Haloes and clustering in light, neutron-rich nuclei

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Abstract. Clustering is a relatively widespread phenomenom which takes on many guises across the nuclear landscape. Selected topics concerning the study of halo systems and clustering in light, neutron-rich nuclei are discussed here through illustrative examples taken from the Be isotopic chain. The production and detection of multineutron clusters is also briefly presented.

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1 Introduction

Until relatively recently, cluster studies have been confined to the region encompassing the line of beta-stability where the role of α-clustering has long been established [1]. As clustering is expected to manifest itself most strongly near thresholds [2], exotic structures might be expected to form in the more weakly bound systems found near the neutron and proton driplines. In practical terms the exploration of clustering in nuclei far from stability has become technically feasible over the last 15 years through the advent of radioactive beams and associated techniques.

In the present paper selected topics concerning the study of halo and molecular states in light, neutron-rich nuclei which have undergone developments since the previous conference in this series are discussed. Following a brief review of work on $x\alpha$:Xn molecular states, emphasis is placed on new techniques for probing correlations in two-neutron halo nuclei. Very recent work exploring the means to produce and detect multineutron clusters is also presented.

2 Nuclear molecular clusters

It has long been established that the α-particle plays an important role in the structure of light α-conjugate ($A = 4n$) nuclei [1]. Theoretical [3,4] and recent experimental work [5,6] indicate that molecular-type structures such as α-chains "bound" by valence nucleons may also occur. The persistence of such cluster structures in systems lying away from the line of beta-stability is well illustrated, as will be discussed here, by the beryllium isotopes, for which the α-α system may be regarded as the basis.

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From a theoretical point of view, prescriptions such as the Molecular-Orbital model (MO) [3] or the Two-Centre Shell Model [7], in which valence nucleons are added to the single-particle orbits arising from the two-centre potential, provide a successful and conceptually appealing framework within which to describe the properties of these nuclei. Moreover, these orbits may be viewed as the analogues of the σ- and π-orbitals associated with the covalent binding of atomic molecules. The development of Antisymmetrised Molecular Dynamics calculations (AMD), as discussed by Horiuchi in this conference, is of particular interest as the A-nucleon system is modelled without any *a priori* imposition of an underlying cluster structure. Recent calculations, in particular, suggest the existence of two-centred structures in the Be, B and C isotopic chains with valence neutron density distributions exhibiting the features of molecular orbitals [4].

From an experimental perspective, von Oertzen [5] has compiled systematic evidence for the existence of dimers in $^{9\text{-}11}$Be and $^{9\text{-}11}$B. In the case of ^{9}Be, for example, the presence of a valence neutron results in a bound (Borromean) system, the ground and excited states of which may be understood in terms of a three-body α:n:α molecular structure. In particular, the rotational bands based on the ground and low-lying states exhibit large deformations consistent with the associated molecular configurations.

In the case of ^{10}Be, the experimental evidence for molecular configurations is rather less well documented. Beyond the established 0_2^+, 2_2^+ and 1_1^-–4_1^- states, the locations of the $J = 5$ [5] and 6 members of the negative-parity band, as well as the $J = 4$ and 6 members of the positive-parity band have been postulated following recent studies of the α-^{6}He breakup of ^{10}Be* [8,9]. As displayed in fig. 1 [9], the spin-energy trajectories for the bands based on the 0_2^+ and 1_1^- states at ~ 6 MeV are consistent with large deformations as expected for
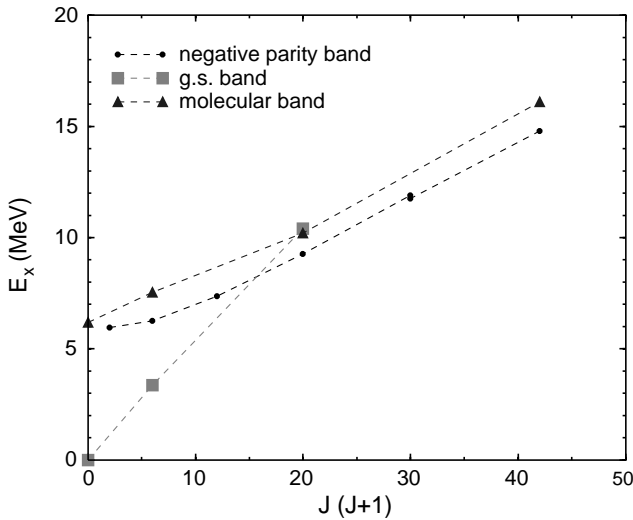
Fig. 1. Spin-energy systematics for states observed in ^{10}Be (from [9]). The trajectories for the postulated positive- and negative-parity molecular bands are indicated.

