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The Inelastic Scattering of Fast Neutrons in Lead and Bismuth*

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The energy spectrum of 14-Mev neutrons from the $(T-D)$ reaction after transmission through 6 cm of lead, or bismuth, has been measured by the photographic emulsion method. Approximate agreement with the Weisskopf theory is found, the nuclear temperatures being 0.8 Mev for lead, 0.9 Mev for bismuth. In lead, there is some indication of a group with a discrete loss of energy of about 5 Mev.

THE inelastic scattering of fast neutrons in lead and bismuth has been investigated by a method essentially similar to that of Stelson and Goodman.[1] Neutrons from the bombardment of a deuterium-zirconium target by a magnetically resolved beam of tritium ions from the Chalk River 200-kev accelerator were allowed to fall on Ilford C2 photographic plates placed in the plane of the target at right angles to the tritium beam. The target was at the end of a $\frac{3}{4}$-inch brass tube, and exposures were made (a) with the target assembly as nearly as possible isolated and (b) with the target surrounded by a sphere of lead or bismuth, 6 cm in radius, through which was drilled a 2-cm diameter axial hole for the target assembly.

Tracks of recoil protons making angles not exceeding 13° with the direction from the source were measured. Corresponding proton energies were deduced from the range-energy curve of Lattes *et al.*,[2] and the distribution in energy of the incident neutrons calculated by correcting for the variation with energy of the neutron-proton collision cross section, using the results of Bailey *et al.*,[3] and for the probability that a track leaves the emulsion.

Results of the experiments using no scattering material (250 tracks) and with 6 cm of lead (300 tracks), normalized to represent equal numbers of neutrons, are shown in Fig. 1. In the first case the majority of the neutrons are concentrated in the region of 14.0 Mev, the width at half-maximum of a smooth curve drawn through the observations being 0.8 Mev, which may be accounted for by straggling and variation of direction of the proton tracks. These neutrons are, therefore, essentially monoenergetic. There is, however, an appreciable background of tracks of lower energy, caused, presumably, by neutrons which have been scattered by surrounding material-analyzing magnet, floor, etc.

The results obtained with lead show that about 40 percent of the incident neutrons have been inelastically scattered, most if not all of these having energies now below 4 Mev. The small group at 8 Mev is probably, but not certainly, real, being based on only 10 tracks.

Weisskopf[4] has given an equation for the energy distribution of inelastically scattered neutrons for the case where the incident neutron interacts with all the nucleons of the target nucleus, and the spacing of energy

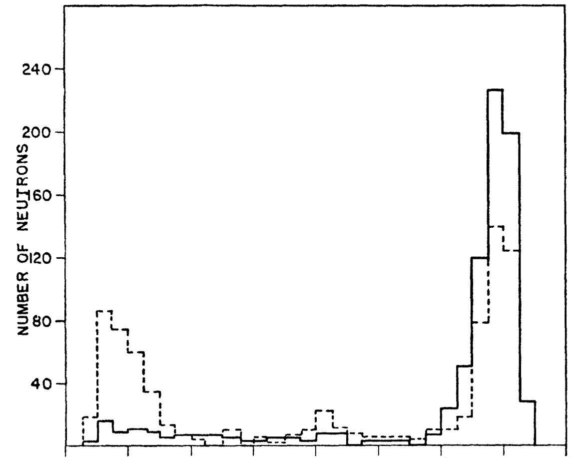

FIG. 1. Energy distribution of fast neutrons scattered by lead. The solid line represents the distribution from the source alone; the broken line represents the distribution from the source surrounded by a 6-cm lead sphere.

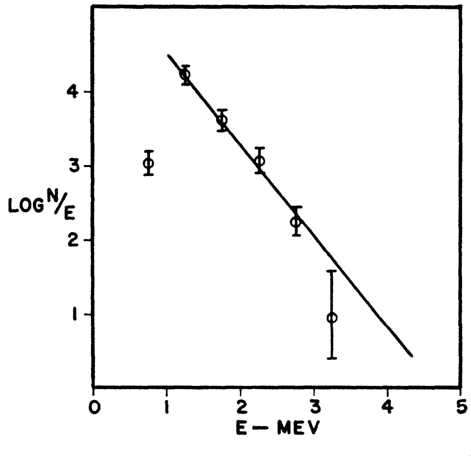

FIG. 2. Energy distribution of fast neutrons scattered by lead (background subtracted). Equation $N(E)=AE\exp(-E/T)$ fitted by a straight line, giving $T=0.8$ Mev.

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[1] P. H. Stelson and C. Goodman, Phys. Rev. **82**, 69 (1951).

[2] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 884 (1947).

[3] Bailey, Bennett, Bergstrahl, Nuckolls, Richards, and Williams, Phys. Rev. **70**, 583 (1946).

[4] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).

