Chronology of the three-body dissociation of $^8$He

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Abstract. The space and time configurations of the dissociation of $^8$He into $^6$He+$n+n$, on C and Pb targets, have been explored simultaneously for the first time. The final-state interactions in the $n$-$n$ and $^6$He-$n$ channels are successfully described within a model that considers independent emission of neutrons from a Gaussian volume with a given lifetime. The dissociation on C target exhibits a dominant sequential decay through the ground state of $^7$He, consistent with neutrons being emitted from a Gaussian volume of $r_{nn}^{\text{rms}} = 7.3^{\pm0.6}$ fm with a $n$-$n$ delay in the sequential channel of $1400^{\pm400}$ fm/$c$, in very good agreement with the lifetime of $^7$He. The lower-statistics data on Pb target correspond mainly to direct breakup, and are well described using the $n$-$n$ volume measured, without any $n$-$n$ delay. The validity of the phenomenological model used is discussed.

Keywords: neutron correlations, three-body decays, halo nuclei

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1. Introduction

Along the neutron dripline some nuclear systems develop an extreme clustering structure already in their ground state, in which the weakly bound neutrons form a halo around the rest of the system or core [1]. The most exciting of these are the Borromean two-neutron halo systems, $^6$He, $^{11}$Li and $^{14}$Be, exhibiting a bound core-$n$-$n$ structure where all the two-body subsystems are unbound [2]. As such, these systems are unique for the study of three-body correlations and the N-N interaction at low densities. Other heavier candidates, $^{17,19}$B and $^{22}$C, have not been explored in detail yet, and the structure of $^8$He seems to be dominated by an α core plus four neutrons [3].

The breakup of these genuine three-body systems unveils a complex interplay between the nature of their decay, either direct or sequential [1, 5], and the resonances and final-state interactions (FSI) in the two-body channels. Two-neutron haloes, in particular, convey a clearer picture of the decay due to the absence of Coulomb interactions. The population of core-$n$ resonances dictates the sequential nature of the decay, and the $n$-$n$ interaction may modify the final state at low relative momentum [6, 7, 8]. In particular, Ref. [8] links this modification with the space-time proximity of the neutrons, assuming they are emitted independently by a Gaussian source, exploiting the principle that the effect of the short-range attractive nuclear force will be stronger the closer they are.

The dissociation in the field of a Pb target can be used to induce direct breakup of the two-neutron halo into its three constituents [9]. In that case, no core-$n$ resonances should be significantly populated and, following the formalism of Ref. [8], the only parameter characterizing the decay would be the space dimension of the neutron emission. This approach was exploited to estimate the $n$-$n$ separation at breakup for $^6$He, $^{11}$Li and $^{14}$Be [10], of $r_{nn} \sim 6$–7 fm. However, in the case of $^{14}$Be it was found that breakup on a lighter C target introduced a sequential channel through various resonances in $^{13}$Be [11], that induced an average delay between the emission of the neutrons and therefore decreased the $n$-$n$ signal. The delay, $150\pm250$ fm/c, was attributed to a set of different resonances in the $^{13}$Be system, their number, energy and/or width being not well-known at the time.

The ability to induce direct or sequential dissociation, coupled to the possibility to measure a neutron delay generated by the lifetime of a core-$n$ resonance, represents a unique opportunity to map the space-time decay of a three-body system. The optimal case of study would be the breakup of a core-$n$-$n$ system in which the core-$n$ subsystem has few, well-known states, and if possible with a narrow width (long lifetime), that would introduce a significant delay between the emission of the neutrons. While the ground state of $^8$He is understood as a four-neutron halo or skin [3], the three-body $^6$He+$n+n$ breakup channel exhibits the characteristics noted above: only one state is known in $^7$He decaying into $^6$He+$n$, and it is narrow enough ($\Gamma = 150 \pm 20$ keV [12]) to significantly delay the emission of the second neutron ($\hbar c/\Gamma = 1320 \pm 180$ fm/c).

