Neutron spectrum at 0° from 83.7 MeV deuterons on beryllium

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The neutron spectrum measured at 0° from 83.7 MeV deuteron bombardment of a thick beryllium target is bell-shaped with a peak at about 34 MeV and a full width at half maximum of about 22 MeV. Measurements down to 4 MeV show no indication of an evaporation peak. While the shape of the spectrum calculated on the basis of the Serber model for deuteron stripping is similar to the observed shape, the width of the calculated spectrum is broader than that observed. The broadening occurs primarily on the low-energy side of the spectrum. The same features are revealed in further calculations of the 0° spectrum from 53.8 MeV deuterons on a thick beryllium target.

NUCLEAR REACTIONS ^{9}Be(d,n), $E=83.7$ MeV; measured relative neutron yield $Y(0°, E_n)$ down to 4 MeV; calculated spectra at 83.7 and 53.8 MeV on basis of Serber model for deuteron stripping.

I. INTRODUCTION

Neutron spectra from deuteron bombardment of thick targets have been reported by several authors for deuteron bombarding energies from 8.3 to 80 MeV. These include measurements by Skaggs *et al.*[1] at 8.3 MeV, Weaver *et al.*[2] at 8.8 and 18.1 MeV, Tochilin and Kohler[3] at 15, 20, and 24 MeV, Parnell, Page, and Chaudri[4] at 16 MeV, Meulders *et al.*[5] at 16, 33, and 50 MeV, Theus[6] at 35 MeV, Schweimer[7] at 40 and 54 MeV, and Harrison, Kubiczek, and Robinson[8] at 80 MeV. Thin-target measurements have been reported by Weaver *et al.*[2] at 8.8 and 18.1 MeV, Hadley[9] at 190 MeV, and Madey and Waterman[10] at 447 MeV. The thin-target measurements of Hadley *et al.* and Madey and Waterman agree with the predictions of the Serber[11] theory for deuteron stripping.

Schweimer[7] measured the energy and angular distributions of neutrons from 40 to 53.8 MeV deuteron bombardment of 14 thick targets including beryllium. The spectra of neutrons emerging at 0° were measured with a time-of-flight technique; the angular distributions were measured with threshold detectors. The neutron yields and angular distributions observed by Schweimer at 54 MeV are in agreement with those observed by Meulders *et al.* at 50 MeV. Schweimer obtained the differential cross sections for neutron production at 0° from 53.8 MeV deuteron bombardment of 13.8 MeV thick targets by taking the difference between the measured yields at 53.8 MeV and at 40 MeV. Schweimer compared these cross sections with theoretical (Serber stripping) cross sections for deuteron breakup at the nuclear surface.[11] The agreement between the observed and calculated cross sections is poor. Schweimer compared his results also with theoretical cross sections for deuteron breakup in the Coulomb field of the nucleus.[12] The observed differential cross section at 0° for beryllium is about 3.5 times greater than that predicted by nuclear breakup and about 6 times greater than that predicted by Coulomb breakup. Similarly, Millburn *et al.*[13] observed the cross section for neutron production from beryllium and carbon targets bombarded by 160 MeV deuterons to be about 3 times higher than predicted by Serber stripping. Although the observed and predicted cross sections do not agree, Schweimer concludes that the energy and angular distributions are indicative of a deuteron breakup process and, in the first approximation, the energy and angular distributions can be described by a superposition of the internal motion of the deuteron and its center-of-mass motion in the manner derived by Serber. August *et al.*[14] have used the Serber model for deuteron stripping to calculate the neutron spectrum at 0° from 35 MeV deuteron bombardment of a thick beryllium target. August *et al.* report that this calculated spectrum agrees reasonably well with that measured at the same bombarding energy.

In this paper, we report a measurement made at the University of Maryland cyclotron of the neutron spectrum at 0° from 83.7 MeV deuteron bombardment of a thick beryllium target, and compare this energy spectrum to a thick-target calculation based on the Serber model for deuteron stripping. We have computed also the neutron spectra from 53.8 MeV deuteron bombardment of thin and thick targets and compared these calculations with the measurements of Schweimer at the same energy.

II. EXPERIMENTAL TECHNIQUES

Figure 1 is a diagram of the experimental arrangement at the University of Maryland cyclotron. The 83.7 MeV external deuteron beam was stopped in a 1.91 cm diam by 2.22 cm thick beryllium target. The target was backed with 0.438 cm of aluminum and encased in a 7.63 cm diam by 5.08 cm thick aluminum cylinder. The neutron beam at 0° was viewed through an 8.8 cm diam by 107 cm long steel collimator embedded in the 178 cm thick cyclotron shielding wall. Neutrons emitted in the forward direction passed also through a 0.317 cm thick aluminum vacuum window located in front of the collimator entrance.

