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Inelastic Scattering of 14-Mev Neutrons from Carbon and Beryllium*

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The angular distributions of the neutrons from the reactions $Be^9(n,n')Be^{9*}$, $Q=-2.43$ Mev, and $C^{12}(n,n')C^{12*}$, $Q=-4.43$ Mev, have been measured from 25° to 140°, employing 14-Mev incident neutrons. Neither distribution is symmetric about 90°; the inelastically scattered neutrons are peaked in the forward direction. The $C^{12}(n,n')$ first-level angular distribution, which agrees with a recent measurement of the $C^{12}(p,p')$ distribution, is in good agreement with the prediction of the Levinson-Banerjee direct interaction theory. The integrated inelastic scattering cross sections for the Be^9 and C^{12} first levels are 0.17 ± 0.03 barn and 0.22 ± 0.03 barn, respectively.

The 4.43-Mev de-excitation gamma rays from C^{12*} are symmetric about 90°. The gamma-ray production cross section at 90° is 13.1 ± 2.0 mb/sterad. No gamma rays associated with Be^{9*} are seen. It is concluded that about one-third of the $(n,2n)$ cross section at 14 Mev is a two-stage process proceeding via the 2.43-Mev level in Be^9.

INTRODUCTION

THE angular distributions of the protons from the reaction $C^{12}(p,p')C^{12*}$, $Q=-4.43$ Mev have been extensively investigated[1,2] in the energy region from 7.3 to 19.5 Mev. In contrast, inelastic scattering of neutrons from C^{12} in this energy region has not yet been investigated. The development of fast-neutron time-of-flight spectroscopy[3,4] capable of resolving neutron groups from inelastic scattering in the light elements, has enabled us to investigate inelastic scattering of neutrons from the first levels[5] in Be^9 and C^{12}. Carbon was also chosen since it was felt that it might be interesting to compare the $C^{12}(n,n')$ with the $C^{12}(p,p')$ angular distributions at the same energy.

Neutrons of 14-Mev nominal energy[6] were obtained by bombarding a tritium-loaded titanium target with 0.5-Mev deuterons from a Cockcroft-Walton accelerator. The time-of-flight system has been described in a previous paper.[4] The experimental details were similar to those used in the measurement of the elastic-scattering cross sections for beryllium and carbon.[6]

RESULTS

Figure 1 shows a time spectrum for carbon at a scattering angle of 40°. The gamma rays, elastically scattered neutrons, and first-level inelastically scattered neutrons are clearly resolved. The carbon ring cross section was 1 in.×2 in., and the detector was biased at 3.8-Mev neutron energy (1.28-Mev gamma-ray energy). At a lower detector bias, the neutron group corresponding to the 9.6-Mev level in C^{12} is also resolved. However, an accurate measure of the cross

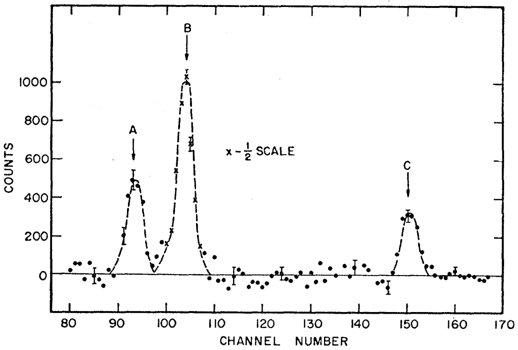

FIG. 1. Time-of-flight spectrum for carbon at a scattering angle of 40°. The time scale is 1 mμsec per channel, and increasing flight time is towards the left. C is due to the 4.43-Mev gamma ray from the inelastic scattering of neutrons from carbon, B to elastically scattered neutrons, and A to carbon first-level inelastically scattered neutrons.

