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Scattering of 14-Mev Neutrons by Carbon

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Differential and total cross sections have been determined for scattering of 14.1-Mev neutrons from several levels in carbon. The data were measurements of scattered neutrons made by means of the proton recoil reaction in nuclear emulsion plates. The inelastic cross sections were 203 mb for the 4.4-Mev level, 96 mb for the 9.6-Mev level and 124 mb for the unresolved higher levels. The shape of the angular distribution for the 4.4-Mev level indicated the possibility of some direct interactions. No significant amount of scattering was observed due to the 7.6-Mev level. The elastic scattering angular distribution showed a forward peaked diffraction type structure and yielded a cross section of 805 mb. Comparisons are made with other data on the elastic and 4.4-Mev level scattering.

INTRODUCTION

THE measurement of the energy and angular distribution of the scattered neutrons from C^{12} is desirable for two purposes. Data on these scattering processes are of interest generally as contributing to our fundamental knowledge of nuclear structure and also in the solution of more immediate practical problems.

The energy spectrum of the inelastically scattered neutrons enables one to determine energy levels in the residual nucleus and partial widths for the decay of the compound nucleus to the various levels. The angular distribution for each level would in principle give the spin and parities involved. Both the energy and angular distributions of the scattered neutrons would give a measure of the absorption of a neutron beam in carbon.

Most of the previous work on inelastic scattering of neutrons on carbon has been done by studying the gamma rays resulting from the decay of C^{12*} to its ground state. Because of its difficulty, most work on direct neutron measurements has been toward determining total cross sections or trying to fit inelastic energy distributions by a statistical model. Early measurements of this sort have been reported by Phillips,[1] Graves and Davis,[2] and Graves and Rosen.[3] Whitmore[4] succeeded in resolving neutrons scattered from the 4.43-Mev level in C^{12}. Coon *et al.*[5] and Nakada *et al.*[6] have measured elastic scattering angular distributions for carbon.

EXPERIMENTAL

The neutrons for this experiment were produced by the $H^3(d,n)He^4$ reaction using a Cockcroft-Walton accelerator at the Los Alamos Scientific Laboratory. The targets were zirconium tritide on a tantalum backing. 14.1-Mev neutrons were emitted at an angle 90° to the 250-kev incident deuteron beam and impinged on the carbon scatterer, a cylinder $1\frac{1}{4}$ in. in diameter and $1\frac{1}{4}$ in. long. The axis of the cylinder was aligned with the axis of the incoming collimated beam. The collimator, developed by Rosen,[7] consisted of an iron pyramid with its apex directed toward the neutron source and having a collimating hole drilled through perpendicular to its base. The scatterer was surrounded by 200 micron thick Ilford C2 nuclear emulsion plates spaced at 10° intervals and arranged from 30° to 150°. The entire assembly of plates and scatterer was surrounded by a paraffin shield.

The plates were developed and read by techniques similar to those described by Rosen[8] using a Leitz Ortholux binocular microscope equipped with a goniometer eyepiece and calibrated movable stage. A total of 3534 tracks was measured on the signal plates and 1238 on the background plates exposed with no scatterer in place.

ANALYSIS

Four types of error may be present in experiments of this type, namely, statistical errors, those due to nonideal geometry, those due to the inherent qualities of and methods used to analyze the nuclear emulsions, and observer differences.

In an effort to estimate the agreement or disagreement between various observers, the three microscopists compiling the present data scanned the same portion of emulsion in a test plate and measured all acceptable tracks as usual. About seven eighths of the total number of tracks measured were seen by all observers. A study was also made as to how differences in angle, projected length, and diving angle influenced acceptance.

After making suitable measurements on the tracks, the distances and angles are reduced to true lengths of protons in the emulsion and then proton energies by means of correction charts and nomograms. The integrated neutron flux is then obtained from the

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[1] Phillips, Davis, and Graves, Phys. Rev. **88**, 600 (1952).

[2] E. R. Graves and R. W. Davis, Phys. Rev. **97**, 1205 (1955).

[3] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).