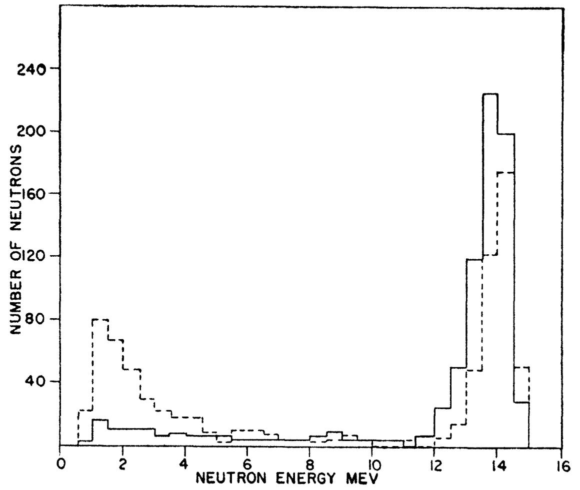

FIG. 3. Energy distribution of fast neutrons scattered by bismuth. The solid line represents the distribution from the source alone; the broken line represents the distribution from the source surrounded by a 6-cm bismuth sphere.

levels of this nucleus is small compared with the energy of the incident neutron. It is

$$N(E)dE=AE\exp(-E/T)dE,$$

where $N(E)dE$ is the number of neutrons having energies between E and $E+dE$, and T is the "temperature" of the nucleus.

To test the applicability of this equation, the background was subtracted from the calculated distribution, and $\log(N/E)$ plotted against E, as shown in Fig. 2. Agreement with the formula does not appear complete although in view of the statistical errors the results are not definitely inconsistent with it. The drop observed at low energies may be due to failure to identify the short tracks involved. Drawing a straight line through the observations as indicated leads to a value of 0.8 Mev for the parameter T. This gives an energy level spacing in the lead nucleus of 0.05 Mev, since $T=(aE_0)^{\frac{1}{3}}$, where E_0 is the incident neutron energy and a is the level spacing at an excitation energy corresponding to several Mev above neutron binding, i.e., to about 10–11 Mev above ground.

The spacing of the lower energy levels of all lead isotopes appears to be much greater than this,[5] but here we are dealing with levels in the neighborhood of an excitation energy of 11 Mev.

Two further factors may affect the observed distribution. First, since as many as 40 percent of the incident neutrons are inelastically scattered, it might be expected that a considerable proportion of them would be twice so scattered. However, the relatively low energy of the once-scattered neutrons and the wide spacing of the lower energy levels in lead might prevent this. Experiments with a thinner layer of scattering material are planned to test this point. Secondly, since the available energy is high, an $(n,2n)$ reaction may occur. The threshold for this reaction, being the same as that for the (γ,n) reaction, is at most 7.4 Mev for any lead isotope.[5] Finally, it is not certain that the background is sensibly unchanged by the presence of the scatterer.

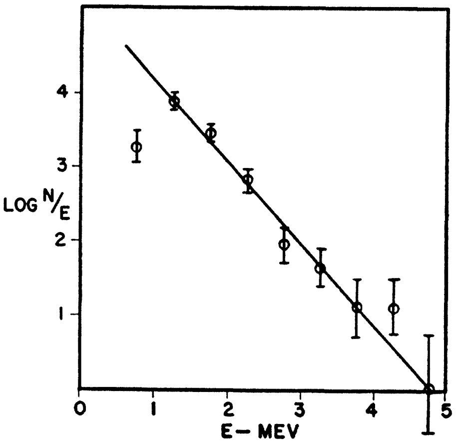

FIG. 4. Energy distribution of fast neutrons scattered by bismuth (background subtracted). Equation $N(E)=AE\exp(-E/T)$ fitted by a straight line, giving $T=0.9$ Mev.

From the fraction of the neutrons scattered the inelastic scattering cross section can be calculated, on the assumption that only the (n,n) reaction occurs, which, as discussed above, may be in error. A value of 2.6×10^{-24} cm^2 was obtained, which seems a little high. The "geometrical" cross section πR^2 with $R=1.40\times10^{-13}A^{\frac{1}{3}}$ cm is 2.2×10^{-24} cm^2. If the background is assumed due to fast neutrons crossing the photographic emulsion obliquely, a value of 2.35×10^{-24} cm^2 is obtained.

The results for bismuth, shown in Figs. 3 and 4, are remarkably similar to those for lead, but there is in this case no evidence of any group of neutrons with energies between that of the incident beam, and those in the main scattered group below 4 Mev. The agreement with Weisskopf's theory seems better than in the case of lead, the values deduced for the parameters being $T=0.9$ Mev, $a=0.05$ Mev.

In the case of bismuth the $(n,2n)$ threshold is about the same, 7.5 Mev.[5] The inelastic scattering cross section, calculated again assuming no $(n,2n)$ reaction, is 3.3×10^{-24} cm^2. This strongly suggests that the $(n,2n)$ reaction occurs frequently, but again no numerical estimate can be given.

The results of the experiments on lead are in good agreement with those of Stelson and Goodman,[1] who, using 15-Mev neutrons, found $T=0.7$ Mev.

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[5] Kinsey, Bartholomew, and Walker, Phys. Rev. 82, 380 (1951).