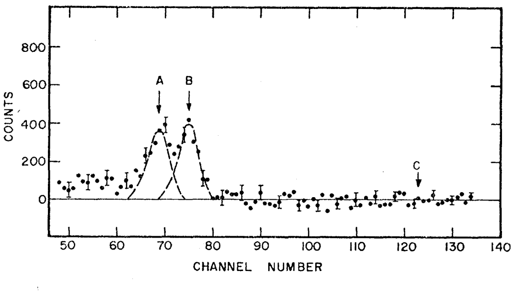

FIG. 2. Time-of-flight spectrum for beryllium at a scattering angle of 90°. The time scale is 1 mμsec per channel, and increasing flight time is towards the left. C denotes the expected position for Be^9 gamma rays following inelastic scattering of neutrons. B is due to elastically scattered neutrons from Be^9, and A to Be^9 first-level inelastically scattered neutrons.

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[1] H. E. Gove and H. F. Stoddard, Phys. Rev. **86**, 572 (1952); W. E. Burcham *et al.*, Phys. Rev. **92**, 1266 (1953); G. E. Fischer, Phys. Rev. **96**, 704 (1954); H. E. Conzett, Phys. Rev. **105**, 1324 (1957).

[2] R. W. Peelle, Phys. Rev. **105**, 1311 (1957).

[3] L. Cranberg and J. S. Levin, Phys. Rev. **103**, 343 (1956).

[4] Anderson, Gardner, Nakada, and Wong, Phys. Rev. **110**, 160 (1958).

[5] By "Be^9 first level" is meant the 2.43-Mev level. There is some evidence, from charged particle interactions [$Li^7(He^3,p)Be^9$], for the existence of states at 1.8 and 3.1 Mev. However, there is no evidence for the excitation of these two states by inelastic scattering of electrons, protons, deuterons, or alpha particles [see F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955)]. Our data are consistent with the excitation of just the 2.43-Mev level.

[6] Nakada, Anderson, Gardner, and Wong, Phys. Rev. **110**, 1439 (1958).

section could not be obtained because of the background of neutrons from the direct breakup of C^{12} into three alpha particles. Within the experimental accuracy, no scattering was detected from the 7.65-Mev level in C^{12}. A rough estimate is $\sigma_{7.65\ \mathrm{Mev}}(\theta)/\sigma_{4.43\ \mathrm{Mev}}(\theta) < 1/10$.

Figure 2 shows a time spectrum for beryllium at a scattering angle of 90°. The beryllium ring cross section was 1 in.×1 in., and the detector was biased at 3.8-Mev neutron energy (1.28-Mev gamma-ray energy). The elastically scattered and 2.43-Mev-level inelastically scattered neutrons are adequately resolved. Within statistics, the energy region below the 2.43-Mev neutron group appears to be a continuum.

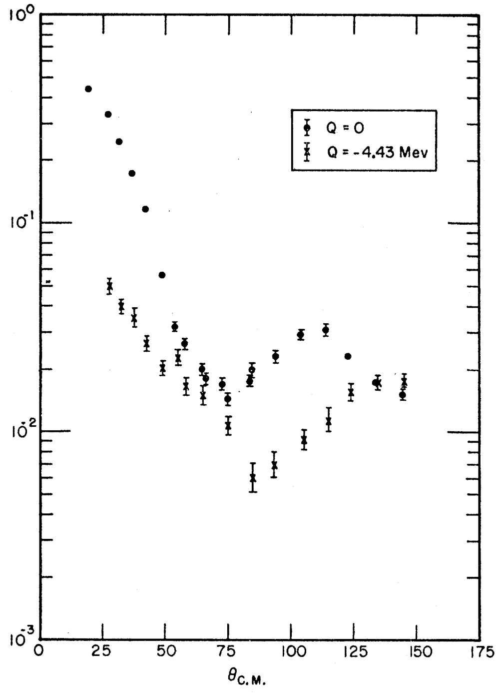

FIG. 3. Angular distributions of the elastically scattered and first-level inelastically scattered neutrons from the scattering of 14-Mev neutrons on carbon. The elastic scattering data are obtained from reference 6.

