Collision Cross Sections for 25-Mev Neutrons

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Collision cross sections of a number of elements for high energy neutrons have been measured. Neutrons with a maximum energy of 25.4 Mev were obtained by bombarding lithium with 10.2 Mev deuterons. The reaction $C^{12}(n, 2n)C^{11}$, which has a measured threshold energy of approximately 21 Mev, was used as an energy sensitive detector for the transmission measurements. The cross section obtained for the neutron-proton collision process was $0.39 \pm 0.03 \times 10^{-24}$ cm^2. This is higher than the cross section calculated for s-scattering (0.35×10^{-24} cm^2), but agrees well with the value of 0.40×10^{-24} cm^2 predicted by the symmetrical meson theory of Rarita and Schwinger. Measurements on other nuclei ranging from carbon to mercury show that the collision radius is given by $R' = b + r_0 A^{\frac{1}{3}}$, with $b = 1.7 \pm 0.4 \times 10^{-13}$ cm and $r_0 = 1.22 \pm 0.15 \times 10^{-13}$ cm. These measurements are in good agreement with the inelastic cross-section measurements of Grahame and Seaborg. The value of r_0 is somewhat lower than the values deduced from p-n reactions, Coulomb energies, and α-particle decay.

INTRODUCTION

KITTEL and Breit[1] have calculated the dependence of the proton-neutron collision cross section on the energy of the incident neutrons. They have shown that the experimentally determined cross sections up to an energy[2] of 15 Mev can be explained on the basis of s-wave scattering. The magnitude of p wave scattering is small at 15 Mev, and is masked by the spherical scattering. The present experiment was undertaken to extend the measurements of the collision cross section to 25 Mev. At this energy, the s-wave scattering is reduced to 50 percent of its value at 15 Mev, while the p-wave scattering is increased.

High energy neutrons can also be used to test current theories of nuclear radii. It is generally assumed that the nuclear radius R is given by

$$R = r_0 A^{\frac{1}{3}}, \tag{1}$$

where A is the atomic mass, and r_0 is a constant. At present, the experimental evidence is in approximate agreement with Eq. (1), although the values of r_0 deduced from excitation functions, α-particle decay, and Coulomb energies range[3-5] from 1.3 to 2.2×10^{-13} cm. These experiments are generally confined to small regions of the periodic table and the radii are obtained indirectly. Scattering experiments with neutrons can be performed with elements selected from a major part of the periodic table. Transmission data yield the nuclear radii directly, since the results are not obscured by Coulomb scattering.

The geometrical radius R will be obtained from collision experiments if the neutron energy is sufficiently high. At 3 Mev strong resonances have been observed.[6] However, at higher energies, the compound nucleus will have an excitation energy in the region where the width of levels is large compared with their separation. Resonance effects will be minimized and the inelastic scattering cross section[3,7] will be πR^2. This condition will be reached when $\lambda\!\!\!^{-} = \lambda/2\pi$ is much smaller than the nuclear radius, where λ is the wave-length of the incident neutron. For the light nuclei, the neutron energy should be $\gg 8$ Mev.

Since the high energy neutron sources now available have a heterogeneous spectrum, it is necessary to discriminate against the low energy fraction by using a detector insensitive to these neutrons. At present, the only experiments which satisfy this condition are those of Salant and Ramsey,[2] and Graham and Seaborg.[8] The

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[1] C. Kittel and G. Breit, Phys. Rev. **56**, 744 (1939).
[2] E. O. Salant and N. F. Ramsey, Phys. Rev. **57**, 1075A (1940).
[3] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[4] H. A. Bethe, Rev. Mod. Phys. **9**, 166 (1937).
[5] R. D. Present, Phys. Rev. **60**, 28 (1941).
[6] See for example, W. H. Zinn, S. Seeley, and V. W. Cohen, Phys. Rev. **56**, 260 (1939).
[7] H. A. Bethe, Phys. Rev. **57**, 1125 (1940).
[8] D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 795 (1938).

former used the reaction $Cu^{63}(n, 2n)Cu^{62}$ with a threshold at 12 Mev, but measured only the neutron-proton and neutron-carbon cross sections at 14–15 Mev. Graham and Seaborg measured the inelastic scattering cross sections for a number of nuclei by using (Ra+Be) neutrons with maximum energy of 13.7 Mev. They used the reaction $Fe^{56}(n, p)Mn^{56}$ to give a radioactive detector insensitive to neutron energies below 7 Mev. Their results will be discussed below.

