# Neutron Spectra from $Li^7(d,n)Be^8$ and $F^{19}(d,n)Ne^{20}$ for 1.98-MeV Deuterons

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The neutron spectrum from $Li^7(d,n)Be^8$ was studied at 120° with respect to the beam of deuterons incident on a lithium metal target. The average deuteron energy in the target was 1.98 MeV. Up to an excitation of 9 MeV in $Be^8$, only the ground state and the first excited state are observed. The neutron group to the excited state has a peak corresponding to 3.1±0.1-MeV excitation in $Be^8$ and a width of 1.75±0.1 MeV in the center-of-mass system; however, the interpretation of these numbers in terms of the level parameters is obscured by the presence of a continuum from three-body decay. The relative differential cross section for the neutron groups leaving $Be^8$ in the ground state and in the first excited state was measured from 0 to 135° and normalized to an absolute value at 0° measured with a LiF target. The cross section for the production of $Be^8$ in the first excited state has some uncertainty because of the contribution from the competing three-body breakup of the compound system. Cross sections at 0° for $F^{19}(d,n)Ne^{20}$ are also given for reactions leaving $Ne^{20}$ in the ground state and first excited state.

## I. INTRODUCTION

MANY exothermic reactions lead to $Be^8$ so that this nucleus is readily accessible to the experimentalist. Extensive experimental evidence[1] suggests that there are only two excited states below 15 MeV—the 2.9-MeV, $J^\pi=2^+$ state and the 11.4-MeV, $J^\pi=4^+$ state; however, some experiments have shown, usually with limited statistics, a multiplicity of levels. Frequently the additional levels have been contradicted by later measurements with better resolution and statistics; but this is not entirely the situation. In particular, Cavallaro *et al.*[2] recently reported an experiment in which two clearly defined groups of $\alpha$ particles are attributed to $Be^8$ states at 7.56 and 13.91 MeV produced in the $Li^7(p,\gamma)Be^8(\alpha)He^4$ reaction. Some earlier reports of the $Li^7(d,n)Be^8$ reaction also indicated a level near 7.5 MeV.

Many experiments that favor a multiplicity of levels have come from nuclear emulsion studies of neutrons from the deuteron bombardment of $Li^7$. Neutrons may arise in several ways from this bombardment, such as,

$$\begin{aligned}
&\text{(a)}\ Li^7+d \to Be^8+n+15.03\ \text{MeV}, \qquad (1)\\
&\text{(b)}\qquad\quad \to 2He^4+n+15.12\ \text{MeV},\\
&\text{(c)}\qquad\quad \to He^5+He^4+14.16\ \text{MeV},\\
&\qquad\qquad\qquad \searrow\\
&\qquad\qquad\qquad\ He^4+n+0.96\ \text{MeV}.
\end{aligned}$$

Reaction (a) yields neutron groups corresponding to different excitation energies in $Be^8$; however, the spectrum is complicated by the presence of neutrons from processes (b) and (c). Process (b) is a three-body breakup which yields neutrons with a continuum of energies up to 80 keV above the ground-state group. The two-step process (c) through the $He^5$ ground state produces a continuum below about 5 MeV and does not interfere with a study of the low-lying $Be^8$ levels; however, this process could cause confusion if $He^5$ were left excited. Thus, a neutron group corresponding to a $Be^8$ level may have to be observed in the presence of a background continuum.

Table I summarizes the nuclear emulsion studies of these neutrons in the period from 1941 to the present.[3–11] Column 3 lists the incident-deuteron energies, varying from 0.6 to 1.2 MeV, and the last column gives the levels reported in $Be^8$. The last report by Spear stands in direct conflict with the others. He made an effort either to confirm or to deny the multiplicity of levels in the other reports, and his results support the view that the only excited state below 9 MeV is the well-known broad level at 2.9 MeV. If this is true, the erroneous results of all of the other reports may be due to false interpretation of statistical fluctuations. All of the data that are summarized in Table I was obtained with rather limited statistics.

Our 1954 letter[12] on the neutron spectrum that was observed at 0° with a recoil-proton telescope for 1.85-MeV incident deuterons was the first to indicate that the only excited state reached below 9 MeV by this reaction is the 2.9-MeV level. Additional measurements

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[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959); and T. Lauritsen and F. Ajzenberg-Selove, in *Landolt-Börnstein Critical Tables*, edited by A. M. Hellwege and K. H. Hellwege (Springer-Verlag, Berlin 1961), Vol. I, p. 16.

[2] S. Cavallaro, R. Potenza, and A. Rubbino, Nucl. Phys. **36**, 597 (1962).

[3] H. T. Richards, Phys. Rev. **59**, 796 (1941).

[4] L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 407 (1949).

[5] B. Trumpy, T. Grotdal, and A. Graue, Nature **170**, 1118 (1952).

[6] J. Catalá, J. Aguilar, and F. Busquets, Anales Real Soc. Espan. Fís. Quím. (Madrid) **A49**, 131 (1953); J. Catalá, J. Aguilar, and F. Senent, Anales Real Soc. Espan. Fís. Quím. (Madrid) **A51**, 173 (1955); J. Catalá, R. Font, F. Senent, J. Aguilar, and M. de la Cuadra, Nuovo Cimento Suppl. **9**, 377 (1958).

[7] W. M. Gibson and D. J. Prowse, Phil. Mag. **46**, 807 (1955).

[8] M. A. Ihsan, Phys. Rev. **98**, 689 (1955).

[9] E. P. Ferreira and P. J. Waloschek, Proc. of the Intern. Conf. Peaceful Uses At. Energy, Geneva **2**, 124 (1956).