In this Letter, we report on the dissociation of a $^8$He beam into $^6$He+$n+n$ on C and Pb targets. The formation of $^7$He has been clearly identified with the help of Dalitz plots, showing that the breakup on C is mainly sequential and goes through the ground state of $^7$He. The description of the three-body final state, using a FSI model whose applicability is discussed in detail, leads to the simultaneous measurement of the $n$-$n$ volume at breakup and the delay between the emission of the neutrons. We obtain a delay in very good agreement with the lifetime of $^8$He, and a source size that describes well the direct breakup on Pb.

2. Experiment

A $^8$He secondary beam of 15 MeV/N and $10^4$ pps was produced at GANIL using SPIRAL. The beam was tracked onto the secondary breakup targets (95 mg/cm$^2$ C and 284 mg/cm$^2$ Pb) on a particle-by-particle basis using a thin plastic detector (100 µm of BC408) and a drift chamber at 11 cm upstream of the target. The $^6$He fragments were identified using two 250 µm Si strip detectors and sixteen 2.5 cm CsI crystals from the CHARISSA collaboration inside the reaction chamber, and the neutrons detected using 90 elements of the DEMON array, placed in a staggered arrangement at forward angles. This configuration was effective in minimizing the contribution of cross-talk, the scattering of one of the neutrons through two or more detectors [13]. With the measured momenta of the three breakup fragments core+$n+n$, we reconstruct the two and three-body invariant masses $M_{cn}$ and $M_{cnn}$, and calculate the decay energy of the system $E_d=M_{cnn}-(m_c+2m_n)$ and the relative core-$n$ energy $E_{cn}=M_{cn}-(m_c+m_n)$, shown in Fig. [1]

The interacting phase-space model introduced in Ref. [11] has been used for the analysis of triple correlations in the data. In brief, the experimental decay energy distribution is used as input to generate events $\vec{p}_c, \vec{p}_n1, \vec{p}_n2$ following three-body or twice two-body phase space [14], respectively for direct or sequential decay. The latter is described as the breakup of the system into the first neutron and a core-$n$ resonance, with a relative energy $E_{cn}$ given by a Breit-Wigner distribution of parameters ($E_R, \Gamma_R$), which is then allowed to decay into the core plus the second neutron. In the $n$-$n$ channel the FSI is introduced via a probability, as a function of the $n$-$n$ relative momentum
strength is systematically concentrated at low $n$ as the integral over the source distribution the neutron-neutron scattering length $\sigma_{nn}$ correlation factor $F$. The final momenta are filtered through a simulation, including the range of projectile velocities arising from the finite target thickness and all experimental effects \[10, 11\], and the different observables are reconstructed and compared to the data.

3. The decay model

In the analog case of the decay of core-$p-p$ systems, the correlations in the $p-p$ channel have been interpreted in terms of the microscopic structure of the two-proton emitter, like for example in the two-proton decay of $^{6}\text{Be}$ and $^{45}\text{Fe}$ \[16\]. Within this formalism, the relative $p-p$ energy is characterized by the configuration mixing of the three-body wave function of the emitter, that may lead to an 'anti-correlation' (strength at high relative energy, back-to-back emission) or even to oscillatory patterns \[10, 13\].

By contrast, the core-$n-n$ final states that have been measured do not exhibit any such patterns. In the $2n$ decay from the continuum of $^{3}\text{H}$ \[17\, 18\], $^{6}\text{He}$ \[10\, 17\], $^{8}\text{He}$ (this work), $^{11}\text{Li}$ \[13\, 19\], $^{14}\text{Be}$ \[10\, 14\], $^{16}\text{Be}$ \[20\], and of $^{18}\text{C}$ and $^{20}\text{O}$ \[21\], the strength is systematically concentrated at low $n-n$ relative energy, as predicted by Refs. \[6\, 7\, 8\]. In fact these systems exhibit a pattern similar to the simplest three-body final state with two neutrons, obtained in the reaction $^{2}\text{H} (\pi^{-}, \gamma) 2n$ that is used to determine the neutron-neutron scattering length $a_{nn}$ \[22\]. The basic principle of this determination is displayed in Ref. \[23\], where the cross-section as a function of $q_{nn}$ is approximated by the $\gamma nn$ phase-space factor, with a smooth $q_{nn}$ dependence, times the s-wave (dominant at low energies) $n-n$ scattering amplitude integrated over the deuteron, that leads to peaks at high $E_n$ and low $q_{nn}$ depending explicitly on $a_{nn}$.

