Reaction Mechanisms for Two-Neutron Halo Breakup

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We describe a reaction mechanism which is consistent with all available experimental information of high energy three-body breakup processes. The dominating channels are removal of one of the three halo particles leaving the other two either undisturbed or absorbed. We compare with the commonly used deceptive assumption of a decay through two-body resonance states. Our predictions can be tested by measuring neutron-neutron invariant mass spectra.

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Introduction.—Halo states are basically characterized as spatially extended weakly bound systems. Two-body halos interacting with a target present a three-body scattering problem, which in practice is much more complicated due to the intrinsic structure of the three constituent particles. Three-body halos present analogously at least a four-body problem, which has to be approximated preferentially by using physical insights. Reactions for high beam energies allow a separation of the degrees of freedom related to the fast relative projectile-target coordinates and the slow intrinsic halo motion.

The properties of halo systems have been discussed intensely over the last decade both in dripline nuclei [1–4] and in molecular systems [5,6]. Precise definitions, classification and occurrence conditions were recently attempted [7,8] although different from an earlier definition [9]. Few-body concepts and techniques are successfully applied in the descriptions [10], which to a large extent focused on nuclear three-body halos. Much effort has been devoted to two-neutron Borromean halos like ^{6}He ($n + n + {}^4$He) and ^{11}Li ($n + n + {}^9$Li) where two neutrons surround a core [11]. The basic structure is essentially agreed upon while reaction descriptions and analyses of measurements still are controversial.

Halo physics is a substantial part of experimental programs with radioactive beams and it is urgent to root out widespread misconceptions and clarify how the reactions proceed. Furthermore these questions are of general interest as basic few-body reaction problems. Since the halo concept now is applied and exploited in molecular physics we also may anticipate similar implications of properly formulated reaction models.

The purpose of this Letter is to (i) establish the reaction mechanism for two-neutron halo breakup in high energy collisions with light targets and in passing clarify the differences to the entirely different mechanism due to the large charges of heavy targets, (ii) investigate the validity of the erroneous but commonly used assumption of breakup through resonances in the two-body subsystems. These questions are crucial and answers are urgently needed for understanding reactions with halo nuclei.

Reaction mechanisms.—The dominating reaction channels for two-neutron halo breakup on light targets are experimentally established [12,13] and theoretically described [10,14] as removal of one neutron or destruction of the core, thereby leaving the final state with the core and the other neutron or with the two neutrons.

The decisive question in this context is which reaction mechanism is responsible for the observed behavior? The reaction time for light targets is short compared to the time scale of the intrinsic halo motion. For spatially extended systems the target can then remove one of the halo particles instantaneously without disturbing the motion of the other two particles. This means that the sudden approximation basically is valid as accepted in several previous publications [12,13,15,16].

The implication is that the remaining two-body system is left in its initial state which, as unbound for Borromean systems, falls apart influenced by the corresponding two-body interaction. This decaying two-body system is thus formed as a wave packet consisting of those parts of the relative two-body wave function present within the original three-body system, which precisely lead to the dominating reaction products [10]. The surviving wave packet then has a large component describing the tail of the two-body wave function. The short distance parts lead to a large extent to removal of more than one particle at a time. All other breakup reactions are analogously described in this participant-spectator model (PSM).

R-matrix formulation.—The observed invariant two-body mass spectra and the momentum distributions are routinely analyzed as arising from the decays of low-lying two-body resonances or virtual s states [12,13,15–17]. These assumptions are in direct contradiction to the short reaction time and the sudden approximation. There is not sufficient time for the remaining two halo particles to adjust their relative motion and populate corresponding resonance states. This requires at least a reaction time comparable to the intrinsic halo time scale.

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Thus these analyses apparently invoke both the sudden approximation and decay through resonances or virtual s states. These assumptions are strictly incompatible except when these two-body states are populated within the initial three-body system. This is clearly seen by constructing a Borromean system by adding a neutron to a neutron-core resonance state. The overlap of this and the real bound state wave function may still be substantial, but rearrangements are necessary to reach the bound three-body state, i.e., a novel few-body system carrying otherwise inaccessible information about the off-shell behavior of the nucleon-nucleon interaction.

The pertinent questions are what we can learn from measured two-body invariant spectra and what information is in fact obtained by the analyses using resonances or virtual s states as intermediate states. The analyses, often erroneously claiming to use Breit-Wigner shapes [12,13,15,17], are in fact based on R-matrix theory [18,19], where a complete basis of two-body continuum states are used after removal of one of the three particles. This basis could consist of "correct" low-lying resonance states supplemented with a discretized or continuum higher lying set of states.

