that O^{18} is known to have zero spin, the stripping theory will therefore require that the 1.468-Mev level in O^{19} have even parity and spin $\frac{1}{2}$.

Figure 6 shows angular distributions calculated from the theoretical formula of Bhatia *et al.*[15] with the angular momentum carried into the target nucleus by the absorbed neutron taken to be two, for two values of the interaction radius. The spin of the ground state of O^{17} has been measured to be 5/2, so that the assumption of $l_n=2$ is justified. The maximum in the distribution observed at about 50° is predicted by the theoretical calculations, which assume as a basic approximation that the proton does not interact with the target nucleus. The neutron is captured in a definite energy state of the final system, and there has been no way yet proposed by which resonance processes can occur with a stripping mechanism. The data show that the part of the angular distribution generally associated with the stripping process behaves in an unpredictable manner, and a more complicated picture of the (d,p) process than has been yet formulated is indicated.

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Liquid Scintillator Measurements of Angular Elastic Scattering of Neutrons from Carbon, Aluminum, and Sulfur*†

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Angular elastic scattering cross sections have been measured for carbon, aluminum, and sulfur using 2.7-Mev neutrons from the D(d,n) reaction. A liquid organic scintillator, terphenyl in xylene, was used as the neutron detector. The differential pulse-height spectra for the neutrons scattered from sulfur and for Co^{60} gamma rays are given.

INTRODUCTION

THE angular distribution of scattered neutrons of a few Mev energy, having wavelengths comparable to nuclear radii, has been the subject of many investigations because the interaction of the neutrons with the scattering nuclei affords one of the simplest methods of attack on the problem of nuclear structure.

Sufficiently intense mono-energetic neutron sources and adequate neutron detector efficiencies have only now begun to yield data accurate enough to select between some of the postulated nucleon-nucleon interactions. The development of a high-efficiency liquid scintillation detector for neutrons prompted the present attempts to measure differential angular scattering cross sections using this detector.

The theory of the experiment is simple and the geometry of a ring scatterer has been used in previous scattering experiments.[1–4] Most of the discussion will concern the analysis of the detector readings since the detector responds with comparable efficiencies to both gamma rays and neutrons. The discussion of the experiments in this article include measurements from which it is felt that the differential angular elastic scattering can be identified without equivocation. A subsequent article will report the measurements being made on iron, copper, cadmium, wolfram, and lead where inelastically scattered neutrons and de-excitation gamma rays make the identification more difficult.

CROSS SECTION CALCULATION

The differential angular scattering cross section, $\sigma(\theta)$, for a thin scatterer is defined as

$$\sigma(\theta)=I_s(\theta)/I_0'N, \quad (1)$$

where θ is the angle between the original velocity of the neutron and its velocity after being scattered, $I_s(\theta)$ is

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[1] Kikuchi, Aoki, and Wakatuki, Proc. Phys.-Math. Soc. Japan **21**, 410 (1939).

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

[3] H. H. Barschall and R. Ladenburg, Phys. Rev. **61**, 120 (1942).

[4] W. D. Whitehead and S. C. Snowdon, Phys. Rev. **92**, 114 (1953).

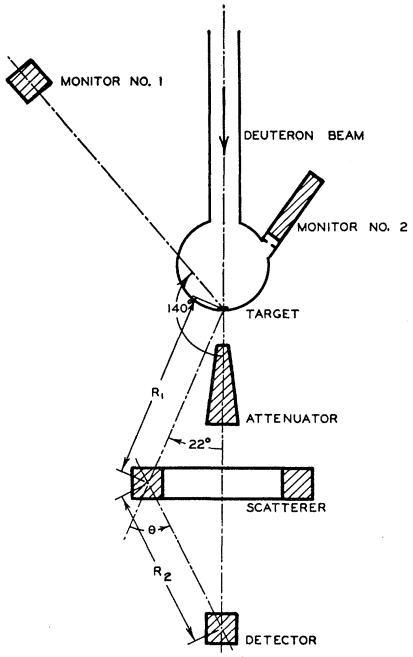

FIG. 1. Experimental arrangement.

the number of neutrons per unit solid angle scattered into the solid angle between θ and $\theta+d\theta$, I_0' is the number of neutrons incident on a unit area of the thin scatterer, and N is the number of scattering nuclei per unit area of the thin scatterer.