In a transmission type of experiment, neutrons are removed from the incident beam by elastic as well as inelastic collisions. Since the geometry one uses is necessarily finite, correction must be made for neutrons scattered into the detector. Inelastic collisions most probably result in the emission of neutrons of considerably reduced energy[9] but if the detector threshold is sufficiently high, the contribution of these neutrons to the measured intensity is negligible. The elastic scattering at high energy is essentially the diffraction of the neutron beam by the absorbing nuclei. The cross section for this process is πR^2, so that the total cross section (elastic plus inelastic) for removal of neutrons is $2\pi R^2$.

The geometrical corrections can be calculated by using the differential cross section given by Placzek and Bethe.[10]

$$\sigma(\varphi) = R^2[J_1(\kappa R\varphi)/\varphi]^2, \qquad (2)$$

where J_1 is a Bessel function of the first kind, φ is the angle of scattering, and κ is the wave number of the incident neutrons. Frankel[11] and Present[5] have shown that Eq. (2) describes satisfactorily the angular distribution of elastically scattered neutrons observed by Wakatuki and his co-workers.[12] Comparison of the scattering data for different elements indicates that the value of R to be used is not that defined by Eq. (1), but rather

$$R' = b + r_0 A^{\frac{1}{3}}, \qquad (3)$$

where b is a constant.

Bethe[7] and Present[5] have suggested that the formula for the neutron collision radius should be of this form. Bethe assumes that the nucleus is an opaque sphere of radius $r_0 A^{\frac{1}{3}}$. However, the "screening" radius for neutrons is increased above this geometrical radius by a quantity b representing the finite range of nuclear forces. This quantity is constant for all nuclei and is $\sim 10^{-13}$ cm. Present discusses the problem of nuclear structure in greater detail. He suggests that the nucleus has a core of constant density and an outer shell of diminishing density of thickness $\sim 10^{-13}$ cm. The latter is independent of atomic weight (for $A > 50$). The constant quantity b is therefore increased to $\sim 2 \times 10^{-13}$ cm. This value is in agreement with the elastic scattering data mentioned above.

EXPERIMENTAL METHOD

Neutrons for the present experiment were obtained by bombarding lithium with 10.2 ± 0.3 Mev deuterons produced by the Harvard cyclotron. The mass values of Allison[13a] give an energy release of 15.2 Mev in the reaction $Li^7 + D^2 \rightarrow Be^8 + n^1$. Cloud chamber experiments by Stephens[14] yielded a neutron distribution which extends from low energies to a maximum corresponding to a Q of 15.1 Mev, with a pronounced group of neutrons corresponding to a Q of 11.8 Mev. The maximum energy of the neutrons for a deuteron energy of 10.2 Mev is calculated to be 25.4 Mev and 22.1 Mev for the two neutron groups.

Carbon was used as an energy-sensitive neutron detector. The reaction $C^{12}(n, 2n)C^{11}$ yields the 20.5-min. positron activity of C^{11}. The threshold calculated from the mass values of Mattauch, Haxby, and Barkas[13b, c, d] is 20.4 Mev. An approximate check on the threshold was obtained experimentally by placing carbon at various angles with respect to the forward direction of the neutron beam. The maximum energy corresponding to each angle of emission of the neutrons from the thick lithium target was calculated. The results are shown in Fig. 1 where the relative activity is plotted against the angle

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[9] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).
[10] G. Placzek and H. A. Bethe, Phys. Rev. **57**, 1075A (1940).
[11] S. Frankel, Phys. Rev. **59**, 216A (1941).
[12] T. Wakatuki, Proc. Phys.-Math. Soc. Japan **22**, 430 (1940).
[13] (a) Allison, Miller, Perlow, Skaggs, and Smith, Phys. Rev. **58**, 178 (1939). (*b*) J. Mattauch, Phys. Rev. **57**, 1155 (1940). (c) Haxby, Shoupp, Stephens, and Wells, Phys Rev. **58**, 1035 (1940). (d) W. H. Barkas, Phys. Rev. **55**, 691 (1939).
[14] W. E. Stephens, Phys. Rev. **53**, 224 (1938).

