Neutron-Neutron Correlations in the Dissociation of Halo Nuclei *

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Abstract

Studies attempting to probe the spatial configuration of the valence neutrons in two-neutron halo nuclei using the technique of intensity interferometry are described. Following a brief review of the method and its application to earlier measurements of the breakup of $^6$He, $^{11}$Li and $^{14}$Be, the results of the analysis of a high statistics data set for $^6$He are presented. The limitations of the technique, including the assumption of incoherent emission in the breakup and the sensitivity to the continuum states populated in the dissociation rather than the ground state, are discussed.

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I. INTRODUCTION

Clustering, which has long been known to occur along the line of $\beta$-stability also appears in exotic forms as the drip-lines are approached. The most spatially extreme form of clustering is that exhibited by neutron haloes which appear as the ground states of very weakly bound nuclei at the limits of particle stability. Perhaps the most intriguing of the halo systems are the two-neutron halo nuclei $^6\text{He}$, $^{11}\text{Li}$, $^{14}\text{Be}$ and $^{17}\text{B}$, in which the two-body subsystems – core-$n$ and $n-n$ – are unbound. Such Borromean behaviour naturally gives rise to the question of the correlations between the constituents. In particular, a long standing issue has been the spatial configuration of the two halo neutrons. Indeed, from an historical perspective, the first attempts to model $^{11}\text{Li}$ employed a core + point dineutron description [1]. Later, more sophisticated three-body modelling lead to the concept of both dineutron-like and “cigar”-type configurations [2], a theme which has resurfaced in recent years [3].

Experimentally the probing of the correlations between the halo neutrons has proved difficult. Attempts have been made to employ two-neutron transfer reactions where, quite apart from the availability of relatively intense beams and the uncertainties in the optical model potentials, the principal difficulty is the need to accurately model both pair and sequential transfer. Such an approach for $^6\text{He}$ has suggested that, within the constraints of the three-body wavefunction used, pair transfer of a dineutron-like configuration dominates [4].

High-energy dissociation reactions have also been explored as a possible probe. Experimentally the very high cross sections and thick targets allow relatively weak beams to be employed and hence the most neutron-rich systems to be studied. Some attempts have been made to relate the measured neutron-neutron momentum or relative-angle distributions to the halo neutron correlations in $^{11}\text{Li}$ [5, 6]. More recently, Nakamura et al. have derived an estimate, based on sum-rule considerations, of the $n-n$ opening angle from a measurement of the dipole strength function in the dissociation of $^{11}\text{Li}$ [7]. Motivated by this work, Hagino and Sagawa have proposed a less model dependent analysis based on the dipole strength function and the total matter radius [8].

In the work described here, we have applied the technique of intensity interferometry and the corresponding correlation function to analyse the neutron-neutron relative momentum ($q$) distributions measured following dissociation at intermediate energies. Assuming that incoherent (ie., independent particle) emission is a reasonable approximation for the disso-
ciation of halo systems, and using an analytical description of the \( n-n \) correlation function with a Gaussian source parameterisation, estimates of the RMS neutron-neutron separation \( (r_{nn}^{rms}) \) at breakup have been derived. It is worthwhile noting at the outset that, within these limitations, the technique is sensitive to the configurations present in the states populated in the continuum by the dissociation rather than the ground state of the projectile. As such, the use of the \( r_{nn}^{rms} \) so obtained to deduce, in a “model independent” manner, the “geometry” of two-neutron halo systems \([8, 9]\) should be proscribed.

It should be stressed that the correlation function analysis presented here is an approximation of sorts to the approach which should in principle be employed; namely a comparison of the measured \( n-n \) relative momenta to the results of a complete calculation based on a realistic halo wavefunction coupled to a full reaction calculation incorporating the final-state interactions in the outgoing channel. To date, however, such calculations have, with the exception of the pioneering work of Esbensen et al. on the Coulomb breakup of \(^{11}\text{Li}\) \([6]\), yet to be attempted.

