anomalous experimental value for $A = 7$ is not yet sufficiently well established to justify an attempt at explanation or interpretation.

It is, of course, conceivable that the entire experimental difference $G-F$ is attributable to the variations of R alone, rather than to a combination of causes, including the difference in L_s and L_a. However, there seems to be no plausible excuse for assuming L_s and L_a to be equal. What is surprising is that the experimental evidence requires them to approach equality for relatively low mass number ($A \sim 20$).

PHYSICAL REVIEW VOLUME 70, NUMBERS 9 AND 10 NOVEMBER 1 AND 15, 1946

Elastic Backscattering of $d-d$ Neutrons

J. H. Manley,* H. M. Agnew,** H. H. Barschall,*** W. C. Bright, J. H. Coon,*** E. R. Graves,
T. Jorgensen,† and B. Waldman††
University of California, Los Alamos Scientific Laboratory, Santa Fe, New Mexico

(Received August 29, 1946)

The backscattering of $d-d$ neutrons was investigated for several materials. A directional thick paraffin detector was used. The detector was sensitive primarily to neutrons which had been scattered elastically or with little energy loss.

INTRODUCTION

The purpose of the present experiments was to measure the cross sections of various materials for the backward scattering of $d-d$ neutrons which had suffered elastic collisions or inelastic collisions with small energy loss. For this purpose a detector was used, the sensitivity of which is a rapidly increasing function of neutron energy. The detector used the recoils originating from a thick layer of paraffin. Such a detector has a high efficiency, can be made directional, and is most sensitive to the neutrons of highest energy. The directional property of recoil protons eliminates the necessity for a shadow cone usually required to keep the large direct beam from completely masking the small fraction of reflected neutrons.

SOURCE

The neutrons were obtained from the $d-d$ reaction by bombarding a thick D_2O ice target with 50–100 μa of 200-kev unanalyzed ions of deuterium accelerated by means of a Cockcroft-Walton set. The target was cooled with a liquid oxygen refluxing system which required only a small amount of material near the target.

The neutron flux was monitored by counting the protons from the companion $D(d, p)H^3$ reaction.

The deuteron beam was collimated by two tungsten diaphragms with $\frac{3}{8}''$ diameter apertures to define the source on the target. For the conditions of the experiment, the neutron spectrum extends from 2.5 to 3.1 Mev with an energy spread of 0.3 Mev at half-maximum.

The angular distribution of the neutrons from this source for the conditions of the experiment

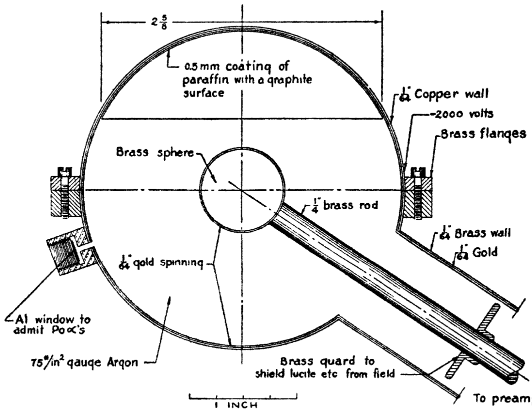

FIG. 1. Spherical ionization chamber. Recoil protons from a thick layer of paraffin are detected.

---

* Now on leave from Washington University.
** Now at the University of Chicago.
*** Now at the University of Wisconsin.
† Now at the University of Nebraska.
†† Now at the University of Notre Dame.

was assumed to be proportional to $(1+0.7\cos^2\eta)$ where η is the angle between the incident deuterons and the emitted neutron. The scatterer subtended an angle of 34° at the source, corresponding to a variation over the scatterer of 10 percent in neutron intensity and 1 percent in neutron energy.