[4] B. G. Whitmore, Phys. Rev. **92**, 654 (1953).

[5] J. H. Coon *et al.*, Phys. Rev. **111**, 250 (1958).

[6] M. P. Nakada *et al.*, Phys. Rev. **110**, 1439 (1958).

[7] L. Rosen and L. Stewart, Phys. Rev. **99**, 1052 (1955).

[8] L. Rosen, Nucleonics **11**, No. 7, 32 (1953), and **11**, No. 8, 38 (1953).

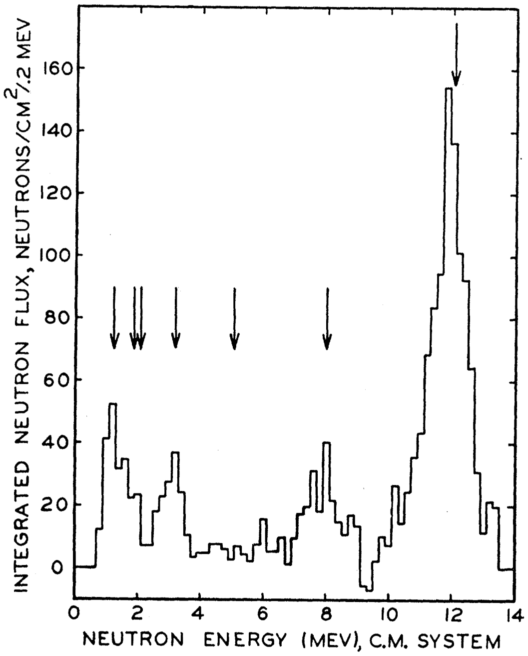

FIG. 1. Integrated neutron flux distribution for all scattering angles as a function of scattered neutron energy in the center-of-mass system. (Arrows indicate the expected neutron energies of the scattered neutrons from each of the known levels in C^{12}.)

following

$$F(E_n)dE_n=\frac{4\pi N(E_p)dE_p}{\Omega_{\rm lab}4\langle\cos\theta_T\rangle_{\rm Av}P(l)\sigma_{np}(E_n)nV(1-a)}, \quad (1)$$

where $F(E_n)dE_n=$ integrated neutron flux on the emulsion per energy interval dE_n where E_n is the energy in the laboratory system, $N(E_p)dE_p=$ corresponding proton tracks measured in volume V, $\sigma_{np}(E_n)=$ total neutron-proton scattering cross section, $\Omega_{\rm cm}/4\pi=\Omega_{\rm lab}\times 4\langle\cos\theta_T\rangle_{\rm Av}/4\pi=$ fraction of solid angle in pyramid of acceptance, $n=$ number of hydrogen atoms per unit volume of emulsion, $V=$ volume of emulsion measured, $P(l)=$ fraction of tracks of a given length l that do not leave the emulsion, and $(1-a)=$ transmission factor of neutron beam in nuclear emulsion material.

The resulting neutron flux distribution for scattering from C^{12} is given by Fig. 1 for all angles as a function of scattered neutron energy in the center-of-mass system. The arrows on the curve show those energies of the scattered neutron to be expected due to scattering through each of the known levels of carbon in the energy range investigated here. The peak at 11.75 Mev is elastic scattering, the peak at 7.95 Mev is from the 4.43-Mev level, and the peak at 3.15 Mev represents scattering from the 9.61-Mev level. The region near 5 Mev should contain the 7.68-Mev level, but very few tracks were found due to this level. The three highest levels reached should give scattered neutrons peaked at energies of 1.2, 1.8, and 2.05 Mev but neutrons in this energy region were not resolved. In dividing the neutrons into groups for plotting of angular distributions, bounding energies were taken arbitrarily at minima in the energy distribution.

