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A Cloud-Chamber Study of the Scattering of Fast Neutrons in Oxygen*

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Neutrons with an energy of 14.1 Mev have been scattered in oxygen gas, and the recoil oxygen nuclei observed in a cloud chamber operated at a pressure of $\frac{1}{2}$ atmosphere. Recoils from elastically scattered neutrons were resolved from recoils due to inelastic scattering. The results indicate a strong asymmetry in the angular distribution of elastically scattered neutrons; the angular distribution has maxima at 0°, 80°, and 180° and minima at 60° and 130°. Within a factor of 2, the angular distribution for the inelastically scattered neutrons is symmetrical. The probability per unit energy interval that the oxygen nucleus will be left excited is about 5 times as large at 6-Mev excitation as at 12-Mev.

The cross section of oxygen for 14.1-Mev neutrons is 0.7×10^{-24} cm^2 for elastic scattering, 0.5×10^{-24} cm^2 for inelastic scattering, and 0.4×10^{-24} cm^2 for disintegration.

EXPERIMENTAL APPARATUS AND PROCEDURE

MONOENERGIC 14.1-Mev neutrons were produced in the Rice Institute Cockroft-Walton accelerator using the $H^3(d,n)He^4$ reaction. Targets were tritium absorbed in zirconium[1] with a thickness of about 300μ g/cm^2. The Cockroft-Walton was operated at about 160 kv, and the unresolved beam containing about 80 percent molecular ions was used. An aperture 5 mm in diameter was placed over the target to define the beam so that the size of the neutron source would be small. The cloud chamber was operated on a cycle of about 70 seconds with an electronic timer, which also pulsed the Cockroft-Walton ion source such that no neutrons were produced until the chamber became sensitive.

The cloud chamber was 24 cm in diameter and was placed with its center 32 cm from the neutron source at 90° to the beam. Stereoscopic photographs were taken with a single camera by photographing one direct view and one image reflected from a front surface mirror. The stereoscopic angle was 20°. The film was observed by removing the cloud chamber and projecting the images on the developed film through the same optical system including the camera. A white screen placed in the position of the chamber was then adjusted until both images of a track coincided; the coincident images gave the true length and orientation in space of the track.

The stopping power of the gas in the chamber was determined by placing a polonium alpha-particle source inside the chamber. The range[2] of the Po alpha-particles was taken to be 3.82 cm. The source was enclosed in a small cylinder the end of which was covered with a shield which could be moved with a small magnet from outside the chamber. At the beginning, in the middle, and at the end of each roll of film, 5 frames were taken of the alpha-particle tracks.

An upper limit for the fraction of neutrons which were scattered by surrounding equipment, the floor, etc., and then entered the chamber was obtained by observing the planes of the two forked-tracks from disintegrations produced by the neutrons. The initial direction of particles from a disintegration must be coplanar with the direction of the neutron initiating the disintegration; but, because of scattering of the charged particles, some tracks due to unscattered neutrons may appear noncoplanar. From the measurements, 80 percent of the neutrons came from within 10° of the direction to the source. The glass chamber wall ($\frac{3}{8}$ in. thickness) would scatter only 12 percent of the neutrons coming from the source, and most of the scattering would be at very small angles.

The chamber was refilled with 99.5 percent pure oxygen gas each day of the operation to be sure that the chamber filling had a known composition. Water only was used as the vapor in the chamber so that there would be no problem in identifying the tracks.

RESULTS

About 2300 recoil oxygen nuclei on about 450 pictures were measured. The true length of a recoil was taken to be the total length of the track less the width of the track. Recoils were measured down to a length of 0.1 cm, although a few between 0.1 and 0.2 cm may have been missed. It is felt that recoils with lengths greater than 0.2 cm were observed with 100 percent efficiency. The track lengths were estimated to 0.01 cm, and the angles were measured to 0.5°.

Figure 1 is a plot of the number of recoils observed as a function of the track length in certain angular intervals. The ordinate of a point is the number of tracks in a 2 mm track length interval. Points are plotted every mm of track length and so each track is counted twice, once in each plotted point adjacent to it in length. The limits of the angular intervals were chosen such that the recoils from elastically scattered neutrons were divided into 10 equal energy intervals. The short heavy vertical lines on the abscissa in Fig. 1 show the expected length of recoils corresponding to excitation of O^{16} to

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[1] A. B. Lillie and J. P. Conner, Rev. Sci. Instr. **22**, 210 (1951).
[2] H. A. Bethe, Revs. Modern Phys. **22**, 213 (1950).

the amount indicated. Known excited states in O^{16} occur at 6.05, 6.13, 6.9, 7.1, 10.5, 10.8, and 11.2 Mev and perhaps at 8.6 and 9.5 Mev. In addition there are 5 states between 12.44 and 13.24 Mev.[3]