The thickness of the scatterer in the experiments cannot be considered thin; however, the assumption is made that if a neutron is scattered in going through the ring it is scattered only once. On this assumption, the neutron flux incident on any layer of thickness dx at depth x in the scatterer is given by $I_0 \exp(-n\sigma x)$ where I_0 is the flux incident on the scatterer surface at $x=0$, n is the number of scattering nuclei per unit volume of the scatterer, x is the depth of the layer in the scatterer, and σ is the total cross section of the scattering nuclei. An average incident flux for the total thickness of the ring scatterer is given by

$$I=(I_0/n\sigma d)[1-\exp(-n\sigma d)]. \quad (2)$$

A schematic diagram of the experimental arrangement is shown in Fig. 1. The scatterer, when used, is always in the same location relative to the source. The scattering at various angles is obtained by moving the detector along the axis of symmetry to various distances from the source. To increase the ratio, at the detector, of the neutrons from the scatterer to the neutrons from the source an attenuator is placed between the source and detector. The attenuator used reduces the counting rate of the neutrons from the source by a factor of seven.

The total cross section, σ, appearing in (2) was measured using the same scintillation detector with a cylindrical sample of the scattering ring material in an experimental arrangement described previously.[5] The total cross-section scatterer was placed at the same angle Φ, from the source as was the corresponding ring scatterer in order to use neutrons of the same energy.

The number of scattering nuclei per cubic centimeter, n, was calculated from the measured dimensions and mass of cylindrical scatterer for aluminum and of the ring scatterers for carbon and sulfur.

The thickness, d, of the ring scatterer is one of the measured dimensions of the ring.

The flux, I_0, incident on the scattering ring was obtained in the following way. The detector was placed a distance R and angle Φ from the source at the location of the scattering ring (with the ring removed), and a counting rate N_D was observed. All counting rates are given relative to the neutron monitor counting rate N_M so that N_D/N_M represents the counting rate of the neutrons incident on the area, A_D, of the detector per unit monitor counting rate. The detectors have an appreciable background counting rate N_B which is obtained by removing any scatterers and interposing a 100-fold attenuating aluminum cylinder between the detector and the source. If A_S is the area of the scatterer ring perpendicular to the neutron beam and E is the detector efficiency, then

$$I_0=EA_S(N_D/N_M-N_B/N_M)/A_D.$$

The number of neutrons per unit solid angle scattered between θ and $\theta+d\theta$ is obtained in the following way. With the scatterer in position as shown in Fig. 1 and the detector at some angle θ, a counting rate of N_S is observed. Again N_S/N_M gives the observed counting rate per unit monitor counting rate. The scatterer is removed and another counting rate, N_A, is observed. The difference $[(N_S/N_M-N_B/N_M)-(N_A/N_M-N_B/N_M)]$ is attributed to the neutrons scattered from the ring into the detector. If R_2 is the distance from the scattering ring to the detector and A_D is again the area of the detector, then

$$I_S(\theta)=E[(N_S/N_M-N_B/N_M)-(N_A/N_M-N_B/N_M)]R_2^2/A_D.$$

The expression for the differential angular scattering cross section in terms of the measured quantities becomes

$$\sigma(\theta)=\frac{R_2^2\sigma[(N_S/N_M-N_B/N_M)-(N_A/N_M-N_B/N_M)]}{[1-\exp(-n\sigma d)]A_S(N_D/N_M-N_B/N_M)}. \quad (3)$$

EXPERIMENTAL CONDITIONS

The neutrons were generated in the 0.030-inch thick copper wall of the vacuum system by the D(d,n) reaction. The target deuterium nuclei are those deuterons remaining in the wall from the bombardment of a beam

[5] H. R. Dvorak and R. N. Little, Phys. Rev. **90**, 618 (1953).