After dividing the flux of neutrons into energy groups, the cross sections for each level may be found by means of the following equation:

$$F_n(E_n,\Phi)dE_n=FT\rho GV\sigma(E_n,E_{n'},\Phi)\frac{4\pi}{4\pi\langle r_2\rangle_{\rm Av}}dE_n, \quad (2)$$

where $F=$ neutron flux incident on scatterer at its center, assuming no attenuation in the scatterer, $F_n=$ neutron flux incident on nuclear emulsion at angle Φ, $\sigma(E_n,E_{n'},\Phi)=$ differential scattering cross section, $T=$ attenuation factor, $\rho=$ density of scatterer, $V=$ volume of scatterer, $\langle r^2\rangle_{\rm Av}=$ average value of r^2 over scatterer weighted with attenuation factor, etc., and $G=$ number of atoms per gram in scatterer.

Corrections have been made for multiple scattering as calculated by the Monte Carlo method and very kindly furnished by members of the staff of the Los Alamos Scientific Laboratory.

Corrections were also made for (n, charged particle) reactions in the emulsion and for a small number of low-energy neutrons present in the incident beam.

ELASTIC SCATTERING

In the case of neutrons of not too high energies, say less than 100 Mev, but for which $\bar{\lambda}$ is appreciably less than R, the nuclear radius, the limiting concept of the black nucleus is found useful in explaining the angular distribution of elastic scattering. Here one assumes that all neutrons striking the nucleus, that is, for which $l\bar{\lambda}<R$, are absorbed.

The angular distribution of elastic scattering is given by Bethe and Placzek[9] as

$$\frac{d\sigma_{\rm sc}}{d\Omega}\cong R^2\left|\frac{J_1(R\theta/\bar{\lambda})}{\theta}\right|^2, \quad (3)$$

on the basis of the Fraunhofer diffraction pattern of a circular obstacle, where θ is the scattering angle, R is the nuclear radius and J_1 is a first order Bessel function.

Feld *et al.*[10] have made extensive calculations of angular distributions of elastic scattering on the basis of the continuum theory of nuclear reactions. They give the following as the most accurate analytical expression for the angular distribution:

$$d\sigma_{\rm sc}/d\Omega=\tfrac{1}{4}(R+\bar{\lambda})^2\cot^2(\theta/2)\{J_1[k(R+\bar{\lambda})\sin\theta]\}^2. \quad (4)$$

However, they caution that comparison with exact calculations shows that the foregoing is accurate only within the first lobe, being only qualitatively correct for larger θ. At large angles the angular distribution

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[9] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).

[10] B. T. Feld *et al.*, Atomic Energy Commission Report NYO-636, 1951 (unpublished).

has several lobes occurring with an angular spacing of $\bar{\lambda}/R$. The major part of the scattering is confined to the first lobe where $\theta \lesssim \bar{\lambda}/R$.

In the present experiment, the diffraction scattering concepts are expected to hold since the wavelength associated with 14.1-Mev neutrons was $\bar{\lambda}_{\text{c.m.}} = \hbar/(2mE_{\text{c.m.}})^{\frac{1}{2}} = 1.31 \times 10^{-13}$ cm while R as determined by the total cross sections experiments of Cook and Bonner[11] is $R = 3.41 \times 10^{-13}$ cm. Thus $\bar{\lambda}$ is considerably less than R.

Since there are many channels available for decay of the compound nucleus C^{13*}, the probability of decay to the ground state of C^{12}, i.e., compound elastic scattering, is small and therefore almost all of the elastic scattering is expected to be potential or diffraction type. This assumption of no compound elastic scattering is one of the basic features of the continuum theory of nuclear reactions. That the continuum region has indeed been reached for scattering of 14.1-Mev neutrons on carbon is shown by the fact,[12] that the total cross section for the bombardment of carbon by neutrons above 9 Mev is a smoothly varying function of energy.

The present experiment was designed primarily to obtain data on inelastic processes. Results on elastic scattering were nevertheless obtained and are shown in Fig. 2.

Also shown are the experimental results of Coon *et al.*[5] and of Nakada *et al.*[6] on elastic scattering of neutrons from carbon. The data of Coon were taken at 14.1-Mev incident energy as were those of the present experiment, while the work of Nakada was done with 14.6-Mev incident neutron energy.