In practice one proceeds by reducing the unspecified and unknown basis to a few terms, i.e., usually one or two states. This reduction of model space may be allowed if the basis consistently is renormalized, i.e., the new basis includes properties of the excluded states. Thus fitting in this context by use of a small basis seems to prohibit interpretation in terms of the correct two-body resonance states. In principle maintaining the basis without renormalization would be correct but this presupposes exactly that knowledge about these states, which is the very aim of the analyses. This problem cannot be solved by increasing the employed model space until convergence is reached and no renormalization is needed. A larger space implies more parameters in the fitting procedure and reproduction of the data is not unique. The problem becomes overdetermined and the extracted parameters inaccurate or directly unreliable.

The analyses using two-body resonances or virtual s states therefore assume (i) that no renormalization due to truncation of model space is needed, (ii) a reaction mechanism where only the "clean" two-body resonance states or virtual s states are populated, and (iii) no other (known or unexpected) reaction channel contributes. These assumptions are at least inaccurate. The difficulties are enlarged when more than one resonance or more than one reaction channel contributes. When the assumptions are fairly well fulfilled the interpretation would also be approximately correct.

Computations.—We shall concentrate on ^{6}He and ^{11}Li colliding with light targets. We shall use the PSM formulation, where one halo particle (the participant) interacts with the target while the other two halo particles (the spectators) are left undisturbed [10]. The participant-target interaction is described by the phenomenological optical model while the spectators are treated in the black sphere approximation, i.e., they are absorbed within a given radius from the target and otherwise they continue undisturbed. This model faithfully exploits the consequences of a short reaction time. We compute the population of the two-body continuum states after the instantaneous removal of the third particle.

The R-matrix expressions of the invariant mass spectrum $d\sigma/dE$ of the spectator system and the relative spectator momentum distribution P_{long} are [12,15,17]

$$\frac{d\sigma}{dE} = \frac{\sigma_l}{2\pi}\frac{\Gamma(E)}{(E - E_r)^2 + 0.25\Gamma^2(E)}, \qquad \Gamma = \Gamma_0 \frac{E^{l+0.5}}{E_r^{l+0.5}}, \tag{1}$$

$$P_{\text{long}}(p) = \int_{E_{\min}}^{\infty} \frac{dE}{\sqrt{E}}\frac{d\sigma}{dE}, \qquad E_{\min} = p^2/2\mu, \tag{2}$$

where σ_l is the total cross section, l is the orbital angular momentum, μ is the reduced mass, E_r and Γ_0 are position and width parameters. The distributions are correlated and should not be fitted independently. Precisely the same procedure applies both when the core and a neutron are the participant, i.e., the final state consists of two neutrons or a neutron-core system, respectively.

The chosen observables amplify the effects of the assumed reaction mechanism. We can then compare the experimental distributions both with the PSM predictions [10] and the R-matrix results obtained by the decay through resonance assumption. This provides evidence about the basic reaction mechanism.

Neutron removal.—Absorption of one neutron from ^{6}He produces a neutron-^{4}He continuum state, which mainly is of $p_{3/2}$ character, since the $p_{1/2}$ neutron-core state has a higher energy and the $s_{1/2}$ wave is repulsive. The corresponding invariant mass spectrum and the relative momentum distribution are shown in Fig. 1. The PSM computation agrees fairly well with the measured invariant mass spectrum [12]. The peak position reflects the energy of 0.77 MeV of the neutron-^{4}He $p_{3/2}$ resonance with the width of 0.5 MeV used in the PSM computation. Any value of Γ_0, see Eq. (1), from 0.4 to 0.8 MeV also reproduces the experiment fairly well.

For consistency the momentum distribution should now follow with the same parameters. Indeed we see in Fig. 1 that the PSM results resemble the (almost) width independent R-matrix fits, confirming that the width parameter for the n-^{4}He resonance cannot be determined in this way. We also note the characteristic flat maximum of p waves.

