CONCLUSIONS

The diffraction patterns which are found in the angular distributions of alpha particles scattered elastically from light and intermediate elements determine approximately the alpha-particle interaction radius. A complete understanding of the details of the diffraction patterns awaits a detailed calculation based on a model for the nucleus which incorporates the properties which are indicated by a superficial treatment of the data, namely, opacity of the central part of the nucleus and diffuseness of the edge.[7]

The trend with increasing energy indicates that at sufficiently high energies, the angular distributions of elastically scattered alpha particles will probably exhibit strong diffraction patterns over the entire range of the periodic table and, therefore, should provide a good measure of nuclear parameters. Heavier ions, such as C or N, which presumably interact even more strongly with nucleons, should also give diffraction patterns at sufficiently high bombarding energies and could possibly give a better measure of nuclear radii. Finally, angular distributions of 20-Mev deuterons elastically scattered from Al and Au also show similar phenomena.[18] It would be of interest to compare the interaction radius of the deuteron and the alpha particle.

ACKNOWLEDGMENTS

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[18] In addition to the unpublished work at 20 Mev by the authors, H. E. Gove [Massachusetts Institute of Technology Progress Report, July 1, 1950 (unpublished), pp. 139–144] has observed similar distributions at 17 Mev.

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Energy of the Delayed Neutrons from the Fission of U^{235}

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The energy distribution of neutrons from the short-lived neutron emitters produced in the thermal fission of U^{235} has been determined with a cloud chamber. A continuous energy distribution was obtained with a maximum number of neutrons at the lowest energies and a few neutrons with energies of at least 2.4 Mev. A linear plot of (number of neutrons)$^{1/5}$ *versus* the neutron energy is obtained indicating an extrapolated neutron energy of 3.5 Mev.

DELAYED neutrons which follow the fission of U^{235} have been extensively studied[1] and the latest experiments[2] find six neutron emitters with half-lives of 54, 20, 5.5, 2.1, 0.44, and 0.11 sec. The three emitters with the longest periods[3] have been shown to be Br^{87}, I^{137}, and Br^{89} or Br^{90}; the three emitters of shorter period have not been definitely identified. Experiments of Hughes, Dabbs, Cahn, and Hall[1] on the diffusion of delayed neutrons through paraffin showed that the average energy of these delayed neutrons varied from 0.25 to 0.62 Mev. The purpose of the present experiments was to obtain more detailed information about the energy distribution of the delayed neutrons. Since it is not possible to separate completely the effects of the different neutron emitters, the method employed was to operate so as to maximize the effects of the 2.1-sec emitter which gives the largest yield of neutrons[2] and also has the highest average neutron energy.[1]

Experiments were carried out by sending a "rabbit"

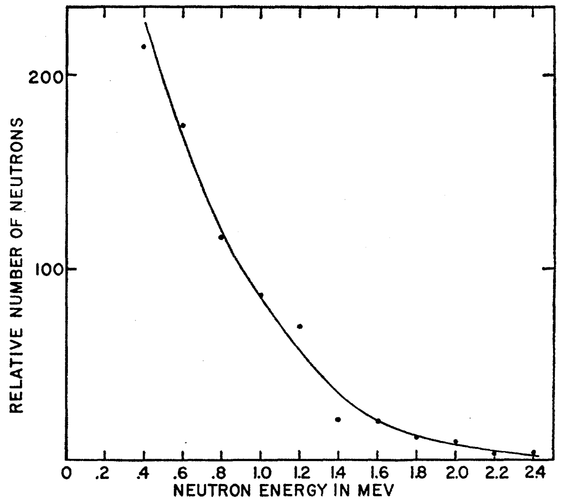

FIG. 1. The energy distribution of the delayed neutrons.

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[1] Brostrom, Koch, and Lauritsen, Nature **144**, 830 (1939); Roberts, Meyer, and Wang, Phys. Rev. **55**, 664 (1939); Snell, Nedzel, Ibser, Levinger, Wilkinson, and Sampson, Phys. Rev. **72**, 541 (1947); Hughes, Dabbs, Cahn, and Hall, Phys. Rev. **73**, 111 (1948); de Hoffmann, Feld, and Stein, Phys. Rev. **74**, 1330 (1948).

[2] G. R. Keepin and T. F. Wimmett, Proceedings of Geneva Conference on the Peaceful Uses of Atomic Energy, August, 1955 (to be published).

