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Manifestation of the halo structure in momentum distributions from ${}^6\text{He}$ fragmentation

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Abstract

Experimental data on momentum distribution in the fragmentation of a 240 MeV/u ${}^6\text{He}$ beam on a carbon target are compared with several models of the ${}^6\text{He}$ nucleus based on different physical assumptions. It is shown that a lack of a strict theoretical description of the fragmentation mechanism and, in particular, of the final state interaction prevents from any *contra* or *versa* arguments for these models. The requirement of a fragment (${}^5\text{He}$) survival or spatial localization of a fragment in the ${}^6\text{He}$ wave function is an essential point in the reaction mechanism. The analysis of the ${}^5\text{He}$ momentum (sum of the neutron and the α -particle momenta) distribution is free from the effect of final state interaction and thus more promising. It is shown that due to the requirement of fragment survival this distribution is determined mainly by the asymptotic of the ${}^6\text{He}$ wave function. Large sensitivity to the outer part of the halo structure gives a unique possibility to estimate the admixture of *s*-waves in the ground states of ${}^{11}\text{Li}$ and ${}^{14}\text{Be}$ directly from the momentum distribution of ${}^{10}\text{Li}$ (in fragmentation of ${}^{11}\text{Li}$) and from the momentum distribution of ${}^{13}\text{Be}$ (in fragmentation of ${}^{14}\text{Be}$). The shell structure of these nuclei is of great interest in understanding the neutron-halo properties.

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1 Introduction

Physics of nuclear clusters is a broad and interesting field. In this field, a large variety of different and sometimes striking phenomena have been found. Quasimolecular states, α -cluster states at very high excitation energy, nuclear dimers (chain of α -particle configurations, α - n - α - n ...-chains) and, finally, neutron-halo states* have to be mentioned. Many aspects of cluster physics have not yet been solved and some of them have only been touched.

An intense scientific activity, both experimental and theoretical, has over the last decade been performed in order to understand the basic structure of the halo states [1, 2, 3]. Special attention has been focused on nuclei showing a halo state consisting of two neutrons. These two-neutron halos are Borromean [3], i.e., three-body systems with no bound binary sub-systems.

The lightest Borromean nucleus is ${}^6\text{He}$. With its two-neutron separation energy of 975 keV, it shows evidence for a halo structure [4, 5]. There are essential advantages of a study involving ${}^6\text{He}$: the basic α - n and n - n interactions are well known, and good wave functions built on different microscopic three-body models are available [6, 7, 8, 9, 10, 11, 12]. However, while part of these models are based completely on the $\alpha+n+n$ configuration [6, 7, 8, 10], others [9, 12] consider a triton-triton (t - t) configuration to be important as well. Coexistence of several cluster configurations in stable nuclei is quite a known phenomenon. One may refer to α - d and ${}^3\text{He}$ - t clusters in ${}^6\text{Li}$ [13] or to the more exotic case when n - ${}^7\text{Li}$, n - ${}^7\text{Li}^*$, t - ${}^5\text{He}$ configurations have to be taken into account together with ${}^4\text{H}$ - α to get a proper description of ${}^8\text{Li}$ [14]. Coexistence of a halo structure with t - t clustering seems to be strange for a neutron-halo nucleus but cannot be excluded a priori. An experimental confirmation of such an effect is very essential.

One of the main sources of information about halo states originates from investigations of fragmentation reactions. Most of these experiments have aimed at determinations of the fragment momentum distributions. The momentum distributions of fragments are influenced by the internal motion of nucleons inside the projectile [15, 16] and thus can be considered as a probe of different microscopic models of the projectile. In this paper, we review the publications relevant for the analysis of the neutron and the α -particle momentum distributions in fragmentation of ${}^6\text{He}$ (namely Ref. [17] based on a model described in Ref. [7] and Refs. [11, 12]) and compare the results of these calculations with the results of a recent experiment on the fragmentation of a 240 MeV/u ${}^6\text{He}$ beam in a carbon target [18, 19].

