

ANALYSIS OF NEUTRON AND ALPHA SPECTRA IN THE  
INTERACTION OF NEUTRONS WITH  ${}^9\text{Be}$  AROUND 14 MeV

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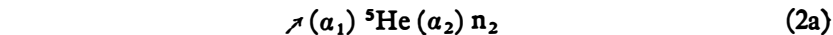
The published alpha and neutron spectra resulting from the interaction of 14 MeV neutrons with  ${}^9\text{Be}$  have been analyzed to determine the importance of the simultaneous breakup process which yields phase space like contributions to the inclusive spectra. The analysis has established the importance of the three body simultaneous breakup mode ( $n\alpha$   ${}^5\text{He}$ ), and the coherence of the alpha and neutron spectra in shape and magnitude.

*1. Introduction*

Neutron induced four body breakup  $n + {}^9\text{Be} \rightarrow 2n + 2\alpha$  has a large cross section ( $51 \text{ fm}^2$ ) around 14 MeV. It has also a low threshold and yields two neutrons per each interaction. Nuclear data for neutron induced reactions on  ${}^9\text{Be}$ , leading to the alpha and neutron emission, are therefore considered as high priority data for fusion reactor technology, specifically for blanket application. Besides the cross section, the reaction mechanisms and the angular distributions of the outgoing particles should be known as well, since they both may influence considerably the spectrum of secondary particles, though the total cross section is unchanged.

The reactions which may contribute to the yield of neutrons and  $\alpha$  particles are:





Except for the processes (1) and (3) all the other reactions yield two neutrons and two  $\alpha$  particles in the final state.

The neutron scattering experiments have been performed repeatedly<sup>1,2,3)</sup> spanning a large angular range and a full spectral range (almost down to  $E_n = 0$  MeV).

Alpha particle spectra have so far been measured mainly with the aim to determine the contributions of  $\alpha_0$  and  ${}^6\text{He}$  particles from reactions (3), and the alpha particles corresponding to the reaction (4) with the 1.8 MeV excitation of  ${}^6\text{He}$ . For both processes the angular distributions and total cross sections have been extracted<sup>4)</sup> around 14 MeV ( $\sigma_{\text{tot}}(\alpha_0) = 0.98 \text{ fm}^2$ ,  $\sigma_{\text{tot}}(\alpha_1) = 1.75 \text{ fm}^2$ ). In a coincidence measurement<sup>5)</sup> the presence of reaction sequence (4) with  ${}^6\text{He}$  in excited state of 6 MeV was stated. A large alpha continuum has always been observed, however, it was not studied in details.

Recently the alpha particle spectra for neutron incoming energy of 14.6 MeV have been measured to study the continuum particle yield<sup>6,7)</sup>.

Evaluated  $n + {}^9\text{Be}$  data are presented by ENDF/B IV(V) tables, but considerable discrepancies have been observed, when these are compared to recent experimental results<sup>2,3)</sup>. Due to the importance of these data, Perkins et al.<sup>8)</sup> constructed a model which would be capable to yield double differential cross sections,  $(E_i, \theta_i; i = n, \alpha)$  up to 20 MeV. To obtain a satisfactory fit with the experimental data they have been forced to introduce in the model many different levels of  ${}^9\text{Be}$  that are usually only weakly excited both in  $(p, p')$  and  $(n, n')$  inelastic scattering experiments.

Recent studies of the continuous particle spectra from the reaction and particle scattering on light nuclei have shown<sup>9)</sup> that a considerable part of the total cross section is due to a simultaneous n-body breakup, a process with a constant matrix element and hence with a phase-space-like energy distribution.

It is the aim of the present paper to consider the simultaneous breakup mechanism as one of the participating processes and to determine its contribution to the neutron<sup>1,2,3)</sup> and alpha<sup>6,7)</sup> particle spectra from the neutron induced breakup of  ${}^9\text{Be}$ .

