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2014 J. Phys.: Conf. Ser. 569 012033

(http://iopscience.iop.org/1742-6596/569/1/012033)

Structure and decay correlations of two-neutron systems beyond the dripline

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Abstract. The two-neutron unbound systems of ^{16}Be, ^{13}Li, ^{10}He, and ^{26}O have been measured using the Modular Neutron Array (MoNA) and 4 Tm Sweeper magnet setup. The correlations of the 3-body decay for the ^{16}Be and ^{13}Li were extracted and demonstrated a strong correlated enhancement between the two neutrons. The measurement of the ^{10}He ground state resonance from a ^{14}Be($-2p2n$) reaction provided insight into previous predictions that wavefunction of the entrance channel, projectile, can influence the observed decay energy spectrum for the unbound system. Lastly, the decay-in-target (DiT) technique was utilized to extract the lifetime of the ^{26}O ground state. The measured lifetime of $4.5^{+1.1}_{-1.5}$ $(stat.) \pm 3 (sys.)$ ps provides the first indication of two-neutron radioactivity.

1. Introduction

The addition or removal of neutrons from stable isotopes has been shown in many cases to drastically alter the structure and properties of the nucleus [1–6]. Radioactive-ion beam facilities have made it possible to produce and study these exotic nuclei existing far from stability. Furthermore, techniques such as invariant-mass spectroscopy can allow for the study of nuclei that exist beyond the driplines providing a view into systems with the most extreme neutron-to-proton ratios (N/Z) possible.

These exotic dripline nuclei can exhibit unique types of decay which can offer additional insight into the structure of the nucleus. For example, Goldansky was the first to propose that the simultaneous emission of two protons could be observed given a scenario in which the intermediate state was positioned above the initial state [7]. Studies of two-proton decays have confirmed the presence of the direct two-proton decay mechanism and also presented more complex mechanisms, in some cases termed democratic decays, in which the intermediate state is very broad [8]. Therefore, the decay is not truly sequential or direct. Insight into the decay mode and wavefunction of the two-proton unbound system can be accessed through comparison of the measured and theoretical 3-body correlations [6, 9]. This provides a powerful tool for exploring nuclei beyond the proton dripline.

The discovery of the two-neutron halo system, ^{11}Li, initiated significant interest in the correlations within the 3-body system ($n+n+core$) [10]. Theoretical calculations have indicated that there is a strong dineutron component to the wavefunction of the two-neutron halo nuclei. Experimental measurements of the low-lying dipole strength distribution of ^{11}Li [11] and the ^{9}Li momentum distribution following a two-neutron knockout from ^{11}Li [12] provide support for a dineutron-like configuration. Two-neutron unbound systems provide a unique system in which the correlations of the neutrons from the ground state decay can be measured. The MoNA collaboration has developed a program to explore nuclei existing two neutrons beyond the dripline. Much like the unbound two-proton systems, measurements of the 3-body decay correlations should provide a connection to the wavefunction of the two-neutron unbound nucleus. In the following proceedings, the results from the MoNA collaboration measurements of the ^{16}Be [13], ^{13}Li [14], ^{10}He [15], and ^{26}O [16, 17] two-neutron unbound systems are presented.

2. Experiment

The Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University was used to produce radioactive ion beams at energies between 50-80 MeV/u. The two-neutron unbound nuclei of interest were then populated from reactions with the radioactive beams. The details of each experiment discussed in the proceedings are presented in Table 1.

Table 1. Details of the experiments for the measurements of the two-neutron unbound nuclei.