Ref. \[8\] can be seen as an extension of Refs. \[6\, 7\], taking explicitly into account the influence of the two-nucleon proximity on the effects of their interaction. In a simplified form it can be written as:

$$\sigma(q_{nn}) \approx \sigma_0(q_{nn}) \times \int W(r_{nn}) F(r_{nn}, q_{nn}) \, dr_{nn} \quad (1)$$

The two-particle cross-section is factorized into $\sigma_0$, the one the particles would exhibit without their mutual influence, times the correlation function $C_{nn}$, expressed as the integral over the source distribution $W$ of the correlation factor $F$, that contains the effect of the s-wave n-n FSI. The correlation function can be thus seen as a probability distribution that modulates the phase-space factor, as in Ref. \[23\]. This formalism has provided an accurate description of the low energy peaks observed in the $n-n$ final state of previous works \[10\, 14\, 17\, 19\, 20\, 21\], although contrary to Refs. \[22\, 23\] the value of $a_{nn}$ was fixed and it was the size of the source that was allowed to vary.

However, the parametrization of Ref. \[8\] was developed for a Gaussian source emitting independent neutrons. Obviously, we do not pretend that the wave function of $^{8}\text{He}$ is Gaussian, nor the two valence neutrons independent. First, in Ref. \[8\] the fact that the neutrons move independently in a Gaussian source was in part exploited for analytical ease, as in that case the distribution of relative distance is also Gaussian \[8\, Eq. (16)\]. However, since $C_{nn}$ does not depend on each neutron's position in the source but on their relative distance, we can directly assume a Gaussian shape for the latter in Eq. \[11\], and not for the overall matter distribution of $^{8}\text{He}$. The validity of this assumption is displayed in Fig. 2 where $W(r_{nn})$ distributions as different as Gaussian, Yukawa-like and spherical (provided their rms radii are equal) lead roughly to
similar Gaussian-like distributions for $W(r_{nn})$.

In Eq. 11 though, internal momentum correlations in the source of the form $W(r_{nn}, q_{nn})$ are neglected. In the following, we will assume that those potential correlations are small, or that they have a negligible impact on $C_{nn}$ after averaging over the whole source. The ability of the model to describe, at least at first order, the very specific channel subject of this work represents a severe test that will confirm or refute the validity of these two approximations.

4. Sequential decay and time

In Ref. 10, the analysis of the dissociation of halo nuclei on a Pb target assumed simultaneous emission of both neutrons in the Coulomb field of the target. When there is no emission delay, the correlation function of a Gaussian source becomes analytical [8 Eq. (24)]. If the dissociation is sequential, however, the emission of the neutrons cannot be considered simultaneous and a space-time analysis is needed. In [8 Eq. (16)] the effect of the $n$-$n$ FSI depends then on the two space and time parameters $(r_0, \tau_0)$, that correspond to the sigma of the Gaussian space-time source.

In the case studied here, the $^6$He projectile is considered to be excited by the C/Pb target into the continuum, and the unbound $^6$He+$n+n$ system decays in flight, either directly into three-particle phase space, either through a $^6$He+$n$ resonance. Therefore, the only free parameters of our interacting phase-space model are three: $r_{nn}^{rms}$, the root-mean-square $n$-$n$ distance ($\sqrt{6}r_0$); $P(^7\text{He})$, the probability of sequential decay through $^7\text{He}_{gs}$; and $\tau$, the neutron delay introduced by this resonance ($\sqrt{2}\tau_0$).

The Dalitz plot of the three-body decay after dissociation on a C target is shown in Fig. 3 as a function of the $n$-$n$ and $^6\text{He}$-$n$ invariant masses normalized to the available decay energy $E_d$ [11]. In the absence of interactions/correlations, the whole plot should be populated uniformly, and the projections should follow the dotted lines. On the other hand, the attractive $n$-$n$ interaction would overpopulate the low $m_{nn}^2$ part, and resonances due to the $^6$He-$n$ interaction would lead to horizontal bands [11].