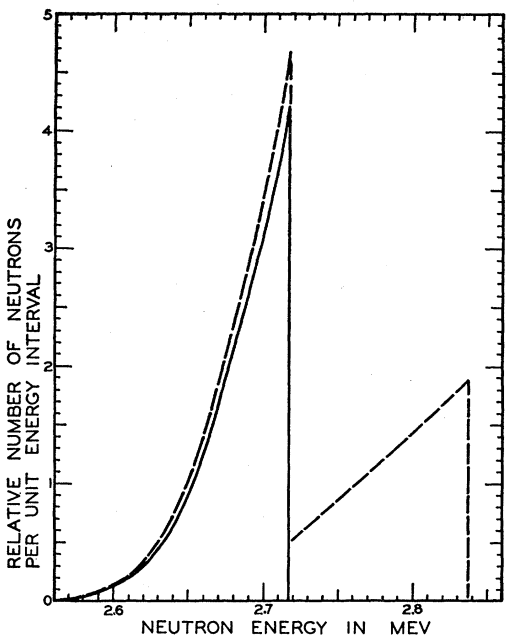

FIG. 2. Calculated spectrum of neutron source. The dotted line gives the spectrum from a 100-kv unanalyzed ion beam. The solid line gives the spectrum from the analyzed D_2^+ ions accelerated by 100 kv.

of accelerated deuterons. The deuteron-accelerating potential was 100 kilovolts. For carbon a magnetically analyzed beam of molecular ions was used and for aluminum and sulfur a mixed atomic and molecular beam was used. The ratio was approximately 80 percent of molecular to 20 percent of atomic ions by a beam current measurement.

Figure 2 shows the calculated energy spectrum of the neutrons from a uniform thick target using $Q=3.268$ Mev[6] and the $D(d,n)$ cross-section data measured at Los Alamos.[7] The solid line gives the spectrum for the analyzed molecular beam and the dotted line gives the spectrum for the unanalyzed beam used on aluminum and sulfur. The energy spread at half-height for the 100-kev molecular beam (50-kev deuterons) is 0.038 Mev, the energy which separates the neutrons into two equal groups is 2.69 Mev and the most probable energy is the maximum energy 2.72 Mev. In the case of the unanalyzed beam, the energy which divides the neutrons into two equal groups is approximately 2.71 Mev and will depend on the atomic to molecular ratio. The range of neutron energies is considerably greater than in the case of the analyzed beam.

The neutron monitor, numbered 2 in Fig. 1, used in the case of carbon counted the protons from the companion reaction $D(d,p)$ at an angle of 120° from the target. The detector used was an Amperex CB-150 Geiger counter used with 1050 volts on the center wire for action in the proportional counting region. The counter had an end window 3.5 mg/sq cm thick and 1 inch in diameter. The solid angle for the protons from the source was defined by a circular aperture 0.375 inch in diameter located near the counter window and 13.5 cm from the center of the target.

The neutron monitor, numbered 1 in Fig. 1, used for aluminum and sulfur was a scintillation detector identical to that used to measure the scattered neutrons. It was located 50 cm from the target and at an angle of 140°. The high potential, 925.5 volts, to the photomultiplier tubes in the detector and in the monitor was furnished by a common supply.

The dimensions of the scatterer rings are given in Fig. 3. The carbon ring was made from graphite having a possible ash content of 0.06 percent. The sulfur was cp sulfur flowers cast in an aluminum container of 0.016-inch wall thickness. The sulfur was left in the container and for the background runs, N_A, with the sulfur ring out, a similar empty container was placed in the position of the scatterer ring. The aluminum was commercial grade 17S containing 95 percent aluminum, 4 percent copper, 0.5 percent manganese, and 0.5 percent magnesium by weight.

