THE ORIGIN OF NEUTRON GROUPS IN Be(α,n) SOURCES

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The neutron spectra of an 80 g PuBe source and an 11 Ci PoBe source were measured by differentiation of proton track distributions sampled from nuclear emulsion. Special analysis of the track distributions revealed peaks at 0.54, 0.78, 1.1, 2.3, 3.2, 4.8, 5.6, 7.8 and 9.8 MeV in both spectra. The common features and the differences in the two sources are interpreted by use of a numerical graphical analysis based on published differential and integral cross sections for the 9Be(α,n) reaction. In contrast to earlier theoretical and semiempirical attempts, this analysis successfully explains the major features of various measured 9Be(α,n) source neutron spectra. Partial-wave (resonance) theory predictions of the reaction anisotropy of the neutron groups in such spectra are made and discussed.

1. Introduction

The nature and properties of the neutrons emitted in the Be(α,n) reaction have been the subject of some hundreds of investigations since the early 1930's, and there is presently considerable interest in this reaction because it leads to excited states in the 12C nucleus, important in the synthesis of elements, and because it is the basis for several types of widely-used laboratory neutron sources. Two notable early measurements were made by Chadwick with polonium alpha rays1) and by Dunning with a mixture of radon, RaA and RaC12). The results of the early work indicated the approximate energy distribution and anisotropy of the major neutron groups and brought forth the important concepts of resonance in excited states of 13C and decay with neutron emission to the ground and excited states of 12C.

The development of nuclear emulsion technique permitted detailed measurements of the neutron spectra of PoBe3,4) and PuBe5,6) sources, while concurrent studies with accelerated alpha-particle beams directed onto Be foils were providing numerous measurements of angular distributions7-11), angular correlations12-14) and polarizations15) of the emitted neutrons and gamma rays. Taken together, however, the latter measurements have provided only an incomplete explanation of the features of the neutron source spectra found by use of emulsions and the more recently developed crystal spectrometers16,17).

The complex angular form of the emissions and the gaps in our knowledge of them have made exact analytical computations of source spectra extremely difficult6,9). Furthermore, an attempt to predict the spectrum of such sources theoretically by explicitly ignoring the anisotropy in neutron emission was not particularly successful18).

Because of the potential increase in resolution of emulsion-derived neutron spectra when large track samples are analyzed by a differentiation technique19), it seemed worthwhile to measure standard-size laboratory PoBe and PuBe neutron sources in an attempt to reconcile the observed spectra with the beam foil data. In order to make this comparison a numerical-graphical method is employed to estimate and predict the thick source spectra.

2. Materials and methods

One by 3 inch Ilford L.4 emulsions, 600 μm thick, were exposed in a standard emulsion holder19) 37 cm from a 11 Ci PoBe source suspended at the center of a large empty room, and 52 cm from an 80 g PuBe source+, located 1 m above the roof of a small building. The pellicles were developed by use of a modified cold cycle process20), sampled as detailed below by use of random-drift scanning, and the tracks were analyzed by a differentiation technique.

In order to equalize the number of tracks per channel in the low and high energy portions of the spectra, which can only partially be accomplished by progressively increasing the channel width for the more energetic tracks, the pellicles were scanned as follows. Approximately 10000 tracks lying in a forward cone of half-angle 60° were selected and measured by the random-drift method, and the tracks were analyzed by a differentiation technique.

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† ISC-2691, Isotopes Specialties Corp., Burbank, California. The source had decayed from a nominal 30 Ci to 11 Ci at the time of exposure.

+ M-593, Mound Laboratories, Miamisburg, Ohio.
would be obtained from an unrestricted sample of the same size. An independent sample of 2500 tracks was then taken from each pellicle with no angular restriction. The latter samples were normalized to the unbiased “tail” of the former in order to furnish them with accurate short-track “heads”. This procedure provides substantially increased detail, per track sampled, in the important 2–10 MeV portion of the track spectrum. This detail is especially valuable in the subsequent analysis by differentiation. Further, because of the rapid decline of the number of tracks with energy, the number of short tracks per channel is not appreciably below that of the longer tracks.