## 2. Three-body simultaneous breakup with one unstable particle

The kinematically available final states for statistical simultaneous breakup are the  $(n, {}^5\text{He}, \alpha)$  and  $(n, n, \alpha, \alpha)$  channels (reactions (6a) and (6b)). The specificity of the channel (6a) is that it contains an unstable particle —  ${}^5\text{He}$  which decays into  $n + \alpha$ . Therefore, one has to consider  $\alpha$  particles and neutrons stemming both from the three body simultaneous breakup, and from the subsequent decay of  ${}^5\text{He}$ . The 3 and 4-body simultaneous breakup spectra for  $\alpha_1$  and  $n_1$  can be calculated analytically. However, if one of the particles in the three-body final state is unstable and decays further on, one should generate a complete event described by the magnitude and direction of the momentum for at least that particle which undergoes further decay. Since the programme should serve for general purposes, a computer programme was developed which generates a complete three-body vertex event in a nonrelativistic case. It allows a sequential decay of the unstable particle and takes into account the width of the unstable state.

In the three-body decay  $m_0 + m_T \rightarrow m_1 + m_2 + m_3$ , ( $Q_{123}$ ) governed by the phase space considerations, the physical region in the kinetic energy space in the  $(m_0, m_T)$  center of mass system (the Dalitz plot) has a uniform density of events. This fact has been exploited in generating a random 3-body vertex event. The energy  $E_1$  of particle 1 is chosen randomly between zero and the respective kinematic maximum according to the phase space distribution

$$\omega = (E_1 (E_{1\max} - E_1))^{1/2}. \quad (1)$$

The energy  $E_2$  of particle 2 is set to be uniformly distributed between its boundaries on the Dalitz plot at  $E_1$ . The maximum and minimum values are obtained taking  $\cos \Theta_{1,2} = \pm 1$  in the expression

$$E_2 = (A E_1^{1/2} \cos \Theta_{1,2} - (E_1 (A^2 \cos^2 \Theta_{1,2} - B) - CE)^{1/2})^2 \quad (2.1)$$

where

$$A = \frac{(m_1 m_2)^{1/2}}{2(m_2 + m_3)} \quad (2.2)$$

$$B = \frac{m_2 + m_3}{m_1 + m_3} \quad (2.3)$$

$$C = \frac{m_3}{m_2 + m_3} \quad (2.4)$$

$$E = E_1 + E_2 + E_3 = \frac{m_T}{m_0 + m_T} E_0 + Q_{123} - E_3^* \quad (2.5)$$

$\Theta_{1,2}$  is the angle between particles 1 and 2 and  $E_3^*$  is the excitation energy of the unstable particle. For a given  $E_1$  and  $E_2$ , the energy of the third particle  $E_3$ , as

well as  $\cos \Theta_{1,2}$  are uniquely determined. The momenta of the three particles can now be determined by

$$\begin{aligned} \vec{p}_1 &= \{p_1 \cos \varphi, p_1 \sin \varphi, 0\} \\ \vec{p}_2 &= \{p_2 \cos (\Theta_{1,2} - \varphi), p_2 \sin (\Theta_{1,2} - \varphi), 0\} \\ \vec{p}_3 &= -\vec{p}_1 - \vec{p}_2 \end{aligned} \quad (3)$$

where  $p_i^2 = 2m_i E_i$  ( $i = 1, 2, 3$ ) and  $\varphi$  is a random angle uniformly distributed in  $(0, 2\pi)$ .

The events  $(\vec{p}_1, \vec{p}_2, \vec{p}_3)$  are confined in a single plane ( $z = 0$ ). To obtain random events in the whole space one allows the end point of the normal vector to the  $(\vec{p}_1, \vec{p}_2, \vec{p}_3)$  plane to be uniformly distributed over the unit sphere.

The sequential decay of the unstable particle  $m_3$ ,  $m_3 \rightarrow m_4 + m_5 (Q_{45})$  is assumed to have isotropic angular distribution in the center of mass of the unstable particle. The random choice of  $\cos \Theta_4$  and  $\varphi_4$  fixes the direction of particle 4. The momenta of particles 4 and 5 are

$$|\vec{p}_4| = |\vec{p}_5| = \left( 2 \frac{m_4 m_5}{(m_4 + m_5)} (E_3^* + Q_{45}) \right)^{1/2} \quad (4)$$

and their directions are of opposite signs.