The prediction of Eq. (4) reproduces the initial slope of our data quite well for small angles, beginning to fall off faster at larger angles. The first diffraction minimum as given by the theory should fall at about 85°. The experimental data does not resolve this minimum, the only indication of its possible presence being the leveling off at about 60°.

It was found that Eq. (4) is not greatly sensitive to small changes in the value of the nuclear radius. When R was varied by about 5% and a new curve computed, it was found to fit the experimental points in the region from 30° to 70° about as well as the one shown in the figure. At angles less than 30°, where no data was taken in this experiment, the two values of R lead to more widely differing results. For angles greater than 70°, changing R caused large shifts in the positions of the secondary maxima, but in this region Eq. (4) is not expected to hold very well.

It might be noted that if the present data were to be fitted by the Bethe-Placzek results, Eq. (3), a radius of about 5×10^{-13} would be required. This seems unreasonably large on the basis of the total cross-section measurements.

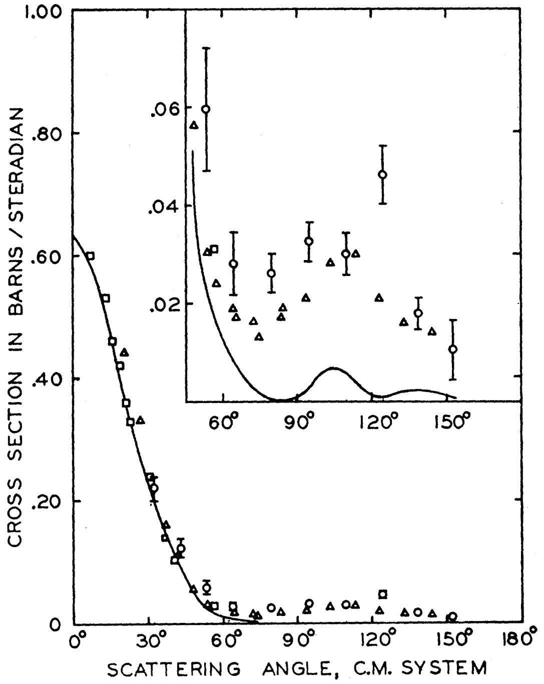

FIG. 2. Cross section as a function of center-of-mass scattering angle for elastic scattering of 14.1-Mev neutrons on carbon. The curve is calculated from diffraction scattering theory. Circles are data of the present work. Squares are from reference 5. Triangle points are from the work of reference 6.

A forward-peaked diffraction-type angular distribution has been obtained also by Conner[13] in elastically scattering 14-Mev neutrons from oxygen and by Smith[14] in scattering from nitrogen.

Taking a weighted sum over angles of the differential cross sections yields 805 millibarns as the total elastic cross section. Feshbach and Weisskopf[15] have shown that a good approximation for black-nucleus cross sections in the energy region of interest here is $\sigma_{\text{sc}} = \sigma_r = \pi(R+\bar{\lambda})^2$. For an $R = 3.41 \times 10^{-13}$, there follows $\pi(R+\bar{\lambda})^2 = 700$ millibarns as compared with our value of 805.

INELASTIC SCATTERING

Inelastic scattering processes may be divided, in general, into three categories on the basis of the number of levels involved in the compound and residual nucleus. In the first category, in which only a single or at most two or three levels are involved, the statistical model is not valid. In this case calculations may be made by considering the detailed contributions of all angular momenta including interference terms. In order to compare the results of such calculations with experiment, considerably more precision is required than was

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[11] C. F. Cook and T. W. Bonner, Phys. Rev. **94**, 651 (1954).

[12] N. G. Nereson *et al.*, Los Alamos Scientific Laboratory Report LA-1655, 1954 (unpublished).

[13] J. P. Conner, Phys. Rev. **89**, 713 (1953).

[14] J. R. Smith, Phys. Rev. **95**, 730 (1954).

[15] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).