3. Results

3.1. Experimental

The experimental spectra are shown in fig. 1, where they are displayed at 250 keV resolution* and normalized at the 4.8-MeV peak. The error bars represent statistical uncertainty only, and were obtained by allowing the points of the integral track spectrum to vary randomly within statistical limits, and by re-drawing several times the smooth curve for differentiation. The well-known peaks at 3.2, 4.8, 7.8 and 9.8 MeV are clearly present in both spectra. In addition, small peaks at 1.1 and 2.3 MeV and a prominent shoulder at 5.6 MeV are evident. When normalized at 4.8 MeV the two source spectra differ slightly in the regions of the 9.8, 5.6, 3.2, 2.3 peaks, and in the region below 1.5 MeV. These differences are discussed below.

In order to obtain the detail of the neutron spectra below 2 MeV it was necessary to abandon the analysis by differentiation and to employ an indirect method, because the track samples contained large numbers of tracks from stray scattered neutrons19). The number of tracks per channel that originate by collision with unscattered neutrons was found as follows. The 2500-track samples were re-analysed by computer in order to compare channel by channel with the total sample, the number of tracks that lay in a cone of half-angle 30-deg defined by the beam axis. Only 13.3% of randomly oriented tracks of length l and track-length energy \( E(l) \) will lie in the 30° solid angle, but all the tracks in that length channel that arise by collision with neutrons in the primary beam having energies near \( E(l) \) will lie in this solid angle. In comparing track-length channels, an abrupt jump in the fraction of tracks in the 30°-sample/total-sample ratio indicates a peak at the neutron energy corresponding to the proton track-length energy of that channel19). The size of the fractional and the absolute increase of tracks provides a good estimate of the magnitude of the peak, even though this spectral detail is otherwise completely obscured by tracks generated by stray neutrons. This method of analysis also verifies very sensitively the positions and relative magnitudes of the peaks in the higher energy channels that are not subject to the scattering problem.

In this fashion minor peaks at 1.4, 1.1, 0.78 and 0.54 MeV were uncovered in both source spectra. The positions of these peaks are indicated by arrows in fig. 1. Although the channels in this region are about 100 keV wide, the data, because of their approximate nature, are plotted in 250 keV intervals. The low-energy portion of the neutron spectrum as obtained by differentiation of the uncorrected track-energy spectrum is also shown for comparison. This spurious curve depicts the correct spectrum of neutrons that exposed the emulsion; it differs from the emitted source spectrum by a large component of low-energy scattered neutrons.

The agreement of the principal features of the spectra with the crystal spectrometer measurements21,22) and with some of the more detailed emulsion spectra4,6) is good. With respect to future measurements, it appears that nuclear track emulsions may provide equal or better resolution at the lower energies (<4 MeV) due to the fact that their size minimizes the low-energy neutron scattering problem, while the crystal spectrometers may, because of their ability to measure in a reasonable time the order of 100 000 tracks, provide better resolution at the higher energies.

* 400 keV resolution above 6.8 MeV.
3.2. Analytical

In an attempt to improve the computed estimates of neutron source spectra, the following numerical-graphical approach has been taken. The total 4π cross section measurements\(^{23}\) clearly show that the neutron emission from the \(\text{Be}(\alpha,n)\) reaction occurs as a series of broad overlapping resonances. In addition, the relative and absolute differential cross sections to the ground and excited states of \(^{12}\text{C}\) have been reported for a good many energies in the 0.5 to 12 MeV region\(^{7-14,24-26}\). By use of these data, it has been possible to assemble partial cross sections over most of the energy range below 6 MeV for neutron emissions leading to the ground and excited states of \(^{12}\text{C}\) (fig. 2).

In order to obtain the total number of neutrons in a resonance group the area under the resonance in the partial cross section was found graphically from fig. 2 and weighted by the corresponding value of the \(dx/dE\) curve, the "steady state" alpha particle energy distribution in the source\(^{27}\). The number of neutrons in each such group was distributed in energy as determined by the 2-body \(Q\) equation\(^{28}\) and the appropriate differential cross section measurements (fig. 3). The source of each neutron group is listed in table 1 and the composite result of this graphical-numerical analysis is presented in fig. 4.

