# The Energy Spectrum of the Delayed Neutrons from $O^{17}$

EVANS HAYWARD
*Radiation Laboratory, University of California, Berkeley, California*

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Following the $\beta$-decay of $N^{17}$ an excited state of $O^{17}$ is formed that is unstable against neutron emission. The energy distribution of these neutrons has been measured with a hydrogen-filled cloud chamber. The results indicate that the $\beta$-decay of $N^{17}$ leaves the $O^{17}$ nucleus in one or more excited states and that, if there is only one excited state, it is at least 0.6 Mev wide.

WHEN bombarded with high energy deuterons, the elements just above oxygen in the periodic table have been found to yield delayed neutrons[1] analogous to those found in fission products.[2] The neutrons are emitted with a period that corresponds to a 4.14-second half-life.[1] The nucleus responsible for this period has been identified by Alvarez[3] to be $N^{17}$, which $\beta$-decays to give an excited state of $O^{17}$, which in turn emits a neutron and becomes $O^{16}$.

Alvarez[3] has some preliminary data which indicate that there is a spread in the energy of the neutrons from $O^{17}$ and hence that the energy level from which they come is broad. The object of this investigation was to determine the neutron energy spectrum from the ranges of the knock-on protons in a hydrogen-filled cloud chamber. The cloud-chamber equipment was essentially the same as that used in a previous experiment[4] except that the chamber was removed from the magnet. The target was a LiF crystal ($\frac{1}{2}''\times\frac{1}{2}''\times\frac{1}{4}''$) which was clamped to a spool and blown back and forth between the cyclotron and the cloud chamber through a pneumatic tube. The spool was stopped at a position in the tube such that the target was three feet outside of the concrete shielding and six feet from the cloud chamber (see Fig. 1). The target was bombarded by the circulating 195-Mev deuteron beam of the cyclotron for thirty seconds and then blown out to the cloud chamber which was expanded manually a few seconds after the target came to rest. The cloud-chamber clearing field was not turned off until the time of the expansion so that those ions that were formed before the target stopped moving were swept out before the vapor could condense on them. The cyclotron was turned off after the bombardment, and since the target spent about ten seconds moving out to the cloud chamber, we may be certain that those events that occurred in the chamber were due to the target.

The neutron energy is related to the energy of its knock-on proton by the equation $En = Ep/\cos^2\theta$, where $\theta$ is the scatter angle. The proton range and the angle that the proton makes with the direction of the incident neutron have been measured by reprojection.[4] The range-energy curve (Fig. 2) for the chamber pressure, which was 129.4 cm of $H_2$ saturated with a 2:1 alcohol-water mixture, has been calculated by A. A. Garren.

A region in the cloud chamber was chosen for selecting the tracks such that all those that started within this region would also end in the illuminated

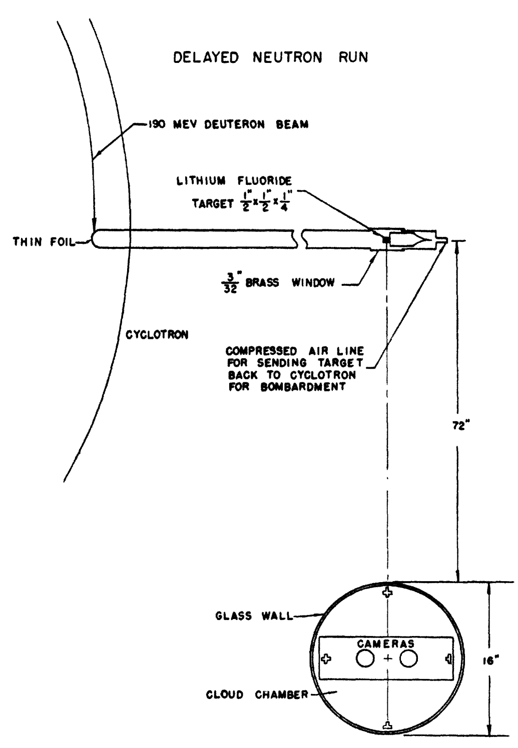


FIG. 1. The experimental arrangement showing the position of the cloud chamber relative to the pneumatic tube, target, and cyclotron.

