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The Inelastic Scattering of Fast Neutrons in Carbon and Lead

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The inelastic scattering of 14-Mev neutrons in carbon and lead has been investigated by the photographic emulsion method. In carbon, evidence of the excitation of the first-excited level is found, as well as excitation corresponding to Weisskopf's evaporation theory. Comparison with previous results for lead gives no evidence for double inelastic scattering in a thick scatterer.

MEASUREMENTS of the energy distribution of originally monoenergetic neutrons, which have been inelastically scattered by the nuclei of a material, allow the energy taken up by the scattering nucleus to be determined. Such measurements have been used in particular to test the Weisskopf "evaporation" theory for the emission of the scattered neutron from the compound nucleus. It might also be expected that in certain cases, with light elements, evidence of discrete nuclear energy levels could be obtained. In line with previous experiments,[1] measurements have been carried out by the photographic emulsion method using carbon and lead as scattering elements.

CARBON

Recently Graves and Rosen[2] have published the results of inelastic scattering experiments with a number of elements, including both carbon and lead. In their experiments, the scattering substance was, as is usual, in the form of a sphere surrounding the neutron source. This introduces a spread in energy in the laboratory system for neutrons emitted from the compound nucleus with definite energy, owing to the recoil of the compound nucleus. This spread is inappreciable for heavy elements, but considerable for carbon, and might mask any weak monoenergetic scattered neutron group. The carbon scatterer was therefore made in the form of a double cone, the apexes being at the neutron source and photographic plate, respectively, of such proportions that the maximum angle of scattering for a neutron reaching the plate was 70°. Elastically scattered 14.0-Mev neutrons will then reach the plate with an energy range from 12.6 to 14.0 Mev; those which have given, e.g., 10 Mev as internal energy to the scattering nucleus will have a range of energies from 3.1 to 3.7 Mev.

The neutron source was a tritium target bombarded with a 150-kev deuteron beam in the Chalk River accelerator. Exposures were made with and without the scattering substance in position to correct for background. The source and plates were as far as possible from surrounding materials, about 5 ft above a concrete floor. Ilford C2 emulsions, 400μ thick were used, and the developed plates scanned using a Leitz Ortholux microscope, with 90× objective and 6× eyepieces. Tracks making initial angles up to 20° with the original neutron direction were accepted, and neutron energies calculated assuming all neutrons to have been traveling in this original direction. Since they actually reach the plate in all directions within a cone of semivertical angle 10°, a small error is made in this assumption. Number of tracks measured was 1300.

The results, corrected for neutron-proton cross section and loss of tracks in the usual way, are shown in Figs. 1 and 2.

The curve with scatterer shows the usual low-

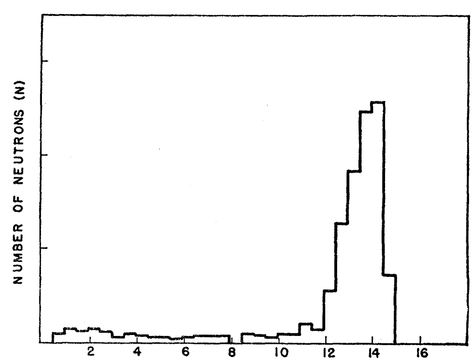

FIG. 1. Energy distribution of neutrons from a d-T source. "Background" without scatterer; number of tracks, 408.

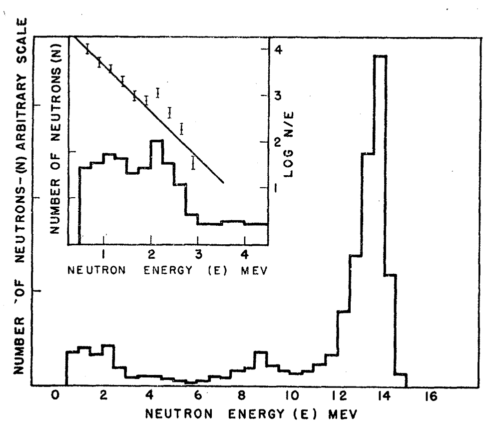

FIG. 2. Energy distribution of neutrons from a d-T source, scattered by carbon. Number of tracks, 1300; inset—region below 3.0 Mev in 0.25-Mev intervals; 800 tracks.

[1] B. G. Whitmore and G. E. Dennis, Phys. Rev. 84, 296 (1951).
[2] E. R. Graves and L. Rosen, Phys. Rev. 89, 343 (1953).

energy group of neutrons, but also a clearly marked group at about 8.75 Mev.