4. Discussion
4.1. Experimental and Analytical Spectra

For some time there has been a puzzling lack of detailed agreement between measurements of neutron sources\(^{5,6}\). Real differences arising from variations in construction of laboratory PoBe sources are partly responsible\(^{17}\); in addition, certain minor spectral...
TABLE 1

<table>
<thead>
<tr>
<th>Neutron group</th>
<th>Excited by alphas (MeV)</th>
<th>Principal resonance level in $^{12}$C†</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>1.2–3.0</td>
<td>12.44</td>
</tr>
<tr>
<td>$a_1$</td>
<td>1.2–3.0</td>
<td>11.97</td>
</tr>
<tr>
<td>$b_0$</td>
<td>3.0–3.8</td>
<td>12.44</td>
</tr>
<tr>
<td>$b_1$</td>
<td>3.0–3.6</td>
<td>11.97</td>
</tr>
<tr>
<td>$c_0$</td>
<td>3.8–4.8</td>
<td>13.54</td>
</tr>
<tr>
<td>$c_1$</td>
<td>3.6–4.2</td>
<td>13.41</td>
</tr>
<tr>
<td>$c_2$</td>
<td>3.8–4.8</td>
<td>13.54</td>
</tr>
<tr>
<td>$d_1$</td>
<td>4.2–4.8</td>
<td>13.77</td>
</tr>
<tr>
<td>$e_0$</td>
<td>4.8–5.3*</td>
<td>14.39</td>
</tr>
<tr>
<td>$e_1$</td>
<td>4.8–5.3*</td>
<td>14.11</td>
</tr>
<tr>
<td>$e_2$</td>
<td>4.8–5.3*</td>
<td>14.39</td>
</tr>
</tbody>
</table>

* Energy limit of $^{210}$Po alpha rays.
† Based on results in 25, 26.

differences that depend upon the source, size and age have been predicted for PuBe sources\(^6\). However, a good many laboratory sources are now being made in the following standard fashion. Plutonium filings are fused with Be metal in a tantalum container under inert gas at 2000°C to form PuBe\(_{13}\) alloy. Subsequently the Ta container is sealed into a stainless steel outer container. In the fabrication of PoBe sources, \(^{210}\)Po is electroplated onto a platinum gauze, placed in an inner stainless steel container, and packed tightly with beryllium powder. The container is weld-sealed in inert gas and fired to 750°C, at which temperature the polonium plates onto the beryllium powder grain surface. In such sources, it is most unlikely that neutrons originate in any significant numbers from reactions other than $^9$Be($\alpha$,n). Moreover, when the alloying or plating is done uniformly the possibilities for variations in the $dx/dE$ distribution are minimized. Radiographic analysis has shown however, that the alloy or powder is not always uniformly distributed inside the inner container\(^6\)). For this reason it is clear that no two sources are physically identical.

It is significant, however, that major features of the most carefully measured laboratory PoBe and PuBe source spectra do coincide (sect. 3) and heretofore could only partially be understood in terms of fundamental thin target measurements. In particular, Anderson and Bond\(^9\) were unable to predict on the basis of unpublished measurements by Rez-Schmidt et al.\(^{29}\), a major peak at 3.2 MeV and a shoulder at 5.5 MeV, prominent features in the measured source spectra. Furthermore, their analysis could resolve neither the twin peaks at 6.7 and 7.8 MeV, observed by the crystal spectrometer measurements, nor the small peak at 2.3 MeV. In contrast, the analytical composite spectrum in fig. 4 predicts these features and explains and interprets the entire region above 1.2 MeV as revealed in the better-measured source spectra.

The graphical analysis by neutron groups does not admit the possibility of a major peak at 0.8–1 MeV, one which is seen in most measurements. Some theoretical treatments do predict a peak in this region from a supposed 3-body break up\(^{18}\), but the variability of the size of this measured peak in different measurements, and the 30° sample analysis (above) suggest that this peak may instead arise largely from scattering of neutrons by the detector and associated apparatus. Detailed consideration of such scattering in nuclear emissions under conditions where scattering was minimized, has shown how serious this experimental problem can be\(^9\).

A neutron group S has been added to fig. 4 in order to indicate for a particular detector a possible low energy group which originates by means of scattering external to the source. The effect on the overall spectrum of scattering inside the source, and various minor nuclear reactions in the source have been considered and found to be small\(^6\). Fig. 4 is not corrected for them. However, the 0–0.3 MeV group L, which was measured and studied by St. Romain et al.\(^{30}\) is included for completeness. Including L and excluding S, the average energy of the spectrum of fig. 4 is 4.28 MeV, in close agreement with the 4.2 MeV value for a similar source measured by Hess and Smith\(^{31}\). Schöneberg et al.\(^{32}\) have measured neutrons emitted by decay of the 2.43 state of $^9$Be, which may be excited in PoBe sources by an ($\alpha$,x'') reaction. These neutrons form a continuum

Fig. 4. The neutron groups composing a PoBe source. Composite graphico-numerical analysis.
below 0.76 MeV, but since it was impossible to estimate
their relative contribution, they are not included in
fig. 4.