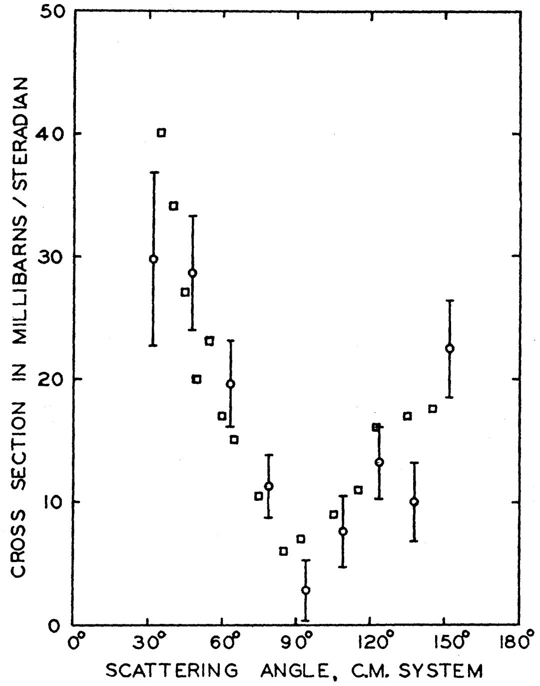

FIG. 3. Cross section as a function of center-of-mass angle of scattering for scattering of 14.1-Mev neutrons from the 4.43-Mev level of carbon. Circles are from the present work. Square points are from reference 18.

attained in this work, since one needs to know the angular distribution expansion coefficients well enough to distinguish between various assumed values of the spins and parities of the compound nucleus.

For the second category of inelastic scattering processes, the statistical model is assumed to be valid for the compound nucleus in which many levels are involved but not for the residual nucleus. The third category includes those cases which may be treated statistically since many levels in both the compound and residual nuclei are involved. Both these latter categories have been analyzed by Hauser and Feshbach[16] and by Wolfenstein.[17] For the second category they obtain generally anisotropic angular distributions which are symmetric about 90°, while for category three they show that the angular distributions are always isotropic.

In the present experiment, angular distributions have been determined for three groups of inelastically scattered neutrons and are plotted in Figs. 3, 4, and 5.

In Fig. 3 is shown the angular distribution for neutrons scattered from the 4.43-Mev level into energies between 5.55 and 8.95 Mev. In this case anisotropy shows up as might be expected for a process falling into the second category of inelastic scattering processes. However the lack of symmetry about 90° precludes, according to the Hauser-Feshbach theory, the possibility that only compound nucleus interactions are involved here and suggests that some fraction of direct interactions be assumed. The total cross section for the 4.43-Mev level, obtained by adding up the differential cross sections weighted with the appropriate solid angle factor, is 203 mb.

The angular distribution of this level has recently been measured by Anderson *et al.*[18] using a time-of-flight technique. Their data is also given in Fig. 3 and shows good agreement with that of the present experiment.

The angular distribution for the 9.61-Mev level is shown in Fig. 4, representing neutrons scattered to energies between 2.35 and 3.55 Mev. The total cross section for the level is 96 mb.

Those neutrons scattered into energies between 3.75 and 5.35 Mev, which should come from the 7.68-Mev level in C^{12} are so few in number and the statistical errors in counting so great that no distribution curve can reasonably be presented.

It has been previously concluded[2] that either the 7.5-Mev level is not formed with any degree of abundance or else that it decays by alpha emission of such low energy as to be unobservable. The present data seem to confirm the former possibility.

Figure 5 shows the angular distribution of neutrons scattered with energies between 1.15 and 2.15 Mev, representing the energetically possible contributions from levels in carbon-12 of energies 10.8 Mev, 11.1 Mev,