The pulses from the photomultiplier were fed into an Atomic model 204-B linear amplifier, then into a single-channel analyzer and then into an Atomic model 101-M scaler. The single-channel analyzer was used only to set an accurately maintained discriminator against noise and other low-energy pulses. The channel

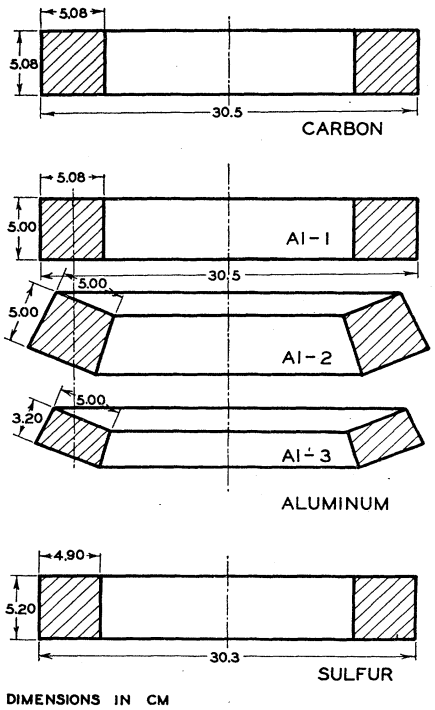

FIG. 3. Dimensions of scatterers.

[6] Li, Whaling, and Fowler, Phys. Rev. **83**, 512 (1953).
[7] Arnold, Phillips, Sawyer, Stovall, and Tuck, Phys. Rev. **93**, 483 (1954).

width was wide enough to include all pulses above the discriminator cutoff point.

A pulse-height spectrum, however, was taken of the scintillations produced for the neutrons direct from the source and also for the neutrons scattered from sulfur. Within experimental error the two spectra were the same and the results of the two measurements is given in Fig. 4. Also in Fig. 4 is the pulse-height spectrum for Co^{60} gamma rays normalized so that the relatively flat portion of the spectrum has the same value for the three spectra.

RESULTS

Figures 5, 6, and 7 give the differential angular scattering cross sections measured for carbon, aluminum, and sulfur, respectively.

The uncertainties arising in the experiment are due to: (1) the assumption that the neutrons detected have been scattered only once; (2) the assumption that the

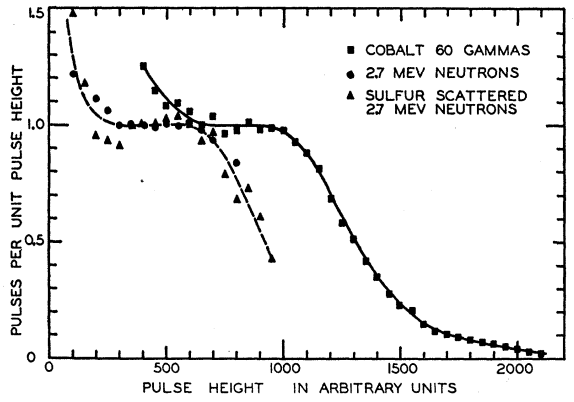

FIG. 4. Pulse-height spectra of Co^{60} gamma rays, direct neutrons, and sulfur scattered neutrons.

detector count represents neutrons and not gamma rays; (3) an assumption that the counter efficiency is constant for all neutrons (direct and inelastically scattered); (4) an uncertainty in the scattering angle because of the finite sizes of the sources, the scatterers, and the detector; (5) an uncertainty in the purity of the material in the scatterers; (6) an uncertainty in the dimensions and densities of the scatterers; and (7) the normal statistical uncertainty in the counting rates.

The most serious uncertainty is in the first assumption, that the neutrons are scattered only once. The dimensions of the scatterers are of the order of one mean free path for scattering (6.8 cm for C, 5.8 cm for Al, and 8.5 cm for S) so that some of the neutrons will be scattered again before leaving the scatterer. Methods of calculating the multiple scattering effects have been given by several authors,[8–10] and a simplified stochastic

[8] S. A. Goudsmit and J. L. Saunderson, Phys. Rev. **57**, 24 (1940).
[9] J. Blok and C. C. Jonker, Physica **18**, 809 (1953).
[10] E. P. Wigner, Phys. Rev. **94**, 17 (1954).