DETECTOR

The detector used in the experiment is shown in Fig. 1. It consists of a spherical collector electrode, $\frac{3}{4}''$ in diameter, surrounded by a concentric spherical high voltage electrode, $3''$ in diameter. The inside surface of a segment of the high voltage electrode was coated with a layer of paraffin, 0.5 mm thick. This layer was covered by graphite to avoid accumulation of charges on the paraffin. The chamber was filled with pure argon to a pressure of 6 atmos.

The chamber was connected to a pulse amplifier by means of a coaxial lead, $18''$ long, in order to eliminate scattering material in the neighborhood of the detector. The amplifier had a rise time of 10μ sec. The output of the amplifier was fed through a discriminator into a scale of 64 counter. The operation of the detecting equipment was checked both by means of artificial pulses from an electronic pulse generator and by observing α-particles which could enter the chamber through a window. In order to establish an energy scale the maximum pulse height due to recoiling protons from $d-d$ neutrons was measured in terms of artificial pulses. The assumption was made that the relation between recoil energy and voltage change of the collecting electrode is linear. The artificial pulses were used to set the discriminator to the desired bias. All pulses greater than this bias were counted.

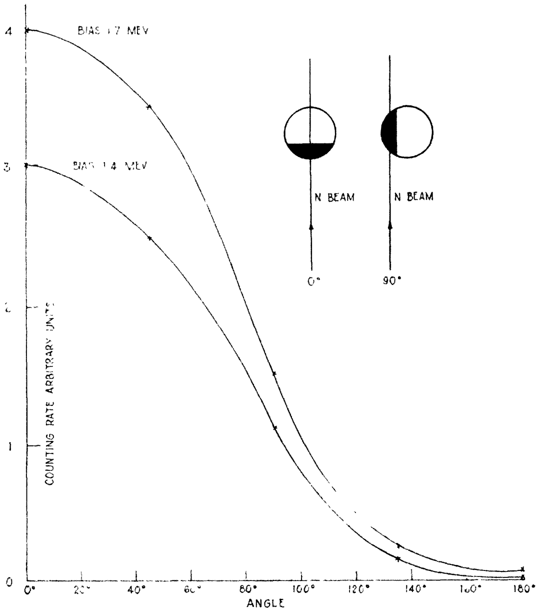

FIG. 2. Response of ionization chamber as a function of angle of incidence of neutron beam,

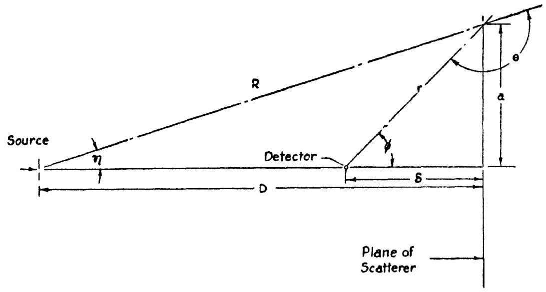

FIG. 3. Geometry for scattering measurements.

As first constructed, the chamber was about 20 times as sensitive to neutrons incident on the convex surface of the radiator as for those incident on the concave. An investigation as to the origin of this background led to the conclusion that it must be due to disintegrations in the copper electrodes of the chamber. Lining the chamber with gold sheet increased the ratio for the two directions of neutron incidence to 100. The counting rate as a function of the angle of incidence is shown in Fig. 2.

GEOMETRY

In order to specify the geometry, the center of the detector is defined as a point $\frac{3}{8}''$ from the pole of the paraffin cap toward the center of the sphere, a point approximately at the center of sensitivity of the detector. The position of the scatterer was taken as its median plane. These points are used to specify the distance, D, from the target to the scatterer, and the distance δ from the scatterer to the detector. The scatterers used were disks, $10''$ in diameter.