molecular-like α:2n:α structures. Moreover, the location of the bandheads just below the threshold for $\alpha + {}^6$He decay is in accordance with the considerations of Ikeda describing the formation of clusters [2]. Theoretical support for the postulated molecular states may be found in AMD calculations, whereby well-developed α:2n:α configurations are predicted for the 0_2^+ and 1_1^- bands [4]. Coupled-channel calculations presented in these proceedings by Ito and collaborators also provide support for the molecular nature of the band based on the 0_2^+.

Given the existence of such molecular-type structures in ^{10}Be, the question naturally arises as to the existence of similar structures in more neutron-rich systems. In this context the dripline nucleus ^{12}Be has been investigated via inelastic scattering at 35 MeV/nucleon. Evidence was found in this measurement for the breakup into ^{6}He + ^{6}He and $\alpha + {}^8$He of states ($J = 4, 6, 8$) in the excitation energy range 10–20 MeV which exhibited spin-energy systematics characteristic of a rotational band [6]. Moreover, the inferred momenta of inertia ($\hbar^2/2\Im = 0.15 \pm 0.04$ MeV) and bandhead energy (10.8 ± 1.8 MeV) of the observed states are consistent with the cluster decay of a molecular structure which may be associated with α:4n:α configurations. As reported at this conference by Saito *et al.*, an experiment undertaken very recently at RIKEN using two-neutron removal from an energetic ^{14}Be beam has uncovered evidence for a possible 0^+ state some 1.7 MeV above the ^{6}He + ^{6}He breakup threshold. Interestingly, this state conforms well to the spin-energy systematics established in our original study.

Indirect evidence for the existence of molecular structures in ^{12}Be may also be found in the observation of highly excited states in the ^{9}Be(^{15}N, ^{12}N)^{12}Be reaction which are consistent with the spin-energy systematics of a deformed rotational band [10]. The theoretical investigation of molecular configurations in ^{12}Be represents a somewhat more challenging venture than the lighter-mass

Be isotopes. Nevertheless, efforts are being made, as evidenced by the contribution to this conference by Ito and coworkers and recent papers by Itagaki *et al.* [11] and Descouvemont and Baye [12].

As suggested by von Oertzen [5] and, more recently, by Itagaki *et al.* [13], the neutron-rich C isotopes may be expected to exhibit 3α:Xn cluster structures. In this context, we have attempted to observe such states in the ^{12}C(^{16}C, ^{16}C$^* \rightarrow {}^6$He + ^{6}He + ^{4}He; ^{10,12}Be + ^{6,4}He) reactions at 35 MeV/nucleon [14]. Careful analysis of the fragment coincidences could, however, only put upper limits of ~ 2 and ~ 30 μb, respectively, on the yields to these decay channels. The inability to access such states by inelastic scattering may arise from a much smaller overlap between the ^{16}C ground state and the cluster states than in the case of ^{12}Be. In this context transfer reactions using projectiles (^{6,8}He) and targets (^{6}Li, ^{9}Be, ^{12}C) exhibiting cluster structure may provide a more efficient means of accessing molecular states in neutron-rich nuclei.

Beyond the extension of cluster studies to more exotic systems, one of the most pressing issues is the determination of partial decay widths. Clearly, this is not a trivial task, as evidenced by the difficulties encountered in the study of clustering in stable nuclei. In the case of the light, neutron-rich nuclei discussed here, the presence of relatively few decay channels and the more favourable signal-to-background ratio when employing radioactive beams may, however, facilitate such measurements.