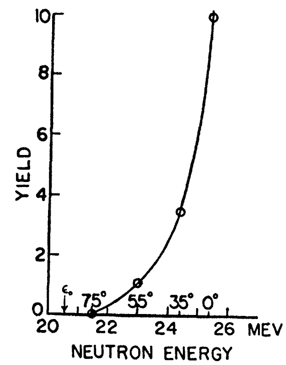

FIG. 1. Excitation function for the reaction $C^{12}(n, 2n)C^{11}$.

of emission and the corresponding maximum energy. At 75° the intensity was less than 1 percent of the 0° activity, indicating that the threshold for the n-$2n$ reaction is in the neighborhood of 21.5 Mev, in agreement with the calculated value. This excitation curve indicates that the effective energy of the neutrons lies between 24 and 25 Mev. The high gradient of the excitation function indicated that little difficulty would be experienced with neutrons scattered by the cyclotron. The massive parts of the latter which might reflect neutrons into the detector either were several feet away or could reflect only neutrons of reduced energy.

The experimental arrangement for the transmission experiments is shown in Fig. 2. The effective area of the lithium target was 2.0×0.3 cm^2. The target was prepared by pounding metallic lithium into a cylindrical depression in a $\frac{1}{4}$-inch water-cooled brass plate. The thickness of the lithium was $\frac{1}{32}$ inch. This was sufficient to reduce the energy of the deuterons below 7 Mev, lower energies being useless for the present experiment. It was thin enough to eliminate the necessity of more elaborate cooling of the target for beam currents of 50 to 60μa.

The deuteron beam was monitored by a graphite disk placed 1 inch in front of the target. Both monitor and detector were irradiated simultaneously to avoid corrections for bombardment time and fluctuations in the beam intensity. The detector[15] was made by quartering a hollow graphite cylinder (4.5 cm long) parallel to its axis. During irradiation the four pieces were stacked together and placed longitudinally with respect to the neutron beam. The cross section of the dectector was 1.9×1.6 cm^2 and its center was 22.4 cm from the target. The scatterers had a cross section of 1 sq. in. and were placed midway between the target and detector. Detector and scatterers were supported by thin wooden cradles. Wooden clamps and braces were used to minimize the effect of scattered neutrons. Target, monitor, scatterer, and detector were partially aligned by a set of pins. Final adjustments were made visually, a procedure found to be sufficiently accurate.

After irradiation for 40 minutes with deuteron currents of 50–60 μa, the monitor and detector were removed. The radioactivity induced in the monitor was observed with a Lauritsen electroscope, while the detector was wrapped about a thin-walled Geiger counter which fed into a "scale of 32" recording unit. Both electroscope and counter were calibrated with a U_2O_3 standard several times during each run to correct for the small variations in the sensitivity of the counter. These rarely exceeded a few percent during the several hours of observation. Typical decay curves are shown in Fig. 3, where the backgrounds of 0.16 div/min. and 0.6 counts/sec. have been subtracted from the observed activities. Preliminary observations indicated a weak activity with a period of several hours in the detector, but this activity was eliminated by surrounding the detector with a thin layer (0.8 g/cm^2) of Cd. It is seen that the decay curves are simple over the observable range. The half-periods varied between 20 and 21 min., in agreement with previously determined values.