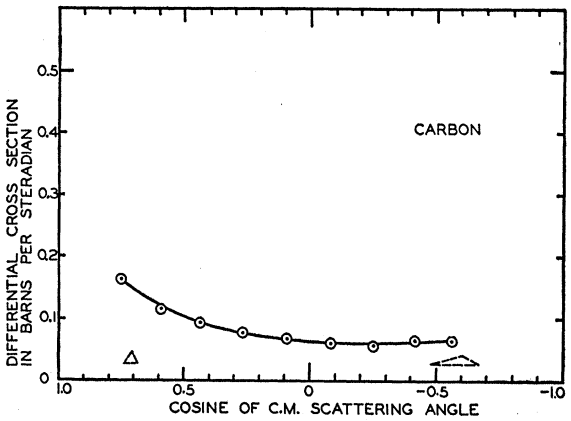

FIG. 5. Differential elastic scattering cross section of carbon.

calculation was used by Walt and Barschall[11] to correct their experimental results. In the present experiment two different thicknesses of aluminum ring (called Al-2 and Al-3) were used to change the ratio of the multiply scattered fraction to the singly scattered fraction of the neutrons reaching the detector. The results from the two rings are shown in Fig. 6. The curve for Al-3, thinnest scatterer, is not as flat (distribution less isotropic) as the curve for Al-2 but not enough different to justify a correction within the accuracy of the experiment. Al-1 is a scatterer whose cross section is a square with horizontal and vertical sides instead of the shape used in Al-2 where the neutron beam enters the scatterer normally and each neutron "sees" the same thickness of scatterer. It is clear from comparison of the Al-1 and Al-2 data in Fig. 6 that the scatterer shape can be the more easily machineable one (Al-1) without affecting the results of the experiment seriously. The scatterers for carbon and sulfur were made with a square cross section as shown in Fig. 3.

The second assumption, that all detector counts are

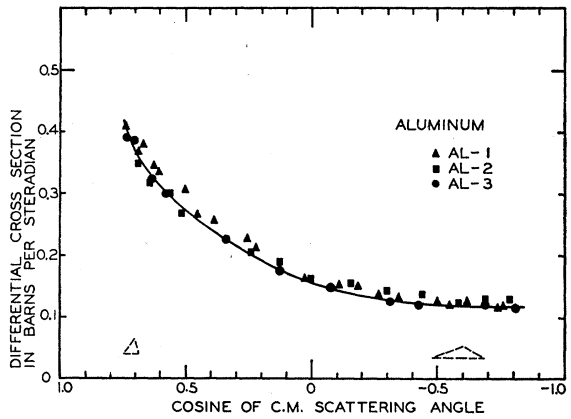

FIG. 6. Total differential scattering cross section of aluminum. The curve is drawn through the points measured for the thinnest scatterer, Al-3.

[11] M. Walt and H. H. Barschall, Phys. Rev. **93**, 1062 (1954).

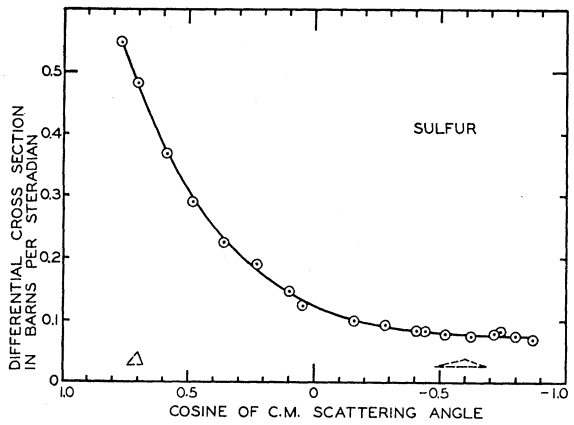

FIG. 7. Differential elastic scattering cross section of sulfur.

