Clustering and Correlations in Neutron Haloes

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In the present paper clustering and correlations within two-neutron halo systems are explored. In particular, the application of neutron-neutron interferometry and Dalitz-plot type analyses is presented through the example provided by the dissociation of $^{14}\text{Be}$.

§1. Introduction

Clustering, which has long been known to occur along the line of beta stability, also appears in more exotic forms as the drip-lines are approached. For example, $2\alpha-2n$ molecular-like configurations have been observed in excited states of $^{10,12}\text{Be}$. The most spatially extreme form of clustering are the neutron haloes which occur as the ground states of some nuclei at the limits of particle stability. Perhaps the most intriguing of the halo systems are the Borromean two-neutron halo nuclei ($^6\text{He}$, $^{11}\text{Li}$ and $^{14}\text{Be}$), in which the two-body subsystems (core-$n$ and $n-n$) are unbound. Such behaviour naturally gives rise to the question of the correlations between the constituents. Even in the case of the most studied of these nuclei, $^6\text{He}$ and $^{11}\text{Li}$, little is known in this respect. Here we explore the nature of these correlations through the application of interferometry and Dalitz-plot type analyses to kinematically complete measurements of dissociation.

§2. Correlations in two-neutron halo nuclei

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 1950’s and 60’s and later extended to source size measurements in high energy collisions. 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 — in the case of halo neutrons the overwhelming effect is that of the FSI. 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,

$$C_{nn}(p_1,p_2) = \frac{d^2n/dp_1 dp_2}{(dn/dp_1)(dn/dp_2)},$$

(2.1)

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* A more detailed version, including the discussion of the search for multineutron clusters, may be found as nucl-ex/0201017 at http://arXiv.org.

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where the numerator is the measured two-particle distribution and the denominator the product of the independent single-particle distributions.\textsuperscript{5)} As is generally the case, the single-particle distributions have 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.\textsuperscript{5)} Experimentally care needs to be taken to eliminate cross talk.\textsuperscript{6)}

As a first step, the kinematically complete measurements of breakup on a Pb target of \(^6\text{He}, \(^{11}\text{Li}\) and \(^{14}\text{Be}\) were analysed.\textsuperscript{5)} 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.\textsuperscript{7)} Neutron-neutron separations of \(r_{nn}^{\text{rms}} = 5.9 \pm 1.2\) fm (\(^6\text{He}\)), \(6.6 \pm 1.5\) fm (\(^{11}\text{Li}\)) and \(5.6 \pm 1.0\) fm (\(^{14}\text{Be}\)) were thus extracted. These results appear to preclude any strong dineutron component in the halo wavefunctions at breakup; a result which, for \(^6\text{He}\) is in line with a recent radiative capture experiment we have performed.\textsuperscript{8)}

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 \(^{14}\text{Be}\) by a C target, in order to investigate the influence of the reaction mechanism. A result which hints at a somewhat larger separation, \(r_{nn}^{\text{rms}} = 7.6 \pm 1.7\) 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.\textsuperscript{7)} 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.\textsuperscript{4)} 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 using 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 1950’s.\textsuperscript{9)} In 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 \((E_d)\). The \(E_d\) 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,

\[
m_{ij}^2 = \frac{M_{ij}^2 - (m_i + m_j)^2}{(m_i + m_j + E_d)^2 - (m_i + m_j)^2},
\]

which ranges between 0 and 1 (that is, a relative energy \(E_{ij} = M_{ij} - m_i - m_j\) between
Fig. 1. Dalitz plot for the simulated decay of $^{14}\text{Be}$ (see text). In the left panel no FSI are included.

0 and $E_d$) 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 $^{14}\text{Be}$ are illustrated in Fig. 1, whereby events have been simulated according to the simple interacting phase-space model described in Ref. 10). The inputs were an $E_d$ distribution following that measured,\(^{11}\) the $C_{nn}$ obtained with the C target, and a core-$n$ resonances 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.\(^{10}\)

The Dalitz plot for the data from the dissociation by Pb (Fig. 2, upper panel) presents a strong $n$-$n$ FSI and a uniform density for $m_{nn}^2 \sim 0.5$. Indeed, the $n$-$n$ FSI alone describes very well the projections onto both axes, and therefore suggests that core-$n$ resonances are not present to any significant extent. This result confirms the hypothesis of simultaneous $n$-$n$ emission employed in the original analysis of the dissociation of $^{14}\text{Be}$ by Pb.\(^{5}\) The $r_{nn}^{\text{rms}}$ so extracted, $5.6 \pm 1.0$ fm, may thus be considered to represent the $n$-$n$ separation in the halo of $^{14}\text{Be}$.