[10] L. Drška, I. Chudáček, F. Štěrba, Czech. J. Phys. **8**, 648 (1958).

[11] R. H. Spear, Australian J. Phys. **11**, 502 (1958).

[12] C. C. Trail and C. H. Johnson, Phys. Rev. **95**, 1363 (1954).

TABLE I. Nuclear-emulsion investigations of neutron spectra from $Li^7(d,n)Be^8$.

| Authors | Year | Incident deuteron energy (MeV) | Levels reported (MeV) |
|---|---|---|---|
| Richards[a] | 1941 | 1.2 | 2.8, 7.5, 10 |
| Green and Gibson[b] | 1949 | 0.93 | 2.8, 4.05, 4.9, 7.5 |
| Trumpy *et al.*[c] | 1952 | 0.6 | (2.2), 2.9, 4.1, 5.0 |
| Catalá *et al.*[d] | 1953–58 | 0.93 and 1.08 | 15 levels below 15 MeV |
| Gibson and Prowse[e] | 1955 | 0.93 | 2.1, 2.9, 4.05, 5.25 |
| Ihsan[f] | 1955 | 0.7 | 2.98, (5.30), 7.53 |
| Ferreira and Waloschek[g] | 1956 | 0.9 | 2.8, 3.4, 4.2, 5.0 |
| Drška *et al.*[h] | 1958 | 0.6 and 0.85 | 3.4, 5.5, 7.5, 10.5, 12.7 |
| Spear[i] | 1959 | 0.7 | only 2.9 below 9 MeV |

[a] See Ref. 3. [b] See Ref. 4. [c] See Ref. 5. [d] See Ref. 6. [e] See. Ref. 7. [f] See Ref. 8. [g] See Ref. 9. [h] See Ref. 10. [i] See Ref. 11.

at 1.98 MeV were given in a 1954 abstract[13] but were not published in detail. Details are given in this paper which reports the spectrum at 120° and the differential cross section for producing neutrons with center-of-mass energies exceeding 9 MeV. Only the ground state and the broad 2.9-MeV state are observed for $Be^8$ excitation energies below 9 MeV. A discussion based on recently measured[14] level parameters is made concerning the relative contribution to the continuum from three-body breakup and from the tails of the broad resonances. Some data are also presented regarding the $F^{19}(d,n)Ne^{20}$ reaction cross section at 0° for 1.98-MeV deuterons.

This report and the report by Spear[11] give no data for excitation energies above 9 MeV. Juna *et al.*[15] have made time-of-flight measurements for incident 0.8-MeV deuterons and find only one strong broad level, corresponding to the 11.4-MeV state, in the region of about 7- to 15-MeV excitation.

## II. APPARATUS

The neutron spectrometer for this work is a proton-recoil telescope which has been described elsewhere.[16] Briefly, protons which recoil near zero degrees from neutron impact in a polyethelene radiator pass through two proportional $dE/dx$ counters and stop in a NaI(Tl) scintillator. A triple coincidence of the counters gates a 20-channel pulse-height analyzer which then records the height of the NaI(Tl) pulse involved in the coincidence. A wheel arrangement permits a choice of five radiators of various thicknesses and also a $Pu^{239}$ $\alpha$ source and a blank for determining backgrounds. The entire assembly is housed in a single container filled with $\frac{1}{3}$ atm of argon-3% $CO_2$, which serves as the proportional counter gas.

The telescope was tested with the 13.7-MeV neutrons that are emitted at 117 deg in the $T(d,n)He^3$ reaction. Figure 1 shows the counts/channel versus pulse height obtained for a radiator which is 5.7% thick for 13.7-MeV recoil protons. Other effects increase the width of the peak to 7%. A subtraction has been made for the distributed background which remained when the radiator was replaced by the blank; the integrated background was 7% of the total yield under the peak. A primary reason for including this figure is to show that monoenergetic 13.7-MeV neutrons produce almost no low-energy tail but that some tail is definitely present. This tail is uniformly distributed with a total area of 13% of the area under the peak. Rough calculations indicate that a uniformly distributed tail results from multiple Rutherford scattering[17] of protons from a wall in the counters; and measurements with a later model telescope[16] have confirmed these estimates. The calculations also show that the combined effect of the energy dependences for Rutherford scattering and for energy loss in the wall are such that the ratio of the tail area to the peak area is independent of recoil-proton energy. The observed ratio in Fig. 1 has been used for wall-scattering corrections to all spectra reported here.

Figure 2 shows the experimental arrangement. Deuterons with an energy of 2.11 MeV from the ORNL 3-MV Van de Graaff bombarded a rotating target of

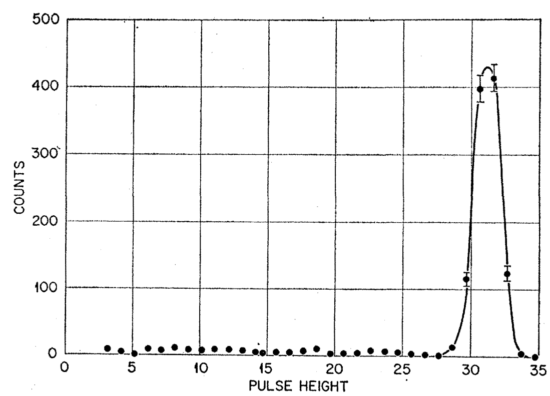


FIG. 1. Pulse-height distribution observed with the neutron spectrometer for 13.7-MeV neutrons. A small background has been subtracted. The remaining tail, whose integrated area is 13% of the area under the peak, results from proton scattering from a wall in the proportional counters.

