

Correlations in 2 and 3 particle decay

Haik Simon

*Institut für Kernphysik, Technische Universität Darmstadt
Schloßgartenstr. 9, D-64289 Darmstadt, Germany*

E-mail: h.simon@gsi.de

Abstract

Nuclear knockout reactions at relativistic energies provide a sensitive tool to determine the ground state properties of nuclei close to the drip line. Studies with kinematically complete measurements allow to reveal the initial correlations in the reacting systems as well as to yield spectroscopic informations on the continuum states populated in the unbound intermediate systems in the decay channel. The coincident data of charged fragments and neutrons allows to unveil as well the possible influence of the reaction mechanism to the interpretation of the measurements. Two- and three- body correlations can be observed and allow to determine the internal momentum distributions of halo nuclei as well as the assignment of spins and parities to the populated states in the intermediate systems in the breakup process.

1 Introduction and Experimental method

In this paper, we investigate the ground state properties of the Borromean nuclei ^{14}Be , ^{11}Li , $^{6,8}\text{He}$ and the unbound ^5H system. One-neutron knockout-reactions at high energy, used to study halo neutron momentum distributions via the recoiling $A - 1$ system, constitute a sensitive tool [1] to investigate the single-particle or cluster structure of the projectiles. For ^{11}Li , the $(1s_{1/2})^2$ admixture in the ground state configuration has been determined to be $(45 \pm 10)\%$ using this technique [2]. Similar studies [3, 4] allowed to extract spectroscopic factors for the lighter $^{11,12}\text{Be}$ isotopes and showed direct evidence for a vanishing neutron-shell closure for $N = 8$. This is further supported by the observation of large quadrupole deformation parameters for $^{10,12}\text{Be}$ in inelastic proton scattering experiments [5].

Reactions of a mixed beam consisting of $^{6,8}\text{He}$, ^{11}Li and ^{14}Be at beam energies of about 0.25 GeV/nucleon impinging on a carbon target have been performed. The secondary beams were produced at the accelerator complex of

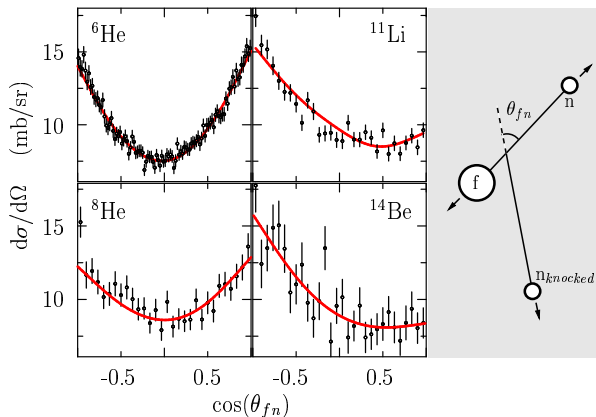


Figure 1: Differential cross section as function of the angle θ_{fn} between the momentum of the recoiling $A - 1$ system (sum of fragment (f) and neutron (n) momenta) and the relative momentum between fragment and neutron (difference of their momenta). Data are shown for the breakup products of ${}^6,8\text{He}$, ${}^{11}\text{Li}$, and ${}^{14}\text{Be}$. The solid lines represent polynomial fits in $\cos(\theta_{fn})$ to the data, including corrections for experimental effects.

the *Gesellschaft für Schwerionenforschung* (GSI), in a fragmentation reaction of a ${}^{18}\text{O}$ beam coming from the *Schwerionensynchrotron* (SIS). The secondary beam was then separated by magnetic rigidity analysis in the *Fragment Recoil Separator* (FRS) and transported to the *Aladin-LAND* reaction setup where the one proton or neutron knockout channels have been investigated. Advantageous in this case is that the momentum transfer in the reaction is small ($\lesssim 20 - 30$ MeV/c) and the data can be analyzed in the framework of the sudden approximation. The kinematically complete measurement allowed to reconstruct the relative momenta of all particles in the observed final states. Momentum distributions, relative energy spectra together with partial energy distributions (e.g. $\varepsilon = E_{nn}/E_{tnn}$) and angular correlations could thus be deduced in this experiment.