RESULTS

The results are summarized in Table I. The first and second columns give the element and

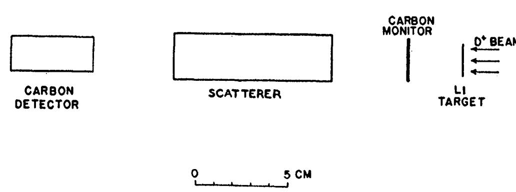

FIG. 2. Experimental arrangement for transmission measurements.

[15] The author is indebted to the National Carbon Company of Cleveland, Ohio, for providing him with the high grade artificial graphite necessary for this experiment.

the composition of the scatterer. The third column gives the thickness of scatterer in grams per cm^2. The fourth column gives the ratio of the activities of detector to monitor. These ratios are converted to percent transmission in the fifth column. The sixth column gives the corresponding values of the experimental cross section (in 10^{-24} cm^2) obtained by use of Eq. (4) below. The last column gives the cross sections after the corrections described below were applied to the observed values. Only single measurements were made for Al, Cl, Ag, and Hg. Because of the consistency of the previous data and the fact that these runs satisfied the criteria adopted in judging a run satisfactory, these measurements have been listed in Table I. These criteria were: stable operation of the cyclotron; absence of damage to the Li film; and stability of the detecting devices. The errors of the measured cross sections (column 6) are estimated from the consistency of the data to be less than 8 percent for hydrogen, 5 percent for carbon, and 10 percent for the other elements. The values for hydrogen and carbon have been corrected for the chemical composition of the paraffin and the natural graphite used.

No correction has been made for neutrons scattered into the detector by the surroundings. Because of the weak intensity of the induced activity this effect could not be accurately determined by inverse square measurements. The small absorption cross sections precluded the possibility of absorbing out the direct neutrons. The detector showed no detectable activity when irradiated directly above and below the target. This indicated negligible contribution by those neutrons leaving the target in the forward direction and being scattered back by the magnet yoke, water tanks, etc. Neutrons leaving at larger angles had reduced energy and had to travel more than a foot before striking the cyclotron. These two factors and the small probability of large angle scattering make one reasonably sure that the effect of scattered neutrons could be neglected.

TABLE I. Summary of experimental results.

Element	Compound used	g/cm^2	Ratio det./mon.	Percent trans.	$\sigma_{obs}\times 10^{24}$ cm^2	$\sigma_{corr}\times 10^{24}$ cm^2
No scatterer			2.06			
			2.05			
			2.06			
			2.06			
			2.06			
H	paraffin	5.35	1.31	63.6		
			1.39	67.5		
		7.39	1.09	52.9		
			1.13	54.9	0.39*	
			1.19	57.8		
			1.13	54.9		
			1.15	55.9		
C	C	8.70	1.32	64.0		
			1.34	65.0		
		13.1	1.09	52.9	1.07*	1.29
		17.4	0.84	40.7		
			0.80	38.8		
O	H_2O	7.82	1.22	59.3		
			1.19	57.8	1.27	1.60
			1.18	57.3		
check	$C_2H_4O_2$	8.20	1.22	59.2	6.35	
Al	Al	20.65	1.06	51.5	1.43	1.85
Cl	CCl_4	12.4	1.48	71.9	1.42	1.88
Cu	Cu	27.8	1.27	61.9	1.79	2.50
		39.2	1.06	51.5		
Ag	Ag	44.3	1.13	54.9	2.41	3.70
Hg	Hg	106	0.743	36.0	3.18	5.25

* Corrected for chemical composition.

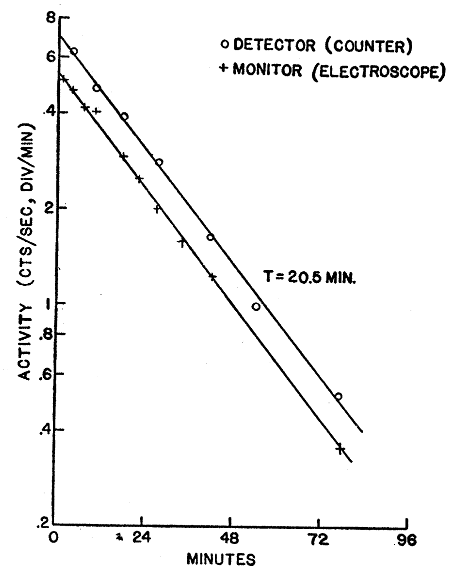

FIG. 3. Decay of C^{11} radioactivity induced in detector and monitor.

