Effects of a low-lying resonance in ^{19}C on the ^{18}C momentum distribution after fragmentation

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We have investigated the ^{18}C longitudinal momentum distributions from fragmentation of ^{19}C, calculated in a binary coupling model. We have found that inclusion of a low-lying resonance in the ^{19}C, with $E_{\rm res}$ ~ 0.2 MeV, and sequential decay of this state together with the one-neutron stripping process, can simultaneously describe the different fragmentation data measured at intermediate and high projectile energies. [S0556-2813(99)04604-X]

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I. INTRODUCTION

The question of the halo nature of ^{19}C and its underlying structure is one of the interesting current questions in dripline physics. The spin of the ^{19}C ground state has not yet been measured experimentally but different calculations [1–3] all predict a $J^{\pi}=1/2^{+}$ ground state, with the valence neutron in an $1s_{1/2}$ orbit. However, both the shell model [1] and the dynamical core polarization (DCP) approach [3] gives low-lying $3/2^{+}$ and $5/2^{+}$ states, and the proximity of the s and d states makes the ground-state configuration uncertain.

Nuclear fragmentation of ^{19}C was studied experimentally at MSU [4,5], where the ^{18}C longitudinal momentum distribution was measured at the ^{19}C beam energy 88 MeV/nucleon and at GANIL [6] where the neutron transverse momentum distribution from core breakup reactions was measured at the ^{19}C beam energy 30 MeV/nucleon. The observed narrow momentum distributions were interpreted as evidence for a one-neutron halo structure in the ^{19}C ground state, where a halo neutron, with an average separation energy $S_n=0.24\pm0.1$ MeV (note that the separation energy for ^{19}C, is not known well [5]), is orbiting around the ^{18}C ground state with angular momentum $l=0$. However, the measured Coulomb dissociation cross section contradicts such a prediction which overestimates the measured cross section [5,7].

The longitudinal momentum distribution of ^{18}C fragments from the ^{19}C breakup reactions has recently been measured at the GSI [3]. The data were taken on a carbon target at an energy of 914 MeV/nucleon. The width of the distribution, full width at half maximum (FWHM) $=69\pm3$ MeV/c, was significantly larger than the investigation of ^{19}C at an energy of 88 MeV/necleon, where a width of 42 ± 4 MeV/c was reported [5] on a beryllium target. The main differences between the experiments are the projectile energies and the target materials (carbon and beryllium). It should be noted that in earlier measurements of longitudinal momentum distributions for the halo nuclei ^{11}Be and ^{11}Li, no significant dependence of the width on beam energy or target materials has been observed [8]. In this paper we speculate that the difference in the measured momentum widths of the ^{18}C fragments could be due to the specific structure of ^{19}C with closely spaced low-lying states.

II. THE NEUTRON STRIPPING PROCESS

The measured longitudinal momentum distribution in two-body breakup reactions depends on the intrinsic momentum distribution between the two fragments as well as on the reaction mechanism. The black disc model [9], the opaque limit of the Serber model [10] for neutron stripping, was used in Ref. [11] to calculate the momentum distributions from two-body wave functions extracted from coupled channel calculations using a deformed Woods-Saxon potential. The corresponding formulas and cutoff parameters are given in [11]. The wave functions [11] contained an admixture of single particle s and d waves built either on the 0^{+} ground state or the first 2^{+} excited state at 1.62 MeV of the ^{18}C core. The momentum distributions offer an opportunity to discriminate between s- and d-wave neutrons, since the presence of an $l=2$ centrifugal barrier confines the d-wave neutron close to the core, leading to a much wider momentum distribution with FWHM values in the order of 200 MeV/c. An upper limit for the longitudinal momentum widths for an s-wave neutron can be estimated from a zero-range Yukawa wave model leading to FWHM$=\sqrt{8\mu S_n}\sim41$ MeV/c, where μ is the reduced mass, the Woods-Saxon wave function gives FWHM~33 MeV/c, and the reaction further decreases these values to ~32 MeV/c for an s-wave neutron coupled to the ground state of ^{18}C, see Ref. [11].