The geometric relations involved in this experiment are shown in Fig. 3. The counting rate C for this case due to the presence of a scatterer of N atoms/cm² is given by[1]

$$C = C_0 D_0^2 N \int_{\theta_{\min}}^{\pi} I\sigma(\theta)d\omega \qquad (1)$$

$$I = F(\eta)S(\varphi)/(D-\delta)[(Dr/R)-(\delta R/r)],$$

where in addition to the quantities defined by Fig. 3:

$C_0D_0^2$ = counting rate due to direct beam times the square of the distance from the source at which it is measured ($\eta=0$);

$F(\eta)$ = number of neutrons emitted per unit solid angle by the source normalized to unity at $\eta=0$;

$S(\varphi)$ = angular sensitivity of the detector (Fig. 2);

$\sigma(\theta)$ = scattering cross section per unit solid angle;

$$\theta_{\min} = \sin^{-1}\frac{a(D-\delta)}{Rr};$$

$$d\omega = 2\pi \sin\theta d\theta.$$

For most of the experiments D was chosen to be 16″, and $\delta = 1\frac{7}{8}$″. These dimensions define a minimum scattering angle $\theta_{\min} = 128°$.

Examination of Eq. (1) shows that, in the geometry used, neutrons scattered through various angles θ between $\theta_{\min}$ and 180° contribute to the measured average scattering cross section according to the geometric weighting factor I. In Fig. 4 I is plotted against θ. The rapid rise of I at the edge of the disk has its origin in the relatively large area subtended by a given $d\theta$ as θ increases. Taking into account the variation of I with θ, the effective average scattering angle used in the experiment was about 137°.

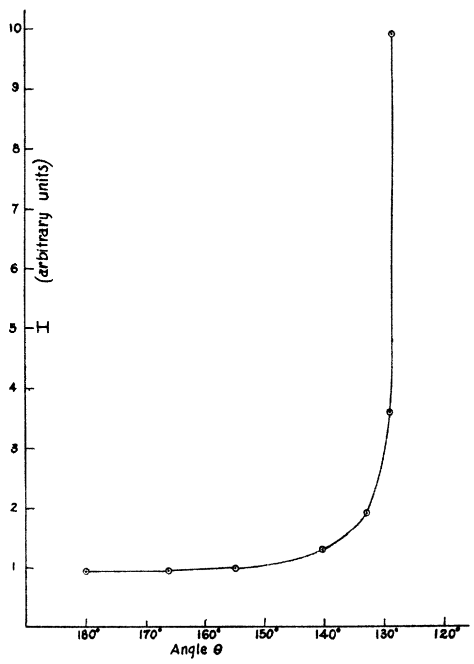

FIG. 4. Weighting factor I as a function of scattering angle θ, showing the relative contribution of different scattering angles to measured average scattering cross section. The plotted points are at radii on disk of 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 inches.

TABLE I. Samples used in scattering experiments.

Substance	Thickness of sample (cm)	Area cm²	Mass kg	Mol. or atoms/cm²×10⁻²⁴
C	3.81	506	3.09	0.306
BeO	6.35	513	5.02	0.235
BeO	4.37	511	3.91	0.185
Al (dural)	2.54	506	3.58	0.153
SiC	4.44	515	3.39	0.099
Fe	5.08	506	20.1	0.428
Fe	2.54	506	10.0	0.214
SiO_2	6.35	512	5.06	0.099
Al_2O_3	6.35	504	4.03	0.0472
Pt	2.54	506	27.6	0.168
Au	2.54	506	24.9	0.150
Pb	2.54	506	14.6	0.0836

The geometric data on the scatterers used are given in Table I.

PROCEDURE

The counting rate C was obtained as the difference between that with a scatterer in place and that with the scatterer removed.

The number of counts with the scatterer was at least twice that without in all cases. C_0 was determined by rotating the chamber through 180° to a position on the axis, D_0 inches from the target. For this measurement the background could be neglected. To secure sufficient statistical accuracy most of observation time was the time for recording scattered neutrons, since the counting rate due to scattered neutrons was never more than 7 percent of that due to the direct beam.

All measurements were taken at two biases (1.4 Mev and 1.7 Mev). It should be emphasized that the sensitivity of the detector increases rapidly with neutron energy and that neutrons with an energy close to the bias energy are detected with very low efficiency. Calling the sensitivity of the detector for 3.1-Mev neutrons 100, the sensitivity of the detector for lower energies for the two biases used is given in

---

[1] Calculation by P. Olum.