[13] C. C. Trail and C. H. Johnson, Phys. Rev. **98**, 249(A) (1955).
[14] T. A. Tombrello and L. S. Senhouse, Phys. Rev. **129**, 2252 (1963). This paper summarizes the earlier work of others.
[15] J. Juna, P. Horváth, and K. Konečný, Czech. J. Phys. **10**, 715 (1960).
[16] C. J. Johnson and C. C. Trail, Rev. Sci. Instr. **27**, 468 (1956).
[17] H. S. Snyder and W. T. Scott, Phys. Rev. **76**, 220 (1949).

99.8% $Li^7$ metal[18] which had been evaporated in place onto a 0.010-in. tantalum backing. The target thickness was found from the observed separation of the threshold and the maximum in the $Li^7(p,n)Be^7$ long-counter yield curve. The resulting thickness was 220 keV for the 2.11-MeV deuterons; however, comparison with the yield from a LiF target suggests that the lithium was deposited nonuniformly with an average thickness of 280 keV. Furthermore, a 20-keV carbon layer was deposited during the experiment. Thus, the average deuteron energy was 1.98 MeV with about $\pm 0.02$ MeV uncertainty. Most data were obtained with this metallic lithium target; however, the normalization to absolute cross sections was determined with a 1.453 g/cm$^2$ natural LiF target which was evaporated onto aluminum and weighed in open air.

The telescope is indicated in the figure with its principal axis at a variable angle $\theta$ to the deuteron beam. An iron disk, 1.3 cm thick and 2.5 cm in diameter, was placed between the source and the radiator in order to attenuate the $\beta$ rays from the $Li^7(d,p)Li^8(\beta)Be^8$ reaction which would otherwise overload the counting equipment. A neutron monitor, which is a 40-cm-long 1-atm propane proportional counter, is shown at a fixed 30° angle. This monitor has good discrimination against background so that it gives positive detection of the high-energy neutrons from the lithium target.

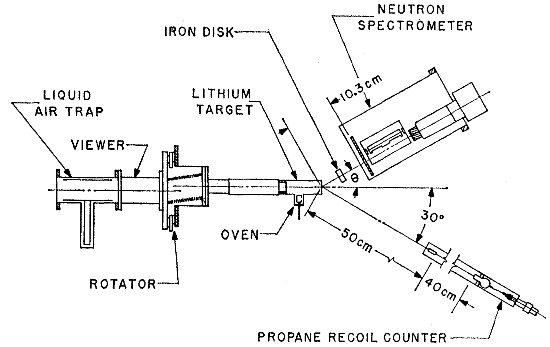


FIG. 2. Experimental arrangement. The deuteron beam enters the target assembly from the left.

### III. MEASUREMENTS

Three sets of measurements were made. The first set at $\theta = 120°$ comprises a high-resolution measurement for which the 20-channel analyzer was operated, in effect, as a 92-channel analyzer. Three bias settings were chosen for obtaining data in channels 37 to 57, 54 to 74, and 72 to 92; and three corresponding radiators were used in order that the energy loss by the protons in the radiator would always be less than 5%. The second set of measurements was made with poorer resolution at 13 angles from 0 to 135 deg in order to determine the differential cross sections. For this set the amplifier gain for the scintillation counter was reduced by a factor of 0.38, and only one bias setting, corresponding roughly to channels 20 to 40, was used at each angle. A single radiator was used which was 4% thick for the 16.5-MeV recoil protons from the ground-state neutrons at 0° but increased to 19% for the 7.7-MeV recoil protons in the lowest channel at 135°. The third set of data, which determines the absolute cross section, was taken at 0° with the LiF target. A current integrator measured the charge deposited by the deuterons incident on the LiF.

The raw data from the apparatus are the counts/channel per monitor count versus channel number, but we wish to present the results in units proportional to the neutrons/MeV per monitor versus the neutron energy in the center-of-mass system. The following corrections are to be made before the data are presented. The first is the conversion to the energy scale and the remaining ones, which refer to the yield, are arranged in logical order proceeding from the scintillation detector to the source.

*Channel-to-energy conversion.* The procedure for each datum point is to convert the pulse height to proton energy, add a small energy for the average loss in the argon-$CO_2$ gas and in the radiator,[19] and convert the resulting neutron energy in the laboratory to that in the center-of-mass system. The energy calibration has been chosen so that the ground-state group in the 120° data falls at the center-of-mass energy 14.74 MeV, which is predicted from the known[1] 15.03-MeV $Q$ value. The calibration at other energies is based on the proportional response[20] of the NaI(Tl) pulse amplitude with proton energy, and is found to give the correct position of the ground-state group for all of the low-resolution data and also for the 13.7-MeV neutrons from the $T(d,n)He^3$ reaction.

*Corrections for background, wall scattering, and dead time.* A subtraction was made for the background which was observed with the blank in position; negligible corrections were required for the low-resolution data. The subtraction for wall scattering, which was discussed above, was zero for the ground-state group but rose to 16% for the lowest channel in the 120° data. A dead-time counting loss results from large singles rates, 5 to $20 \times 10^3$ counts/sec, which are produced primarily from $\beta$ rays and $\gamma$ rays in the three counters. The loss was estimated from the counting rates and known circuit parameters and also from the variation of coincidence rates with beam intensity, and the resulting correction is a constant for a given spectrum but varies from 2% at 135° to 4% at 0°.

*Variations in radiator efficiency and in the solid angle subtended by the radiator at the target.* The observed yield of recoil protons was converted to a number

[18] The enriched lithium was furnished by the Stable Isotopes Division at Oak Ridge National Laboratory.