The counts of first-level inelastically scattered neutrons from Be^9 and C^{12} were converted to cross sections, and errors were assigned according to the methods discussed in references 4 and 6. By utilizing a Monte Carlo code on the UNIVAC, the inelastic scattering cross sections have been corrected for multiple scattering, absorption, and angular resolution due to finite ring size. Correction was not made for the angular resolution due to the detector size, but this correction amounts to less than ±1°. The corrected inelastic scattering cross sections for the C^{12} and Be^9 first levels are plotted in Figs. 3 and 4. Upon extrapolation of these angular distributions to 0° and 180°, the integrated inelastic scattering cross sections for the Be^9 and C^{12} first levels are 0.17 ± 0.03 b and 0.22 ± 0.03 b, respectively.

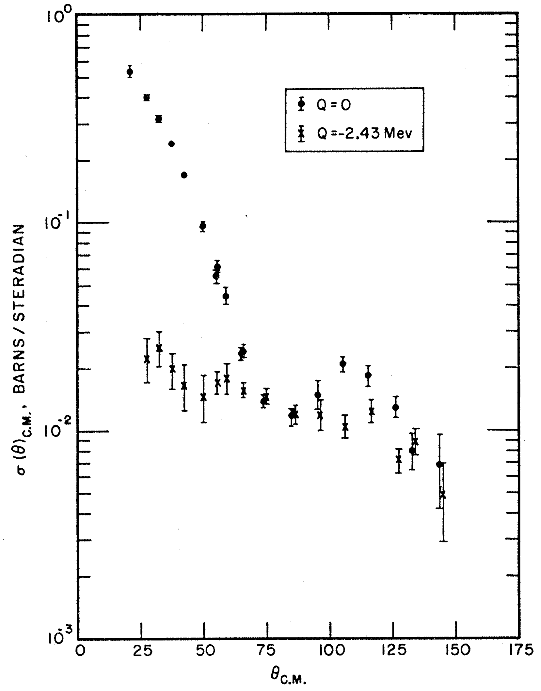

FIG. 4. Angular distributions of the elastically scattered and first-level inelastically scattered neutrons from the scattering of 14-Mev neutrons on beryllium. Elastic scattering data are obtained from reference 6.

Figure 1 also shows the gamma-ray counts from a carbon scatterer when the detector is biased at 1.28-Mev gamma-ray energy. Measurements were also made at lower detector biases, namely, at 0.25- and 0.51-Mev gamma-ray energies. The gamma-ray angular distributions for the three biases were similar in shape. The final combined angular distribution of the gamma rays from carbon under 14-Mev neutron bombardment is shown in Fig. 5. Battat and Graves[7] attribute the gamma rays entirely to the de-excitation of the 4.43-Mev level in C^{12}. Hence, by normalizing the gamma-ray distribution to yield an integrated value of 0.22 barn, the 90° gamma-ray production cross section is calculated to be 13.1 ± 2.0 mb/sterad. Within experimental error, the gamma-ray distribution appears to be symmetric about 90°, and can be fitted with an expression of the form

$$\sigma(\theta) = \sigma(90^\circ)(1 + a\cos^2\theta - b\cos^4\theta),$$

where $a = 1.75 \pm 0.18$ and $b = 1.20 \pm 0.31$.

As shown in Fig. 2, counts due to gamma rays following inelastic scattering of neutrons from Be were not detected. Since the detector was biased at 1.28-Mev gamma-ray energy, this implies the absence of 2.43-Mev gamma radiation from Be^{9*}. At a detector bias of 0.25 Mev, however, gamma rays were observed from the beryllium scatterer, but they were due pre-

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[7] M. E. Battat and E. R. Graves, Phys. Rev. **97**, 1266 (1955).

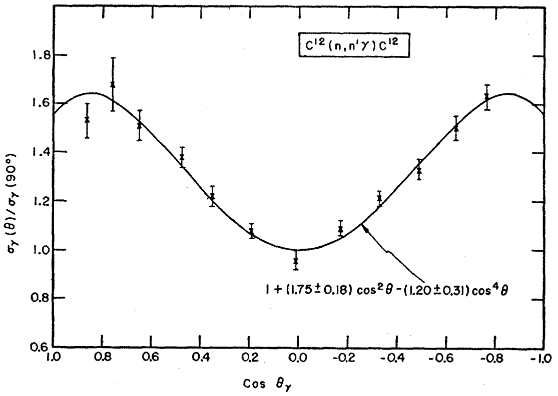

FIG. 5. Angular distribution of the 4.43-Mev gamma ray from carbon under 14-Mev neutron bombardment.

