PHYSICAL REVIEW VOLUME 82, NUMBER 1 APRIL 1, 1951

The Inelastic Scattering of 15-Mev Neutrons by Lead, Iron, and Aluminum*

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(Received December 19, 1950)

A tritium-zirconium target bombarded by 1.0-Mev deuterons from the Rockefeller electrostatic generator was used as a source of high energy (~15-Mev) neutrons. This source was surrounded by lead, iron, and aluminum scatterers with dimensions of approximately one mean free path for inelastic scattering. The resulting neutron spectra were measured by means of proton recoils in photographic emulsions. An exposure without scatterer permitted an evaluation of the upper limit for the neutron background. The spectra indicate that most of the neutrons are inelastically scattered to energies below 3 Mev in the case of the lead and iron scatterers and to below 5 Mev with the aluminum scatterer. The data can be represented by a curve of the form (const $Ee^{-E/T}$) as predicted by the Weisskopf statistical theory. The values obtained for the nuclear temperatures, T, are 0.7, 0.6, and 1.1 Mev for lead, iron, and aluminum, respectively. The fact that the measured temperatures for iron and lead are approximately the same supports the hypothesis that lead nuclei have a closed shell structure and therefore have properties similar to much lighter nuclei.

I. INTRODUCTION

THE process of inelastic scattering of neutrons with energy large compared to the spacing of the low-lying levels of the target nucleus has been treated in a quantitative manner by Weisskopf.[1] According to Weisskopf's statistical theory, the energy distribution of the inelastically scattered neutrons is approximately maxwellian with a mean energy $2(aE_0)^{\frac{1}{2}}$, where E_0 is the kinetic energy of the incident neutrons and a is a parameter dependent on the nuclear structure. The quantity $(aE_0)^{\frac{1}{2}}$ is therefore analogous to a temperature, T, and is interpreted as the temperature of the excited residual nucleus. From the available data on nuclei, it was estimated that $a\cong 0.05$ to 0.2 Mev for heavy nuclei ($A>100$). The theory predicted, therefore, that 10-Mev neutrons incident on heavy nuclei should be inelastically scattered to a mean energy of about 2 Mev.

The statistical theory for the emission of neutrons from highly excited nuclei does not depend on the method of excitation and is therefore also applicable to (p, n), (d, n), and (α, n), etc., reactions, provided the energies of the incident particles are large enough to allow a statistical interpretation. Gugelot[2] has carried out an extensive investigation of the neutron spectra resulting from (p, n) reactions with incident protons of 16 Mev. The resulting spectra are maxwellian as predicted by the theory, but the nuclear temperatures obtained are somewhat lower than those predicted.

There have been comparatively few inelastic neutron scattering experiments which permit an effective comparison with the theory. The work of Barschall, *et al.*,[3] and that of Dunlap and Little,[4] in which incident neutron energies of 3 Mev or less were employed, have been interpreted by Feld[5] in terms of the statistical theory and in terms of a detailed theory of individual levels applicable when only a few levels of the target nucleus are involved. He finds that the inelastic scattering of wolfram at incident neutron energies of 1.5 and 3.0 Mev does agree with the prediction of the statistical theory; the value deduced for a is 0.08 Mev. However, the data on iron and lead do not fit the statistical theory and are more readily interpreted in terms of the detailed level theory, thus indicating a large level spacing for these nuclei.

Recently, Gittings, Barschall, and Everhart[6] performed an experiment in which 14.5±0.5-Mev neutrons produced by the $H^3(d, n)He^4$ reaction using low energy deuterons were scattered by lead and the resulting spectrum measured by threshold detectors. Two threshold detectors were used: the $Al(n, p)$ reaction with a threshold[6a] of about 3 Mev, and the $Cu^{63}(n, 2n)$ reaction with a threshold of about 11 Mev. Their result, which depends on the values assigned to the cross sections for the threshold reactions, suggests that the inelastically scattered neutrons which are degraded in energy below the copper threshold are also degraded below the aluminum threshold, indicating that a 14.5-Mev neutron loses at least 11 Mev in its first inelastic collision.