The experimental Dalitz plot exhibits a clear crescent shape as a result of both interactions, a slight increase at low $m_{nn}^2$, and two horizontal bands at $m_{cn}^2 \sim 0.15$ and 0.85, leading to a depletion at the center. This is more easily observed in the projections of the plot shown on the same figure, where the slight increase towards $m_{nn}^2 = 0$ and the two peaks on the wings of the $m_{nn}^2$ distribution become more evident with respect to the expected phase-space distribution (dotted line). Both interactions are clearly present since none of them (dot-dashed and dashed lines) is able to reproduce the data on its own.

The probability of sequential decay can be easily extracted from the $^6\text{He}+n$ energy distribution, $E_{cn}$ in Fig. 4 thanks to the characteristic narrow peak of the ground state of $^7\text{He}$. The value obtained for the data on C target was $P(^7\text{He}) = 70 \pm 10\%$. Using this result, we have combined both decay scenarios, direct and
sequential, and varied the two parameters \((r_{nn}^\text{rms}, \tau)\) of \([8\text{ Eq. (16)}]\) describing the space-time characteristics of the neutron source. The determination of the values of \((r_{nn}^\text{rms}, \tau)\) that describe best the data has been undertaken through the calculation of the \(\chi^2\) between each simulation and the experimental distributions, leading to the \(\chi^2\) surface shown on the insert of Fig. 3. A clear minimum appears at \(r_{nn}^\text{rms} = 7.3 \pm 0.6 \text{ fm}\) and \(\tau = 1400 \pm 400 \text{ fm/c}\). The simulation corresponding to this minimum is represented by the solid line in the projections of Fig. 3.

The measured delay between the emission of the two neutrons in the sequential decay corresponds well to the expected scenario, the lifetime of the ground state of \(^7\text{He}\) \((1320 \pm 180 \text{ fm/c})\). Regarding the size of the \(n-n\) volume, it should be viewed as an average value for the \(^8\text{He}\) continuum states in the 0–5 MeV range beyond the \(^6\text{He}+n+n\) threshold \((S_{2n} = 2.1 \text{ MeV})\). We note that the principle exploited here is analogous to the one used in Ref. [21], in which the \(\chi^2\) between the experimental and theoretical \(C_{nn}\) was minimized in order to extract the size and lifetime of a compound nucleus [21 Fig. 2].

5. Direct decay and space

The dissociation on a Pb target lead to a smaller number of events, that prevented the Dalitz plot analysis or the construction of the \(\chi^2\) surface. Nevertheless, in Fig. 4 we have plotted the corresponding invariant masses in order to compare their shape to the ones obtained on C target. In fact, the two peaks observed in the \(m_{nn}^2\) distribution in Fig. 3 that come from the horizontal bands in the Dalitz plot and are the signature of the sequential part of the decay, disappear completely with the Pb target. Instead, we observe the single, wider central peak characteristic of direct breakup, together with a much stronger effect of the \(n-n\) FSI at low \(m_{nn}^2\), clearly above the expected phase-space distribution (dotted line). We note, however, that the decay energy spectrum is very similar to the one in Fig. 4 suggesting that we are populating the same continuum region in \(^8\text{He}\).

Therefore, if our analysis of the sequential decay on C is well founded, and with the Pb target we have been able to switch off the sequential branch, the data set on Pb should correspond to the 30% direct contribution extracted from the C set, with the same spatial parameters. For completeness, we have compared the Pb data to the simulations of direct breakup using \(P(7\text{He}) = 0\) and the spatial \(n-n\) configuration obtained, \(r_{nn}^\text{rms} = 7.3 \text{ fm}\) (Fig. 4). The very good agreement with the data suggests that the breakup into \(^6\text{He}+n+n\) on Pb target does populate states in the continuum of \(^8\text{He}\) in the same energy range and with similar spatial characteristics, but that decay mainly through the simultaneous emission of both neutrons. This different decay mode can be understood by the effect of the stronger Coulomb field of Pb [9], that by acting only on the core subsystem hinders the probability of core-\(n\) resonances (here \(^7\text{He}\)) being formed.