due to neutrons, could cause uncertainty in the experiment since the detector also responds to gamma rays. The sources of gamma rays which might give detector counts are (1) 100-kev bremsstrahlung from electrons returning up the accelerating column, (2) de-excitation gammas from nuclei capturing neutrons, and (3) de-excitation gammas from nuclei which scatter neutrons inelastically. The 100-kev x-rays are perceptible in an unshielded detector; however, the detector was enclosed in a 1-mm thick lead cover which made the x-ray contribution negligible. Capture gamma rays could come from either the direct neutron attenuator or the scatterer. The contribution of these gammas from the attenuator was checked by a measurement made with the detector in the scatterer position and readings made with and without the attenuator in place. A three percent increase in counting rate occurred in the presence of the attenuator. The relative values of the scattering and the capture cross sections for fast neutrons indicate that the increase was essentially scattered neutrons. The distances in this measurement and in the angular scattering measurements are comparable so that the contribution of capture gammas from the attenuator is concluded to be negligible. A further demonstration that the capture gamma-ray contribution is small from either attenuator or scatterer is given in the small fraction of gammas appearing in the pulse height spectrum for neutrons from sulfur shown in Fig. 4. The capture gamma rays from C, Al, and S will have energies of at least 4.9, 7.7, and 8.6 Mev, respectively. A significant contribution of such hard gammas would show clearly in the pulse-height distribution for the scattered neutrons and the maximum contribution that could have been present is 2 or 3 percent. The third possible gamma source is from nuclei in the scatterer which have been struck inelastically by the neutrons. The three elements, carbon, aluminum, and sulfur, were chosen because inelastic gammas would be either very few or nonexistent. The only level which could be excited in carbon is at about 1 Mev in the 1.1 percent carbon 13 isotope. The levels possible in sulfur are at 2.25 Mev in the 95 percent sulfur 32 isotope, 0.79, 1.90, and 2.17 in the 0.7 percent sulfur 33 isotope, and 0.82 and 1.9 in the 4 percent sulfur 34 isotope. The only major possibility, the 2.25-Mev level in sulfur 32 with a cross section of 0.38 barn at 2.5 Mev,[12] does not show any appreciable amount of gammas of this energy in the pulse-height spectrum of the scattered neutrons. The inelastically scattered neutrons from this level give pulses below the discriminator bias against tube noise. From aluminum, inelastic gamma rays of energies 0.8, 1.1, and 2.2 Mev have been reported for 2.5-Mev neutrons,[13] but it is felt that the small size of the inelastic cross section compared with the elastic cross section makes the assumption of no inelastic gammas introduce an uncertainty of only a few percent.

The third uncertainty listed, the assumption that the detector had a constant efficiency for all the neutrons counted, is introduced because the elastically scattered neutrons have lost a small amount of energy. The maximum energy loss, 0.66 Mev, occurs for neutrons scattered from carbon at 120°. Preliminary measurements on neutrons from the D(d,n) reaction indicate that a correction proportional to the (n,p) total cross section in this energy range would be suitable. The correction was not made on the curves in Figs. 5, 6, and 7 so that the error on the highest angle data point for carbon may be in error by about 3 percent. For all other points the error is negligible.

The fourth uncertainty, the uncertainty in angle, is caused by the use of scatterers and detectors large in size relative to the separation distances involved. For the scatterers an upper and lower limit on the scattering angle can be established for each angle. These limits range from about $\pm 5°$ at 30° to about $\pm 15°$ at 120°.

The fifth, sixth, and seventh of the uncertainties are small in comparison with the four just discussed. The physical measurements of weight and dimensions were made to approximately 1 percent accuracy and the purity of the materials is known within 1 percent or 2 percent. Enough counts were taken so that the difference between two repeated runs is due to the difference in the physical setup and not the statistical uncertainty. The statistical error on any point was never greater than 1 percent.

It is a pleasure to acknowledge the assistance of G. H. Olewin, J. E. Wills, and Pablo Okhuysen in carrying out many details of this work.

[12] Grace, Beghian, Preston, and Halban, Phys. Rev. **82**, 969 (1951).

[13] Garrett, Hereford, and Sloope, Phys. Rev. **92**, 1507 (1953).