II. TECHNIQUE

Intensity interferometry was developed as part of the pioneering work on stellar interferometry (using optical wavelength photons) of Hanbury-Brown and Twiss in the 1950’s and 60’s \([10]\). The method was later extended to source size measurements using pions in high-energy physics \([11]\). 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 (QSS) \([12]\) — in the case of halo neutrons the overwhelming effect is expected to be that of the FSI \([13]\) (Fig. \(\text{1}\)). 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,

\[
C_{nn}(p_1, p_2) = \frac{d^2n/dp_1dp_2}{(dn/dp_1)(dn/dp_2)} \tag{1}
\]

where the numerator is the measured two-particle distribution and the denominator the product of the independent single-particle distributions \([13]\) — that is, the distribution a
particle would exhibit if it were not influenced by the other. As is generally the case, the single-particle distributions have been generated via event mixing. Importantly, in the case of halo neutrons special consideration must be given to the strong “residual correlations” which are present in the event-mixed distributions [13]. Here, an iterative technique developed in the spirit of that employed by Zajc et al. [14] was used to produce the final event-mixed distribution [13]. The neglect of the effects engendered by the residual correlations can result in a significant overestimate of the corresponding apparent source size [30]. Experimentally much care needs to be taken to eliminate cross talk (ie., a single scattered neutron that is registered in two detectors), which will tend to enhance the number of events at low-relative momentum and hence artifically diminish the apparent source size [18].

In the case of neutron pairs, the QSS are governed by Fermi statistics and the FSI by the strong interaction. In our work we have employed the formalism developed by Lednicky and Lyuboshits [19], where analytic expressions for the neutron-neutron correlation function in the s-wave channel, with explicit dependence on the distribution of their relative four-distance, were derived. In Fig. 1 the sensitivity of $C$ to different halo-neutron configurations is demonstrated, where for simplicity Gaussian source parameterisations have been used. As pointed out in Ref. [19], the repulsive contribution of the QSS is overwhelmed at low $q$ by the attractive FSI, and $C$ may take on much higher values – $C(0) \sim 10–20$ – than is possible in other cases (eg., bosons or charged fermions [12, 16] or evaporated neutrons with emission over a long time scale [17]), where $C(0) < 2$. Two-neutron interferometry thus presents the additional advantage for probing haloes that it may, within the context of the approximations outlined here, be applied to data sets of relatively poor statistical quality – an important feature given the generally low beam intensities and triple coincidence requirement of the experiments.

III. RESULTS AND DISCUSSION

As a first step, measurements of the dissociation by a Pb target of intermediate energy beams of $^6$He, $^{11}$Li and $^{14}$Be to the core-n-n [20] were analysed [13] (the details of the experiment may be found in Refs [13, 20]). The choice of data acquired with a high-Z target was made to privilege Coulomb induced breakup, whereby, in a scenario similar to that argued for by Ieki et al. [15], the halo neutrons were, to a first approximation, expected
to act as *spectators*, and for which simultaneous emission might be assumed to occur (see below). The correlation functions derived from the data (Fig. 2), assuming simultaneous emission, were compared to the analytical formalism based on a Gaussian source \[31\]. Such a parametrization describes well the experimental correlation functions and neutron-neutron separations at breakup of \(r_{nm}^{\text{rms}} = 5.9 \pm 1.2\) 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 deduced. These results appeared, within the limitations of the technique, to preclude any strong compact dineutron component at breakup; a result which for \(^6\text{He}\), assuming that the “spectator” hypothesis is valid, would be in line with a complementary radiative capture study reported by us in Ref. \[22\]. It is interesting 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 was applied to dissociation of \(^{14}\text{Be}\) by a C target, in order to investigate the influence of the reaction mechanism \[21\]. A result which hinted at a somewhat larger separation at breakup, \(r_{nm}^{\text{rms}} = 7.6 \pm 1.7\) fm, was obtained. This raised the issue as to whether simultaneous emission could be assumed a priori \[21\]. The three-body nature of the system breaking up suggested that any delay in the emission of one of the neutrons would arise from core-\(n\) FSI/resonances in the exit channel; a process that might be expected to be enhanced in nuclear induced breakup owing to the significant contribution to dissociation attributable to diffractive breakup \[20\].