The total momentum width is mainly determined by the s-wave component, since the d waves only contribute to the tail of the distribution. From the calculations in [11] it is difficult to reproduce the the narrow width of 42 MeV/c but a good agreement with the value 69 MeV/c [3] is obtained if the ^{19}C ground state is $3/2^{+}$ or $5/2^{+}$, and the wave function has an appreciable amount of s motion coupled to the 2^{+} state of ^{18}C. Note that the authors of [5] also discussed the opportunity to construct the ^{19}C ground state by coupling the s-wave valence neutron to the ^{18}C(2^{+}) state. To simplify the discussion we show in Fig. 1 separately the longitudinal momentum distribution for an s-wave neutron coupled to the 2^{+} excited state, and a d-wave neutron coupled to the 0^{+} ground state of ^{18}C. One can easily see that a pure s-wave configuration describes the experimental width measured at GSI well. If one considers admixtures of these two waves the resulting curve should be broader. Then we immediately face two problems. First, we cannot reproduce the narrow width of 42 MeV/c measured at the MSU with admixtures of the s

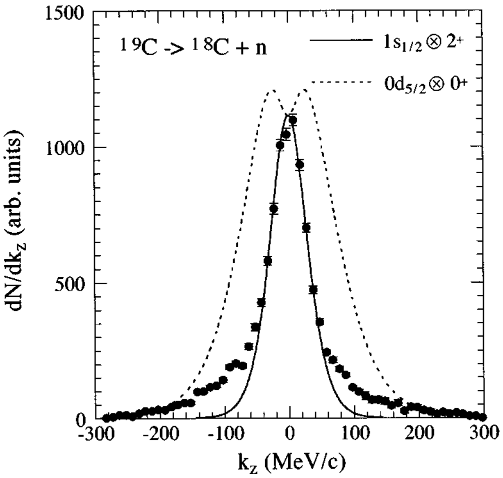

FIG. 1. Longitudinal momentum distribution of ^{18}C fragments from ^{19}C breakup reactions. The experimental data are taken at 914 MeV/nucleon on a carbon target [3]. The dotted (solid) curve shows a calculation with a valence neutron in a *d*-wave (*s*-wave) coupled to the ground state (first excited 2^+ state) of the ^{18}C core. The curves have been calculated for the ^{19}C wave function $\{5/2^+,0.50,0.24\}$ [11] according to Eq. (11) in Ref. [11] with parameters $R_c=3.0$ fm, $R_t=2.38$ fm, and $R_n=0.8$ fm.

and the *d* waves shown in Fig. 1, and second, the GSI data shown in Fig. 1 has a pronounced tail, for which we need a large *d*-wave component in the wave function, but then we can no longer describe the narrow part of the momentum spectra.

This leads us to speculate that some additional reaction mechanism may be responsible for the narrow part of the momentum spectra and this mechanism may explain the difference between the two measurements [3] and [5]. Let us look at different opportunities. First of all we have used a black disc model for the neutron stripping reaction. In this model the momentum distribution does not depend on the projectile energy. But in the stripping model the results depend mainly on the shadowing effect and they are not very sensitive to the cutoff function. More elaborate calculations [12] have demonstrated that the neutron stripping cross section changes only a little for projectile energies between 90 and 900 MeV/nucleon, so we cannot get the explanation from the stripping process. Secondly, the ^{18}C fragments can appear also from diffraction dissociation from ^{19}C on a light target, but for this process the cross section depends strongly on the projectile energy decreasing with a factor of 3–4 from 90 to 900 MeV/nucleon for the ^{11}Be nucleus, as shown in Ref. [12]. Unfortunately there is one problem with diffraction also. It is known [13] that if we consider the diffraction process in a simple approach with structureless continuum for outgoing fragments then the ^{18}C longitudinal momentum distribution will be similar to the one from the stripping process. The situation can, however, be quite different if there is a low-lying resonance state in the ^{18}C$+n$ continuum.

III. THE RESONANCE STATE

In the following we will assume that there is a low-lying resonance in ^{19}C, and we assume also that part of the fragmentation of ^{19}C is going through this resonance. There are two facts which justify the assumption about the resonance. First, several theoretical calculations, mentioned above, predict a few closely lying states for ^{19}C, and second, in the near ^{17}C nucleus a low-lying excited state is known , but it is situated below the ^{16}C$+n$ threshold. We can expect that such a state in ^{19}C may be situated above the ^{18}C$+n$ threshold if the neutron separation energy for ^{19}C is smaller than for ^{17}C.