This paper presents the results of an experiment in which the fast neutrons produced by the $H^3(d, n)He^4$ reaction are scattered by the elements lead, iron, and aluminum and the resulting spectra measured by means of proton recoils within photographic emulsions.

II. EXPERIMENTAL METHOD

A diagram of the experimental arrangement is shown in Fig. 1. The dimensions of the scatterers were chosen

* This work was supported by the ONR and the Bureau of Ships.
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[1] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).
[2] P. C. Gugelot, Phys. Rev. **81**, 51 (1951).
[3] Barschall, Battat, Bright, Graves, Jorgensen, and Manley, Phys. Rev. **72**, 881 (1947); Barschall, Manley, and Weisskopf, Phys. Rev. **72**, 875 (1947).
[4] H. F. Dunlap and R. N. Little, Phys. Rev. **60**, 693 (1941).
[5] B. T. Feld, Phys. Rev. **75**, 1115 (1949).
[6] Gittings, Barschall, and Everhart, Phys. Rev. **75**, 1610 (1949).
[6a] The "thresholds" for the $Al(n, p)$ and $Cu^{63}(n, 2n)$ are also quoted as 4.5 Mev and 12 Mev, respectively. The value depends on the definition; i.e., whether this is the energy required just to initiate the reaction or to give a practical yield. See R. M. Kiehn, Technical Report No. 40, Laboratory for Nuclear Science and Engineering, M.I.T. (May 5, 1950).

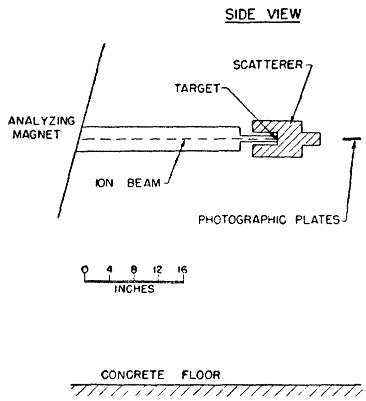

FIG. 1. Diagram, drawn to scale, of experimental arrangement used to measure the inelastic scattering of fast neutrons produced by the $H^3(d, n)He^4$ reaction.

to be approximately one mean free path for inelastic scattering λ_i of 15-Mev neutrons. Smaller dimensions reduce the ratio of the inelastically scattered neutron flux to the background neutron flux, while larger dimensions introduce distortion due to multiple inelastic scattering. Assuming $\lambda_i = 1/n\pi R^2$, where n is the number of nuclei per cm³ and (the radius) $R = 1.4 \times 10^{-13} A^{\frac{1}{3}}$ cm, we obtain for Pb, Fe, and Al, $\lambda_i = 14$ cm, 13 cm, and 30 cm, respectively. Since $\lambda_i(\text{Pb}) \approx \lambda_i(\text{Fe}) \approx \lambda_i(\text{Al})/2$, the dimensions of the three scatterers were made identical in order to simplify geometrical considerations.

The fast neutrons from the $H^3(d, n)He^4$ reaction were produced by allowing 1.0-Mev deuterons from the Rockefeller electrostatic generator to strike a thick tritium target of the type described by Graves, *et al.*,[7] in which tritium gas is absorbed in a layer of zirconium metal on a wolfram backing. Since 1.0-Mev deuterons, the lowest energy deuterons for which an appreciable beam current could be obtained from the generator, were incident on a thick target and since the scatterers subtended a large solid angle, the incident neutrons had a considerable variation in energy. From a consideration of the variation of cross section with deuteron energy and the variation of neutron energy with emergent angle for the $H^3(d, n)He^4$ reaction,[8] it is estimated that with the scatterer arrangement used the neutron energy is about 15 Mev with a spread of approximately ±1.5 Mev.