The ^{11}Li system is different due to the core spin of $3/2$ and the mixture of s and p waves in the subsystems. The computed three-body wave function contains around 60% of s wave and 40% of p^2-wave neutron-core configurations. The neutron-^{9}Li system has a low-lying virtual s

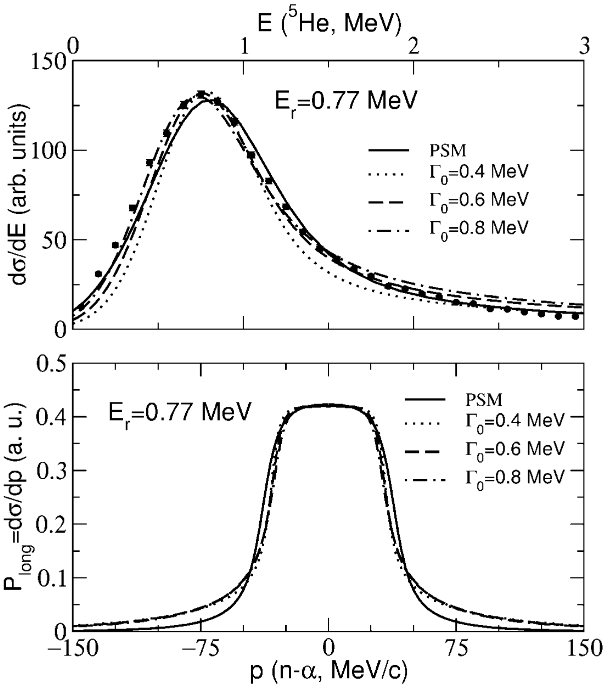

FIG. 1. Neutron-^{4}He invariant mass spectrum (upper) and longitudinal relative momentum distribution (lower) for breakup of 300 MeV/nucleon ^{6}He projectile on a carbon target. Experimental data from [12]. The solid curves are the PSM calculations [10] and the broken lines are obtained from Eqs. (1) and (2) with $l = 1$. The invariant mass curves have been convoluted with the instrumental response [20].

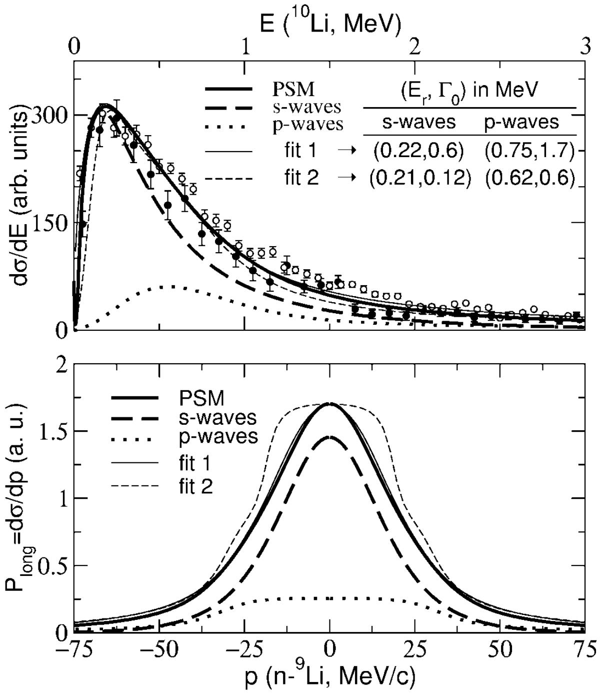

FIG. 2. The same as Fig. 1 for neutron-^{9}Li for a ^{11}Li projectile. Both sets of experimental data [15,17] are normalized to the same maximum as the computed spectrum. The thick solid curves are the PSM calculations consisting of contributions from both neutron-core relative s (thick dashed curves) and p (dotted curves) waves. The thin solid and dashed lines are weighted averages of two distributions from Eqs. (1) and (2) corresponding to s and p resonances with parameters given in MeV.

state at 240 keV and a p resonance at 0.5 MeV [10]. Neutron removal results in the distributions shown in Fig. 2. The contribution to the invariant mass spectrum from s waves peaks at a very low energy determined entirely from the phase space constraint and independent of the position of the virtual s state [19]. In contrast the p-wave contribution peaks at the two-body resonance energy. The measured spectrum is fairly well reproduced by the PSM computation, again supporting the assumed initial three-body structure and the reaction mechanism.

We compare in Fig. 2 with two different R-matrix fits. In the first the computed s and p contributions are fitted separately thereby maintaining the same p-wave content. In the second fit we use the parameters in [15], which also reproduces rather well the experimental (and PSM) data. The ^{10}Li structures underlying these fits differ substantially as expressed clearly through the different widths. The p-wave contents also differ substantially, i.e., about 35% for the first and 70% for the second fit [15].

In the lower part of Fig. 2 we show the corresponding relative momentum distribution. The PSM computation and the first fit produce a very similar momentum distribution, while the second fit differs in the central part due to the large fraction of p waves that create the plateau at low relative momentum. Therefore different fits of invariant mass spectra of similar accuracy can produce rather different momentum distributions due to emphasis of different features of the distribution.