We assume that a ^{19}C projectile impinging on a target nucleus is excited to a low-lying resonance with some probability. It will then decay as a Breit-Wigner resonance and the longitudinal momentum distribution of the core is given by

$$\frac{dN_{\rm res}}{dk_z}\sim\int\frac{dk_x\,dk_y}{(\mathbf{k}^2/2\mu-E_{\rm res})^2+\Gamma^2/4}$$
$$\sim 1-\frac{2}{\pi}\arctan\left[\frac{2}{\Gamma}\left(\frac{k_z^2}{2\mu}-E_{\rm res}\right)\right], \qquad (1)$$

where μ is the reduced mass, $E_{\rm res}$ is the resonance energy above the ^{18}C$+n$ threshold, and Γ is the width of the resonance. Note that for a low-lying resonance the decay channel ^{18}C$(2^+)+n$ is closed. The neutron stripping, calculated in a black disc model also contributes to the cross section and the sum of these two gives the total ^{18}C longitudinal momentum spectrum. A similar idea about the influence of a low-lying resonance on the momentum distribution from fragmentation, has been used in [14] with application to two-neutron halo nuclei. The resonance energy $E_{\rm res}$, and the width Γ, together with the probability to excite the resonance are fitted to describe the experimental data. It is known from studies of fragmentation at low energies, that the sequential decay through excitation of low-lying levels of loosely bound projectiles dominates for beam energies around 10 MeV/nucleon [15,16]. Note that the resonance parameters and the ground-state function should be the same for both experiments, and one expects that the relative weight of the process going through the resonance state decreases as the projectile energy increases [14].

IV. RESULTS

In our calculation we use the different neutron-^{18}C relative motion wave functions shown in Fig. 1. The wave function WF100 is a pure *d*-wave coupled to the ^{18}C ground state, while the wave function WF70 (WF50) contains 70% (50%) of *d* waves coupled to the ^{18}C ground state and 30% (50%) of *s* waves coupled to the ^{18}C first excited state. For each wave function the longitudinal momentum distribution originated from the neutron stripping process is calculated. To simultaneously describe the two experimental data sets [3] and [5], part of the fragmentation process goes through the ^{19}C resonance. The ratio of the two breakup channels (neutron stripping and ^{19}C resonance), together with the resonance energy $E_{\rm res}$ and the width Γ are free parameters which are fitted to best describe the two data sets. Note, that for all cases the neutron separation energy is fixed equal to 0.24 MeV.