CALCULATION OF CORRECTED CROSS SECTIONS

If the geometry were ideal, the neutron intensity would vary exponentially with absorber thickness:

$$I = I_0 \exp\left[-N(\sigma_i + \sigma_e)x\right], \qquad (4)$$

where N is the number of absorbing nuclei per cm^2, σ_i and σ_e are the inelastic and elastic scattering cross sections, and x is the scatterer thickness in cm. Because of the finite size of the source, and scatterer and detector, correction must be made for obliquity of neutron paths and

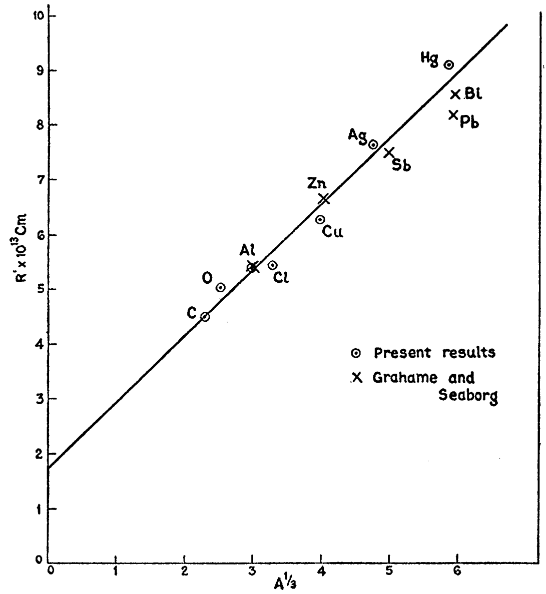

FIG. 4. Measured values of nuclear radius *vs.* (atomic mass number)$^{\frac{1}{3}}$.

for neutrons elastically scattered into the detector by the absorber. (Weisskopf's formula[9] indicates that a negligibly small number of inelastically scattered neutrons have energies greater than 20 Mev.) The transmission equation under these conditions may be expressed by

$$I = I_0 a(x) \exp\left[-N(\sigma_i+\sigma_e)x\right] \times \{1+Ax+Bx^2+\cdots\}, \quad (5)$$

where $a(x)$ represents the correction for obliquity of neutron paths, and A and B are constants giving the contribution to the measured intensity of singly and doubly scattered neutrons, respectively. A and B are determined by the differential scattering cross section $\sigma(\varphi)$, given by Eq. (2), by the sensitivity of the detector for the scattered neutrons, and by the geometry. Formulae for making these corrections were developed by Dr. C. L. Critchfield and gave the results described below.

The obliquity factor $a(x)$ has a value of 0.998 for the thickest scatterer and can therefore be replaced by unity. The single scattering coefficient A is about 17 percent of $N(\sigma_i+\sigma_e)$ for carbon and increases to a value of 40 percent for Hg. These corrections are large because the diffraction formula gives an elastic scattering predominantly in the forward direction; if the scattering were spherically symmetrical, A would not exceed 3 percent. The double scattering coefficient B is negligible except for Ag and Hg; for Hg, the contribution of doubly scattered neutrons is 38 percent of the single scattering. The total cross sections calculated from Eq. (5) are given in the last column of Table I. The calculations include the assumption that $\sigma_e=\sigma_i=\pi R'^2$.

DISCUSSION

(a) Hydrogen

Dr. C. L. Critchfield calculated the neutron-proton cross section for 25 Mev neutrons for the case of *s*-scattering[1] and obtained a value of 0.345×10^{-24} cm^2 for the cross section to be observed under the present geometrical conditions. Similar calculations based on Rarita and Schwinger's symmetrical, charged, and neutral meson theories[16] gave values of 0.395, 0.43, and 0.89×10^{-24} cm^2, respectively. These calculations include the effect of *p*-wave scattering as well as the *s*-wave interaction. The theoretical cross sections are to be compared with the observed value of $0.39\pm0.03\times10^{-24}$ cm^2. The agreement with the symmetrical meson theory is quite good. However, the experimental accuracy is not adequate to exclude the *s*-wave and charged meson theories. The neutral meson theory gives a cross section which is much too large.