2 Ground state wave function of ${}^6\text{He}$

We shall consider the three following models:

- a model, based on an hyperspherical harmonic expansion to solve the system of coupled Schrödinger equations in coordinate space (HHS) [7].

*A large diluted spatially prolonged distribution of nucleons around a compact tight core is called a nuclear halo. The halo nuclei are weakly bound against separation of nucleons forming the halo.

- a model, based on an adiabatic hyperspherical expansion to solve the Faddeev equations in coordinate space (HHF) [11].
- a microscopic multiconfiguration model, the refined resonating group method (RRGM) [12].

The first two (HHS and HHF) are three-body models essentially based on the α - n - n configuration. Different two-body α - n and n - n potentials which reproduce the experimental s - and p -wave phase shifts have been considered in the models. A common problem for both models is underbinding of the ${}^6\text{He}$ nucleus. The calculated binding energy is several hundred keV lower than the experimental value when the two-body potentials from free particle scattering data are used in the calculation. This underbinding problem cannot be solved by choosing different types of potentials. The repulsive s -wave α - n potential as well as the attractive potential with forbidden states underbinds ${}^6\text{He}$. The α - n potential in s -wave and the spin-orbit interaction was changed in [11] to get the experimental value for the ${}^6\text{He}$ binding energy. A similar result was obtained in [7] by increasing the range of all α - n potentials. Underbinding was also found in the variational calculation [6] with different types of α - n and n - n interactions.

Table 1: Binding energies, r.m.s. matter radii and charge r.m.s. point nucleon radii for ${}^6\text{He}$.

Reference	E_{th} [MeV]	$\langle r_m^2 \rangle^{1/2}$ [fm]	$\langle r_{ch}^2 \rangle^{1/2}$ [fm]
[7]	0.731	2.58	1.90
[11]	1.0	2.50	
[12]	0.85	2.47	1.84

The contribution of t - t clustering was substantial in the RRGM model. Omitting the t - t configuration decreases the binding energy by ≈ 700 keV [12]. This result is in agreement with that obtained in Ref. [9].

The calculated binding energies, matter and charge radii are compared with experimental data in Table 1. The three models give nearly the same values for the matter and the charge radii.

The internal momentum distributions of the halo-neutrons in ${}^6\text{He}$ calculated in the different models are shown in Fig. 1. These distributions were obtained by a Fourier transformation of the coordinate space wave functions [7, 11, 12]. The HHS and HHF models, where only the α - n - n configuration was considered, give similar Gaussian-like distributions with standard deviation $\sigma \approx 73$ MeV/c. The RRGM model with α - $2n$, ${}^5\text{He}$ - n and t - t configurations results in a broader distribution with $\sigma \approx 95$ MeV/c. This difference in the distributions gives hope to find a direct proof for one of the models in the experimentally measured momentum distribution of neutrons. However, for a comparison with experimental data, one should take into account also the reaction mechanism, which is discussed in the next section.

Figure 1:

Density distribution of neutrons in the ${}^6\text{He}$ ground state wave function as a function of one Cartesian component of its momentum. The solid line corresponds to the calculation made in [17], the dashed line is the result of [11], the dotted curve displays the calculations made in [12].

3 Fragmentation mechanisms

We shall assume a light target and ignore the long-range Coulomb interaction. Two fragmentation mechanisms are commonly considered in calculations of fragment momentum distributions:

- **The transparent limit of the Serber model.** In the Serber model [20], any influence of the reaction mechanism of the fragmentation as well as final state interaction (FSI) are neglected. The fragment momentum distribution is obtained by a Fourier transformation of the coordinate space wave function integrated over not observed momentum coordinates. In the ${}^6\text{He}$ fragmentation, the calculated neutron momentum distribution are then the ones shown in Fig. 1.
- **The opaque (or black disc) limit of the Serber model.** The influence of the target was considered in the model developed in Refs. [15, 16, 21]. It was assumed that the detected fragment has no interaction with the target while the rest of the nucleus is under strong influence of the interaction. One may refer to this

assumption as to the requirement of fragment survival. In the sudden approximation, the momentum distribution of the fragment is determined by the ground state projectile wave function (in the original Goldhaber model by the sum of the momenta of the projectile nucleons forming this fragment). The requirement of the fragment survival is considered by the Fourier transform of a cutoff portion of the wave function instead of transforming the full wave function. Note, that in a cluster model, this is equivalent to the requirement of fragment localization.