dominantly to Compton scattering of gamma rays produced at the target. At the forward angles, the gamma-ray angular distribution agrees qualitatively with that expected from Compton scattering. In addition, the arrival time of the gamma rays was very insensitive to ring position, indicating that they do not originate in the beryllium. These observations are consistent with the almost total absence of gamma rays produced by 14-Mev neutrons interacting with the beryllium. In the present experiment, a weak gamma ray was observed at the back angles where the Compton-scattered gamma rays are too low in energy to be detected. The energy of this gamma ray is about 480 kev[8] and is attributed to the reactions

$$\mathrm{Be}^9+n\rightarrow\mathrm{Li}^{7*}+\mathrm{H}^3;\quad \mathrm{Li}^{7*}\rightarrow\mathrm{Li}^7+\gamma(477\text{ kev}).$$

DISCUSSION

As seen in Figs. 3 and 4, the angular distributions of neutrons inelastically scattered from C^{12} and Be^9 are not symmetric about 90°; the inelastically scattered neutrons are peaked in the forward direction. Also shown plotted in Figs. 3 and 4 are the elastic-scattering angular distributions for C^{12} and Be^9.[6] The inelastically scattered neutrons are more isotropic, and there is no correspondence between the minima and the maxima of the elastic scattering and the inelastic scattering distributions.

In Fig. 6 is shown plotted the $C^{12}(n,n')C^{12*}$, $Q=-4.43$ Mev, neutron angular distribution as a function of the momentum transfer to the carbon nucleus. Also shown plotted are the $C^{12}(p,p')C^{12*}$, $Q=-4.43$ Mev, proton angular distribution measured by Peelle[2] for 14-Mev incident protons. The solid curve is the prediction of the direct-interaction theory[9–11] as calculated by Levinson and Banerjee.[12] The theory predicts the proton and neutron distributions to be only slightly different at 14 Mev, since Coulomb effects are relatively unimportant. The good agreement between proton and neutron inelastic scattering distributions confirms this prediction.

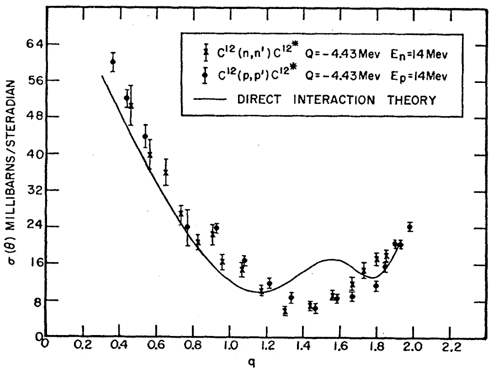

FIG. 6. Angular distributions of protons and neutrons inelastically scattered from the first level in carbon. The proton results are Peelle's measurements at 14 Mev. The solid curve is taken from reference 12 and is the prediction of the Levinson-Banerjee direct-interaction theory. The abscissa q is the momentum transfer in units of $\hbar/(1.4\times10^{-13}\text{ cm})$.

The fact that a 2.43-Mev gamma-ray is not seen when beryllium is bombarded by 14-Mev neutrons implies that the 2.43-Mev level in Be^9 decays by particle emission. The only particle-decay process energetically possible is neutron emission. Since the $(n,2n)$ cross section is 0.53 ± 0.04 barn,[13] this implies that about one-third of the $(n,2n)$ cross section at 14 Mev is a two-step process proceeding via the 2.43-Mev level in Be^9.

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[8] J. Benveniste *et al.* (private communication).

[9] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).

[10] J. R. La Marsh and H. Feshbach, Phys. Rev. **104**, 1633 (1956).

[11] C. A. Levinson and M. K. Banerjee, Ann. Phys. **2**, 471 (1957).

[12] C. A. Levinson and M. K. Banerjee, Atomic Energy Commission Report NYO-8012 (to be published).

[13] V. J. Ashby *et al.*, Phys. Rev. (to be published).