The neutron spectrum at 0° was measured with a self-contained two-parameter spectrometer for neutrons from about 5 to 200 MeV. Since this spectrometer is described in detail elsewhere,[15] only a brief description is given here. The spectrometer consists of two primary scintillation counters shown as D1 and D2 in Fig. 1, and two anticoincidence detectors A1 and A2. The principle of the spectrometer requires an incident neutron to scatter elastically through an angle θ from a hydrogen nucleus in D1, travel over the flight path between D1 and D2, and interact in D2. The A1 and A2 anticoincidence counters veto events resulting from charged particles in the incident and scattered neutron beams. The parameters measured are the pulse height of the proton recoil in D1 and the flight time of the scattered neutron. These data were stored on magnetic tape and later converted to kinetic energies. The incident neutron energy is the sum of the recoil proton and scattered neutron kinetic energies.

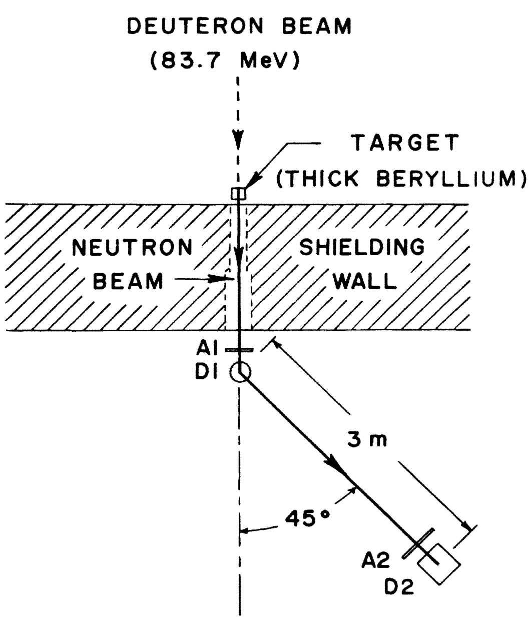

FIG. 1. The experimental arrangement at the University of Maryland cyclotron (not drawn to scale.)

For this experiment, the D1 detector was centered in the neutron beam 4.3 m from the target. The D2 detector was positioned 3 m from D1 and at an angle of 45° with respect to the direction of the incident neutrons. A 10.16 cm diam by 10.16 cm high NE-228 liquid scintillator mounted on an Amperex 58 DVP photomultiplier was used for D1. The D2 detector consisted of a 22.86 cm diam by 20.32 cm thick NE-102 plastic scintillator mounted on an Amperex 58 DVP photomultiplier by means of a tapered lucite light pipe. The thresholds of both the D1 and D2 detectors were set at 2 MeV proton energy. The A1 and A2 anticoincidence detectors consisted of 0.632 cm thick slabs of NE-102 plastic scintillator, 15.2 cm by 15.2 cm and 25.4 cm by 25.4 cm, respectively, mounted on Amperex 58 AVP photomultipliers. The A1 and A2 detector thresholds were set at 1 MeV proton energy.

There are three sources of background present in the spectral measurement. In addition to accidental or chance coincidences between random events in the D1 and D2 detectors, background arises from neutron inelastic interactions with carbon nuclei in D1 and also from neutrons that scatter more than once in D1. The following paragraph describes the techniques used to subtract these backgrounds.

The two-parameter data are compiled in a two-dimensional array of time of flight versus recoil-proton pulse height. The time-of-flight and pulse-height axes are calibrated in units of the scattered neutron and recoil proton kinetic energies, respectively.[15] The background from accidental coincidences is determined from regions of the two-dimensional array that contain only accidental coincidences.[15] Background events from neutron-carbon interactions and plural-scattered neutrons are separated from n-p elastic scattered events by the kinematic requirement for n-p elastic scattering. Recall that the neutron scattering angle is fixed by the geometry of the detectors. For neutrons that scatter elastically from protons, the ratio of the recoil proton T_p' to scattered neutron T_n' kinetic energy is a constant value specified by

$$\tan^2\theta = T_p'/T_n' . \qquad (1)$$

Since neutron-carbon reactions or plural-scattered neutrons are not restricted by n-p kinematics, the "recoil proton" and "scattered neutron" energies from these background events are not required to occur in the ratio specified by Eq. (1).