Consider a projectile ground state wave function which describes the relative separation between the observed fragment and the portion of the projectile removed by the interaction with the target. In fact, we only need to know the portion of the wave function with large relative separation between these two subsystems of the projectile. The fragment, which not necessarily has to be bound, may decay in flight close to the reaction zone (in this case the fragment distributions will be influenced by the target) or far from the target. In the last case, the interaction of the decay products with the target nucleus can be neglected and the formalism of FSI [22, 23, 24] can be used. The measured momentum distributions of the decay products of this fragment are thus no more determined by their internal motion in the projectile only. Note, that the spatial localization gives a natural way to introduce the FSI effects.

In the case of an unstable fragment, FSI essentially influences the distribution of its decay products (in the particular case of the ${}^6\text{He}$ fragmentation, α - and neutron momentum distributions). In spite of intensive discussion of the second scenario [11, 12, 17], the transparent limit of the Serber model was used in all models under consideration. The FSI was introduced in [11], for example, by an overlapping integral between the full three-cluster wave function and the final state distorted two-body wave function:

$$\frac{d^2\sigma}{d\mathbf{p}_{n-an}d\mathbf{p}_{a-n}} = \sum_{j,\mu} | \langle e^{i\mathbf{p}_{n-an}\mathbf{r}_{n-an}} w_{j,\mu}(\mathbf{p}_{a-n}, \mathbf{r}_{a-n}) \psi(\mathbf{r}_{n-an}, \mathbf{r}_{a-n}) \rangle |^2, \quad (1)$$

where $\mathbf{p}_{n-an}$ and $\mathbf{p}_{a-n}$ are the usual Jacobi coordinates in the α - n - n three-body system, j and μ are the spin of the α - n final state and its projection, $\psi(\mathbf{r}_{n-an}, \mathbf{r}_{a-n})$ is the three-body wave function in coordinate space. The distorted two-body function $w_{j,\mu}(\mathbf{p}_{a-n}, \mathbf{r}_{a-n})$ was obtained by solving the Schrödinger equation with a two-body potential which reproduces the known property of the α - n interaction. Without FSI, the differential cross section is proportional to the square of the Fourier transform of the full ground state wave function. Similar approaches have been used in [17, 12]. The Fourier transform of the full wave function was multiplied either by a Watson-Migdal factor [12], or both by a Watson-Migdal factor and by a factor which takes into account the neutron knock-out process [17].

Note here, that these approaches are not equivalent and give close but not the same results. This method may certainly be employed in cases when the interaction with the third particle can be neglected. In other words, the subsystem must be considered to be produced in a *localized decaying state*. This is not the case in the transparent limit model. The opaque model gives more ground for an application of FSI or sequential decay mechanisms.

4 Comparison with experimental data

4.1 Experimental data

We shall compare the theoretical predictions with the results of a recent experiment on the fragmentation of a 240 MeV/u ${}^6\text{He}$ beam in a carbon target [18, 19]. The experiment was performed at GSI, Darmstadt, where the ${}^6\text{He}$ secondary beam was produced in a beryllium production target by a 340 MeV/u primary ${}^{18}\text{O}$ beam. The complete information on the momenta of the incoming beam and of all outgoing particles obtained in this experiment makes a combined analysis of momentum distributions, invariant-mass spectrum and different types of angular and energy correlations for α -particles and neutrons possible. In the analysis of the experimental data it was found that one-neutron knock-out is the dominating reaction mechanism in peripheral fragmentation of the halo nucleus ${}^6\text{He}$. The fragmentation mechanism has the following features:

- In the fragmentation of ${}^6\text{He}$, the probability to find two neutrons in the Goldhaber peak[†] is quite low [19]. This experimental fact demonstrates the dominance of a neutron knock-out reaction.
- The knock-out of a neutron results in an unstable ${}^5\text{He}$ nucleus mainly in its ground state.
- The momentum transferred to ${}^5\text{He}$ in the reaction is small. This, in particular, reveals itself in a strong alignment of the ${}^5\text{He}$ spin. The phenomenon of spin alignment directly indicates that in the ${}^6\text{He}$ rest frame, the resulting ${}^5\text{He}$ momentum is equal to the primary momentum of the knocked out neutron, but in opposite direction (see Refs. [18, 25] for details).
- The unstable ${}^5\text{He}$ decays into an α -particle and a neutron. The resulting momentum distributions are not sensitive to the angular distribution of the decay products in the ${}^5\text{He}$ rest frame.
- The shapes of the ${}^5\text{He}$ momentum distributions in the longitudinal and transverse directions are the same. This holds as well for the momentum distributions of its decay products.
- The sequential-fragmentation model with a sudden neutron knock-out, leading to a particle unstable $(3/2^-)$ ${}^5\text{He}$ resonance, can reproduce the measured momentum distributions, as well as the invariant-mass spectrum of the α - n sub-system.

This analysis of the experimental data gives more arguments to the opaque Serber model.

[†]In fragmentation reactions, the projectile products have a bell-like momentum distribution peaked at a velocity close to the velocity of the projectile [15].

4.2 Neutron and α -particle momentum distributions and FSI

In Fig. 2, the neutron momentum distributions calculated in different models are compared with the experimental data. In spite of significant differences in the internal momentum distributions (see Fig. 1), finally, after corrections for α -neutron FSI all the models give similar results which are quite close to the experimental data. The calculation which has started from the wide distribution (dotted line in Fig. 1) leads finally to a result [12] (shown in Fig. 2 by a dotted line) which is just in between those from the two models with narrow distributions [7, 11] (see the dashed line and the thin solid line in Fig. 2). Obviously, the ambiguities in treating the FSI effects prevent from a definite conclusion. One cannot say if one of these models is more appropriate than the others. It is worthwhile to notice here that the different ways how FSI was taken into account not only give different results but are as well not selfconsistent. Note first, that in the α - n - n system all two-body interactions have equal importance and none of them can be neglected. One needs, strictly speaking, to fulfil the requirement of

Figure 2:

Neutron transverse momentum distribution from ${}^6\text{He}$ break-up. The thin solid line represents the calculation made in [17], the dashed line is the result of [11], the dotted curve displays the calculations made in [12]. The result of the opaque Serber model of the sequential fragmentation for the knock-out of a $l_n = 1$ neutron is shown by the thick solid curve. The influence of the detector set-up was taken into account for all calculated data. The experimental data [19] are shown by the error bars.

spatial localization of the subsystem before the two-body FSI corrections can be applied. The neglect of this requirement results in an artificial effect. As it might be clearly noticed in equation (1), the α - n FSI influences not only the relative momenta

of these particles but as well their center-of-mass (c.m.) movement. The usage, for example, of the Watson-Migdal formulation for the FSI results in a distribution of the α - n c.m. momenta which is by a factor of ≈ 0.6 more narrow than the original one. This can be considered only as an artifact connected with the model simplification. The results of such calculations are more qualitative than quantitative. Thus, the achieved agreement of calculated and experimental data is more by chance. Contrary to the neutron momentum distribution, the α -particle momentum distribution is not such strongly influenced by the FSI. The momentum distribution of this "heavy" fragment is as well not under influence of the admixture of t - t clustering. In Fig. 3, we demonstrate that all the calculations are in good agreement with the experimental data. One may conclude that due to the complexity of the reaction mechanism, including the role of FSI, the extraction of quantitative information on the structure of the halo nucleus from the α -particle and the neutron momentum distributions is not reliable with the present models. Progress in this area is a significant theoretical challenge.

Figure 3:

Transverse momentum distribution of α -particles from ${}^6\text{He}$ break-up. The thin solid line represents the calculation made in [17], the dashed line is the result of [11], the dotted curve displays the data from [12]. The result of the opaque Serber model of sequential fragmentation for the knock-out of a $l_n = 1$ neutron is shown by the thick solid line. Experimental data [19] are indicated by error bars.