[19] C. H. Johnson, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960), Part I, Chap. II, C.

[20] F. S. Eby and W. K. Jentschke, Phys. Rev. **96**, 911 (1954).

proportional to the incident flux by use of the measured areal density of the radiators and the differential cross section[21] for 180° scattering of neutrons from hydrogen. Small corrections were made to normalize the measurements at each angle to the same solid angle as that used for the 0° absolute measurement.

*Neutron attenuation by materials between the source and the radiator.* The iron disk, which served to attenuate $\beta$ rays, also scattered and absorbed neutrons. If the dimensions were such that the source, disk, and detector constituted "good" geometry, the correction for neutron attenuation could be made simply by multiplying the observed counts by $\exp(N\sigma_T)$, where $N$ is the number of iron atoms per cm$^2$ and $\sigma_T$ is the neutron total cross section.[22] In the energy region of interest, 6 to 16.5 MeV, this factor varies from 1.37 to 1.24. Actually, a smaller correction is required in order to allow for the in-scattering associated with the forward peak[23] in the elastic part of the total cross section, and this is complicated by the fact that neutrons scattered in from the edge of the disk do not produce recoil protons of the correct full energy. The effects reduce the above correction factors by about 8%. Similar corrections are required for the parts of the telescope housing and the target holder which lie between the source and radiator. A combined factor, ranging from 1.36 for 6-MeV neutrons down to 1.21 for higher energy neutrons, has been applied to the data; the uncertainties in the corrections are about ±5%.

Finally, the yields in the laboratory system were converted to the center-of-mass system.

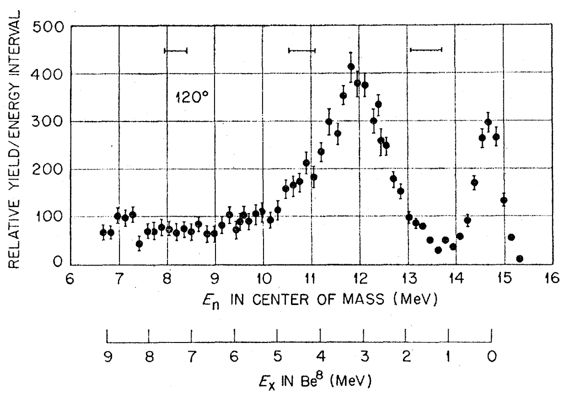


FIG. 3. The center-of-mass neutron spectrum from the deuteron bombardment of Li$^7$. The average incident-deuteron energy is 1.98 MeV and the angle of observation is 120° (laboratory system). Horizontal bars in the upper part of the figure indicate typical full widths at half-maximum for the resolution function.

[21] J. L. Fowler and J. E. Brolley, Jr., Rev. Mod. Phys. 28, 103 (1956).

[22] D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory, Report No. BNL 325, 1958 (unpublished).

[23] R. J. Howerton, Lawrence Radiation Laboratory Report No. UCRL-5573, Vol. 1, Part III (unpublished).

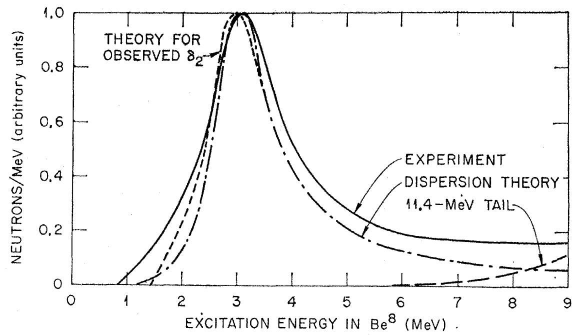


FIG. 4. A comparison of experimental and theoretical neutron-energy spectra associated with the broad excited states of Be$^8$ and with three-body breakup of Be$^9$. The solid experimental curve was derived from a smooth fit to the data in Fig. 3 with corrections for resolution and for the presence of the ground-state group. The dispersion theory curve was calculated from level parameters based on the $\delta_2$ phase shift for $\alpha-\alpha$ scattering (see Ref. 14). The curve labeled "Theory for observed $\delta_2$" was calculated directly from the observed $\delta_2$ by use of Eq. (5) of the text, and the 11.4-MeV tail was calculated in the same manner from the $\delta_4$ phase shift. All normalizations are arbitrary; the experimental curve and the two theoretical curves for the 2.9-MeV state are all normalized at their peaks, and the 11.4-MeV tail is normalized so that the sum of the theoretical tails equals the experimental value at 9 MeV.

## IV. RESULTS AND DISCUSSION

### A. The Neutron Energy Spectrum

Figure 3 shows the neutron spectrum obtained with good resolution at 120° with respect to the deuteron beam. The ordinate gives the relative neutron yield, and the abscissa gives both the neutron energy and the excitation energy in Be$^8$. The error bars denote the statistical uncertainties in the points. The energy resolution, which is indicated at three energies in the upper part of the figure, decreases from 6.8% at 7 MeV to 4.5% at the ground state and has 1% discontinuities near 10 and 12 MeV. These resolution figures are based partly on the observed width of the ground-state group and partly on knowledge of the radiator thickness, solid angles, crystal resolution, channel width, and target thickness. Only the ground state and the first excited state are evident in Fig. 3. We estimate that no other group is present with more than 10% of the intensity of the ground-state group. These results confirm our earlier measurements[12] at 1.85 MeV and are consistent with most measurements[1] regarding the levels of Be$^8$ but disagree with all but the last of the nuclear emulsion reports in Table I.