From a pragmatic point of view, given the statistical quality of the data, the relatively simple (Gaussian) parameterisation of the neutron source and the other approximations inherent in the technique, such considerations are probably not yet relevent. Moreover, as demonstrated by the comparison presented in Fig. 1d, the difference between correlation functions (for a source with \(r_0 = 3\) fm) for simultaneous emission and passage via an intermediate resonance with a lifetime of 50 fm/c (\(\Gamma \sim 4\) MeV) is negligible. Indeed, a lifetime of order 1000 fm/c or less (\(\Gamma \leq 0.2\) MeV) would be required before the effects would be significant for the interpretation of the data presented here.

In addition to the influence of such two-step breakup, it must also be recognised, as pointed out earlier, that the neutron-neutron configuration being probed is not that of the projectile ground state but rather the average over the states in the continuum populated in the breakup which subsequently decay to the core-\(n-n\) channel. Indeed, it was in this spirit that our first analyses (as described above) were undertaken of data acquired for Coulomb
dominated breakup, whereby dipole excitations with a large overlap with the ground state \( n-n \) configuration were argued to occur.

In order to explore in more detail these issues and the technique in general, a dedicated study of the breakup of \( ^6\text{He} \) was undertaken, the details of which may be found in Ref. \[23\]. Experimentally \( ^6\text{He} \) presents the advantage that it can be produced as a relatively intense beam (here \( \sim 3 \times 10^4 \) pps \[32\] at 30 MeV/nucleon). Theoretically \( ^6\text{He} \) is the two-neutron halo nucleus which can be modelled the most reliably and for which the core-\( n \) system, \( ^5\text{He} \) \[33\], is the most well established.

The correlation functions derived from the data acquired for reactions on both C and Pb targets are displayed in Fig. 3. As in our earlier work, a Gaussian source parameterisation based on the formalism of Ref. \[19\], was employed to derive estimates of the RMS \( n-n \) separation at breakup of 7.7\( \pm \)0.8 (C) and 9.4\( \pm \)0.8 fm (Pb) for the reactions on the two targets. As noted above, the \( n-n \) configurations being probed are those of the unbound states in \( ^6\text{He} \) populated in the reaction which subsequently decay to \( \alpha-n-n \). The difference in the apparent source sizes presumably arises then from a different selectivity in the states populated in the two cases. To pursue this conjecture further the decay energy spectrum (\( E_d = E_x - S_{2n} \)) for the \( ^6\text{He}^* \) have been reconstructed from the measured momenta of the \( \alpha \) and two neutrons.

As may be seen in Fig. 4 the spectra are markedly different – that arising from reactions on the C target is dominated by the well established \( 2^+_1 \) state at \( E_x = 1.8 \) MeV, whilst in the case of the Pb target the spectrum is relatively featureless, with the \( 2^+_1 \) state being much more weakly populated \[34\]. Given that breakup on the Pb target would be expected to be dominated by Coulomb induced reactions, the excitation-energy spectrum should contain significant E1 strength. Interestingly, three-body models predict an E1 distribution with a peak at around 1-1.5 MeV decay energy (a feature hinted at in Figs 4 and 5) and a strong, slowly decaying “tail” towards higher energies \[26, 27\].

In Fig. 5 the decay energy spectra are shown after subtraction of the uncorrelated distribution generated by event mixing. As the E1 strength is not expected to be associated with well defined three-body resonances \[28\], such a comparison should suppress it and any other non-resonant structures. In this context, we note that the calculations of Danilin \textit{et al.} \[28\] suggest that the monopole strength, which may be expected to be preferentially populated by reactions on the C target, does not present a strongly correlated character either.
Danilin et al. [28] have investigated theoretically spatial correlations in the three-body continuum of $^6$He and conclude that the $2^+_1$ state presents a relatively compact structure – with a “most probable” n-n separation of $\sim 5$ fm – compared to the $1^-_1$ continuum states. This is qualitatively in line with the results obtained here of a larger $r_{nn}$ at breakup for reactions on the Pb target as compared to the C target.