4.3 ${}^5\text{He}$ momentum distribution

The most promising way is to investigate the distribution of the α - n c.m. velocities (this distribution is equivalent to the ${}^5\text{He}$ momentum distribution or to the momentum

distribution of the knocked-out neutron inside ${}^6\text{He}$). The distribution of α - n c.m. velocities is not under influence of the α - n FSI and, as mentioned above, reflects in a most straightforward way the internal momentum distribution of the neutrons in the ${}^6\text{He}$ ground state wave function. Fig. 4 shows a comparison between experimental data and calculations in different models made in the frame of the transparent limit of the Serber model [7, 11, 12]. Neither one of the models under consideration can describe the experimental distribution. The reason for such a disagreement is connected with the fact that the transparent limit of the Serber model is not adequate here. The more appropriate opaque Serber model has carefully been considered in application to one-neutron halos and good agreement with experimental data was obtained [26, 27]. The model is based on the assumption that the fragment momentum distribution is completely determined by the external part of the projectile wave function or, in other words, by the single particle wave function of the removed neutron which is determined mainly by the neutron binding energy S_n .

Figure 4:

Transverse momentum distribution of ${}^5\text{He}$ from ${}^6\text{He}$ break-up. The thin solid line is the result of the HHS model [7], the dashed line represents the HHF model [11], the dotted curve displays the calculation with the RRGm model [12]. The thick solid line corresponds to the opaque Serber model of the sequential fragmentation for the knock-out of a $l_n = 1$ neutron. The dash-dotted line was calculated for $l_n = 0$ and demonstrates the large sensitivity to the angular momentum of the removed neutron. Experimental data [19] are shown by error bars.

The requirement of fragment survival was satisfied by implying a cylindrical cut, R_{cut} , over the distance between neutron and core. Analytical expressions for the longitudinal momentum distributions have been derived for halo neutrons in the s - or p -shell. Unfortunately, analytical expression cannot be obtained for the transverse momentum distribution. However, numerical calculations show that, in the region of the Goldhaber peak, the longitudinal and transverse distributions are similar. For an s -state, the black disk model results in a diffraction minimum at transverse momenta around 80 MeV/c (see dash-dotted curve in Fig. 4).

As far as the internal part of the wave function is cut away and does not influence the distribution of the reaction products any more, one may expect that the same picture is valid also for two-neutron halo nuclei and write similar expressions for the single particle wave function of the removed neutron in the case of the three-body system. First we introduce Jacobi coordinates:

$$\begin{aligned} \mathbf{r}_{n_1-\alpha n_2} &= \mathbf{r}_{n_1} - \frac{\mathbf{r}_\alpha m_n + \mathbf{r}_{n_2} m_\alpha}{m_n + m_\alpha}, \\ \mathbf{r}_{\alpha-n_2} &= \mathbf{r}_\alpha - \mathbf{r}_{n_2}, \end{aligned} \quad (2)$$

where $\mathbf{r}_{n_1}$, $\mathbf{r}_{n_2}$, and $\mathbf{r}_\alpha$ are neutron and α -particle coordinates in the ${}^6\text{He}$ center of mass, $\mathbf{r}_{n_1-\alpha n_2}$ are the relative coordinates between the removed neutron and the rest subsystem center of mass, $\mathbf{r}_{\alpha-n_2}$ is the distance between the α -particle and the neutron in this subsystem. The asymptotic expression for the valence neutron can be written in the following form:

$$\psi(r_{n_1-\alpha n_2}) \sim h_l(ip_0 r_{n_1-\alpha n_2}) Y_{lm}(\vartheta, \varphi). \quad (3)$$

Here, $h_l(ikr)$ is the first spherical Hankel function, ϑ and φ are the polar and azimuthal angles. The parameter $p_0 = \sqrt{2\mu S_n}/\hbar$ is expressed in terms of the reduced mass $\mu = \frac{m_n(m_\alpha+m_n)}{m_\alpha+2m_n}$ and the neutron separation energy S_n .