Table II. Energy sensitivity of detector.

Neutron energy (Mev) \ Bias (Mev) →	1.4	1.7
3.1	100	100
2.5	46	38
2.0	14	5
1.5	1	0

Table II. The sensitivities are calculated for a thick paraffin radiator, assuming that the hydrogen cross section varies as $E^{-\frac{1}{2}}$ and the range as $E^{\frac{3}{2}}$.

RESULTS

The results of the measurements are listed in Table III. The calculation of the cross section assumes that $\sigma(\theta)$ is constant in the angular range from $\theta_{\min}$ to π. The cross sections are given as $4\pi\sigma(\theta)$ for ease of comparison with total cross sections although it is recognized that the scattering is not isotropic. The results of Table III have not been corrected for energy loss in elastic collisions with light elements, nor for multiple scattering. In the case of compounds the cross sections are given per molecule. The errors listed are average deviations from the mean deduced from the internal consistency of various runs.

In view of the fact that the detector is predominantly sensitive to elastically scattered neutrons, it is surprising to find differences in the data taken at the two biases. In order to see if such effects can be real, the bias effect expected in carbon and aluminum because of energy loss in elastic collisions was calculated from the theoretical energy sensitivity for a thick paraffin radiator, and compared with the observed bias effect. The ratio of the cross sections for the two biases would be expected to be 1.4 and 1.1 for carbon and aluminum, respectively, while 1.6±0.1 and 1.3±0.1 were observed. The difference between theoretical and experimental results which is somewhat greater than the experimental error may be partly explained by multiple scattering. It is believed that in the heavier elements the observed effect is caused by inelastic scattering.

The effect of multiple scattering was studied by using two thicknesses of beryllium oxide and iron. The results are given in Table III. The data are not sufficiently accurate to state more than that the change in cross section is not unreasonable.

The only previously published results which should be comparable with the present ones are those of Barschall and Ladenburg[2] in which helium recoils of energy greater than 1.1 Mev were counted. Their results for iron and lead (Fe: 0.6×10^{-24} cm²; Pb: 2.5×10^{-24} cm²) are in good agreement with the results given in Table III, while their results for carbon and aluminum (C: 1.2×10^{-24} cm²; Al: 1.1×10^{-24} cm²) are higher than the ones reported in Table III. The difference may be caused by the different energy sensitivity of the detectors used in the two experiments. The results of Wakatuki and Kikuchi[3] cannot be compared with the present work since their detector was sensitive to neutrons of lower energy, and the cross sections would, therefore, include more inelastic scattering.

Table III. Cross sections (in units of 10^{-24} cm²) for backscattering of 3.1-Mev neutrons.

Substance	Cross section	
	1.4-Mev bias	1.7-Mev bias
C	0.79±0.06	0.49±0.03
BeO (sample 6.35 cm thick)	0.80±0.06	0.59±0.05
BeO (sample 4.37 cm thick)	0.68±0.04	0.37±0.03
Al	0.66±0.04	0.53±0.05
SiC	1.5 ±0.1	1.1 ±0.1
Fe (sample 5.08 cm thick)	0.61±0.03	0.54±0.03
Fe (sample 2.54 cm thick)	0.81±0.03	0.62±0.04
Al_2O_3	2.5 ±0.1	2.0 ±0.1
Pt	0.47±0.03	0.44±0.04
Au	0.59±0.04	0.50±0.08
Pb	2.5 ±0.1	2.3 ±0.1

This work was carried out under contract between the University of California and the Manhatten District, Corps of Engineers, War Department.

---

[2] H. H. Barschall and R. Ladenburg, Phys. Rev. **61**, 129 (1942).

[3] T. Wakatuki and S. Kikuchi, Proc. Phys. Math. Soc. Japan **21**, 656 (1939).