The Scattering of Neutrons by Magnesium†

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2.5-Mev neutrons from the D on D reaction were scattered through magnesium. Energies of the scattered neutrons were measured in a cloud chamber. The neutron energy spectrum showed that Mg has its lowest excited level at 1.30 Mev above the ground state. Approximate values of the elastic and inelastic scattering cross section were calculated as 1.6×10^{-24} and 0.6×10^{-24} cm², respectively.

INTRODUCTION

THE energy distribution of 2.50-Mev neutrons after scattering by magnesium has been determined. The method used was similar to that used for the scattering of neutrons by lead.[1] The inelastically scattered neutrons form a group with mean energy about 1.08 Mev.

APPARATUS

The neutrons used in the experiment were the 2.5-Mev neutrons from 0.1-Mev deuterons on a thick deuterium target in the form of heavy paraffin. The 0.1-Mev deuterons were accelerated by a Cockcroft-Walton voltage doubler and rectifier. The ion source was similar to one described by Finkelstein.[2] A vertical section of the ion source and the accelerating tube is shown in Fig. 1. In normal operation the potential drop, V_1, from the gas chamber, C, to the filament, B, was 300 volts. C and the metal cylinder D, which rests on the first accelerating electrode E, were kept at the same potential. A vertical magnetic field of 400 oersteds (at the center) was maintained along the axis of the ion source by a Helmholtz coil arrangement. The filament was a platinum ribbon $\frac{1}{8}$ inch wide, coated with a mixture of barium and strontium oxides and gave an electron emission of about 100 milliamperes at 300 volts. This voltage was not enough to produce a saturation current. The filament required 18 amperes at 4 volts for heating. Since the neutron detecting apparatus was a cloud chamber, the deuteron beam was

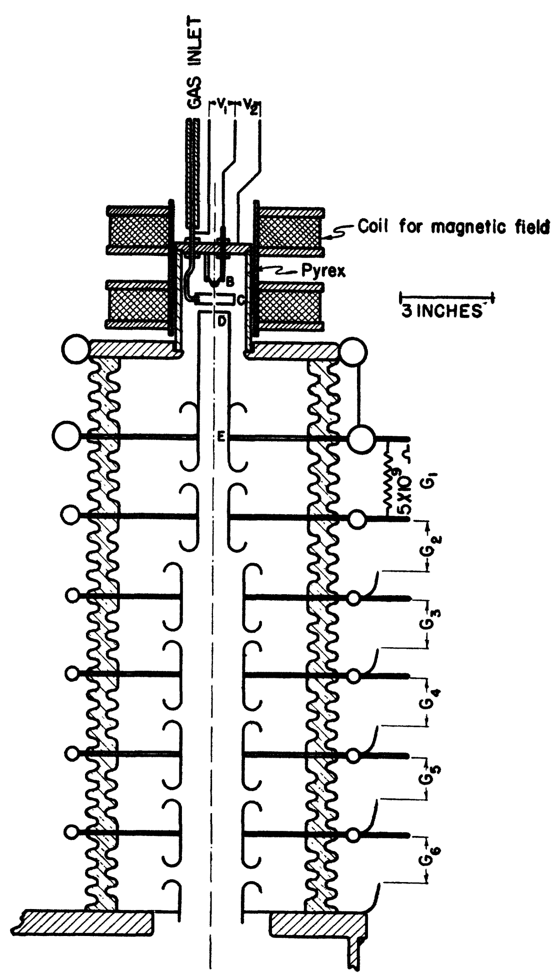

FIG. 1. Vertical section of ion source and accelerating tube.

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[1] H. F. Dunlap and R. N. Little, Phys. Rev. 60, 693 (1941).

[2] A. T. Finkelstein, Rev. Sci. Inst. 11, 94 (1940).