3 Correlations in two-neutron halo nuclei

Clustering also appears in the guise of neutron haloes in ground states near the neutron dripline. Arguably, the most intriguing are the Borromean two-neutron halo nuclei (^{6}He, ^{11}Li and ^{14}Be), in which the two-body subsystems are unbound. Such behaviour naturally gives rise to the question of the correlations between the constituents. Over the last three years we have developed a number of techniques for exploring the correlations within two-neutron halo systems [15,16].

We have explored the spatial configuration of the halo neutrons at breakup through the application of the technique of intensity interferometry —an approach first developed for stellar interferometry by Hanbury-Brown and Twiss in Australia in the 1950s and '60s [17] and later extended to source size measurements in high-energy collisions [18]. The principle behind the technique is as follows: when identical particles are emitted in close proximity in space-time, the wave function of relative motion is modified by the FSI and quantum-statistical symmetries[1] [19]. Intensity interferometry relates this modification to the space-time separation of the particles at emission as a function of the four-momenta of the particles through the correlation function C_{nn}, which is defined as

$$C_{nn}(p_1, p_2) = \frac{\mathrm{d}^2 n/\mathrm{d}p_1 \mathrm{d}p_2}{(\mathrm{d}n/\mathrm{d}p_1)\,(\mathrm{d}n/\mathrm{d}p_2)}, \tag{1}$$

[1] In the case of halo neutrons the overwhelming effect is that of the FSI (Final-State Interactions) [15].
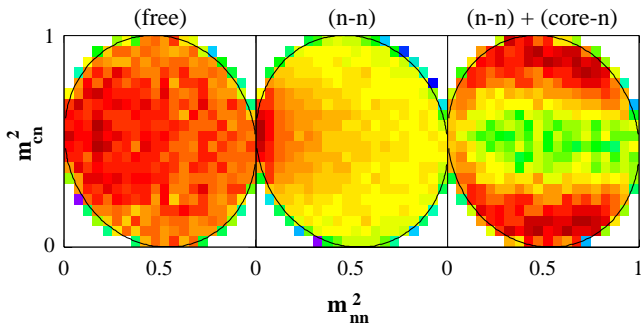
Fig. 2. Dalitz plot for the simulated decay (see text) of ^{14}Be. In the left panel no FSI are included.

where the numerator is the measured two-particle distribution and the denominator the product of the independent single-particle distributions [15]. As is generally the case, the single-particle distribution has been generated in our work via event mixing. Importantly, in the case of halo neutrons special consideration must be given to the strong residual correlations [15]. Experimentally care needs to be taken to eliminate cross talk [20].

As a first step, kinematically complete measurements of breakup on a Pb target of ^{6}He, ^{11}Li and ^{14}Be were analysed [15]. The choice of a high-Z target was made to privilege Coulomb-induced breakup, whereby the halo neutrons may in a first approximation act as spectators and for which simultaneous emission may be expected to occur. The correlation functions derived from the data, assuming simultaneous emission, were compared to an analytical formalism based on a Gaussian source [21]. Neutron-neutron separations of $r_{\rm nn}^{\rm RMS} = 5.9 \pm 1.2$ fm (^{6}He), 6.6 ± 1.5 fm (^{11}Li) and 5.6 ± 1.0 fm (^{14}Be) were thus extracted. These results appear to preclude any strong dineutron component in the halo wave functions at breakup. It is interesting in this context to compare these results to the RMS neutron-proton separation of 3.8 fm in the deuteron (the only bound two-nucleon system).

The same analysis has been applied to dissociation of ^{14}Be by a C target, in order to investigate the influence of the reaction mechanism. A result which hints at a somewhat larger separation, $r_{\rm nn}^{\rm RMS} = 7.6 \pm 1.7$ fm, was obtained. This raises the question as to whether simultaneous emission can be assumed *a priori*. In principle, the analysis of the correlation function in two dimensions, transverse and parallel to the total momentum of the pair, would allow for the unfolding of the source size and lifetime [21]. Such an analysis requires a much larger data set than presently available. The two-neutron halo, however, is far less complex than the systems usually studied via interferometry (such as heavy-ion collisions [19]). Moreover, the simple three-body nature of the system breaking up suggests that any delay in the emission of one of the neutrons will arise from core-n FSI/resonances in the exit channel, a process that may be expected to be enhanced for nuclear-induced breakup.