For dissociation by the C target (Fig. 2, lower panel), despite the lower statistics, two differences are evident. First, the $n$-$n$ signal is weaker, indicating that a significant delay has occurred between the emission of each neutron. Second, and more importantly, the agreement between the model including only the $n$-$n$ FSI and the data for $m_{cn}^2$ is rather poor. In order to verify whether this disagreement corresponds to the presence of core-$n$ resonances the core-$n$ relative energy, $E_{cn}$, has been explored. It has been reconstructed for the simulations incorporating only the $n$-$n$ FSI and compared in Fig. 3 to the data (the model calculations have been normalized to the data above 4 MeV). For dissociation by Pb, the inclusion of only the $n$-$n$ FSI provides a very good description of the data, with the exception of small deviations below 1 MeV. This is in line with the Dalitz-plot analysis discussed above.

The deviations observed for the C target between the measured $m_{cn}^2$ and the simulation including only the $n$-$n$ FSI clearly correspond to structures in the $E_{cn}$ spectrum. Moreover, these structures are located at energies that are in line with those of states previously reported in $^{13}\text{Be}$: the supposed $d_{5/2}$ resonance at 2.0 MeV\(^{12},13\) and a lower-lying state(s).\(^{14},13,15\) The model-to-data ratio is about $1/2$, indicating that the peaks correspond to resonances formed by one of the neu-
trons in almost all decays; the solid line accounts for the contribution of the neutron not interacting with the core. In the case of dissociation by Pb, the lowest-lying level(s) appears to be present in at most 10% of events.

The different results obtained for the Pb and C targets may be attributed to the associated reaction mechanisms. In the case of the Pb target, the dominant process is electromagnetic dissociation,\(^{11}\) whereby the halo neutrons behave to first order as spectators and only the charged core is acted on by the Coulomb field of the target. Qualitatively then, the \(n-n\) FSI may be expected to influence most strongly
Fig. 3. Core-\(n\) relative energy distributions (left) and \(n-n\) correlation functions (rightmost panels) for the dissociation of \(^{14}\text{Be}\) by Pb and C. The lines in the \(E_{\text{cn}}\) spectra are the result of the phase-space model simulations with \(n-n\) FSI (solid) plus core-\(n\) FSI (dashed, see text). The histograms presented in the middle panels are the difference between the data and the \(n-n\) FSI simulations. The solid lines in the panels at the right are the \(C_{nn}\) for \(r_{\text{rms}}^{nn} = 5.6\) fm and \(\tau_{nn} = 0\); the dashed lines correspond to the limits of the range \(r_{\text{rms}}^{nn} = 6.6-4.6\) fm and \(\tau_{nn} = 0-400\) fm/c.

the decay. In the case of the C target, nuclear breakup dominates and the reaction takes place at smaller impact parameters, in general through the interaction of one of the halo neutrons with the target. As such the population of states in the core-\(n\) system is favoured.

By combining the information extracted from the core-\(n\) channel with the \(n-n\) correlation functions, the analysis can be extended to extract the average lifetime of the core-\(n\) resonances. If the \(n-n\) separation in \(^{14}\text{Be}\) is fixed to that obtained for dissociation by Pb, \(r_{\text{rms}}^{nn} = 5.6 \pm 1.0\) fm, the delay between the emission of the neutrons \(\tau_{nn}\) needed to describe the \(n-n\) correlation function for the C target may be introduced. As discussed above, this delay should correspond to the lifetime of the resonances. The result of a \(\chi^2\) analysis, represented by the dashed lines in Fig. 3 (bottom right panel), suggests an average lifetime of \(150^{+250}_{-150}\) fm/c.

§3. Conclusions

An experimental programme to explore clustering and correlations in halo systems has been described. New approaches have been developed, including the application of neutron-neutron interferometry and Dalitz-plot analyses to the dissociation of two-neutron halo nuclei.

Very recently a high statistics measurement of the dissociation of \(^6\text{He}\) has been carried out. Given that \(^6\text{He}\) is structurally the most well known two-neutron halo system, this work should provide a good test of the techniques described here to probe
correlations. Furthermore, correlation function analyses employing the longitudinal and transverse neutron-neutron relative momenta should provide an independent means to disentangle the halo neutron-neutron separation and time delay in emission. Measurements in the coming year with a $^8$He beam should allow multineutron correlations to be explored.

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