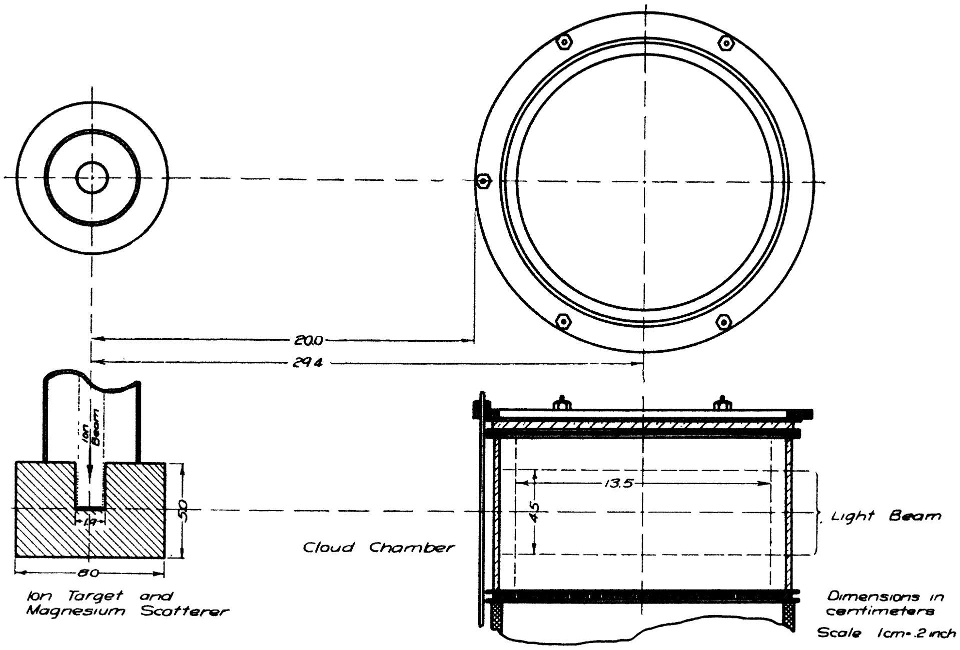

FIG. 2. Relative positions of target, scatterer, and cloud chamber.

wanted only at intervals, and the whole apparatus was controlled by an automatic timing system. The quantities which were operated intermittently to get a beam of short duration were the deuterium flow, the accelerating potential V_1 between filament and box C in the ion source, and the magnetic field. The ion source magnetic field could be left on continuously, but it was found that the deuteron current increased very much for stronger fields and a current was used in the coils which would have given overheating on continuous operation. The deuteron beam hitting the target measured between the limits of 350 to 550 microamperes.

The relative positions of the target, magnesium scatterer, and cloud chamber are shown in Fig. 2. The deuteron beam is directed vertically downward on a thick target of heavy paraffin at the center of a cylinder of magnesium. The scatterer has an average radial thickness from the center of the target of 3.88 cm.

The neutrons were detected by means of proton recoils in a cloud chamber containing ethane at atmospheric pressure as a gas and a mixture of four parts ethyl alcohol to one part water. The stopping power of this combination was found to be 1.43 by calibration with polonium alpha-particles. About 8000 stereoscopic photographs of the expansions were taken and in these pictures there were 863 tracks within 10° of a radial line from the neutron source. Both the spatial orientations and recoil track lengths were observed by reprojection of the photographs through the same camera lens system. These recoil track lengths were then used to calculate the energies of the neutrons observed.

RESULTS

The 863 recoils were grouped in length intervals of 4 mm and a tabulation made of number per interval as a function of the mean range of the intervals. Since the cloud chamber is a detector of finite extent, the probability of observation of complete tracks is greater for short recoil tracks than for long recoil tracks. A correction to compensate for this error factor was made by use of the formula

$$P=[\pi r^2-L(r^2-L^2/4)^{\frac{1}{2}}-2r^2\sin^{-1}(L/2r)]/\pi r^2,$$

where P is the ratio of the volume in which tracks of length L may start in the chamber and lie completely within the chamber to the total volume of the chamber. The radius of the chamber is r.

