus *et al.*[8] have observed inelastic scattering of neutrons by direct interaction from bombardment of a number of elements by 14.5-Mev neutrons. An estimate of the integrated angular distribution has been made by Coon,[9] resulting in a cross section of 0.088 barn for neutrons scattered inelastically between 9 and 14 Mev from Pb. These cannot be neutrons from the (n,2n) reaction, and would indicate that the Pb nonelastic reaction does not proceed entirely by the (n,2n) process. The experimental errors in the nonelastic and (n,2n) cross sections of Pb mask any verification of this small direct-interaction cross section for Pb.

Blatt and Weisskopf[10] have derived the following expression for the (n,2n) cross section:

$$\sigma_{n,\,2n}=\sigma_c\left[1-\left(1+\frac{\Delta E}{T}\right)e^{-\Delta E/T}\right],$$

where ΔE is the difference between the incident neutron energy in the center of mass system and the energy required to separate a neutron from the target nucleus, σ_c is the cross section for formation of the compound nucleus, and T is the nuclear temperature associated with the emission of the first neutron. Nuclear temperatures were estimated using our values of $\sigma_{n,\,2n}$, using σ_{nx} for σ_c, and experimental values[11] of neutron binding energies when available, or values calculated from Levy's[12] empirical atomic masses. These estimates of nuclear temperatures are given in column 8, of Table I. The uncertainty in T is a result of the experimental errors in $\sigma_{n,\,2n}$ and σ_{nx}. Of course, it is possible to obtain at most only an upper limit for T when $\sigma_{n,\,2n}$ is nearly equal to σ_{nx}.†

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[8] Nicodemus, Coon, Davis, and Felthauser, Bull. Am. Phys. Soc. Ser. II, 2, 378 (1957).

[9] J. H. Coon (private communication).

[10] J. H. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 484.

[11] *American Institute of Physics Handbook* (McGraw-Hill Book Company, Inc., New York, 1957), pp. 8–135.

[12] J. Riddle, Atomic Energy of Canada Limited, Report CRP-654, July, 1956 (unpublished).

† *Note added in proof.*—Dr. M. P. Nakada of this laboratory has pointed out that, in the Blatt and Weisskopf formula as we have presented it, σ_c should be replaced by the cross section for the first neutron emission from the compound nucleus, [i.e., $\sigma_{nx}-$(cross scetion for neutron emission through direct interaction) $-\sigma_{n,\,p}-\sigma_{n,\,\alpha}-\cdots$]. $\sigma_{n,\,p}$ for Fe and Cu is about 0.1 barn, and there are indications from data of Coon[9] and M. H. MacGregor (private communication) that the direct interaction cross section for these two elements may be of the order of 0.2 barn. These corrections reduce the calculated nuclear temperatures of Fe and Cu to 1.6 Mev.