Aside from the low energy region, where the gra-
phico-numerical results will no doubt be improved
when more detailed basic information is available for
the c₂ and e₂ neutron groups, fig. 4 is instructive on
several counts.

First, the effects on the neutron emission spectra of
using α-emitters with varying energies are easily seen.
In particular, the relative prominence of the 3.2 MeV
peak and the 5.5 MeV shoulder will be directly related
to the extent that the dx/dE spectrum exceeds 4.8 MeV
and that the large resonance at 5.1 MeV to the 4.43
MeV state is included in the emission spectrum. This
consideration alone is sufficient to explain the minor
differences in the PoBe and PuBe spectra above 2 MeV
(fig. 1). If sources are made in the future which include
only α-emitters with energies less than 4.8 MeV, the
neutron groups e₀, e₁ and e₂ would be entirely absent.
Conversely, sources containing more energetic α-
emitters would be expected to include proportionately
more neutrons in the e groups, neutrons from higher
resonances, and neutrons generated by means of direct
reaction mechanisms (stripping, knock-out)¹¹,²³,³³–
³⁵).

Second, the emission spectra from sources where α-
particles of diverse energies are used, such as Rn and
daughters, can be predicted by constructing appropriate
“steps” in the dx/dE steady state spectrum, and
proceeding with the graphico-numerical analysis as
above. In similar fashion this method permits one to
predict the effects on the neutron groups of various
hypothetical disturbances in the dx/dE spectrum
arising from differences of construction and inhomoge-
neities in the emitting alloy.

Finally, fig. 4 permits an interpretation of the differ-
ences in the published Be (α,n) source spectra. The
graphico-numerical method predicts increasing strength
in neutron groups having peaks at 2.3, 3.2, and 5.6 MeV
as the dx/dE spectrum of the alpha rays in the source
exceeds 4.8 MeV. As predicted, these features are partic-
ularly prominent in ²⁴¹Am α (5.48 MeV)Be spectra³⁶,³⁷).
These peaks are less prominent, as predicted, in the
present work and in other studies of the ²¹⁰Po α (5.3
MeV)Be spectrum³,²¹). The fact that these features are
almost absent in the spectrum of Notarrigo et al.¹⁷)
suggests there was less than optimum annealing of Po
onto the beryllium when their source was fabricated.

The three peaks are smaller yet, as predicted, in the
present work and in other studies of the ²³⁹Pu α (5.15
MeV) ¹³Be neutron spectrum⁵,⁶,²²). With regard to
²²⁶Ra α (4.78 MeV) Be source spectra, the comparison
is complicated by the presence of the alpha-emitting
daughters ²²²Rn (5.49 MeV), ²¹⁸Po (6.00 MeV) and
²¹⁴Po (7.68 MeV). The prominence of the 2.3-, 3.2- and
5.6-MeV peaks will depend upon how intimately these
daughters are in contact with the source beryllium.
The absence of prominent peaks at these energies³⁷,³⁸)
suggests that the daughters do not contribute strongly
to the dx/dE spectrum above 5 MeV in these sources.
In ²²⁷Ac-Be neutron sources, energetic alpha rays are
also emitted by the daughters, but in contrast to
²²⁶Ra-Be relatively strong neutron peaks are observed
at 5.6, 3.2 and 2.2 MeV ³⁹). The reason why the ²²⁷Ac
daughters are effective in exciting these peaks and the
²²⁶Ra daughters are not, is unknown.