Eastman NTB emulsions of 200 microns thickness were used. In addition to exposures with the lead, iron, and aluminum scatterers, an exposure without a scatterer was made to obtain an evaluation of the neutron background. The four exposures were of the same duration (0.6 μamp-hr); and thus the spectra could be normalized in terms of the volume of emulsion measured. The background neutron flux is produced by (1) some of the deuteron beam striking objects within the generator system (sides of the accelerating tube, walls of the analyzing chamber, collimating slits, etc.) to produce (d, n) neutrons and (2) neutrons produced at the target and then scattered, elastically and inelastically, by the large nearby objects such as the concrete floor and the analyzing magnet. The (d, n) background is approximately the same with and without the scatterer; if anything, it is somewhat reduced with the scatterer present because of the partial shielding of the photographic plates by the scatterer. The more important background of scattered neutrons is appreciably different with and without scatterer, but it is difficult to estimate the change in the character of this background flux. Qualitative considerations indicate that the number of background proton recoil tracks is reduced with the scatterer present. The exposure made without a scatterer is therefore considered to be a measure of the upper limit of the background with a scatterer.

When the plates were measured, a given volume of the emulsion was carefully searched at 210× magnification and tracks within ten degrees of the forward direction were accepted for measurement. The acceptance angles and track lengths were measured at 950× with the exception of the very long tracks whose lengths were measured at 210×. The coordinates of the beginning of each track were used for identification to eliminate possible remeasurements. The range-energy relation used to convert proton recoil track lengths to neutron energies was obtained by measuring the $Li^7(p, n)Be^7$ spectrum at several proton bombarding energies and the $D(d, n)He^3$ and $F^{19}(d, n)Ne^{20}$ spectra at a single deuteron bombarding energy.[9] The correction resulting

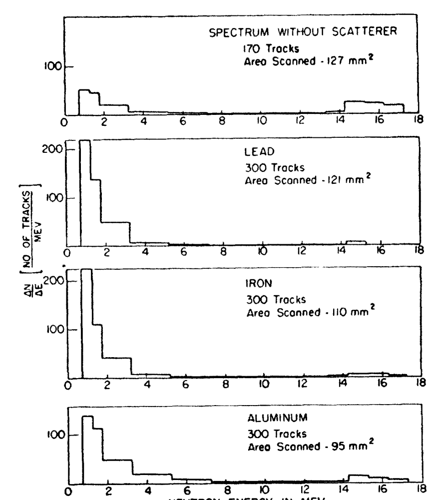

FIG. 2. Histograms of $\Delta N/\Delta E$ vs E, where N is the number of tracks and E is the neutron energy. The correction factors necessary to obtain relative neutron intensity have not been applied to these data. These factors result in a marked increase in the relative magnitude of high energy, primary neutron flux. A lower limit of $E_n = 0.75$ Mev was chosen in plotting the data.

[7] Graves, Rodriques, Goldblatt, and Meyer, Rev. Sci. Instr. **20**, 579 (1949).
[8] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).
[9] P. H. Stelson, Ph.D. thesis, M.I.T. (1950), unpublished.

from the fact that the scatterer is an extended source was not applied to the data.

With a scanning magnification of 210×, the very short tracks ($E_n \leqslant 0.5$ Mev) tend to be overlooked because of the difficulty in distinguishing these tracks from the fog background. It is thought that the region above $E_n = 0.6$ Mev is not distorted by this effect; but, to insure its elimination, a lower limit of 0.75 Mev was chosen in plotting the data.

III. DISCUSSION

The data obtained are presented in Fig. 2 as histograms of $\Delta N/\Delta E$ *vs* E, where N denotes number of tracks and E is neutron energy. Two corrections must be applied to these data to obtain relative neutron intensity: the correction for the variation of the (n, p) collision cross section with energy and the correction for the different probability of leaving the emulsion for tracks of different length. The data were also normalized in terms of the volume of the emulsion measured. The corrected data are given in Fig. 3 as plots of ln [relative neutron intensity/neutron energy] *vs* neutron energy for the lower energy region, where the data are statistically significant. It is seen that the data are represented fairly well by straight lines; according to the statistical theory the negative reciprocal of the slope of these lines is equal to the nuclear temperature, T. The lines designated (1) are the data without the subtraction of the spectrum obtained without a scatterer, while the subtraction has been made for the lines designated (2). The nuclear temperatures calculated from these slopes are: for Pb, $T_1 = 0.8$ Mev, and $T_2 = 0.7$ Mev; for Fe, $T_1 = 0.7$ Mev, and $T_2 = 0.6$ Mev; and for Al, $T_1 = 1.2$ Mev, and $T_2 = 1.1$ Mev. It is seen that the subtraction of the spectrum obtained without a scatterer lowers the nuclear temperature in each case by 0.1 Mev, an amount which is within the statistical uncertainty of the measurements.