In addition to the main groups, there is a continuum which may have contributions from tails of the 2.9-MeV and 11.4-MeV states, direct three-body decay of Be$^9$, and sequential decay through excited states of He$^5$. It is of interest to investigate the tails of the resonances to see if they alone might account for the continuum. For this purpose, in Fig. 4, the observed spectrum of the 2.9-MeV state and of the continuum is shown by the solid curve which was obtained by drawing a smooth line through the data and subtracting the ground-state peak. Resolution corrections, which have been made, raised the peak by 8% but scarcely disturbed the sides of the peak of the continuum.

This experimental curve has its maximum at 3.1 $\pm$0.1 MeV and has a full width at half-maximum of 1.75$\pm$0.1 MeV.

Under the assumption that the compound system decays into a neutron and $Be^8$ in an isolated state $\lambda$, the transition probability can be written[24]

$$N(E)\propto\frac{\Gamma_n\Gamma_\lambda}{(E_\lambda+\Delta_\lambda-E)^2+\frac{1}{4}\Gamma_\lambda^2}, \quad (2)$$

where $\Gamma_n$ is the width for neutron emission, $\Gamma_\lambda$ is the isolated level width (here the width for decay into two $\alpha$ particles), $E_\lambda$ is a constant energy, and $\Delta_\lambda$ is the level shift. The center-of-mass energy $E$ is that available for the decay of the $Be^8$ state into two $\alpha$ particles, i.e., the $Be^8$ excitation energy plus 0.094 MeV. In terms of the wave number $k$ of the two $\alpha$ particles and the amplitude $A$ for their Coulomb wave function,[25]

$$\Gamma_\lambda=2\rho\gamma_\lambda^2/A^2 \quad (3)$$

and

$$\Delta_\lambda=-\gamma_\lambda^2\left(\frac{\rho}{A}\frac{dA}{d\rho}+l\right), \quad (4)$$

where $\rho=kR$ with $R$ being the interaction radius, and $\gamma_\lambda^2$ is the reduced level width. The amplitude $A$ is evaluated for $\alpha$ particles of relative angular momentum $l$ characteristic of the level.

Consider the 2.9-MeV, $2^+$ state. The best information regarding the level parameters seems to be contained in the phase-shift analysis of $\alpha-\alpha$ scattering. Tombrello and Senhouse[14] found the single-level parameters from the $d$-wave phase shift $\delta_2$, which corresponds to the 2.9-MeV state. They found $R=3.5$ $f$, $\gamma^2=3.36$ MeV, and $(E_x)_0=3.18$ MeV, where $(E_x)_0$ is the $Be^8$ excitation energy at which the first term in the resonant denominator vanishes. These parameters fix all but the neutron width which varies as $\rho/A_l^2$ for $l$-wave neutrons.[26] The fact that the relative intensities for neutrons of various $l$ values is unknown is not very critical because $\rho/A_l^2$ varies slowly for all low-$l$ values at these high-neutron energies. Over the neutron-energy range of interest, corresponding to 1- to 9-MeV excitation, the neutron penetration factors $\rho/A_l^2$ change by the ratios 1.4, 1.5, 1.9, and 3.1 for $s$-, $p$-, $d$-, and $f$-wave neutrons, respectively. We will take the factor for $p$-wave neutrons as a reasonable average. Also we take $R=4.35$ $f$ for the neutron interaction radius.

The curve labeled "Dispersion Theory" in Fig. 4 results from these parameters with arbitrary normalization at the peak. Clearly, this theory alone gives a poor fit to the data; the tail is too small and the width of the peak is only 1.30 MeV.

Perhaps a good fit should not be expected because, as Tombrello and Senhouse emphasize, these parameters represent a compromise to $\delta_2$ over a large energy range with rather poor fits at the limits. Let us rewrite Eq. (2) specifically in terms of $\delta_2$,

$$N(E)\propto\frac{\Gamma_n A_2^2}{\rho}\sin^2(\delta_2+\varphi_2), \quad (5)$$

with the subscript 2 denoting $d$-wave $\alpha$ particles. Following a suggestion by Barker and Treacy[27] we now insert the *observed* $\delta_2$ into Eq. (5) and use the potential phase shift calculated from

$$\varphi_2=\tan^{-1}(F_2/G_2), \quad (6)$$

where $F_2$ and $G_2$ are the regular and irregular Coulomb wave functions[25] for $l=2$. The resulting curve, for $R=3.5$ $f$, has about the same tail at high energy as does the strict single-level formula, but the peak and the low-energy side of the resonance are shifted down by about 0.1 MeV as shown in Fig. 4. Thus, the observed phase shift $\delta_2$ produces a 1.4-MeV width, which agrees a little better with the experiment, but still is not good.

Next, consider the possible tail from the 11.4-MeV state which is associated with the $g$-wave $\delta_4$ phase shift. Use of the above theory with the known[14] $\delta_4$ and with the potential phase shift $\varphi_4$ calculated for $R=3.5$ $f$ gives the curve indicated in Fig. 4. The slight energy dependence for the neutron width has been determined for $d$-wave neutrons, and the normalization is arbitrary. The resulting 11.4-MeV tail is negligible over most of our energy region.

An attempt was also made to fit the data with the "density-of-states" function suggested by Phillips *et al.*[28] In this formulation, the density of states is taken proportional to the energy derivative of $(\delta_l+\varphi_l)$ where $\delta_l$ is the observed phase shift but $\varphi_l$ is calculated for an arbitrary radius. Unfortunately, for this theory, a radius which is chosen large enough to predict the continuum also predicts a large yield on the low-energy side of the resonance. As a result, the peak shifts to a lower energy and the calculated curve gives poor agreement with the experiment.