4.2. ANISOTROPIC EMISSION AND THE ENERGY
DISTRIBUTION IN THE NEUTRON GROUPS

The angular distributions of the neutron groups are
of course completely obscured in laboratory neutron
sources, where the alpha emitter is distributed through-
out the source volume. However, because these angular

<p>| Table 2 |
|---|---|---|---|
| Exit channels for ⁹Be(α,x) reaction. |</p>
<table>
<thead>
<tr>
<th>Excitation threshold (MeV)</th>
<th>Type of reaction</th>
<th>Exit channel</th>
<th>Channel spin and parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹⁰C level</td>
<td>E</td>
<td>α, α</td>
<td>⁹Be(3/2\textsuperscript{−}, g.s.) + α</td>
</tr>
<tr>
<td>1. 10.6</td>
<td>0.4</td>
<td>α, γ</td>
<td>¹⁰C(0\textsuperscript{−}, g.s.) + α</td>
</tr>
<tr>
<td>2. 10.6</td>
<td>0.4</td>
<td>α, α</td>
<td>¹⁰C(2\textsuperscript{−}, 4.43) + α</td>
</tr>
<tr>
<td>3. 10.6</td>
<td>0.4</td>
<td>α, n₀</td>
<td>⁹Be(1/2\textsuperscript{+}, 1.67) + α</td>
</tr>
<tr>
<td>4. 10.6</td>
<td>0.4</td>
<td>α, n₁</td>
<td>¹⁰C(0\textsuperscript{−}, 7.66) + α</td>
</tr>
<tr>
<td>5. 12.40</td>
<td>2.50</td>
<td>α, α\textsuperscript{1}</td>
<td>⁹Be(5/2\textsuperscript{−}, 2.43) + α</td>
</tr>
<tr>
<td>6. 12.70</td>
<td>2.80</td>
<td>α, n₂</td>
<td>⁹Be(5/2\textsuperscript{−}, 3.04) + α</td>
</tr>
<tr>
<td>7. 13.10</td>
<td>3.20</td>
<td>α, α\textsuperscript{2}</td>
<td>⁹Be(5/2\textsuperscript{−}, 2.43) + α</td>
</tr>
<tr>
<td>8. 13.70</td>
<td>3.80</td>
<td>α, α\textsuperscript{3}</td>
<td>⁹Be(5/2\textsuperscript{−}, 3.04) + α</td>
</tr>
</tbody>
</table>
**TABLE 3**

Spins and parities of the $^{13}$C states (resonance theory).

<table>
<thead>
<tr>
<th>Neutron group</th>
<th>$E_0$ (MeV)</th>
<th>Most probable $l$</th>
<th>Resonance states consistent with given $l$, $l'$</th>
<th>$E'$ (MeV)</th>
<th>Most probable $l'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>2.0</td>
<td>2</td>
<td>$1/2^-$</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$7/2^-$</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>$a_1$</td>
<td>3.4</td>
<td>3</td>
<td>$(3/2, 5/2)^+$</td>
<td>7.5</td>
<td>2</td>
</tr>
<tr>
<td>$b_0$</td>
<td>3.3</td>
<td>3</td>
<td>$(3/2$ to $9/2)^+$</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>$c_0$</td>
<td>4.3</td>
<td>3</td>
<td>$(3/2$ to $9/2)^+$</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>$c_1$</td>
<td>3.9</td>
<td>3</td>
<td>$(3/2$ to $9/2)^+$</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$c_2$</td>
<td>4.3</td>
<td>3</td>
<td>$(3/2$ to $9/2)^+$</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(1/2, 3/2)^-$</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>$d_1$</td>
<td>4.5</td>
<td>(2)4</td>
<td>$(1/2$ to $7/2)^-$</td>
<td>4.0</td>
<td>1</td>
</tr>
<tr>
<td>$e_0$</td>
<td>5.0</td>
<td>3</td>
<td>$(3/2, 5/2)^+$</td>
<td>8.3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(5/2, 7/2)^{-}$</td>
<td>8.3</td>
<td>3</td>
</tr>
<tr>
<td>$e_1$</td>
<td>5.0</td>
<td>3</td>
<td>$(3/2$ to $9/2)^+$</td>
<td>4.4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(5/2, 7/2)^{-}$</td>
<td>4.4</td>
<td>1</td>
</tr>
<tr>
<td>$e_2$</td>
<td>5.0</td>
<td>3</td>
<td>$(3/2, 5/2)^+$</td>
<td>1.7</td>
<td>2</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$(1/2, 3/2)^{-}$</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>$\alpha, \alpha'$</td>
<td>3.0</td>
<td>3</td>
<td>$(3/2, 5/2)^+$</td>
<td>1.3</td>
<td>2</td>
</tr>
<tr>
<td>$\alpha, \alpha''$</td>
<td>4.0</td>
<td>3</td>
<td>$(3/2$ to $9/2)^+$</td>
<td>1.6</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(3/2$ to $9/2)^+$</td>
<td>1.5</td>
<td>2</td>
</tr>
</tbody>
</table>

* Analysis of experimental data led Risser et al. to conclude this resonance is a mixture of $3/2^+$ and $5/2^+$ states.