The range-energy relation for oxygen nuclei and the stopping power of the gas in the chamber must be known in order to calculate the expected track length of a recoil corresponding to a particular energy. The range-energy curve was obtained from results of Lillie.[4] The stopping power was determined from the length of Po alpha-particle tracks and was found to be 0.193 for the alpha-particles. A small correction to this figure was needed because the stopping power of hydrogen present in the water vapor was not the same for the fast alpha-particles and the relatively slow oxygen recoils. The corrected value of the stopping power for oxygen recoils was 0.197. Values of the stopping power of hydrogen were taken to be 0.35 for the oxygen nuclei and 0.20 for the alpha-particles.[5]

Elastic Scattering

One may see from Fig. 1 that recoils due to elastic scattering were resolved from those due to inelastic scattering; therefore, it was possible to obtain an angular distribution for elastically scattered neutrons. Angular intervals were chosen such that the total solid angle of the scattered neutrons was divided into 20 equal parts. The number of neutrons per unit solid angle was then plotted as a function of the angle of neutron scattering in the center-of-mass system. In order to include tracks due only to elastic scattering, recoils were counted which had a track length within 0.8 mm of the calculated track length. If the plane formed by the track and the incident neutron direction was at an angle greater than 45° to the horizontal, the tracks were not counted. The resulting angular distribution is given by the open circles in Fig. 2.

At small angles this method is subject to large errors in measuring the angles of the recoils. Large angle scattering of the neutrons gives long oxygen recoils, and, therefore, accurate length and angle measurements, while small angle neutron scattering produces short recoils, whose direction cannot be determined as accurately. The data were considered in another way which took advantage of the fact that the length measurements were more accurate than the angle measurements for short tracks. The tracks due only to elastic scattering in all angular intervals were added together, and then the number of tracks with lengths between the calculated track lengths were plotted as the solid circles in Fig. 2. Again the plane formed by the track and the incident neutron was required to be within 45°

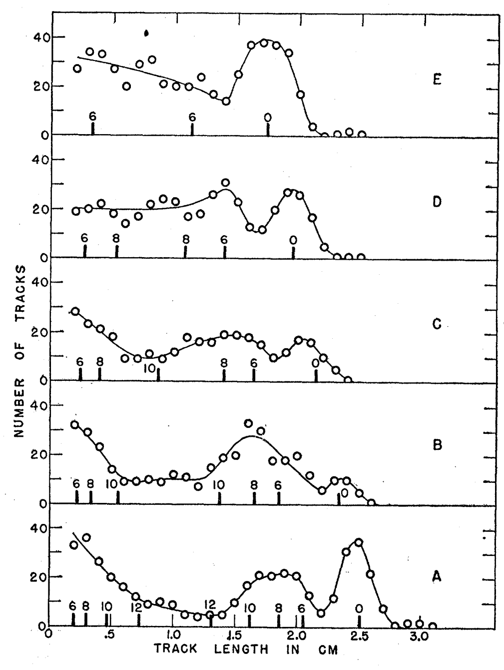

FIG. 1. Plot of number of tracks as a function of track length for tracks up to an angle of 45° in the laboratory system. Tracks due to inelastic scattering cannot take place at angles greater than 48°. The angular intervals of (*A*), (*B*), (*C*), (*D*), and (*E*) are 0° −18.4°, 18.4° −26.6°, 26.6° −33.2°, 33.2° −39.2°, and 39.2° −45.0°, respectively. The heavy short lines on the abscissa indicate the calculated lengths of tracks corresponding to excitation of the oxygen nuclei to an energy of 0, 6, 8, 10, and 12 Mev.

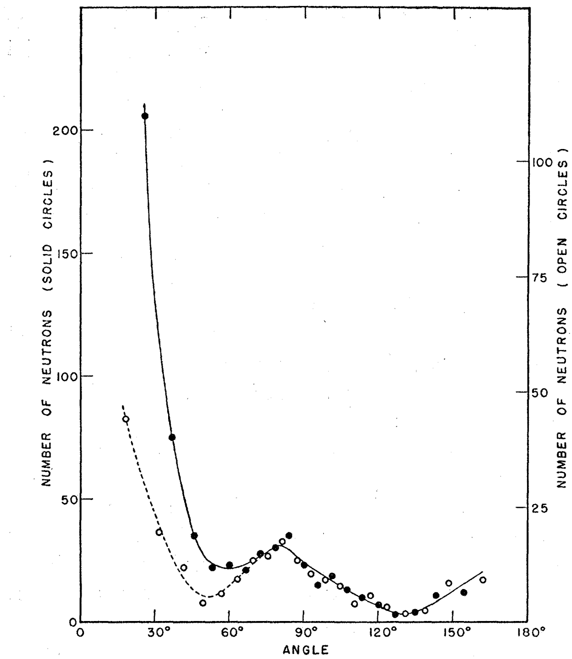

FIG. 2. Angular distribution of the elastically scattered neutrons. The ordinate is the number of neutrons per unit solid angle plotted as a function of the scattering angle in the center-of-mass system. The two methods of obtaining the angular distribution are indicated by the two kinds of points. In each case, the ordinate gives the number of recoil tracks counted.