The vector sum of the velocity of particle 4 (or 5) (given by  $\vec{p}_{4(5)}/m_{4(5)}$ ), the velocity of particle 3, and of the center of mass velocity transforms the event in the laboratory frame for particle 4 (or for particle 5, the alternation given in parentheses) giving for the velocities

$$\vec{v}_{4(5)}^L = \vec{v}_{CM} + \vec{v}_3 + \frac{\vec{p}_{4(5)}}{m_{4(5)}} \quad (5)$$

It is worthwhile to comment the last expression. The maximum value of  $v_4^L$  or  $v_5^L$  (and equivalently  $E_4$  or  $E_5$ ) can be calculated analytically since the magnitudes of all three terms are known and have to be summed algebraically. The last term is the only one which differs for the two outgoing particles  $m_4$  or  $m_5$ . When  $E_3^*$  is small the maximum energy of the lighter particle is the smaller of the two. When  $E_3^*$  is large the situation may reverse as visible from Eqs. (5) and (4).

If the unstable state of particle 3 in process (6a) has a broad resonance, instead of a fixed value  $E_3^*$  in Eq. (4) the selected value  $E_3^* = e$  in limits  $(x_1, x_2)$  is obtained using the density distribution

$$f(E_3^*) = \frac{1}{(E_3^* - E_{30}^*)^2 + \lambda^2} \quad (6)$$

where  $E_{30}^*$  and  $\lambda$  are the nominal values and the half width of the resonance of particle 3, respectively. The integral equation

$$F(e) = \int_{x_1}^e f(E_3^*) dE_3^* \tag{7}$$

where  $F(e)$ , being a random number in limits  $F(x_{min})$  and  $F(x_{max})$ , has an analytical solution for  $e$ , since

$$F(e) = \frac{1}{\lambda} \left[ \text{arc tg} \left( \frac{e - E_{30}}{\lambda} \right) - \text{arc tg} \left( \frac{x_1 - E_{30}}{\lambda} \right) \right]. \tag{8}$$

Typical spectra for  $\alpha_1$  and  $n_1$  components for the three and four body breakup, calculated for  $\Theta_\alpha = 40^\circ$ ,  $E_\alpha = 14.6$  MeV and  $\Theta_n = 32^\circ$ ,  $E_n = 14$  MeV, are shown by lines labeled a and c in Fig. 1, respectively. In the same figure the spectra for

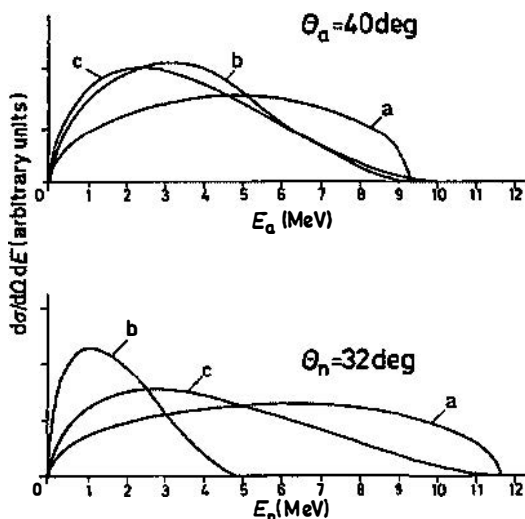


Fig. 1. Phase space spectra of alpha-particles and neutrons at  $40^\circ$  and  $32^\circ$  respectively:

- (a)  $\alpha_1$  and  $n_1$  contributions from the breakup (6a)
- (b)  $\alpha_2$  and  $n_2$  contributions from the breakup (6a)
- (c)  $nna\alpha$  phase space contributions from the breakup (6b).