(b) Other Nucleii

As noted above, the cross sections for nuclei other than the proton are the sum of the elastic

TABLE II. Comparison of the nuclear radii derived from the present experiment with the results of Grahame and Seaborg.

Element	A	$A^{\frac{1}{3}}$	$R'\times10^{13}$ cm Present values	$R'\times10^{13}$ cm Grahame & Seaborg
C	12.0	2.29	4.54	
O	16.0	2.52	5.05	
Al	27.0	3.00	5.43	5.45
Cl	35.5	3.28	5.47	
Cu	63.6	3.99	6.31	
Zn	65.4	4.03		6.70
Ag	107.9	4.76	7.69	
Sb	121.8	4.96		7.55
Hg	200.6	5.86	9.15	
Pb	207.2	5.92		8.24
Bi	209.0	5.94		8.61

[16] W. Rarita and J. Schwinger, Phys. Rev. **59**, 556 (1941).

plus inelastic scattering cross sections. Since each is taken to be equal to $\pi R'^2$, the collision radius is given by $R'=(\sigma/2\pi)^{\frac{1}{2}}$. The values of R' obtained from the last column of Table I are tabulated in the fourth column of Table II. The first, second, and third columns give the element, the corresponding atomic mass number, and the cube root of the latter.

The last column in Table II gives the values of R' obtained from the "absorption plus inelastic scattering" cross sections found by Grahame and Seaborg[8] for neutrons with energies greater than 7 Mev. Since their method eliminates the detection of elastic scattering, their cross sections are equal to $\pi R'^2$. Both sets of data are presented graphically in Fig. 4, giving R' as a function of $A^{\frac{1}{3}}$. The agreement between the two sets of values is within the observational accuracy of 5 percent. It is, however, difficult to estimate the accuracy of the absolute values of R for the heavier elements, since the geometrical corrections were quite large.

It is evident from Fig. 4 that a straight line through the experimental points has a positive intercept, as suggested by Eq. (3), with $b=1.7 \pm 0.4\times 10^{-13}$ cm and $r_0=1.22\pm 0.15\times 10^{-13}$ cm.

Frankel's analysis[11] of elastic scattering data[12] yielded the values $b=2.3\times 10^{-13}$ cm and $r_0=1.25 \times 10^{-13}$ cm, in good agreement with our results. However, other methods of determining r_0 give larger values. Weisskopf and Ewing[3] derived a value of 1.3×10^{-13} cm from a study of p-n reactions in the neighborhood of Cu, while the Coulomb energy differences of light nuclei gave 1.35×10^{-13} cm. Better agreement is found with r_0 calculated by Present[5] from known mass defects, 1.2–1.3×10^{-13} cm. The disagreement between various methods is undoubtedly due in part to uncertainties in the interpretation of the interactions being studied. Present[5] has suggested that the light and heavy nuclei are less dense than those in the region $A=50$. The present data seem to indicate such a trend, but the measurements are not sufficiently accurate to warrant any definite conclusions on this point.

The agreement between the cross sections measured at 25 Mev, and at 14 Mev by Grahame and Seaborg, indicates that the density of levels reached in the excitation of nuclei with $A \geqslant 27$ by neutrons of 14 Mev is sufficiently high to prevent the appearance of important resonances. The carbon cross sections measured by Salant and Ramsey for 14 and 15 Mev neutrons are 1.27 ± 0.04 and $1.36\pm 0.05\times 10^{-24}$ cm^2, in close agreement with our value of 1.29×10^{-24} cm^2, at 25 Mev, indicating that the above-mentioned condition may be satisfied for the very light nuclei at 14 Mev.

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