The meaning of the parameter S_n has some ambiguity in the case of a two-neutron halo. Either it is the binding energy relative to the three body separation $n+n+\alpha$ or relative to the two body separation ${}^5\text{He}+n$. To understand this, we compare the asymptotic of the “exact” three body wave function with the single particle wave function (3). The comparison is shown in Fig. 5, where the parameter p_0 of the Hankel function was chosen to reproduce the asymptotic of the three body wave function of Ref. [7]. The corresponding neutron separation energy of $S_n = 1.75$ MeV is comparable with the binding energy of ${}^6\text{He}$ relative to the separation in ${}^5\text{He}$ and n , which shows that one should choose the two body (${}^6\text{He} - {}^5\text{He}+n$) separation energy as S_n .

We shall use the Fourier transform of expression (3) with a lower cylindrical cut, R_{cut} , in the radial coordinate $r_{n_1-\alpha n_2}$ to describe the ${}^5\text{He}$ momentum distribution. The calculations have been done with a cut-off parameter $R_{cut} = 3$ fm. The result is shown in Fig. 4 by a thick solid line and, as can be seen, good agreement with the experimental data has been obtained. The calculated distribution has its full width at half maximum (FWHM) equal to 128 MeV/c. This width is more narrow than that obtained with the “exact” three body wave function when no cut was applied [7] (FWHM=175 MeV/c).

Figure 5:

The asymptotic of the single particle wave function (3) (the dashed line) with neutron separation energy $S_n=1.75$ MeV (this value corresponds roughly to the binding energy of ${}^6\text{He}$ relative to the separation in ${}^5\text{He}$ and n) and the asymptotic of the ${}^6\text{He}$ three body wave function [7] (solid line) as a function of the distance between neutron and the c.m. of the α -particle and the other neutron.

The R_{cut} was used as a free parameter to fit the experimental data. The r.m.s. value of the radius of the $\alpha+n$ subsystem inside the ${}^6\text{He}$ nucleus calculated with the ${}^6\text{He}$ wave function [7] is equal to 2.3 fm. A larger cut-off radius than this value[†] has to be used to satisfy the fragment survival criteria since the size of the target also influence on the cut-off parameter. An upper limit for R_{cut} might be estimated from the sum of the $\alpha+n$ (2.3 fm) and the target radii, i.e. about 4.5 fm (see Ref. [26]).

The dash-dotted curve in Fig. 4 shows the result for the ${}^5\text{He}$ momentum distribution calculated for $l_n = 0$. The comparison of the calculations for different l_n -values demonstrates a large sensitivity to the angular momentum of the removed neutron. Such a sensitivity gives a perfect tool to investigate, e.g., admixture of s -shell neutrons in the ${}^{11}\text{Li}$ and ${}^{14}\text{Be}$ wave functions directly from the analysis of the ${}^{10}\text{Li}$ and ${}^{13}\text{Be}$ momentum distributions.

[†]The three-body cluster model itself contains limitations, i.e. the wave function is only true outside the radii of the individual clusters. In particular, the part of the wave function corresponding to a halo particle inside the core radius would be unphysical [11].

Table 2: Sensitivity of the width of the ${}^5\text{He}$ momentum distribution to the angular momentum l_n and the cut-off parameter R_{cut} .

R_{cut} (fm)	FWHM (MeV/c)	
	$l_n=1$	$l_n=0$
2.0	157	71
2.5	141	65
3.0	128	61
3.5	119	57
4.0	113	54

The sensitivity of the width of the momentum distribution to the angular momentum l_n and the cut-off parameter R_{cut} can be seen in Table 2, where we show the results for $l_n = 0, 1$ and for various choices of the cut-off parameter.

4.4 Momentum distributions after sequential decay

To calculate neutron and α -particle momentum distributions we assume further that the energy distribution of the decay products in the ${}^5\text{He}$ rest frame can be described by a Breit-Wigner formula. The parameters of the ${}^5\text{He}$ ($3/2^-$) resonance are taken from the R matrix analysis of experimental data on n - α scattering [28].