Distributions do determine the observed laboratory energy distribution of a group, a discussion of angular distributions in individual (cm) reactions, in terms of detailed angular momentum balance and elementary resonance (partial wave) theory is in order.

A knowledge of the angular distribution of a neutron group in the $^9$Be($\alpha$,n) reaction should establish the parity and severely limit the possible spin in the resonance state of the $^{13}$C nucleus. The exit channels available to these states are given in Table 2; and the most probable spin and parity ($J^\pi$) assignments for the states of interest here may be seen in Table 3. The $\gamma$ exit channel (Table 2) is not excited to any appreciable extent by $0$ to $5$ MeV alpha rays. On the other hand, the $\alpha'$ exit channels are excited, and do lead to neutron-emitting excited states of $^9$Be. With the exception of St. Romain et al.'s measurements, little is known about the relative importance of these neutrons. The most probable resonance states associated with these emissions ($\frac{1}{2}$ to $\frac{3}{2}$) suggest an active competition with the $b$ and $c$ neutron groups (Table 3), perhaps accounting for their relatively small neutron intensity.

A number of workers have attempted to learn about the $J^\pi$ of the $^{13}$C resonance states by means of differential cross section measurements of the emitted neutrons. The observed cross sections proved to be complex, however, and could only be interpreted in terms of mixing and overlapping of adjacent levels in the compound nucleus. Further evidence of mixing may be found by an examination of the $a_0$ and $a_1$ groups. The appropriate $^{13}$C resonance levels (Fig. 5) for these groups lie at $11.97$ MeV ($\frac{1}{2}^-$) and $12.44$ MeV ($\frac{3}{2}^-$).

Considering first the $a_0$ neutron group, a $\frac{1}{2}^-$ or $\frac{3}{2}^-$ resonance level can be achieved by means of $d$- or $g$-wave alpha interactions with the $3^-$ ground state of $^9$Be. An analysis in terms of partial wave theory, summarized in Table 3, suggests that the $d$-wave alpha interaction is more likely. Angular momentum and parity considerations restrict the $a_0$ neutron to $p$-wave angular emission from a $\frac{1}{2}^-$ state and to $f$-wave emission from a $\frac{3}{2}^-$ state. In fact, the angular emission is neither pure $p$- nor pure $f$-wave (Fig. 3), and can be explained only by a mixture of the two nuclear states; in this case $p$- and $f$-wave neutron emission is equally probable.

The $2.5$ MeV $a_1$ emission to the $4.42$ MeV $2^+$ state of $^{12}$C may arise from $d$-wave alpha-induced $\frac{1}{2}^-$ or $\frac{3}{2}^-$ resonance levels, either of which permits $p$, $f$ or higher odd integral neutron-emission waves. In fact, at $2.5$ MeV only a $p$-wave emission is consistent with the size of the compound nucleus. Fig. 3 reveals that the $a_1$ emission in the $2$ MeV region has, as predicted, largely $p$-wave character. However, between $2.5$ and $2.7$ MeV the neutron emission abruptly changes into a mixed $p$- and $f$-wave character.
angular dependence of the polarization of the neutrons emitted in the 3.5- to 4.5-MeV region of the Be(α,n) reaction. These examples of how sensitively angular emission depends upon the energies of the bombarding rays are consistent with the essential resonance character of the nuclear interactions.

The angular distribution of the large e₁ group is especially important because it determines two major neutron peaks at 3.2 and 5.5 MeV in ⁹Be(α,n) sources. To a first approximation the experimental angular (CM) dependency is \( \cos^2 \theta \) indicating p-wave character, consistent with one of the two equally probable emissions predicted by partial wave theory.

It should be mentioned that theoretical interpretations of angular distributions of neutrons from this and other similar reactions in the energy region of interest have been reasonably successful when based on direct interaction mechanisms. Therefore, the predictions of this section, summarized in table 3, assuming resonance mechanisms may not be completely adequate. The validity of the graphico-numerical approach employed in sect. 3 above, however, is indifferent to the mechanism of the nuclear reactions. It relies only upon measured angular distributions.

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