[1] Knable, Lawrence, Leith, Moyer, and Thornton, Bull. Am. Phys. Soc. F9 (April 29, 1948); W. W. Chupp and E. M. McMillan, Bull. Am. Phys. Soc. F10 (April 29, 1948).
[2] Snell, Nedzel, Ibsen, Levinger, Wilkinson, and Sampson, Phys. Rev. **72**, 541 (1947); Snell, Levinger, Meiners, Sampson, and Wilkinson, Phys. Rev. **72**, 545 (1947); R. B. Roberts, R. C. Meyer, and P. Wang, Phys. Rev. **55**, 510 (1939); Roberts, Meyer, Hafstad, and Wang, Phys. Rev. **55**, 664 (1939); E. T. Booth, J. R. Dunning, and F. G. Slack, Phys. Rev. **55**, 876 (1939); Hughes, Dabbs, Cahn, and Hall, Phys. Rev. **73**, 111 (1948).
[3] L. W. Alvarez, Bull. Am. Phys. Soc. F11 (April 1948).
[4] Brueckner, Hartsough, Hayward, and Powell, Phys. Rev. (in press).

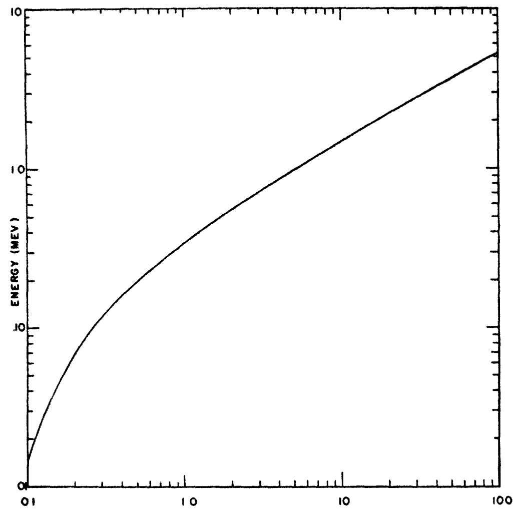


FIG. 2. Range of protons in hydrogen gas, alcohol, and water vapor at a 2:1 ratio by volume (of the liquid), at 129.4 cm Hg, and 20°C.

area. All tracks having scatter angles larger than 30° were excluded in order to minimize the error which is introduced by including recoils from neutrons that have scattered first from the walls of the chamber before producing a knock-on proton in the gas. If all scatter angles are included, the neutron energy distribution contains a few neutrons with energies as high as 10 Mev, but these all arise from protons with large scatter angles and hence are due to neutrons that did not come directly from the target. In the early stages of the experiment a small number of tracks, large scatter angles included, were measured. Out of twenty protons with scatter angles greater than 30°, only two gave exorbitant neutron energies. From this we estimate that about 10 percent of the neutrons included had undergone scattering previous to producing the recoil in the gas. Of course, those protons that have small scatter angles give the most accurate determination of the energy of the neutron producing them. There are not many protons with scatter angles smaller than 10°, but when the neutron energy distribution that they yield is plotted, it is found to agree very well with that obtained when all scatter angles up to 30° are included.

The ranges of all the protons produced by neutrons having energies greater than 0.5 Mev have been measured. The proton ranges were measured to 1 mm. This gives an error in the neutron energy small compared to that caused by the errors in measuring the angles. Tracks of all ages have been included. The width of a track gives a rough estimate of its age. It has been assumed that all "new" tracks, those less than 0.1 cm wide, were produced by protons that traversed the cloud chamber after the expansion and that all those wider than 0.1 cm passed through before the expansion. In obtaining the energy from the proton range, the expanded pressure was used for all "new" tracks and the compressed pressure for all the rest. This seems justifiable since, when the data were divided into four different groups corresponding to four different ages, all gave essentially the same energy distribution. In Fig. 3 the solid histogram represents all the data and the dotted one only those obtained from sharp tracks. More weight should be attached to the new tracks than to the old, since their scatter angles can be measured to $\pm 1°$ whereas the old tracks were measured to only $\pm 3°$. The errors in the neutron energies due to measurement have been estimated to be $\pm 6$ percent for diffuse tracks and $\pm 2$ percent for sharp ones.

One factor that made the determination of the scatter angles difficult was the multiple scattering of the protons by the gas. This is unimportant in the case of the sharp tracks because they are so easy to measure, and since the neutron distributions obtained from either kinds of tracks are essentially the same (Fig. 3), we conclude that there are no large errors in the energy distribution because of multiple scattering.