Correlations in three-particle decays are commonly encountered in particle physics and are typically analysed us-
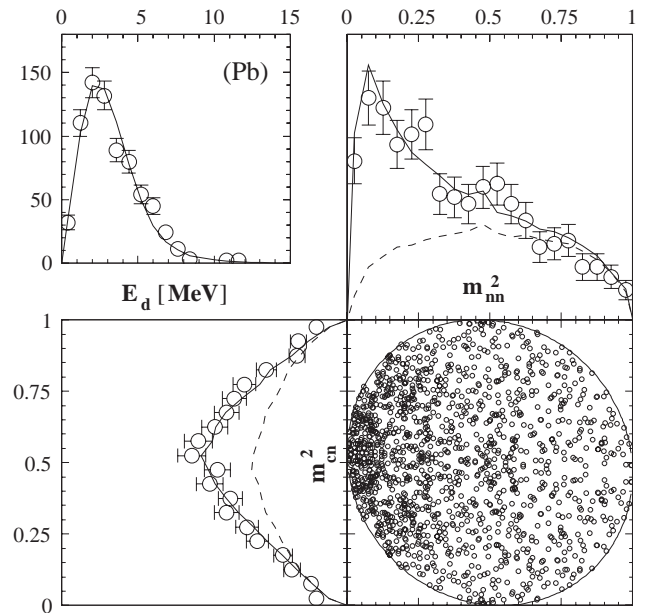

Fig. 3. Dalitz plot and the projections onto the squared invariant masses for the dissociation of ^{14}Be by Pb. The lines are the phase space model simulations with/without (solid/dashed line) n-n FSI. The inset shows the measured $E_{\rm d}$ spectrum.

ing plots of the squared invariant masses of particle pairs (M_{ij}^2, M_{ik}^2), with $M_{ij}^2 = (p_i + p_j)^2$; a technique developed by the Australian physicist Richard Dalitz in the early 1950s [22]. In these Dalitz plot representations, FSI or resonances lead to a non-uniform population of the surface within the kinematic boundary defined by energy-momentum conservation and the decay energy. In the present case, the core $+$ n $+$ n system exhibits a distribution of decay energies ($E_{\rm d}$). The $E_{\rm d}$ associated with each event will thus lead to a different kinematic boundary, and the resulting plot containing all events cannot be easily interpreted. We have thus introduced a normalised invariant mass

$$m_{ij}^2 = \frac{M_{ij}^2 - (m_i + m_j)^2}{(m_i + m_j + E_{\rm d})^2 - (m_i + m_j)^2}, \qquad (2)$$

which ranges between 0 and 1 for all events and exhibits a single kinematic boundary. Examples of how n-n and core-n FSI may manifest themselves in the Dalitz plot for the decay of ^{14}Be are illustrated in fig. 2, whereby events have been simulated according to the simple interacting phase space model described in ref. [16]. The inputs were an $E_{\rm d}$ distribution following that measured [23], the $C_{\rm nn}$ obtained with the C target, and a core-n resonance with $\Gamma = 0.3$ MeV at $E_0 = 0.8$ MeV. Note that due to the normalisation the (squared) core-neutron invariant mass does not present a simple structure directly related to the energy of the resonance/FSI [16].