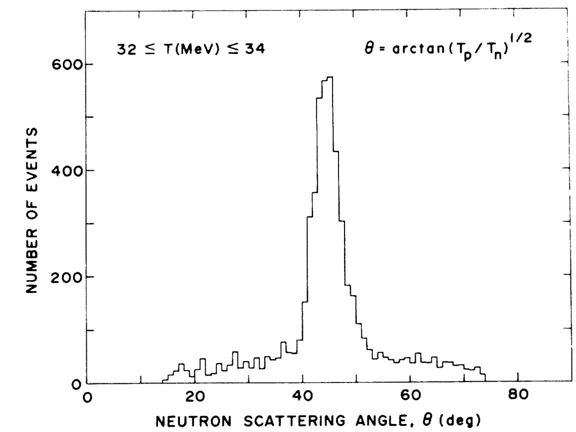

FIG. 2. The distribution of neutron scattering angles associated with incident neutrons in the energy interval from 32 to 34 MeV.

The background subtraction technique is illustrated in Fig. 2. Figure 2 shows the distribution of the neutron scattering angles given by Eq. (1) for those events that give also an incident neutron energy in the interval from 32 to 34 MeV. The neutrons scattered elastically from protons appear as a peak centered at about 45° and superposed on a sea of background extending from about 5° to 80°. The number of n-p elastic scattered events is determined by extrapolating the background through the base of the peak. The number of n-p elastic scattering events was determined in a similar manner for each 2 MeV interval of the spectrum from 4 to 40 MeV and for each 5 MeV interval of the spectrum from 40 to 75 MeV. In the example shown in Fig. 2, background events from neutron-carbon interactions and plural-scattered neutrons comprise 37% of the total number of events observed in the interval from 32 to 34 MeV; however, over the entire energy spectrum, these backgrounds comprised 46% of the events observed.

III. EXPERIMENTAL RESULTS

The measured spectrum of neutrons at 0° from 83.7 MeV deuteron bombardment of a thick beryllium target is plotted in Fig. 3 as a histogram; the smooth curve is a calculated spectrum based on the Serber model of deuteron stripping. (The calculated spectrum is discussed ahead in Secs. 4 and 5.) The error bars denote the statistical uncertainty in the measurement. The observed spectrum is peaked at about 34 MeV with a full width at half maximum (FWHM) of about 22 MeV. The spectrum was measured down to 4 MeV. There is no indication of the large evaporation peak predicted at about 4 MeV by Moyer and reported by Goebel and Miller.[16]

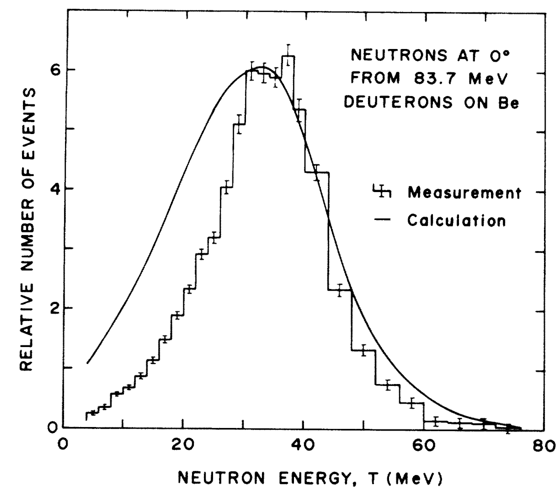

FIG. 3. The measured energy spectrum of neutrons emitted at 0° from 83.7 MeV deuteron bombardment of a 2.2 cm thick beryllium target and that calculated from the Serber (Ref. 11) model for deuteron stripping.

Harrison, Kubiczek, and Robinson[8] have reported a recent measurement of the neutron spectrum at 0° from 80 MeV deuteron bombardment of a thick beryllium target. Harrison, Kubiczek, and Robinson measured the time of flight of neutrons between the beryllium target and a scintillation counter by timing from the arrival of the deuteron beam burst on the target. Their spectrum has the same shape and the same full width at half maximum as our measurement; however, the energy scale in their spectrum is about 4 MeV lower than ours. About 2 MeV of this difference can be accounted for by the difference in deuteron bombarding energies. An analysis of the possible error in our measurement yields an uncertainty of less than 1.5 MeV in determining the neutron energy.