It seems highly probable, therefore, that the continuum has an appreciable contribution from three-body breakup. This is not surprising. Other workers have found evidence for three-body decay under certain conditions. A striking illustration was shown by Dehnhard *et al.*[29] who studied the reactions $B^{11}(p,\alpha)Be^8$ and

[24] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).

[25] I. Bloch, M. H. Hull, Jr., A. A. Broyles, W. G. Bouricius, B. E. Freeman, and G. Breit, Rev. Mod. Phys. **23**, 147 (1951).

[26] J. E. Monahan, L. C. Biedenharn, and J. P. Schiffer, Argonne National Laboratory Report No. ANL-5846, 1958 (unpublished).

[27] F. C. Barker and P. B. Treacy, Nucl. Phys. **38**, 33 (1962).

[28] G. C. Phillips, T. A. Griffy, and L. C. Biedenharn, Nucl. Phys. **21**, 327 (1960).

[29] D. Dehnhard, D. Kamke, and P. Kramer, Z. Naturforsch. **A16**, 1245 (1961) and Phys. Letters **3**, 52 (1962).

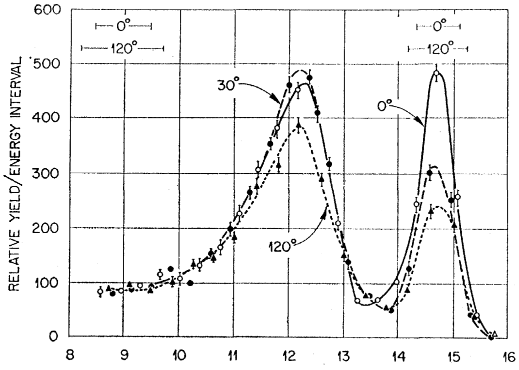


FIG. 5. Center-of-mass energy spectra that were observed at 0°, 30°, and 120° to the deuteron beam. The units for the scale of the ordinate are the same as in Fig. 1. Similar spectra were obtained at ten other angles. The bars in the upper part of the figure indicate typical energy resolutions.

$B^{11}(p,\alpha)2\alpha$. They found that the two-body mode generally predominates but that, at the 163-keV proton resonance, the three-body contribution produces a large continuum and causes an apparent energy shift and a broadening of the group to the 2.9-MeV state. Jones and Bair also observed this effect,[30] and Bronson *et al.*[31] also observed three-body effects at other proton energies. Kavanagh[32] found that the proton spectrum from deuteron bombardment of $Be^7$ changes markedly as the deuteron energy is raised from 1 MeV to 1.475 MeV; the yield for the $Be^7(d,p)Be^8$ reaction to the 2.9-MeV state increased by a factor of about 2 whereas the yield to the continuum remained unchanged. At 1.475 MeV, where the continuum was rather small, Kavanagh found a $1.53\pm0.04$ MeV width for the 2.9-MeV group and made a dispersion-theory analysis to assign the level parameters.

Some evidence also exists that the relative amplitude of the continuum for the $Li^7(d,n)$ reaction is a function of deuteron energy. Spear[11] observed a peak-to-continuum ratio of about 3 for 0.7-MeV deuterons, our earlier measurement[12] at 0° for 1.85-MeV deuterons gave a ratio of about 4, and the present measurement at 120° for 1.98-MeV deuterons shows a ratio of about 6. (The following results show that the ratio is even larger at 0°.) The large change from 1.85 to 1.98 MeV may be related with the rapidly rising cross section.[33,34] Furthermore, the following studies of the spectra at several angles suggest that the yields to states in $Be^8$ have an angular dependence, whereas the continuum may be isotropic.

All reactions that lead to states in $Be^8$ can be accompanied by three-body breakup, and the above considerations suggest that a continuum may be present to a degree which depends on the energy of the bombarding particle and on the angle of observation. If the effect is large, as it appears to be in the present work, the width and position of the 2.9-MeV state is disturbed so that the single-level parameters in the dispersion theory cannot be assigned on the basis of the observed spectrum. Several parameter assignments have been made. These include investigations of $B^{10}(d,\alpha)Be^8$ by Treacy,[35] $Be^7(d,p)Be^8$ by Kavanagh,[32] and $Li^7(p,\gamma)Be^8$ by Gemmell.[36] In each case, the observed resonance was broader than would be predicted on the basis of the phase-shift analysis of $\alpha-\alpha$ scattering. Perhaps the discrepancy results partly from the presence of a continuum.

Recently, however, Purser and Wildenthal[37] observed the $B^{10}(d,\alpha)Be^8$ reaction in a manner which discriminates against the three-body decay. They measured the $\alpha$-particle spectrum in coincidence with the recoil nucleus near 180° to the $\alpha$ particle, an angle at which a coincidence from three-body decay is unlikely, and found a peak width of 1.40 MeV and a shape agreeing very well with that predicted by Eq. (5) from the observed phase shift $\delta_2$. (The theoretical shape, with the neutron penetrability replaced by the *s*-wave $\alpha$-particle penetrability, has a peak width of 1.45 MeV rather than 1.40 MeV but is otherwise very similar to the theoretical curve shown in Fig. 4. Purser and Wildenthal chose parameters to give the best overall fit to their data on the basis of the usual dispersion theory; however, their parameters predict a peak width of 1.6 MeV and a shape which does not agree as well with their experiment as the theory of Barker and Treacy which is used here.)