As described in ref. [16], the data from the dissociation of ^{14}Be on C and Pb targets have been analysed in terms of Dalitz plots and compared to the interacting phase space calculations. The results for breakup on the Pb target are shown in fig. 3. The good agreement obtained through
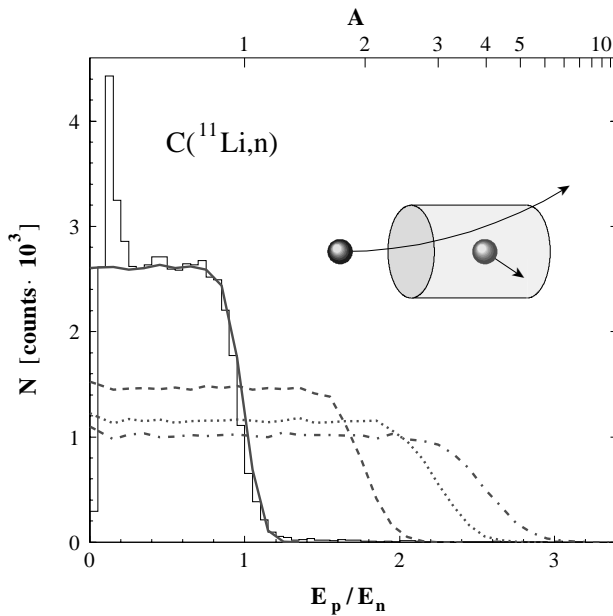
Fig. 4. E_p/E_n for $A = 1$ (solid line), 2 (dotted line), 3 (dotted line) and 4 (dot-dashed line). In the case of $A = 1$, comparison is made to single-neutron events from ^{11}Li + C.

the inclusion of only the n-n FSI suggests that, within the presently available statistics, the two neutrons are emitted essentially simultaneously.

Despite much reduced statistics for the triple coincidence events needed for this analysis, breakup on the C target is consistent with a finite delay between the emission of the two neutrons [16]. This may be related to the population of core-neutron resonances as suggested by more classical analyses of ^{12}Be-neutron events [24]. By fixing the n-n source size to that derived from the C_{nn} for the Pb target, an average delay in the emission for breakup by C of 150^{+250}_{-150} fm/c was estimated.

4 Multineutron clusters

It is interesting to speculate that multineutron halo nuclei and other very neutron-rich systems may contain components of the wave function in which the neutrons present a relatively compact cluster-like configuration. If this were to be the case, then the dissociation of beams of such nuclei may offer a means to produce bound multineutron clusters (if they exist) and, more generally, study multineutron correlations.

To date, the majority of searches for multineutron systems have relied on very low (typically $\sim$1 nb) cross-section double-pion charge exchange (DπCX) and heavy-ion transfer reactions (see, for example, refs. [25,26]). In the case of dissociation of an energetic beam of a very neutron-rich nucleus, relatively high cross-sections (typically $\sim$ 100 mb) are encountered. Thus, even only a small component of the wave function corresponding to a multi-neutron cluster could result in a measurable yield with a moderate secondary beam intensity. Furthermore, the

backgrounds encountered in DπCX and heavy-ion transfer reactions are obviated in direct breakup.

The difficulty in this approach lies in the direct detection of a ^{A}n cluster. One avenue we are exploring is to use the detection of the recoiling proton in a liquid scintillator [27]. The advantage of a liquid scintallator is that neutrons may be discriminated from the γ and cosmic-ray backgrounds. Careful source and cosmic-ray calibrations permit the charge deposited and hence the energy (E_p) of the recoiling proton to be determined. This may be compared to the energy derived from the measured time of flight (E_n): for a single neutron and an ideal detector, $E_p/E_n \leq 1$; for a realistic detector with finite resolution the limit is ~ 1.4. In the case of a multineutron cluster (^{A}n) E_p can exceed the incident energy per nucleon and E_p/E_n will take on a range of values extending beyond ~ 1.4 —up to ~ 3 in the case of $A = 4$ (fig. 4).

Analyses of data already available from the breakup of ^{14}Be by C show some 7 events with $E_p/E_n > 1.4$. Furthermore, 6 of these events appear to be in coincidence with ^{10}Be fragments. Estimates suggest that the detection of two or more neutrons in a single module (the most likely source of background) should produce much less that one event with $E_p/E_n > 1.4$ in coincidence with ^{10}Be. Further detailed analysis of these events and all possible sources of background is being completed [27]. In addition, higher statistics measurements employing beams such as ^{8}He are currently being planned.

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