[3] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).
[4] A. B. Lillie, Phys. Rev. **87**, 716 (1952).
[5] C. M. Crenshaw, Phys. Rev. **62**, 54 (1942).

of the horizontal. This second type of plot is the same as that obtained with an ion chamber and differential pulse-height analyzer in the cases where no inelastic scattering or disintegration takes place.

Note that agreement between the two methods of obtaining the angular distribution is good at large angles. The solid circles are more accurate at small scattering angles. The curves show minima at about 55–60° and at 130° with maxima at 0°, 80°, and 180°. Other measurements with neutrons of about the same energy scattered from lead have indicated a large forward scattering, a minimum at about 25°, and a small maximum at about 40°.[6] Measurements at about 3-Mev neutron energy on several elements show a pronounced forward scattering with no indication of other maxima.[7]

In the present experiment the large forward scattering is about what is predicted for diffraction scattering.[8] The general shape of the curves is similar to that observed in stripping[9] and in the scattering of deuterons by light elements. It seems likely, because of the similarity in the angular distribution, that all these processes may have a common explanation.

Inelastic Scattering

As may be seen from Fig. 1, no angular distribution could be obtained for inelastically scattered neutrons involving a single excited state in oxygen. However, a rough average angular distribution from states with an excitation energy near 6 Mev was derived from the data by considering recoils with track lengths between those calculated for excitation energies of 5 and 7 Mev. The results indicate that the distribution is symmetrical within a factor of 2.

In order to obtain a probability distribution for excitation of oxygen nuclei, the angular distribution of inelastically scattered neutrons was assumed to be on the average symmetrical. Then by considering all tracks due to inelastic scattering, the probability per unit energy that the oxygen nuclei will be left excited was found to decrease by about a factor of 5 from 6-Mev excitation to 12-Mev excitation. This result is somewhat surprising since the density of excited states is expected to increase with increasing excitation. However, several units of angular momentum may be associated with the incident neutron, and the emitted neutron may be required to carry off several units also. The lower penetrability of lower energy neutrons from higher excited states could account for the experimental change in the excitation probability if most of the emitted neutrons had a large angular momentum.

CROSS SECTIONS

For determination of the cross sections the scattering in oxygen was compared to that in hydrogen by taking one roll of pictures with a gas mixture of 6.6 cm Hg hydrogen gas pressure and 12.7 cm Hg oxygen gas pressure in the chamber. The temperature during the run was 23.1°C at which the vapor pressure of water is about 2.2 cm Hg. Thus the ratio of number of atoms of hydrogen to that of oxygen was 0.61 during the time tracks were formed immediately after the expansion. To be counted a track was required to start at least 1 cm inside the light beam and 3 cm from the chamber walls. No measurements on length or angle of the recoils were made. The number of recoils counted was 166, the number of disintegrations was 53, and the number of recoil protons was 56. A value of 0.689 barn was taken for the cross section of hydrogen for 14.1-Mev neutrons.[10] The cross section of oxygen for neutron scattering was found to be 1.2 barns and for disintegration, 0.4 barn, giving a total of 1.6 barns, which is in good agreement with the value obtained from neutron transmission experiments.[11] The fact that some of the shortest tracks were not counted would make the value obtained for the total cross section slightly too small. Tracks of 0.1-cm length correspond to a neutron scattering angle of 9°. It is felt that most of the recoils over 0.1 cm long were counted. The ratio of elastic scatterings to inelastic scatterings as determined from measured tracks was 1.45. Only elastically scattered oxygen recoils are possible at laboratory angles greater than 48°, and at smaller angles the elastic scattering is well resolved from inelastic scattering. The cross section for elastic scattering is 0.7 barn, and that for inelastic scattering is 0.5 barn.

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[7] Kikuchi, Aoki, and Wakatuki, Proc. Phys. Math. Soc. Japan **21**, 410 (1939); T. Wakatuki and S. Kikuchi, Proc. Phys. Math. Soc. Japan **21**, 656 (1939).

[8] G. Placzek and H. A. Bethe, Phys. Rev. **57**, 1075 (1940); Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, Atomic Energy Commission Document NYO-636 (unpublished).

[9] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

[10] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).

[11] L. S. Goodman, Argonne National Laboratory Report, ANL-4602 (1951) (unpublished); D. I. Meyer and W. Nyer, Los Alamos Report LA-1279 (1951) (unpublished).