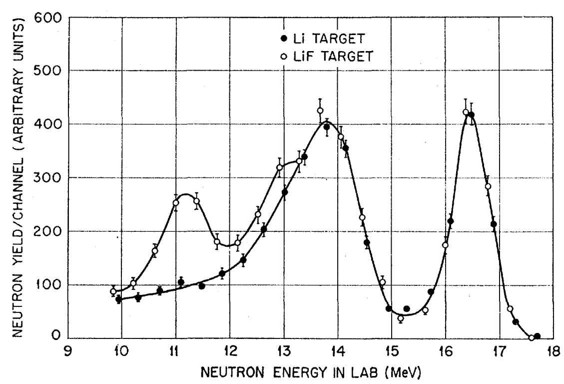


FIG. 6. The neutron spectra observed at 0° for 1.98-MeV deuteron bombardment of Li and of LiF. The relative normalization is arbitrary. Both targets give the spectra from reaction from $Li^7$, and the LiF-target yield shows groups from the $F^{19}(d,n)Ne^{20}$ reaction.

[30] C. M. Jones and J. K. Bair (private communication).
[31] J. D. Bronson, W. D. Simpson, and G. C. Phillips, Bull. Am. Phys. Soc. 8, 125 (1963).
[32] R. W. Kavanagh, Nucl. Phys. 18, 492 (1960).
[33] L. M. Baggett and S. J. Bame, Jr., Phys. Rev. 85, 434 (1952).
[34] J. C. Slattery, R. A. Chapman, and T. W. Bonner, Phys. Rev. 108, 809 (1957).
[35] P. B. Treacy, Phil. Mag. 44, 325 (1953).
[36] D. S. Gemmell, Australian J. Phys. 13, 116 (1960).
[37] K. H. Purser and B. H. Wildenthal, Nucl. Phys. 44, 22 (1963). The abscissa of Fig. 8 in this report should be labeled "$E_X$ of $Be^8+0.094$ MeV." Furthermore, an $E_0$ value of 4.08 MeV would give a better fit than 3.92 MeV (private communication with B. H. Wildenthal).

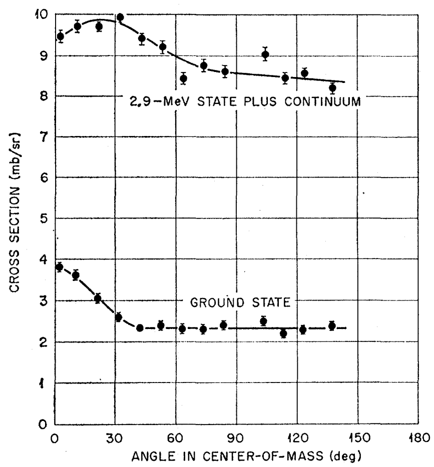


FIG. 7. Center-of-mass differential cross sections for neutron production by 1.98-MeV deuteron bombardment of $Li^7$. The cross section to the $Be^8$ ground state was found by integrating the yield for neutrons with energies greater than 13.75 MeV in the center of mass. The cross section labeled "2.9-MeV state plus continuum" includes neutrons with energies from 9 to 13.75 MeV.

### B. Differential Cross Sections

Differential cross sections were obtained by combining the absolute LiF-target measurements at 0° with the relative Li-target measurements at 13 angles from 0 to 135 deg. Representative spectra at three angles are shown in Fig. 5 which also indicates typical energy resolutions, which ranged from 19% in the lowest channel at 135° down to 6% for the energetic ground-state group at 0°. Peaks for the neutron groups appear at consistent energies at all angles, and the yield of the high- and low-resolution data at 120° are in good agreement. It is disturbing, however, that the peak for the excited-state group appears at 2.9-MeV excitation in these low-resolution spectra whereas it appears at 3.1 MeV in the high-resolution curve in Fig. 3. We believe that Fig. 3 is more reliable and that the shift from 3.1 to 2.9 MeV results in some manner from the use of a thicker radiator.

Figure 6 gives spectra at 0° from both the Li and LiF target, with arbitrary relative normalization. (These results are presented in the laboratory system.) Neutron groups from the $F^{19}(d,n)Ne^{20}$ reaction are present on the low-energy side of the broad group to $Be^8$ but do not interfere with the measurement of the ground-state transition.

Differential cross sections are given in Fig. 7. The upper curve is the integrated cross section for producing neutrons with energies from 9 to 13.75 MeV in the center-of-mass system, and the lower curve is that for energies greater than 13.75 MeV. A clear interpretation of the upper curve is not possible because it includes contributions from the continuum and from the 11.4-MeV state as well as nearly all of the yield to the 2.9-MeV state; however, the lower curve is essentially that for producing $Be^8$ in its ground state. A $\pm 10\%$ absolute uncertainty is estimated for the ordinate of these curves.

These results can be compared to published measurements of the production of neutrons of all energies by deuteron bombardment of $Li^7$. Baggett and Bame[33] observed 40 mb/sr at 90° for 2-MeV deuterons. A comparison with our result, 10.9 mb/sr for neutron energies above 9 MeV, suggests that there is a relatively large yield of low-energy neutrons. Slattery, Chapman, and Bonner[34] found 30 mb/sr at 0° and this also is somewhat larger than our value of 13.2 mb/sr for neutron energies above 9 MeV. These published results have an uncertainty of about $\pm 50\%$.

The general features of the angular distributions can be interpreted qualitatively. A $p$-wave proton is needed to form the $0^+$ ground state of $Be^8$ from the $\frac{3}{2}^-$ ground state of $Li^7$. Plane-wave stripping theory predicts a peak in the forward direction but does not explain the yield at larger angles. Distorted-wave effects could produce the large angle yield and may also modify the predictions of the main peak.[38] Since the data do not rule out the possibility that the cross-section curve may be symmetric about 90°, the entire process could possibly be explained on the basis of the compound-nucleus mechanism. The $2^+$ excited state of $Be^8$ can be formed by both $p$- and $f$-wave protons, and the observed peak in the differential cross section near 30° might be associated with a contribution from either stripping pattern.