IV. CONCLUSIONS

To proceed in a more quantitative manner, $n$-$n$ correlation functions derived from realistic halo wavefunctions, weighted by the relative yields expected in the reactions under study, need to be constructed. Furthermore, the degree to which coherent emission affects the results should be explored. The first steps in this direction have recently been made by Yamashita et al. [29], whereby these issues have been addressed for the first time. Interestingly, the shapes of the correlation functions at low relative momenta ($q \lesssim 80$ MeV/c) are in reasonably good agreement with the data and with the simple formalism based on incoherent emission and Gaussian source parameterisations employed here. It may be speculated that the differences observed at large relative momenta arise from the $l > 0$ components of the $n$-$n$ interaction which were not included in the formalism usec to generate the correlation functions employed here [19] and/or coherence effects.

Future efforts along these lines are to be encouraged, as are complete calculations of the $n$-$n$ relative momenta based on realistic halo wavefunctions coupled to a reaction model and incorporating the effects of the FSI in the outgoing channel. Ultimately, the comparison of such predictions for different wavefunctions with the measured relative momentum distribution should provide the most reliable insight into the halo neutron spatial configurations.

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Interestingly, the first attempt to construct $C_{nn}$ for the breakup of a halo nucleus ($^{11}\text{Li}$) not only failed to recognise the problem of residual correlations, but also interpreted the source size as a direct measure of the overall size of the halo [15].

For a Gaussian source of variance $r_0$ (Eq. (24) Ref. [19]) the n-n separation $r_{nn}$ is a Gaussian distribution of variance $\sqrt{2}r_0$ and $r_{\text{rms}}^{nn} = \sqrt{6}r_0$.

In the present case the intensity was limited by the count rate capabilities of the segmented zero-degree telescope used to detect the charged fragments and beam [24].

The ground state being a resonance some 0.8 MeV above threshold with a width $\Gamma \approx 0.7$ MeV – the latter corresponding to a lifetime short enough to avoid any need to consider the implications of sequential decay.

Broadly similar results have been found by the LAND Collaboration in measurements made at a beam energy an order of magnitude higher than that employed here [25].
FIG. 1: Neutron-neutron correlation functions, $C$, for different halo configurations (note the logarithmic scale for $C$). The calculations are based on Gaussian sources (see text) with sizes, $r_0$, of (a) 6 fm, (b) 3 fm and (c) 2 fm separated by 10 fm. The contributions from Fermi–Dirac statistics and the neutron–neutron FSI are shown by the dashed and dotted lines respectively. Simultaneous emission for a source size of 3 fm (solid line) is compared in (d) to a source with a space-time extent of 3 fm, 50 fm/c (open symbols) [13].
FIG. 2: Correlation functions (right hand panels) constructed for the dissociation of the halo nuclei $^6$He, $^{11}$Li and $^{14}$Be by a Pb target. The solid lines correspond to the fit based on a Gaussian source (see text). On the left, the measured numerator (symbols) and the successively reconstructed event mixed distributions (dotted, dashed and solid lines for $i = 1, 2, 8$, respectively) are displayed – see Ref. [13] for more details. The insets demonstrate the evolution of the source size ($r_0$ fm) with the number of iterations.
FIG. 3: Correlation functions constructed for the dissociation of $^6$He by C and Pb targets \[23\]. The solid lines correspond to the fit assuming a Gaussian source (see text) and the corresponding $r_{\text{rms}}^{nn}$ are indicated.
FIG. 4: Decay-energy spectra for the dissociation of $^{6}$He by C and Pb targets [23]. The relatively narrow peak at $E_d \sim 1$ MeV is the well known $2^+_1$ state ($E_x=1.8$ MeV). Uncorrelated $\alpha - n - n$ distributions generated by event mixing and normalised to the data at high $E_d$ are shown as the dashed and dotted lines (first and final iterations respectively – see Ref. [23]).
FIG. 5: Decay-energy spectra for the dissociation of $^6$He by C and Pb targets after subtraction of the uncorrelated $\alpha - n - n$ distribution obtained via event mixing (dotted distributions in Fig. 4). The resonance parameters used for the three components shown are $^{[23]}$: $E_r = 0.82, 1.5, 4$ MeV; $\Gamma = 0.16, 0.5, 6$ MeV.