$\alpha_2$  and  $n_2$  components stemming from the decay of  $^5\text{He}$  are shown by lines labeled b. As expected, the spectrum of the  $n_2$  component is limited to lower energies than the corresponding  $\alpha_2$  spectrum. From Figs. 1a and b it is visible that the spectrum of the decaying neutron ( $n_2$ ) has quite a different shape from that of the 4-body simultaneous breakup, while the spectrum of decaying alpha-particle ( $\alpha_2$ ) is by chance very similar to a 4-body phase space distribution. To distinguish between channels (6a) and (6b) the analysis of the  $(n, n')$  spectra is therefore decisive. In Fig. 2 are shown the angular distributions in the laboratory frame of

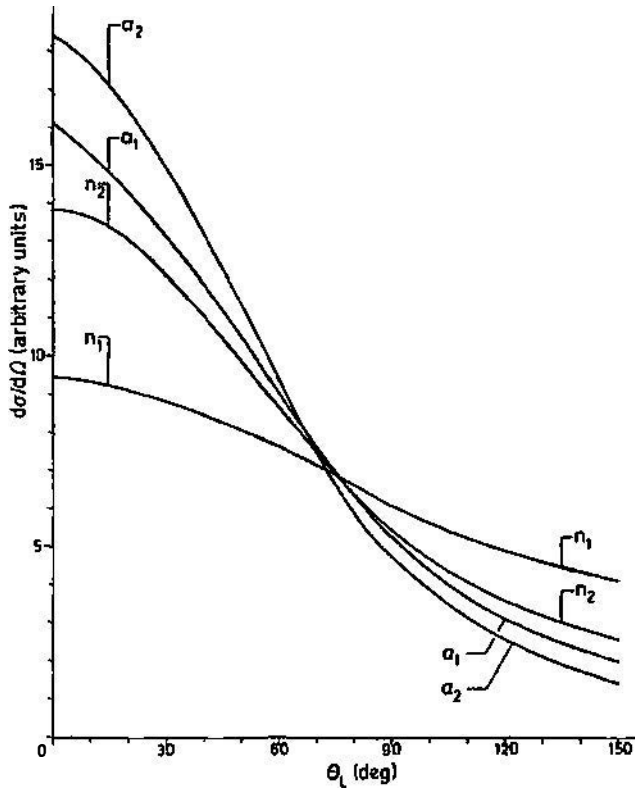


Fig. 2. Angular distribution of the differential cross section for the  $n_1$ ,  $n_2$ ,  $\alpha_1$  and  $\alpha_2$  components calculated under the simultaneous breakup assumption and with isotropic behaviour of the transition amplitude.

components  $n_1$  and  $n_2$  as well as  $\alpha_1$  and  $\alpha_2$  of the process (6a) calculated under the assumption that the amplitude of the process of simultaneous breakup is isotropic. It is visible that large differences between the differential cross sections exist although the total cross section should be the same regardless of the component in question.

### 3. Analysis of data

In course of the analysis of neutron<sup>2)</sup> and  $\alpha$  particle<sup>6)</sup> spectra the following features of the reaction  $n + {}^9\text{Be} \rightarrow 2n + 2\alpha$  around 14 MeV are considered.

— The most important contribution to the neutron inelastic scattering (reaction (2)) is the transition to the 2.43 MeV state of  ${}^9\text{Be}$ .

— The contribution of the reaction (2) to  ${}^9\text{Be}$  levels above 2.43 MeV is relatively small and is unable to account for the continuum observed, for the following reasons:

i) from the inelastic neutron data<sup>2,3)</sup> (see also Fig. 4) one can deduce that the intensity of the transition to 6.76 and 11.28 MeV residual  ${}^9\text{Be}$  states is considerably lower than that to the 2.43 MeV state. At the same time, the particles from the decay of the corresponding states (components  $n_2$  and  $a_2$ ), which have equal intensity in  $4\pi$  as components  $n_1$  and  $a_1$ , are spread over a larger energy region, and hence contribute less in a  $d\sigma/d\Omega dE$  spectrum.