The high excitation energy used in the present experiment suggests that the $(n, 2n)$ process is important. The $(n, 2n)$ threshold, E_t, is equal to the (γ, n) threshold and this quantity has been measured for the Pb isotopes by Palevsky and Hanson[10] and for Al by McElhinney, *et al.*[11] The average value of E_t for the three principal Pb isotopes is 7.6 Mev, and the value of E_t for Al is 14.0 Mev. Unfortunately, a value for the (γ, n) threshold of the main iron isotope, Fe^{56}, has not been reported; a calculation of this threshold based on the semi-empirical mass formula gives a value of 11.6 Mev and is probably accurate to 1 Mev. The values for E_t indicate that the $(n, 2n)$ process is probably the principal mode of decay for lead and iron but is of less importance in the case of aluminum. The fact that a nucleus decays by the $(n, 2n)$ instead of (n, n') process complicates the interpretation of the measured nuclear temperature, T. The relatively large low-lying level spacing of Pb and Fe and the low average excitation energy available for the emission of the second neutron (~6.0 Mev for lead, ~2.0 Mev for iron) probably invalidates a statistical interpretation of the second neutron emission. One can state qualitatively that the $(n, 2n)$ process increases the number of lower energy neutrons and thus gives a somewhat lower value for the measured nuclear temperature and that, consequently, the quantity, a, calculated from the expression $T = (aE_0)^{\frac{1}{2}}$ is smaller than if the process were purely (n, n'), for which this formula was derived. The values of a obtained from this formula are 0.03, 0.02, and 0.08 Mev for lead, iron, and aluminum, respectively, where E_0 is taken to be 15 Mev and T is taken as T_2.

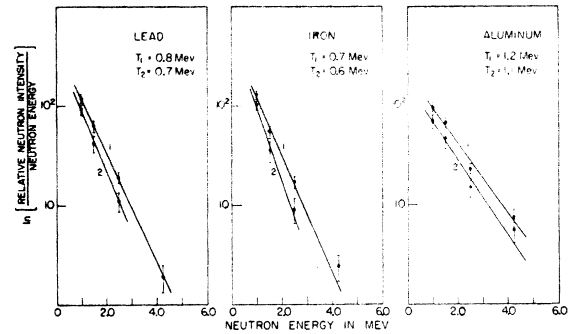

FIG. 3. Semilogarithmic plot of [relative neutron intensity/neutron energy] *vs* neutron energy. The negative reciprocal of the slope is the nuclear temperature, T.

The nuclear temperature is related to the ratio of the level densities of the excited nucleus before and after emission of the neutron. The total excitation energy before emission of the neutron is equal to the kinetic energy of the incident neutron plus its binding energy which, for the present experiment, gives an initial excitation energy of about 22 to 23 Mev. The average excitation energy after the emission of the neutron is the kinetic energy of the incident neutron minus the average energy of the emitted neutron (~$2T$) which is about 13 to 14 Mev. This type of experiment therefore yields information on the ratio of level densities in nuclei at high excitation energies. It is of interest to note that lead, which has approximately four times as many nucleons as iron, has about the same nuclear temperature and hence about the same ratio of level densities at these excitation energies. This can be interpreted as additional support for the hypothesis that lead nuclei have a closed shell structure resulting in a relatively large level spacing characteristic of much lighter nuclei and that this property persists to rather high excitation energies.

The authors wish to thank W. M. Preston, T. T. Magel, H. B. Willard, J. J. McCue, and R. A. Peck, Jr. for their assistance. We also wish to thank Professors V. F. Weisskopf and B. T. Feld for helpful discussion and criticism.

[10] H. Palevsky and A. O. Hanson, Phys. Rev. **79**, 242(A) (1950).

[11] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).