One of the checks made in the experiment was to calculate the number of neutrons scattered per unit solid angle in the center of mass system for three

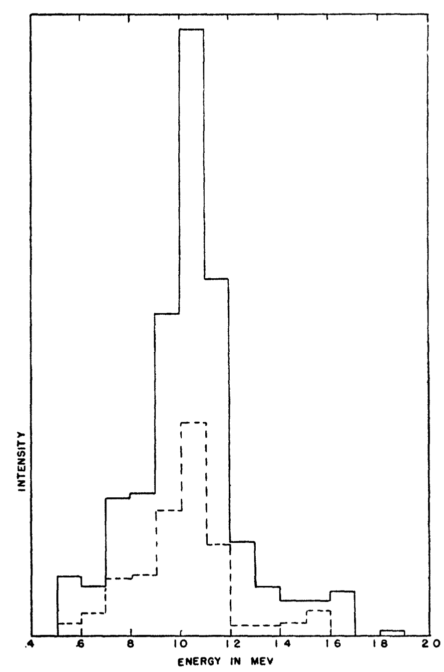


FIG. 3. The solid histograms shows the neutron energy distribution based on all 391 tracks. The dotted histogram is that obtained when only new tracks (those less than 0.1 cm wide) are included; their energies have been corrected for the fact that these particles traversed the cloud chamber after the pressure had fallen by 13 percent.

groups of tracks. This number should be a constant independent of the angle. The results, which agree well within the standard deviations, are $305\pm42$, $276\pm23$, and $270\pm19$. The standard deviations are based on the number of tracks.

The solid histogram in Fig. 3, based on 391 proton recoils, shows the energy distribution of the neutrons; it has been corrected for the variation of the scattering cross section with energy using the experimental data cited by Bohm and Richman.[5] The spread in the curve is about commensurate with that to be expected from experimental error in the measurement of a single energy. However, it should be pointed out that the high energy tail is real since it comes from proton recoils that have energies as high as 1.6 Mev (see Fig. 4). The lower energy end of the curve is not so clear-cut since the recoils responsible for it may be produced by neutrons that have already been scattered before producing knock-ons in the gas of the chamber. This neutron distribution permits one of two conclusions. The first is that the energy level from which the neutron comes is at least 0.6 Mev wide. The other alternative is that there is more than one neutron energy—for example, one at 1 Mev and a second near 1.8 Mev. The higher energy neutron would then be emitted very infrequently compared to the 1-Mev neutron. Alvarez has tried to correlate two such neutron energies with their corresponding $\beta$-rays. His result is not conclusive and certainly not inconsistent with either alternative.

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[5] D. Bohm and C. Richman, Phys. Rev. **71**, 567 (1947).

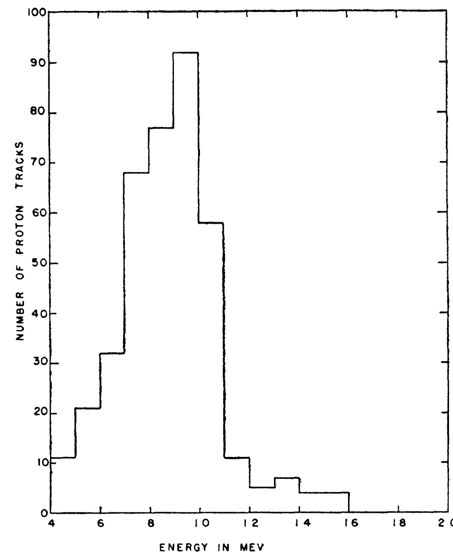


FIG. 4. This histogram shows the energy spectrum of the knock-on protons as they were actually observed. The small, though significant, number of protons having energies above 1.2 Mev indicates that the high energy end of the neutron energy spectrum is real and not due to neutrons that have scattered before producing knock-ons in the gas.

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# Upper Limits of the Fission Cross Sections of Bismuth, Lead, Mercury, Gold, Iridium, and Tungsten for 14-Mev Neutrons*

ANNE N. PHILLIPS, LOUIS ROSEN, AND R. F. TASCHEK
*Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

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A photographic technique was used to set upper limits on the fission cross section of some of the naturally occurring heavy elements below radium when these are bombarded by 14-Mev neutrons; the Los Alamos Van de Graaff, utilizing the $T(d, n)He^4$ reaction, comprised the neutron source. It is established that the fission cross sections of the elements investigated are less than approximately $10^{-5}$ of the cross section of $U^{238}$.

## I. INTRODUCTION

MANY of the investigations of the fissionabilities of various elements, from number 83 down,[1] date back to the early experiments on fission. In all of this work rather weak neutron sources were used, and it is therefore not too surprising that negative results were obtained in nearly all studies. An exception to this was the

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