[3] N. Sugarman, J. Chem. Phys. **17**, 11 (1949).

containing 0.8 g of 95% U^{235} into the thermal column of the Los Alamos Fast Reactor; the "rabbit" was left for 1 sec in the thermal neutron flux and then was allowed to decay for 1 sec before being brought to a cloud chamber, where recoil protons were observed. The cloud chamber was 25 ft beyond the shield of the reactor and the pneumatic tube which carried the sample was bent so that adequate shielding could be placed between the cloud chamber and the port hole of the thermal column. Background fast neutrons from the reactor were less than one percent of that from the sample of U^{235}. In order to reduce the large γ-ray intensity of the sample to a level such that good recoil-proton tracks could be photographed, the source was surrounded with a 2-in. thickness of lead. This lead shield which covered the source did not appreciably change the energy distribution of the neutrons since very little energy is lost in elastic scattering and the cross section for inelastic scattering of 1-Mev neutrons is only 0.4 barn. The cloud chamber was operated on a 55-sec cycle and so the short-lived activities disappeared between expansions and the 20- and 54-sec activities built up to only a few percent of their saturated activities. At the time of expansion of the cloud chamber, the calculated relative numbers of neutrons from the 5.5-, 2.1-, and 0.44-sec emitters are 17, 65, and 18.

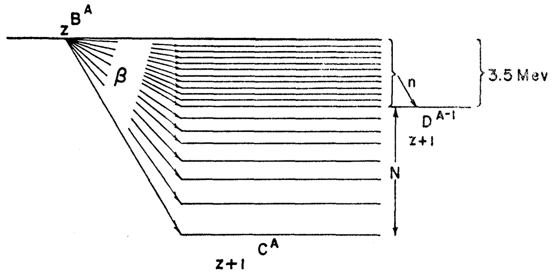

FIG. 2. Decay scheme showing the β emitter $_ZB^A$ which decays to the various excited states of $_{Z+1}C^A$. Those nuclei in states above the neutron separation energy N decay by neutron emission to $_{Z+1}D^{A-1}$.

Experiments were carried out with an expansion cloud chamber filled with $\frac{1}{2}$ or $\frac{2}{3}$ atmospheres of CH_4. Recoil-proton tracks were measured which were within 0° to 15° of the forward direction and so had substantially the energy of the primary neutrons. Three hundred and fifty recoil-proton tracks were measured; after applying corrections for the varying neutron-proton scattering cross section, the energy distribution of the primary neutrons is shown in Fig. 1. The neutron distribution below 0.3 Mev is not plotted because the recoil protons were too short to give reliable results. Figure 1 shows that the number of neutrons decreases rapidly with increasing energy; there are a few neutrons with energies up to at least 2.4 Mev. The average neutron energy cannot be obtained from Fig. 1 without extrapolating the curve to zero energy. Average neutron energies from 0.40 to 0.55 Mev are obtained depending on the type of extrapolation; this result is to be compared to 0.62 Mev which was obtained by Hughes *et al.* from diffusion experiments.

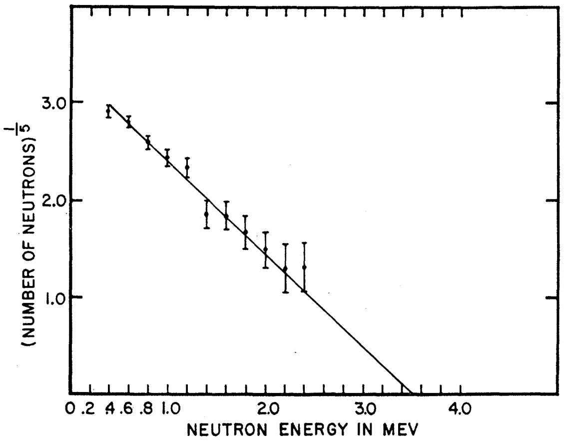

FIG. 3. A plot of (number of neutrons)$^{1/5}$ *vs* neutron energy.

Figure 2 shows a decay scheme of the 2.1-sec β emitter $_ZB^A$ which decays to the nucleus $_{Z+1}C^A$ leaving it either in the ground state or in one of the many excited states. Excited states of this nucleus above the neutron separation energy N can decay by neutron emission to nucleus $_{Z+1}D^{A-1}$. Levels above N will necessarily be wide because of the short time for neutron breakup; since N will be at ~4 Mev of excitation, the levels above N will probably overlap and form a continuum of levels. Under these conditions the β decay of the original nucleus $_ZB^A$ will be expected to be proportional to $E_\beta{}^5$; this will explain qualitatively the rapid decrease in the number of neutrons of higher energies. A quantitative treatment is obtained by plotting the (number of neutrons)$^{1/5}$ as a function of neutron energy as shown in Fig. 3. Within the statistical errors this plot is linear and indicates an extrapolated neutron end point of 3.5 Mev. If the separation energy of the neutron is 4 Mev, β rays with a maximum energy of 7.5 Mev would be expected from $_ZB^A$. Accurate data on the β energies of short-lived fission products are not available for comparison. If the energy of this β transition to the ground state of $_{Z+1}C^A$ were known, the separation energy of the neutron in this nucleus could be computed.