IV. THICK TARGET CALCULATION

The neutron spectrum at 0° from deuteron bombardment of a thick beryllium target was calculated for the Serber[11] model of deuteron stripping. The calculation was performed as a series of thin-target calculations which were then superposed to obtain the thick-target spectrum. The thickness of each successive thin target was selected to represent a 1 MeV energy loss of the incident deuteron beam. The target thicknesses were computed using the range-energy tables of Rich and Madey.[17]

In the Serber model for deuteron stripping, the stripping cross section is independent of the deuteron energy. The total stripping cross section σ is

$$\sigma = \tfrac{1}{2}\pi R R_d , \qquad (2)$$

where R is the radius of the target nucleus and R_d is the radius of the deuteron.

The energy and angular distribution of the stripped neutrons is derived by superposing the internal momentum of the neutron in the deuteron and the center-of-mass momentum of the deuteron. The energy distribution $N(T)$ of neutrons stripped from deuterons with incident energy T_d is

$$N(T)=\frac{T_d\epsilon_d}{[(T-\frac{1}{2}T_d)^2+T_d\epsilon_d]^{3/2}}, \tag{3}$$

where ϵ_d is the deuteron binding energy (2.2245 MeV) and T is the kinetic energy of the stripped neutron. The angular distribution $N(\phi)$ of neutrons stripped from deuterons with incident energy T_d is

$$N(\phi)=\frac{T_d/\epsilon_d}{2\pi(1+T_d\phi^2/\epsilon_d)^{3/2}}, \tag{4}$$

where ϕ is the angle between the direction of the incident deuteron and that of the emergent neutron. As the deuteron energy decreases, the angular distribution broadens; hence, the relative number of neutrons emerging at 0° decreases with decreasing neutron energy. From Eq. (4), it is evident that the relative probability for a neutron emerging within a small solid angle about 0° is proportional to the deuteron energy:

$$N(0°)=T_d/2\pi\epsilon_d. \tag{5}$$

The kinetic energy lost by the deuteron in penetrating the Coulomb barrier of the target nucleus is not taken into account in the Serber model. Also, 2.2245 MeV of the incident deuteron energy is used to overcome the deuteron binding energy. These effects can be accounted for by reducing the kinetic energy of the deuteron when it reaches the nucleus by $T_d-(T_C+\epsilon_d)$, where T_C is the height of the Coulomb barrier. The primary effect of this correction is to shift the center of the thin-target energy distribution to a lower energy by an amount $\frac{1}{2}(T_C+\epsilon_d)$. For beryllium, $T_C=2.2$ MeV.

The neutron energy distribution was computed from Eq. (4) for each thin-target segment; in this calculation, the reduced deuteron bombarding energy was used. The energy spectrum for each thin-target segment was weighted by the incident deuteron energy to account for the decrease in the relative number of neutrons emerging at 0° as the deuteron energy decreases. The thin-target energy distributions were corrected also for nuclear attenuation of the deuterons and neutrons in the target. The thin-target energy spectra were then superposed to obtain the thick-target spectrum.

V. INTERPRETATION OF RESULTS

The neutron energy spectrum at 0° calculated from the Serber stripping model for 83.7 MeV deuteron bombardment of a 2.22 cm thick beryllium target is shown in Fig. 3, together with the measured spectrum. To compare the spectral shapes, the peak amplitude of the calculated spectrum was normalized to that of the measured spectrum. The unreliability of the beam monitor at the low deuteron beam intensity used for these measurements precluded a comparison of the spectra on an absolute basis. While the shape of the calculated spectrum is similar to the observed shape, the width of the measured spectrum is narrower than the calculated width. In Fig. 3, the full width at half maximum of the observed spectrum is about 22 MeV, whereas that of the calculated spectrum is about 31 MeV; thus, the observed width is about two-thirds of the calculated width. It appears that the increase in width occurs primarily on the low-energy side of the spectrum.

We calculated also the neutron spectrum at 0° from 53.8 MeV deuteron bombardment of a thick beryllium target and compared this calculation to Schweimer's measurement at the same bombarding energy. This comparison is shown in Fig. 4. Here again, although the spectral shapes are similar, the width of the measured spectrum is significantly less than that calculated, and the increase in width occurs primarily on the low-energy side of the spectrum.