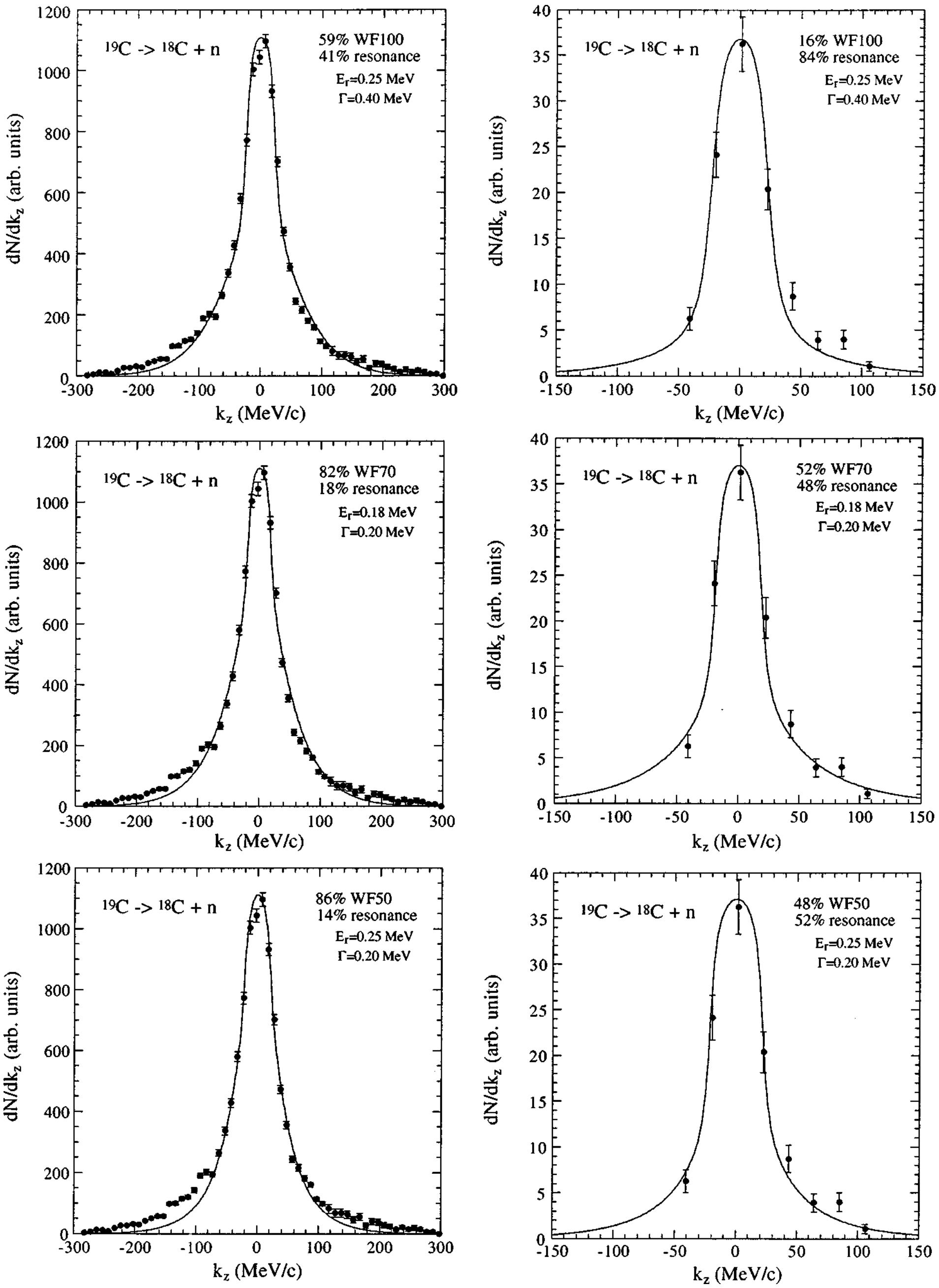

FIG. 2. Longitudinal momentum distributions of ^{18}C fragments from ^{19}C breakup reactions. The experimental data to the left are taken at 914 MeV/nucleon on a carbon target [3] and the data to the right at 88 MeV/nucleon on a beryllium target [5]. The wave functions are admixtures of the *s* and *d* waves shown in Fig 1. In the two top figures we have used a pure *d*-wave configuration and in the middle two (bottom two) figures an admixture of *s* and *d* waves with weights 0.3 (0.5) and 0.7 (0.5), respectively.

In Fig. 2 we show the results of calculations with the three different ^{19}C ground-state wave functions. The weights of the neutron stripping process from WFA ($A=100$, 70, and 50) and the decay through the ^{19}C resonance state to the total one-neutron removal cross section are given. One can see that for all wave functions its possible to simultaneously describe the GSI and the MSU data. The only difference is that for the lower projectile energy more excitation to the resonance state in ^{19}C is needed, according to expectations. All calculations suggest a resonance energy of approximately 0.2 MeV above the ^{18}C$+n$ threshold. The prominent momentum tail in the GSI data cannot be explained if one further increases the relative *s*-wave weight in the wave function.

V. SUMMARY

We have proposed an idea to solve the problem that the widths of the ^{18}C longitudinal momentum distributions from ^{19}C fragmentation are different at intermediate and high projectile energies. The hypothesis is supported by shell model and DCP calculations, both predicting closely spaced low-lying states in^{19}C. For the well established one-neutron halo nucleus ^{11}Be, the ^{10}Be longitudinal momentum distribution after one-neutron removal is independent of the projectile energy. The effect of different widths at different projectile energies can therefore be related to the specific structure of the ^{19}C nucleus. We have shown that the different widths are consistent with excitation of a low-lying ^{19}C resonance at approximately 0.2 MeV above the ^{18}C$+n$ threshold (with different probabilities). The experimental confirmation of such a resonance state should be useful in order to probe the ^{19}C ground state through fragmentation experiments. A recent experiment on Coulomb dissociation of ^{19}C performed at RIKEN [17] indicated a $J^{\pi}=1/2^{+}$ ground state with separation energy of 0.5 MeV for the *s*-wave neutron, which istwice as large as the average separation energy $S_n = 0.24$ MeV used in our calculations. If these values for the separation energy (0.5 MeV) and the spin assignment ($J^\pi = 1/2^+$) will be confirmed it is easy to show that the width of the longitudinal momentum distribution should be about 42 MeV/c, if the reaction mechanism—the neutron stripping process—is taken into account (see Table 3 in Ref. [11]). Then this value corresponds well to the MSU result, but deviates strongly from the GSI result. Moreover, it would be difficult to account for the pronounced tail in the longitudinal momentum distribution clearly seen in the GSI data [3], see Fig. 1. We would like to point out that not only the separation energy but also the spin assignment is crucial for the width of the momentum distribution and its shape. Obviously more experimental data are needed to clarify the situation for the one-neutron halo nucleus ^{19}C.

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