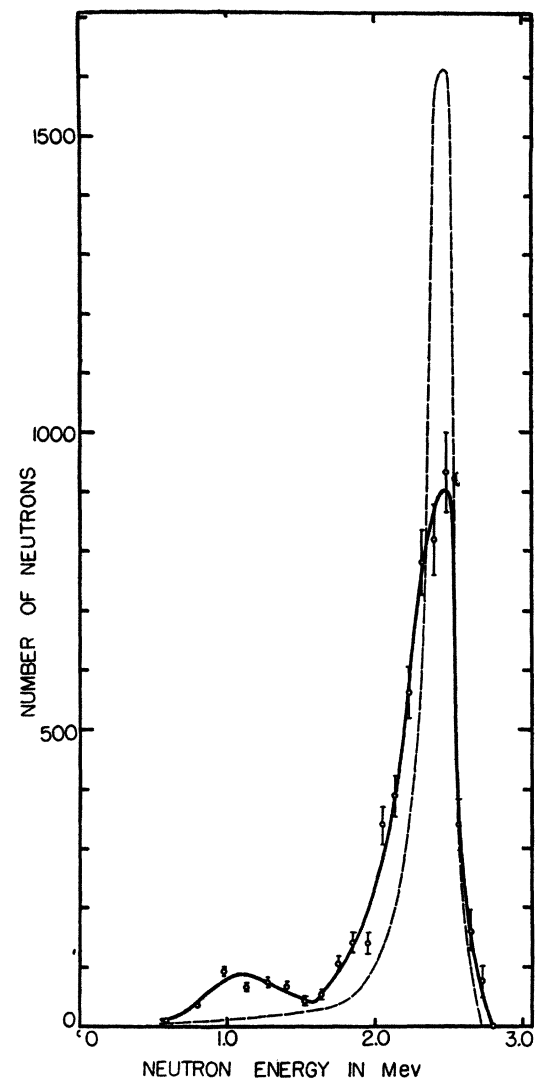

FIG. 3. Energy distribution of neutrons. Solid line with magnesium scatterer; dotted line with no scatterer.

The ranges are converted to energies by the range energy relations given by Bethe and Livingston.[3] Since each ordinate thus calculated did not cover an equal energy interval, each ordinate was divided by the width of the energy interval associated with it. A further correction for variation of neutron proton collision cross section with energy was made by means of relations given by Kittel and Breit.[4] Thus, the area under the curve drawn through the new ordinates between E_1 and E_2 represents the total number of tracks between E_1 and E_2. The curve for the 863 tracks corrected in this manner is shown in Fig. 3 as a solid line. The probable error, e, shown on an observed ordinate was calculated by means of the formula $e=0.67(n)^{\frac{1}{2}}$ where n is the number of observed tracks for that ordinate. Also plotted in Fig. 3 is a curve for the distribution of neutron energies with no scatterer. These data are shown by a dotted curve and were taken by Dunlap and Little in a previous experiment.[5] This latter curve was normalized to make the areas of the two curves equal above $E=1.55$ Mev.

There are two features of the solid curve for scattered neutrons. First, there is a group composed of neutrons direct from the source and neutrons which have been elastically scattered. This group has a most probable energy of 2.46 Mev, but its average energy is 2.36 Mev since the shape of the peak is distorted because of the presence of the elastically scattered neutrons. Second, there is a group composed of inelastically scattered neutrons with a most probable energy of 1.08 Mev. The difference between the average energy 2.36 Mev and the most probable energy 1.08 Mev is not equal to the excitation energy of the first level. Measuring proton recoils with an angle α of the forward direction introduces a difference between the most probable proton recoil energy and the mean neutron energy of $E\alpha^2/2$ where E is the most probable proton recoil energy.[6] This correction brings the mean energy of the inelastic group to 1.09 Mev and the average energy of the elastic and unscattered group to 2.40 Mev. The difference of these two energies still does not give the excitation energy because the recoil nucleus in each case has a different energy. The recoil nucleus energy is given by

$$MV^2/2=m/M(mv^2/2),$$

hence for the inelastic scattering the recoil nucleus has 0.04-Mev energy. The total kinetic energy, E, appearing with the inelastically scattered neutron is 1.13 Mev. A magnesium nucleus which has emitted a neutron of 2.40 Mev energy has a recoil energy of 0.10 Mev. However, in the group which has average energy 2.40

[3] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 268 (1937).
[4] C. Kittel and G. Breit, Phys. Rev. **56**, 747 (1939).
[5] H. F. Dunlap and R. N. Little, Phys. Rev. **60**, 693 (1941).
[6] See reference 3, page 290.