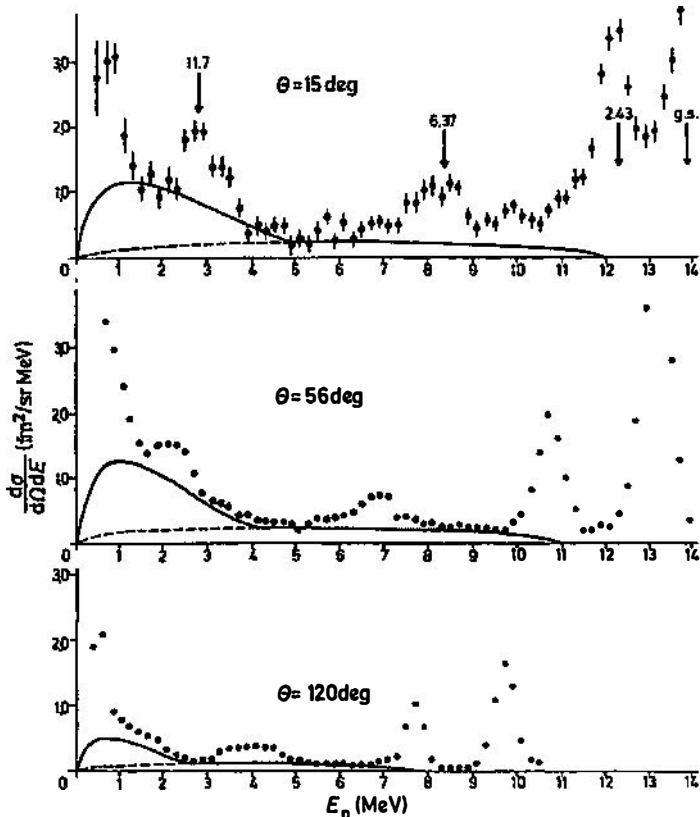


Fig. 3. Neutron energy spectra from the reaction  ${}^9\text{Be}(n, n)$  at nominal incident neutron energy  $E_n = 14$  MeV. The full lines describe the total neutron yield from process (6a) ( $n_1 + n_2$ ). In the part of the spectra where  $n_1$  and  $n_2$  neutrons contribute (see text) the  $n_1$  contribution is shown with a dotted line. The elastic neutron peak is not shown on all spectra.

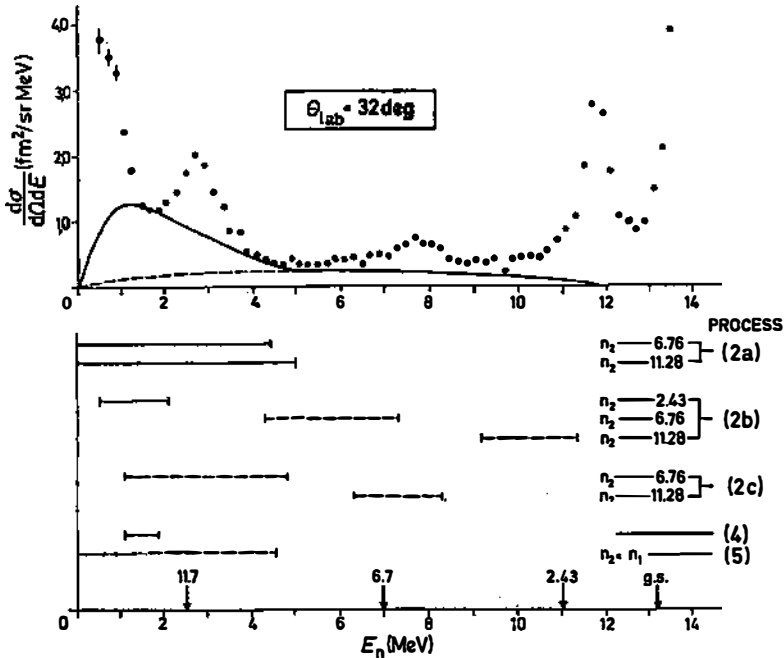


Fig. 4. In the top part the fit to the neutron spectrum at 32° is shown as described in Fig. 3. In the bottom part are schematically shown the ranges of energies accessible to neutrons stemming from decays of unstable states.

ii) The inelastic scattering leading to 6.76 and 11.28 MeV residual <sup>9</sup>Be states is expected to have forward peaked angular distributions, as is the one for <sup>9</sup>Be (n, n') <sup>9</sup>Be<sub>2,4,3</sub> inelastic scattering. This would imply a smaller <sup>9</sup>Be\* yield at forward angles, and consequently smaller contributions of neutrons and alpha-particles from the sequential decay at the forward angles.