2 Results and discussion

2.1 Two-body correlations

We treat the sequential removal of two neutrons [6, 7] in analogy to γ - γ angular correlations [8]. The right hand side of Figure 1 defines the correlation angle θ_{fn} between the recoil direction of the intermediate $A - 1$ fragment in the

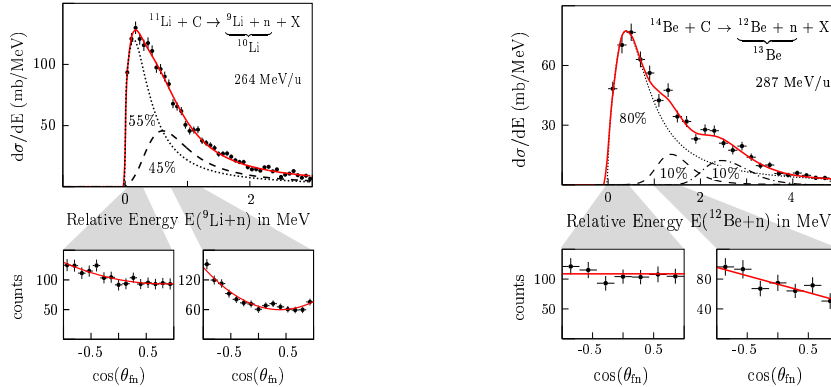


Figure 2: Upper panels: Relative energy spectra between ^9Li and ^{12}Be , and a decay neutron after the one-neutron knock-out reaction on ^{11}Li and ^{14}Be , respectively. The solid lines represent R-matrix fits to the data points. For the ground states the neutrons are assumed to be in a $\ell = 0$ (dotted line) motion relative to the respective cores. The dashed line shows the $0p_{1/2}$ resonance and, in case of ^{13}Be , the $0d_{5/2}$ resonance is drawn dashed-dotted. Lower panels: Relative energy-gated angular correlation functions for two different energy regions. They are predominantly isotropic, consistent with the assumption of s strength in the low energy regions (left parts). For the energy regions where the different parity states $1s_{1/2}$ and $0p_{1/2}$ in ^{10}Li and ^{13}Be contribute to the respective energy spectra, asymmetric angular correlations are observed (right parts).

projectile rest frame after neutron knockout and the relative motion between the charged fragment of mass $A - 2$ and the emitted neutron. To the extent the sudden approximation is valid, the recoil momentum of the intermediate fragment is just opposite to that of the knocked out neutron. Figure 1 thus shows the angular correlation for the sequential two-neutron breakup of ^{14}Be compared to similar data for $^6,^8\text{He}$ and ^{11}Li breakup. In ^6He one observes a parabolic distribution in $\cos(\theta_{fn})$ indicating an almost pure $(p_{3/2})^2$ groundstate with a 7% admixture of $(p_{1/2})^2$ [9]. Also the zero momentum transfer limit in Ref. [10] is fulfilled as the measured distribution is symmetric. In the breakup of ^8He , a similar shape of the correlation function is observed, but the more shallow distribution points to a more complicated structure of the groundstate wave function (e.g., $\alpha + 4n$) [11]. In contrast to the symmetric shapes for the He data, the distributions for Li and Be are skew.

The presence of both s and d components has been suggested for the ground state wave function of ^{14}Be both experimentally and theoretically. The formalism describing angular correlations, here for two-neutron removal, is well established [6, 8]. From that, the interpretation of the ^{14}Be case is straight-

forward without any further model assumptions: (i) The observed skewness proves the presence of intermediate states with different parity and the interference of either s and p waves or p and d waves or both. (ii) If only $s_{1/2}$ and $p_{1/2}$ states would be present, the maximum order of the polynomial in $\cos(\theta_{fn})$ would be one. The 2nd order contribution deviates significantly (two standard deviations) from zero, thus the interplay of a d wave seems to be indicated. (iii) The analysis of the angular correlation for relative energies near threshold (see below) clearly proves the presence of s waves. It can also be employed to determine relative weights of the s , p , (and d) components in the ^{11}Li and ^{14}Be ground state wavefunctions [12]. An analytical formula following the prescription in Refs. [6, 8] is used, also taking into account the relative phases of the different continuum states.