As a final check of the model we have constructed \(C_{nn}\), the observable chosen to parametrize the \(n-n\) FSI, for the dissociation on C target. Following Eq. [1], the experimental distribution \(\sigma(q_{nn})\) was divided by a \(\sigma_0(q_{nn})\) distribution obtained through event mixing, using the iterative technique described in Ref. [10]. The resulting ratio \(\sigma/\sigma_0\), the correlation function, is shown in Fig. 5. The dashed line corresponds to the analytical formula [8 Eq. (24)] for \(r_{nn}^\text{rms} = 7.3 \text{ fm}\), that rises up to a maximum of \(C_{nn}(0) \approx 11\) comparable to the values measured in Ref. [10]. If we use the more general formalism for values of \((r_{nn}^\text{rms}, \tau) = (7.3, 0)\) at 30% and \((7.3, 1400)\) at 70%, in fm and fm/c respectively, we obtain the solid line. The agreement with the data is remarkably good, confirming that the model does not only reproduce a general trend, but the details of the \(n-n\) space-time signal.

6. Conclusions and outlook

We have measured the dissociation of \(^8\text{He}\) into \(^6\text{He}+n+n\) on C and Pb targets. The analysis of triple correlations in the exit channel has given access, for the first time, to the spatial and temporal characteristics of the decay. The use of both targets has proven to be an efficient way to switch on and off the delay between the emission of both neutrons, by selecting a mostly
sequential (C) or a mainly direct (Pb) decay mode. The sequential channel is clearly identified through the population of the ground state of \(^{7}\)He, both in the \(^{6}\)He–n relative energy and invariant mass distributions, and represents 70\% in the case of the C target.

The analysis of the n–n FSI in the C target run leads to a Gaussian volume of \(r_{\text{max}}^n = 7.3 \pm 0.6 \text{ fm}\), corresponding to states in the continuum of \(^{8}\)He a few MeV beyond the \(^{6}\)He+n+n threshold, and to a delay between the emission of both neutrons of \(\tau = 1400 \pm 400 \text{ fm}/c\), consistent with the lifetime of \(^{7}\)He. These results are in agreement with the decay on Pb target, in which no \(^{7}\)He is observed, that is well reproduced using the same n–n volume without any delay. This represents a very stringent test of the technique as femtometer and chronometer of 2n decays. Concerning the spatial information, it would be interesting to compare the result obtained with theoretical calculations of the n–n distribution in the continuum of \(^{8}\)He, similar to those performed for the lighter isotope \(^{6}\)He [25]. However, as noted in the introduction, \(^{8}\)He is better described theoretically as a five-body system, with an \(\alpha\) core surrounded by four neutrons.

In this respect, it would be desirable to apply this technique to a nucleus that could be predominantly described as a three-body system, like a heavier two-neutron halo nucleus, but that at the same time possesses few, narrow states in the core-n subsystem. For example, \(^{17}\)B is considered to exhibit a two-neutron halo [26], and the unbound subsystem \(^{15}\)B seems to have only one low-lying \(^{15}\)B–n resonance that is extremely narrow, \(\Gamma \ll 100 \text{ keV}\) [27] [28]. That resonance, if populated through the sequential decay of \(^{17}\)B, would introduce a delay \(\tau \gg 2000 \text{ fm}/c\) that should strongly hinder any correlation in the n–n channel. We note that the breakup of \(^{17}\)B on C/Pb targets has been recently studied at RIKEN [29] using the SAMURAI–NEBULA detection system, and that the analysis of n–n correlations is in progress.

The reasons behind the sharp contrast in the interpretation of core-p-p and core-n-n final states is unclear. In the proton case, the microscopic structure of the 2p emitter, usually a narrow state, seems to govern the p-p distributions [4,16]. In the neutron case, the n–n distributions appear to be dominated by the effects of the s-wave n–n FSI [10,11,17,18,19,20,21,22,23]. However, one should note a common feature of all the neutron works, the fact that the systems were populated in a broad continuum of decay energies. It would be interesting to study these correlations in a core-n-n system with a well-defined energy, that could reveal the eventual breakdown of the model used here and/or the sensitivity to the microscopic structure of the 2n emitter, as in the proton case. Two such systems have been recently observed at RIKEN, the first excited state of \(^{19}\)B [30] and an excited state of \(^{20}\)F [31], only a few hundred keV above the corresponding 2n thresholds.

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