Core destruction.—The reaction assumptions can be tested by similar investigations of the other important channel corresponding to destruction of the core and leaving the two neutrons as spectators. The final states then consist of two neutrons for both ^{6}He and ^{11}Li. Thus we can separate effects of initial and final state structures. However, this assumes that fragments from the core interacting strongly with neutrons are excluded from the data. In the PSM computations, discussed in connection with Figs. 1 and 2, the spectra are sensitive to the initial three-body structure. The root mean square distance between the neutrons is more than 6 fm for ^{11}Li and less than 4.5 fm for ^{6}He. The neutron-neutron invariant mass spectrum and the corresponding momentum distribution are then both expected to be substantially narrower for ^{11}Li than for ^{6}He. The same consistent PSM model has been tested on many other, relative and absolute values of observables for neutron removal and core breakup reactions for both projectiles [10]. The agreement with available experimental data is overall very convincing.

Further tests of the PSM model (and the R-matrix analyses) would be measurements comparing to the predictions presented in Fig. 3. The neutron-neutron relative s waves

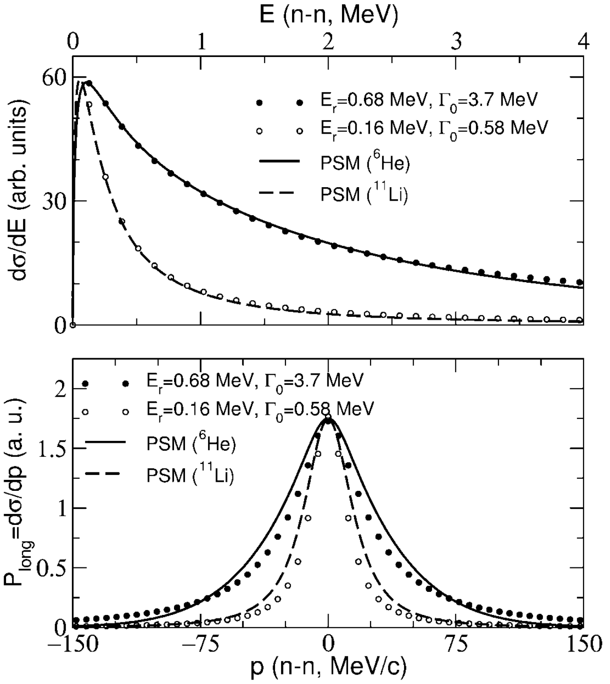

FIG. 3. The same as Fig. 1 for the neutron-neutron system for ^{6}He and ^{11}Li projectiles. The points are the two R-matrix fits given in the figure.

are completely dominating for both ^{6}He and ^{11}Li and consequently the invariant mass spectra have very low-lying peaks. Both spectra and momentum distributions are qualitatively similar for the two cases, but quantitatively the ^{11}Li results are much narrower than those of ^{6}He. The R-matrix distributions fitting the two PSM curves in Fig. 3 correspond to very different energy and width parameters without any connection to the known neutron-neutron scattering properties. The PSM model predicts different neutron-neutron spectra for ^{6}He and ^{11}Li after core breakup. A reaction mechanism populating final state two-body resonances independent of the initial structure must predict identical neutron-neutron invariant mass spectra for both projectiles. Experimental data could distinguish between these models.

Conclusions.—The dominating reaction channels for high energy breakup of Borromean three-body halos on light targets are one-particle removal and subsequent decays of the wave packets created in these processes. The reaction time is short and any resonance structure of the remaining two-body system is populated with the amount already present in the initial three-body wave function. All available experimental data for high energy three-body breakup on light nuclei are consistent with this reaction mechanism. For heavy targets the reaction mechanism for the dominating channel is quite different proceeding through a gentle excitation of the three-body continuum by the Coulomb interaction.

Analyses assuming instantaneous removal of either a neutron or the core, while populating resonances in the remaining two-body system, are conceptually inconsistent. An invariant mass spectrum reproducing the data only reflects that the corresponding energy distribution was present immediately after the final state two-body system was isolated. The problem is especially enlarged when more than one resonance or virtual state are important for the two-body subsystems. The inconsistency is highlighted in spectra obtained after core breakup, where the final states are identical (two neutrons). Then the resulting distributions should also be identical for different two-neutron halo projectiles, even when the initial three-body structure differs substantially. This is in clear disagreement with elaborated consistent model computations reproducing essentially all available data. In any case, the neutron-neutron invariant mass spectra provide direct evidence of the breakup reaction mechanism.

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