The energy spectra, shown in Figure 2, were fitted in an R-Matrix approach [13, 14], where the parameterization for the lowest s state was taken from Refs. [15, 16]. In the ^{10}Li case, the fit is consistent with a scattering state that can be characterized by a scattering length $a_s > -40$ fm. For ^{13}Be , however, the best fit gives complex roots in the S matrix for the s state. We have thus a resonance with $E_r = 0.3(2)$ MeV and a width $\Gamma_0 = 0.4(3)$ MeV in this case. This points to the fact that the structure of the ^{14}Be ground state is not a simple core plus two-neutron state. The structures above the ground state can be fitted with Breit-Wigner parameterizations, and resonance energies E_r and widths Γ_0 be extracted. In the ^{10}Li case, the spectrum is described with a p -wave resonance at $E_r = 0.68(10)$ MeV with a width of $\Gamma_0 = 0.87(15)$ MeV, while for ^{13}Be , two additional resonances are needed for a consistent description of the data. The energy and widths of these are $E_r = 1.4(1)$ MeV ($\Gamma_0 = 0.3(4)$ MeV) and $E_r = 2.3(2)$ MeV ($\Gamma_0 = 0.5(2)$ MeV) where we assign the lower resonance with a p state and tentatively the upper one with a d state [12]. At this energy a d state is proposed in all earlier references [17, 18, 19, 20].

The assumed configuration of the states is verified with help of the energy-gated angular correlation spectra shown in Figure 2, where the typical shapes for these components could be observed.

2.2 Three-body correlations: Example ^5H

Experimental studies of heavy hydrogen isotopes have recently attracted much interest and some intriguing results [21] have been reported. The structure of heavy hydrogen nuclei is expected to be similar to that of neutron-rich helium isotopes, i.e., an inert core (here triton) surrounded by valence neutrons. The weights of different configurations in the $t+n+n$ system were determined from experimental data, using a method proposed in Ref. [22]. It is based on a series

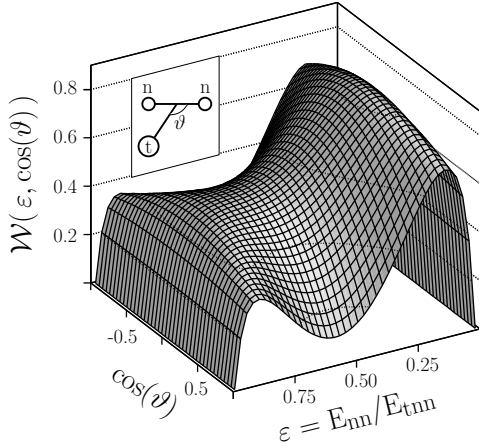


Figure 3: Two dimensional plot of the probability distribution $\mathcal{W}(\varepsilon, \cos(\vartheta))$, as given in Eq. (1) with amplitudes adjusted to the experimental data. The inset sketches the used coordinate system.

expansion of the final state wave function into hyperspherical harmonics and represents a three-body generalization of the expansion in spherical harmonics known from two-body systems. The data are presented in two different coordinate systems in momentum space: (i) the T system shown in the inset in Figure 3 where the lines point along the directions of the relative momenta of all involved particles in the center of mass and (ii) the Y system, where one of the two neutrons is exchanged with the triton. In both coordinate frames the explicit expression for the probability distribution, can be written as:

$$\mathcal{W}(\varepsilon, \vartheta) = \frac{4}{\pi} \sqrt{\varepsilon(1-\varepsilon)} \cdot \left\{ 8\varepsilon(1-\varepsilon) \sin^2 \vartheta \left| C_{1211} \right|^2 + \left| C_{0000} - 2(2\varepsilon-1)C_{0200} + 4\sqrt{\varepsilon(1-\varepsilon)}C_{0211} \cos \vartheta \right|^2 \right\}, \quad (1)$$

where $\mathcal{W}(\varepsilon, \vartheta)$ is normalized to unity. The transformation of the complex amplitudes $C_{SKl_x l_y}$ from T to Y coordinates and vice versa are fixed through Raynal-Revai coefficients. The projections $\int \mathcal{W}(\varepsilon, \vartheta) d\varepsilon$ and $\int \mathcal{W}(\varepsilon, \vartheta) d\cos(\vartheta)$ were fitted to the data in both coordinate systems. As result, the $C_{SKl_x l_y}$ were determined and the corresponding probability distribution $\mathcal{W}(\varepsilon, \cos(\vartheta))$ is shown in Figure 3. The strongest component in the mixed ground state configuration is related to spin and parity $J^\pi = 1/2^+$. This observation is in agreement with recent theoretical work [23], and is further supported by direct comparison of calculated and measured energy spectra of the $t+n+n$ system. The current work [24] presents a successful application of hyperspherical harmonics to the analysis of few body continuum states. The method can readily be extended to reveal information about the three-body continuum structure of heavier exotic nuclei, e.g., ^{11}Li and ^{14}Be .

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