Mev only 1000 in 3830 have been elastically scattered; hence the average recoil nucleus energy for the group as a whole is 0.03 Mev. This makes the average total energy, E^*, appearing with a neutron of the elastically scattered or unscattered group 2.43 Mev. The difference between these two total energies, E^*-E, then gives the excitation energy as 1.30 Mev. This value is to be compared with

1.37 Mev[7]
1.32 Mev[8]

from proton scattering experiments and with the energy differences

1.49 Mev[9]
1.55 Mev[10]
1.46 Mev[11]
1.38 Mev[12]
1.38 Mev[13]
1.31 Mev[14]

which were obtained from gamma-ray measurements.

Comparison of the scattered and unscattered curves (solid and dotted curves) in Fig. 3 also gives an approximate value for the elastic and inelastic scattering cross sections. The curves were normalized to have equal area for energies above 1.55 Mev since this was thought to be an upper bound on the inelastically scattered neutrons and a lower bound on the direct or elastically scattered neutrons. The area then included beneath both curves represents the number of neutrons direct from the source, whereas the number under either curve not included by the other represents the number of elastically scattered neutrons. The neutrons scattered from magnesium can thus be separated into three groups (I, E, D) of inelastically scattered neutrons, elastically scattered neutrons, and neutrons direct from the source with relative numbers.

$$1:E:D=415:1000:2830.$$

From the relations

$$I=N_0[1-\exp(-k_i nx)], \quad (1)$$

$$E=N_0[1-\exp(-k_E nx)], \quad (2)$$

$$N_0=I+E+D, \quad (3)$$

where x is the thickness of magnesium traversed in cm (3.88 cm) and n is the number of magnesium atoms per cc, the two scattering cross sections k_i and K_e can be calculated. These formulae are only approximate, for (1) and (2) assume that the cross sections are small, i.e., that the presence of the two competing scattering mechanisms does not materially affect the number of neutrons available to either scattering mechanism, and (3) assumes that as many neutrons are scattered into the detector by the scattering material which lies outside the solid angle subtended by the detector as are scattered out by the scattering material which lies within the solid angle.

On these assumptions the calculation gives

$$k_i=0.6\times10^{-24}\text{ cm}^2,$$

$$k_E=1.6\times10^{-24}\text{ cm}^2,$$

with a ratio

$$k_E/k_i=2.6.$$

In addition to the obvious inaccuracies in the method for resolving the direct and elastically scattered group, it should be pointed out that the correction factors are more critical for the cross section calculation than for the determination of the excited energy level. As can be seen from the probable errors on the solid curve in Fig. 3, the correction factors are larger for the higher energies. If these were in error, the effect on the location of the most probable energy would be very small, whereas a comparison of the heights of two peaks on the curve would be more greatly affected.

In conclusion, we wish to thank Professor H. A. Wilson, Professor C. W. Heaps, and Dr. W. E. Bennett for their interest and suggestions in this work.

[7] T. R. Wilkins, Phys. Rev. **60**, 365 (1941).
[8] R. H. Dicke and John Marshall, Jr., Phys. Rev. **63**, 86 (1943).
[9] C. Kikuchi *et al.*, Proc. Phys. Math. Soc. Japan **21**, 260 (1939).
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[11] Curran, Dee, and Strothers, Proc. Roy. Soc. **A175**, 546 (1940).
[12] J. Itoh, Proc. Phys. Math. Soc. Japan **23**, 605 (1941).
[13] Elliott, Deutsch, and Roberts, Phys. Rev. **61**, 99 (1942).
[14] C. E. Mandeville, Phys. Rev. **62**, 309 (1942).