— Taking into account the cluster structure of the excited states of <sup>9</sup>Be, the processes via the <sup>8</sup>Be intermediate states (reactions (2b) and (2c)) shall have minor importance.

— The reaction <sup>9</sup>Be(n, <sup>5</sup>He) <sup>5</sup>He (reaction (5)) may be assumed to have approximately the same cross section as the <sup>9</sup>Be(n, <sup>6</sup>He<sub>gs</sub>) reaction, since both can be interpreted as pickup reactions of alpha-particle or <sup>5</sup>He, respectively. Since the cross section for the latter one is of the order of 1 fm<sup>2</sup>, the contribution of the reaction (5) is negligible. The same reasoning applies to reaction (4).

Based on the preceding statements, we conclude that i) the reaction mechanisms (2) are responsible only for a fraction of the continuous alpha-particle spectra, ii) the reaction mechanisms (4) and (5) have negligible contribution, and iii) that the remainder of the total cross section is due to a simultaneous breakup into the available phase space. This is in agreement with observations made in the analyses of continuum spectra in other reactions on light nuclei.

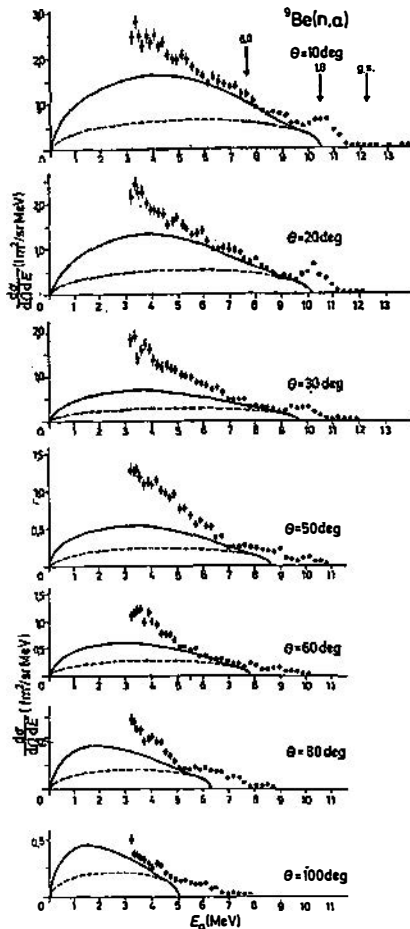


Fig. 5. Alpha particle energy spectra from the reaction  ${}^9\text{Be}(n, \alpha)$  at incident neutron energy  $E_n = 14.6$  MeV. Curves represent the three body phase space contribution of breakup (6a): the dashed curve represents the contribution of alpha particles  $\alpha_1$  from the breakup (6a), and the full curve represents the sum of the contribution of alpha-particles  $\alpha_1$  and  $\alpha_2$  from the breakup (6a).

In Fig. 3 we show a qualitative fit to corrected experimental neutron spectra of Takahashi et al.<sup>2)</sup> The spectra are not fully reproduced, leaving space for the contributions from the decay of  ${}^9\text{Be}$  and  ${}^6\text{He}$  states, which although small should be present. These contributions are limited to specific energy regions, and they are shown schematically in Fig. 4 in conjunction with the neutron spectrum at  $\theta_n = 32^\circ$ . For completeness, the energy ranges of all the continuous contributions (reactions (2), (4) and (5)) are shown, but those expected to have a negligible contribution (reactions (4) and (5) and the inelastic scattering for 6.7 and 11.7 MeV states of  ${}^9\text{Be}$  via the  ${}^8\text{Be}$  intermediate states — reactions (2b) and (2c)) are shown by dashed lines. In the calculation of these kinematical regions the widths of the  ${}^9\text{Be}$  states as well as the experimental energy resolution have not been taken into