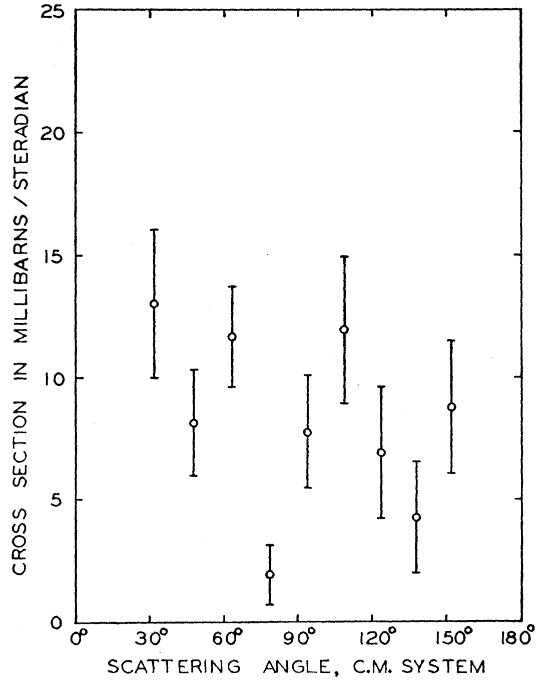

FIG. 4. Cross section as a function of center-of-mass angle of scattering of 14.1-Mev neutrons from the 9.6-Mev level of carbon.

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[16] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[17] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).

[18] J. D. Anderson *et al.*, Phys. Rev. **111**, 572 (1958).

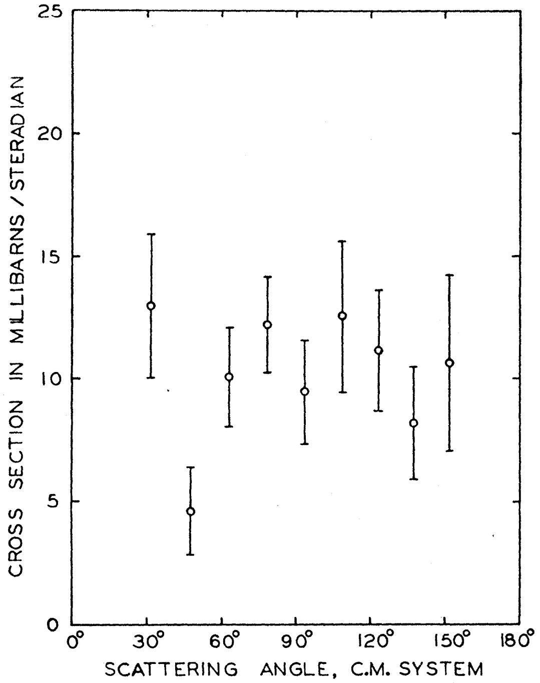

FIG. 5. Cross section as a function of center-of-mass scattering angle for scattering of 14.1-Mev neutrons from the three highest levels of carbon that were excited in the present experiment.

and 11.74 Mev. The level density in C^{13} at the energy of 17.95 Mev, to which it is excited in this experiment, is unknown but is not likely to be very large because carbon is a light element. The incident beam width of 120 kev may not excite more than a few levels in the compound nucleus. However, the fact that, in addition, three or four levels in the residual nucleus contribute might be expected to lead to an isotropic angular distribution. A total cross section of 124 mb was found for these levels.

The total cross section for inelastic scattering is the sum of all points up to 9.15 Mev. Since the region from 0 to 1.15 Mev is missing, the sum will be the emission cross section for inelastically scattered neutrons from this value up rather than the total inelastic cross section. This sum is 444 mb.

Measurements of the inelastic cross section have been made by Phillips *et al.*,[1] who obtained 0.76 barn, and by Graves and Davis[2] yielding 0.47 barn. This includes all processes which result in the neutron energy being reduced below a predetermined threshold and should compare with our value of 444 mb plus whatever is contained in the missing energy region 0 to 1.15 Mev. This value can also be compared to the work of Graves and Rosen[3] which gives 0.52 ± 0.02 barn for the emission cross section from 0.5 to 12 Mev.

Frye *et al.*[19] have measured the cross section for three-alpha decay of carbon as 0.23 ± 0.05 barn. This is to be compared with our cross section for formation of the 9.6 Mev and higher levels in C^{12}, which is 0.22 barn plus contributions from the missing region of 0 to 1.15 Mev scattered neutron energy.

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[19] Frye, Rosen, and Stewart, Phys. Rev. **99**, 1375 (1955).