This must correspond to the excitation of the well-known first-excited state of the C^{12} nucleus at 4.5 Mev though the position of the peak corresponds to an absorption of nearer 5.0 Mev.

In the low-energy region there is also a rather strong indication of a discrete group at about 2.1 Mev, as is shown in the inset of Fig. 2. This would correspond to the preferential absorption of about 11.5 Mev. Statistical variations between partial counts were rather larger than average in this region, and the magnitude of the peak at 2.1 Mev is subject to considerable uncertainity, but its existence seems fairly well-established.

These features would not appear but for the limitation of the scattering angle. This limitation, however, has the disadvantage that only a fraction, calculated in this case to be 0.16, of the scattered flux reaches the plate. This in turn means that the scattered flux is comparable with background. In fact, as was found by Mandeville and Swan[3] in a similar experiment, the total flux of low-energy neutrons with scatterer in position is actually slightly less than background, implying that most of the background came from a direction now screened by the scatterer. The proportion of background so screened is, however, unknown, and any accurate comparison of the observations with Weisskopf's formula is therefore impossible. If one assumes, however, that all the background has been screened off, a plot of $\log(N/E)$ against E (Fig. 2) shows a general slope corresponding to a nuclear temperature of 1.0 Mev. Assuming half the background to have been screened does not greatly affect the results, though statistical errors are increased. These results agree, within the rather large experimental errors, with those of Graves and Rosen,[2] though the plot of Fig. 2 indicates that the evaporation theory may not apply accurately for a nucleus as light as carbon.

LEAD

Results have previously been reported[1] of measurements using a sphere of lead of radius 6 cm surrounding the neutron source. In this case the proportion of neutrons inelastically scattered (about 40 percent) suggested that a considerable fraction of them might be twice so scattered, if the once-scattered neutron had sufficient energy. This it may not in fact have, since there is evidence that the lower excited states of all lead isotopes are widely spaced.[4] There was also a question whether the $(n,2n)$ reaction occurred to any extent.

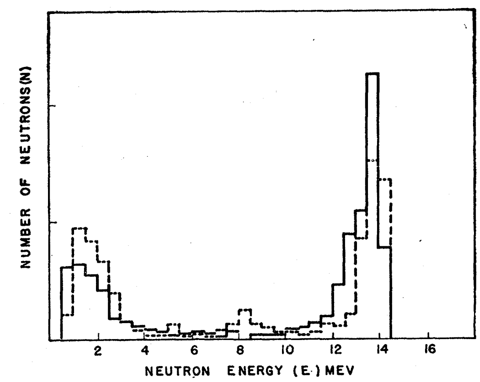

FIG. 3. Energy distribution of neutrons from a d,T source, scattered by lead. Full line—4-cm lead sphere, 1140 tracks; broken line—6-cm lead sphere, 300 tracks.

In an attempt to get further evidence bearing on the first point, these measurements have been repeated using a lead sphere of 4-cm radius around the source. Results of measurements on 1140 tracks, after the usual corrections, are shown in Fig. 3 together with the previous results for 300 tracks using the 6-cm sphere. The exposures were made with the same apparatus and in a similar manner as those with carbon, and separate, "background" plates, though exposed, have not been measured. It is unlikely that they would differ sufficiently from those previously obtained to affect any general conclusions concerning the low-energy region.

It will be seen that the total inelastic scattering has been decreased by about 30 percent, as would be expected from the decreased thickness of scatterer. The doubtful group at 8 Mev in the previous results does not show up, otherwise the low-energy regions are closely similar.[5] The Weisskopf formula again fits approximately, giving a nuclear "temperature" of 0.8 Mev, agreeing with the previous results and with those of Graves and Rosen. There is thus no evidence here of double inelastic scattering.

It was not found possible to measure the absolute neutron flux from the photographic plates sufficiently accurately to determine whether or not the $(n,2n)$ reaction occurred with frequency comparable with that of the (n,n) reaction.

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[3] C. E. Mandeville and C. P. Swann, Phys. Rev. **84**, 214 (1951).
[4] Kinsey, Bartholomew, and Walker, Phys. Rev. **82**, 380 (1951).

[5] It might appear at first sight that this group is as prominent as the similar one in carbon. The total count was, however, much lower in the 6-cm lead experiment, and the statistical error consequently greater.