Finally, we note that a crude spectrum of neutrons from the $F^{19}(d,n)Ne^{20}$ reaction is found by subtraction in Fig. 6. Figure 8 gives this difference and shows neutron groups leaving $Ne^{20}$ in the ground state and the first excited state. Arrows indicate the positions of groups predicted from known reaction energies.[1] By integrating these yields, we find that the differential cross sections for leaving $Ne^{20}$ in the ground state

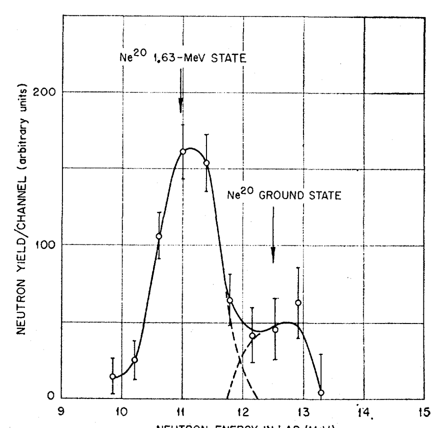


FIG. 8. The neutron spectrum from $F^{19}(d,n)Ne^{20}$ obtained by subtracting the yield of the Li metal target from that of the LiF target in Fig. 6. The arrows indicate the positions of the groups predicted from the known (Ref. 1) $Q$ values.

[38] G. R. Satchler (private communication).

and the 1.63-MeV state are 0.6±0.4 mb/sr and 2.2 ±0.2 mb/sr, respectively. Morita and Takeshita[39] found for 2.17-MeV deuterons that the excited-state yield is about 4 times the ground-state yield at 0°, in agreement with our results.

## V. CONCLUSION

The spectrum of neutrons produced by bombardment of $Li^7$ by 1.98-MeV deuterons gives evidence for only the ground state and well-known 2.9-MeV state in $Be^8$ below 9-MeV excitation. If other neutron groups are present, their intensity is no more than 10% of that for the ground-state group. These results agree with most measurements on $Be^8$. The neutron group to the excited state has a maximum corresponding to 3.1 ±0.1 MeV excitation and a center-of-mass width of 1.75±0.1 MeV; however, these experimental numbers cannot be interpreted clearly in terms of the parameters for the $Be^8$ excited state because the spectrum is distorted by the continuum from the three-body decay. It seems that the relative magnitude of the continuum depends on bombarding energy and on the angle of observation. Since a continuum may also accompany other reactions which lead to $Be^8$, the level parameters accepted for the purpose of interpreting the spectra are based on the observed phase shifts for $\alpha-\alpha$ scattering rather than on spectra from other reactions. Predictions from the $\delta_2$ phase shifts give a peak width of only 1.3 to 1.4 MeV and a tail which is about half the magnitude of the observed tail.

[39] S. Morita and K. Takeshita, J. Phys. Soc. Japan **13**, 1241 (1958).

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# Role of Particle-Hole Correlations in the Inelastic Scattering of Electrons from $C^{12}$, $O^{16}$, and $Ca^{40}$†

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All available experimental data on the inelastic scattering of high-energy electrons from $C^{12}$, $O^{16}$, and $Ca^{40}$ have been analyzed in terms of the particle-hole models of nuclear excitations. The calculations do not involve any free parameters. The results proved quite sensitive to the treatment of nuclear correlations and generally favored the random-phase approximation, which yielded satisfactory agreement with most of the data.

## I. INTRODUCTION

THE purpose of the present analysis is to determine to what extent the inelastic scattering of electrons from complex nuclei can be used to test the wave functions derived from various extensions of the shell model.

We shall consider the closed-shell nuclei $C^{12}$, $O^{16}$, and $Ca^{40}$ wherein the effects of nucleon correlation have been satisfactorily described by two types of approximations.[1–3] Approximation I consists in diagonalizing the effective two-body force in a subspace limited to the configuration of energy $\hbar\omega$. Approximation II has been called the random-phase approximation[4] (RPA), the quasiboson approximation[5] and the extended shell-

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[1] W. M. Visscher and R. A. Ferrell, Phys. Rev. **102**, 450 (1956); J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957); S. Fallieros and R. A. Ferrell, Phys. Rev. **116**, 660 (1959); G. E. Brown, L. Castillejo, and J. A. Evans, Nucl. Phys. **22**, 1 (1961); J. Sawicki and T. Soda, *ibid.* **28**, 270 (1961); N. Vinh Mau and G. E. Brown, *ibid.* **29**, 89 (1962).

[2] V. Gillet and N. Vinh Mau, Nucl. Phys. (to be published).

[3] V. Gillet and E. Sanderson, Nucl. Phys. (to be published).

[4] R. A. Ferrell and J. J. Quinn, Phys. Rev. **108**, 570 (1957). K. Sawada, K. A. Brueckner, N. Fukuda, and R. Brout, Phys. Rev. **108**, 507 (1957); S. Fallieros, Ph.D. thesis, University of Maryland, 1958 (unpublished); G. E. Brown, J. A. Evans, and D. J. Thouless, Nucl. Phys. **24**, 1 (1961).

[5] K. Sawada, Phys. Rev. **106**, 372 (1957); R. Arvieu and M. Veneroni, Compt. Rend. **250**, 922, 2155 (1960).