It is worthwhile to notice here, that the formulations of the FSI [11, 12, 17] and of the sequential decay are not equivalent. The sequential mechanism results in the expression:

$$\frac{d\sigma}{d\mathbf{p}_{n_2}} = \int \left(\int |\psi(\mathbf{p}_{n_1-\alpha n_2}, \mathbf{p}'_{\alpha-n_2})|^2 d\mathbf{p}'_{\alpha-n_2} \right) \times \quad (4)$$

$$W(\mathbf{p}_{\alpha-n_2}) \delta(\mathbf{p}_{n_2} + \frac{m_n}{m_n + m_\alpha} \mathbf{p}_{n_1-\alpha n_2} + \mathbf{p}_{\alpha-n_2}) d\mathbf{p}_{\alpha-n_2} d\mathbf{p}_{n_1-\alpha n_2}.$$

Here, $\mathbf{p}_{n_1-\alpha n_2}$ and $\mathbf{p}_{\alpha-n_2}$ are the Jacobi momentum coordinates conjugated to the spatial coordinates determined in Eq. (2), $W(\mathbf{p}_{\alpha-n_2})$ corresponds to the Breit-Wigner parameterization of the resonance and $\mathbf{p}_{n_2}$ is the neutron momentum in the ${}^6\text{He}$ rest frame. The first integral on $d\mathbf{p}'_{\alpha-n_2}$ in Eq. (4) is very essential for the sequential model and is equivalent to the condition of the localization of the unstable fragment. It means that in the first step, we calculate the probability for the unstable fragment ${}^5\text{He}$ to have momentum $\mathbf{p}_{5He} = -\mathbf{p}_{n_1-\alpha n_2}$ in the ${}^6\text{He}$ c.m. system, and we use the ${}^6\text{He}$ wave function for this purpose. As can be seen from Eq. (4), an artificial influence of the α - n interaction on their propagation velocity which, as it was discussed above, is characteristic for FSI does not appear in this case.

The momentum distributions of neutrons and α -particles were found via transformation by simple kinematical relations to the ${}^6\text{He}$ rest frame. For the calculation of the ${}^5\text{He}$ momentum distribution we used a cut-off parameter $R_{cut} = 3$ fm. This distribution is shown in Fig. 4 by the thick solid line. The results of the calculations for the

neutrons and α -particles are displayed by the thick solid lines in Figs. 2 and 3. The agreement with the experimental data, as can be seen in these figures, is excellent.

5 Summary

Momentum distributions of α -particles and neutrons measured in break-up reactions of a 240 MeV/u ^6He beam have been compared with the predictions of different models. The models are based on different physical assumptions of the ^6He structure. The three cluster (α - n - n) models predict a much more narrow internal neutron momentum distribution than a model with an essential contribution of a t - t configuration. However, it is shown that the influence of the fragmentation mechanism and, especially, of the ambiguities in the estimations of final state interaction effects do not leave any hope to distinguish between the models in the analysis of the neutron momentum distributions. The α -particle momentum distribution is not very sensitive to the different models either. Moreover, it was shown that the method how FSI is taken into account in the transparent limit Serber model is not selfconsistent and results in artificial effects in the velocity distribution of the center-of-mass of the interacting particles.

Much more promising is the analysis of the ^5He momentum (sum of the neutron and the α -particle momenta) distribution, since it is free from the effect of final state interaction. Due to the requirement of fragment survival this distribution is determined mainly by the asymptotic of the single neutron wave function but not by the internal structure of ^6He . The observed momentum distributions, hence, relate to the outer part of the halo structure. This phenomenon opens a very interesting and specific way to probe the halo structure. The large sensitivity to the angular momentum of the removed neutron allows an estimation of a possible admixture of an s -state in ^{11}Li or in ^{14}Be directly from the shapes of the momentum distributions of the unstable fragments ^{10}Li and ^{13}Be . The admixture of an s -state in these nuclei was under discussion already for a long time but the obtained results are very model dependent and no reliable information on the shell structure of these nuclei is available yet.

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