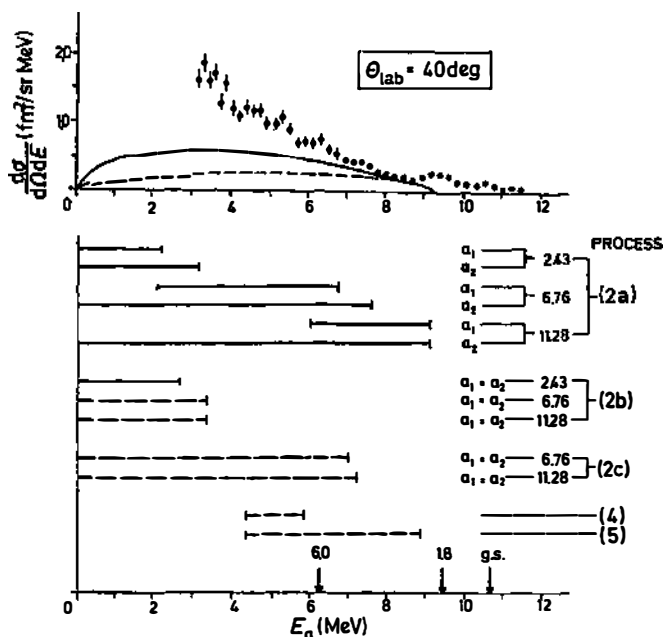


Fig. 6. In the top part the fit to the  $\alpha$  spectrum at  $40^\circ$  is shown as described in Fig. 5. In the bottom part are schematically shown the ranges of energies accessible to  $\alpha$ 's from decays of unstable states.

account. The shapes and intensities of these contributions could be predicted providing total cross sections and angular distributions of particles in both steps of the corresponding sequential decays are known. To the knowledge of the authors these data do not exist so far. However, if one assumes that, for example, the states at 6.76 and 11.7 MeV excitation of  ${}^9\text{Be}$  have about 5 times less intensity than the 2.43 MeV state, they would have, due to their spread over a roughly three times larger energy range around 15 times less average differential cross section  $d\sigma/d\Omega dE$ .

The fits to the neutron spectra shown in Figs. 2 and 4 were achieved respecting the minima in the experimental cross sections in places where the other contributions were judged the smallest (e. g. on the low side of the 11.7 MeV peak). Also, some guidance was taken from the angular distributions shown in Fig. 2 for the  $n_1$  and  $n_2$  components.

The fits to the  $\alpha$  spectra are shown in Fig. 5. Following the results of the fits to the neutron spectra, no four body simultaneous breakup was considered when fitting the  $\alpha$  spectra. The relative contributions of the  $\alpha_1$  and  $\alpha_2$  were determined in the following way. The contribution of the  $\alpha_1$  component was determined by the fit to the calculated three body spectrum to the high energy part of the experimental spectrum and the corresponding  $\alpha_2$  component was extracted following the ratio given by the angular distribution in Fig. 2. The  $\alpha$  spectrum at  $40^\circ$  is shown in Fig. 6 together with the scheme of energy ranges of continuous  $\alpha_1$  and  $\alpha_2$  components.

The spectra belonging to the simultaneous breakup model have been integrated for all spectra treated and the differential cross sections are given in Tables 1 and 2 for neutron and alphas, respectively.

TABLE 1.

$\Theta_{lab}$ (deg)	$\sigma(n_1)$ reaction (6a)	$\sigma(n_2)$ reaction (6a)
15	$2.5 \pm 0.3$	$3.2 \pm 0.5$
32	$2.5 \pm 0.3$	$3.0 \pm 0.4$
56	$1.8 \pm 0.2$	$2.1 \pm 0.25$
120	$0.62 \pm 0.1$	$0.8 \pm 0.15$

Integrated cross sections in (fm<sup>2</sup>/sr) for simultaneous breakup components of the neutron spectra.

TABLE 2.