The neutron spectrum at 0° from 53.8 MeV deuteron bombardment of a 13.8 MeV thick beryllium target was obtained by subtracting Schweimer's

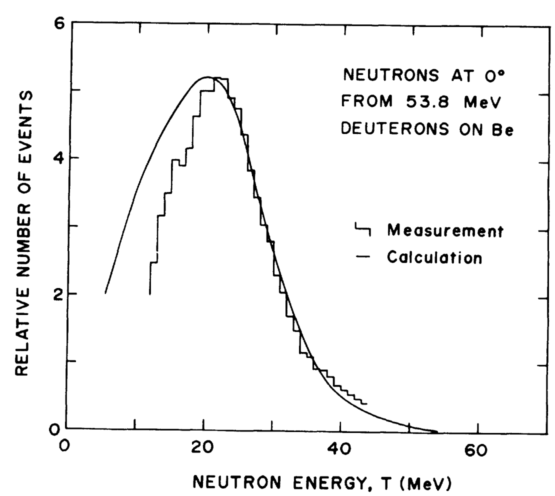

FIG. 4. The energy spectrum measured by Schweimer (Ref. 7) of neutrons emitted at 0° from 53.8 MeV deuteron bombardment of a thick beryllium target and that calculated from the Serber (Ref. 11) for deuteron stripping.

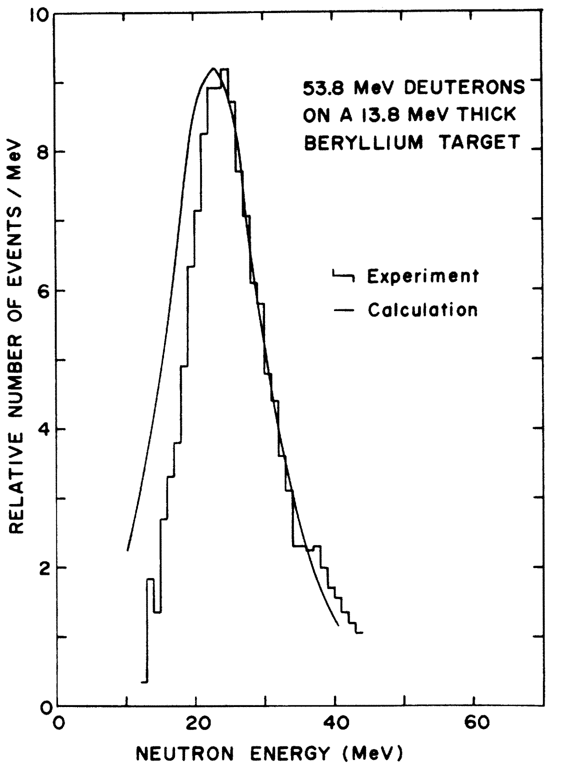

FIG. 5. The energy spectrum of neutrons emitted at 0° from 53.8 MeV deuteron bombardment of a 13.8 thick beryllium target obtained from Schweimer's (Ref. 7) measurements at 53.8 and 40 MeV, and that calculated from the Serber (Ref. 11) model for deuteron stripping.

measurement at 40 MeV from that at 53.8 MeV. This "thin" target measurement is plotted in Fig. 5 together with a calculation of the neutron spectrum from 54 MeV deuteron bombardment of a 14 MeV thick target. The comparison of the observed and calculated spectra for the 13.8 MeV thick target shows the same features as the thick-target spectra; namely, that while the general shapes of the spectra agree, the width of the calculated spectrum is greater. Again, this increase in width occurs on the low-energy side of the spectrum.

While spectral measurements at deuteron bombarding energies of 190 and 447 MeV support the Serber theory for deuteron stripping, it appears that this theory does not account fully for the spectral measurements at deuteron bombarding energies below 100 MeV. Lang, Jarczyk, and Muller[18] have calculated the breakup of deuterons in Coulomb and nuclear fields in the framework of a distorted-wave Born approximation (DWBA). Numerical calculations for a gold target and an incident deuteron energy of 12 MeV give good agreement with experiment. It is suggested that calculations of this type be extended to higher deuteron energies.

VI. CONCLUSIONS

The neutron spectrum measured at 0° from 83.7 MeV deuteron bombardment of a thick beryllium target is bell shaped with a peak at about 34 MeV and a FWHM of about 22 MeV. Measurements down to 4 MeV show no indication of an evaporation peak. The shape of the spectrum calculated on the basis of the Serber model for deuteron stripping is similar to the observed shape; however, the calculations overestimate the width and indicate that the increase in width occurs primarily on the low-energy side of the spectrum. This overestimate of the width on the low-energy side occurs also at a lower deuteron bombarding energy of 53.8 MeV. While spectral measurements at deuteron bombarding energies of 190 and 447 MeV support the Serber theory for deuteron stripping, it appears that this theory does not account fully for the spectral measurements at deuteron bombarding energies below 100 MeV.

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