$\Theta_{lab}$ (deg)	$\sigma(\alpha_1)^{(a)}$ reaction (6a)	$\sigma(\alpha_2)$ reaction (6a)	$\sigma_{exp}$ ( $E_\alpha > 3$ MeV) <sup>(b)</sup>
10	$5.3 \pm 0.7$	$6.0 \pm 0.7$	$10.8 \pm 0.7$
20	$4.4 \pm 0.6$	$5.0 \pm 0.6$	$8.6 \pm 0.5$
30	$2.2 \pm 0.3$	$2.5 \pm 0.4$	$5.5 \pm 0.8$
40	$1.8 \pm 0.3$	$1.9 \pm 0.3$	$4.9 \pm 0.5$
50	$1.6 \pm 0.3$	$1.7 \pm 0.3$	$3.7 \pm 0.6$
60	$1.6 \pm 0.3$	$1.6 \pm 0.3$	$2.8 \pm 0.3$
80	$1.0 \pm 0.2$	$1.0 \pm 0.3$	$1.4 \pm 0.3$
100	$0.8 \pm 0.1$	$0.7 \pm 0.1$	$0.7 \pm 0.1$

Integrated cross sections in (fm<sup>2</sup>/sr) for simultaneous breakup components of the alpha spectra and total experimental differential cross sections for  $E_\alpha > 3$  MeV.

The uncertainties quoted reflect several sources:

- 1) The uncertainty in the contribution of the phase space like spectra to the total spectrum, due to the fact that alpha particles and neutrons stemming from quasi-two-body reactions leading to <sup>5</sup>He, <sup>8</sup>Be and <sup>9</sup>Be unstable levels do contribute as explained in the introduction. We estimate this uncertainty to  $\pm 10\%$ .
- 2) The uncertainty in the absolute cross section. For alphas<sup>6)</sup> the cross section was normalized to the earlier data for the <sup>9</sup>Be(n,  $\alpha$ )<sup>6</sup>He<sub>g.s.</sub> from Ref. 4. This cross section as quoted here is in agreement with Ref. 7. We assign an error of  $\pm 15\%$  to this source. In Table 2 we show in the last column the experimental value of the energy integrated cross section from the maximum energy down to 3 MeV, where the experimental energy cutoff is situated. For neutrons no uncertainties in the differential cross sections were taken into account.

#### 4. Discussion

From the present approach a large portion of the  $n + {}^9\text{Be}$  cross section amounting to  $12 \pm 2 \text{ fm}^2$ , has been assigned to the simultaneous breakup into a neutron, alpha and  ${}^5\text{He}$  particle. This results is justified both by the energy fits achieved in the low energy part of the neutron spectra, and by relative intensities of neutron and alpha components at different angles, which follow the prediction shown in Fig. 2. The departures may be due to the nonisotropic dependence of the reaction amplitude, and the uncertainties in the determination.

The fact that in the  $\alpha$  spectra the simultaneous component apparently fits worse as the angle increases is explicable in terms of angular distributions of the first step inelastic scattering (process 2). Namely, at forward angles the contribution of  $\alpha_2$  particles stemming from forward flying excited  ${}^9\text{Be}$  nuclei is expected to be small. At larger angle, on the contrary, this contribution should rise.

With respect to the existence of the 6 MeV excited state of  ${}^6\text{He}$  it is to our mind impossible to make a definite statement from the  $\alpha$  particle spectra because of the various components that do contribute to the spectra and may introduce a behaviour that is not smooth as visible from Fig. 6 for the alpha particles.

The present analysis proves that satisfactory fits may be achieved to the spectra without the introduction of many weakly excited states as attempted by Perkins et al.<sup>8)</sup> This analysis uses the concept of simultaneous breakup which has been shown in numerous cases to satisfactorily reproduced large parts of inclusive spectra in reactions with light nuclei<sup>9)</sup>.

It is interesting that the four body breakup (process (6b)) at the level of precision of the present analysis was not detected indicating a very strong  $\alpha$   ${}^5\text{He}$  clustering for the ground state of  ${}^9\text{Be}$ .

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## ANALIZA NEUTRONSKIH I ALFA SPEKTARA IZ INTERAKCIJE NEUTRONA SA $^9\text{Be}$ OKO 14 MeV

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Analizirani su spektri alfa čestica i neutrona iz interakcije neutrona od 14 MeV s metom  $^9\text{Be}$ . Ispitivana je prisutnost procesa simultanog raspada koji u totalnom inkluzivnom spektru doprinosi komponente oblika faznog prostora. Analiza je potvrdila značajnu ulogu tročestičnog simultanog raspada ( $n\alpha^5\text{He}$ ), podjednako zastupljenog u alfa i neutronske spektrima.