Unbound nucleus	Primary beam	Secondary beam	Reaction target	Secondary beam rate	Ref.
^{16}Be	120 MeV/u ^{22}Ne	53 MeV/u ^{17}B	470 mg/cm^2 ^{9}Be	250 pps	[13]
^{13}Li	120 MeV/u ^{18}O	53.6 MeV/u ^{14}Be	477 mg/cm^2 ^{9}Be	500 pps	[14]
^{10}He	120 MeV/u ^{18}O	59 MeV/u ^{14}Be	435 mg/cm^2 CD_2	1000 pps	[15]
^{26}O	140 MeV/u ^{48}Ca	82 MeV/u ^{27}F	705 mg/cm^2 ^{9}Be	14 pps	[16, 17]

Coincident detection of the two neutrons and the residual fragment from the decay of the two-neutron unbound system was accomplished using the modular neutron array (MoNA) [18, 19] and the large gap 4 Tm sweeper magnet [20]. The large area neutron detector, MoNA, is composed of 144 plastic scintillator bars. Light guides and photomultiplier tubes are attached to the ends of each bar for detection of the light produced from the interaction of the neutron(s).

The detector bars measure 200 cm × 10 cm × 10 cm each and the array is typically configured with 9 walls, each 16 bars high. The time-of-flight (ToF) of the neutrons to MoNA is measured with respect to a scintillator placed in front of the target. The angle and energy of a neutron can be determined from the interaction point in the detector bar and the ToF, respectively. The sweeper magnet bends the charged particles ∼43° into a suite of position sensitive charged-particle detectors. Both the particle identification and kinematical properties of the charged fragments can be determined from the sweeper magnet detectors (see Ref. [21] for more details). From the measured energy and angle of the neutrons and charged particle, the invariant mass of the 3-body system can be calculated. A detailed Monte Carlo simulation has been developed to simulate the production and decay of the unbound nuclei. While a general discussion of the Monte Carlo simulation is provided in Refs. [21, 22], the simulation of the neutron interactions in MoNA is of particular importance. The MoNA simulation is built upon the Geant4 framework [23, 24], which allows for the tracking of each neutron interaction throughout the array. A custom neutron interaction model, referred to as menate_r [25, 26], was incorporated into the Geant4 framework and allowed for discrete inelastic neutron-carbon interactions to be simulated based on experimental cross sections [22]. The inclusion of menate_r demonstrated a drastic improvement in the ability of the simulation to reproduce experimental neutron scattering [22]. In the following, all the experimental results have had a "causality cut" applied to the data to isolate events in which the first two interactions in MoNA represent true two neutron events. The causality cuts are based on the relative distance and velocity of the first two hits in MoNA (additional details about the cuts for each experiment can be found in Refs. [13–17, 22]).

3. 3-body correlations in the decay of ^{16}Be and ^{13}Li

Measurements of the ground state resonances for ^{16}Be and ^{13}Li indicated that both systems should exhibit a direct two-neutron decay since a sequential decay would be energetically forbidden due to the location of the intermediate states [14, 27, 28]. This offers a unique opportunity to examine the correlations of the two neutrons that are emitted directly from the ground state of the nucleus. The 3-body correlations are described within the Jacobi coordinate system defined in Fig. 1. A complete description of the three-body correlations can be obtained from the relative energy (E_x/E_T) and the angle (θ_k) calculated within the **T** and **Y** Jacobi systems [29, 30]. The relative energy is defined as the energy of the two-body system (frag+n or n+n), E_x, relative to the total three-body energy, E_T.

In Fig. 2 the relative energy and angle for both the **T** and **Y** systems are shown from the experimental data of the ^{13}Li and ^{16}Be ground state decays. The 3-body correlations of the

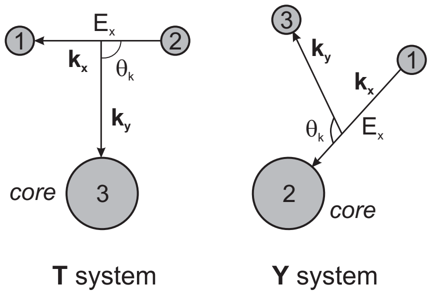

Figure 1. Depiction of the Jacobi coordinate system. In the **T** system θ_k is defined as the angle between the core and neutron-neutron center-of-mass and E_x is the relative energy of the neutron-neutron system. In the **Y** system θ_k is defined as the angle between the neutron-core and the other neutron and E_x is the relative energy of the neutron-core system.

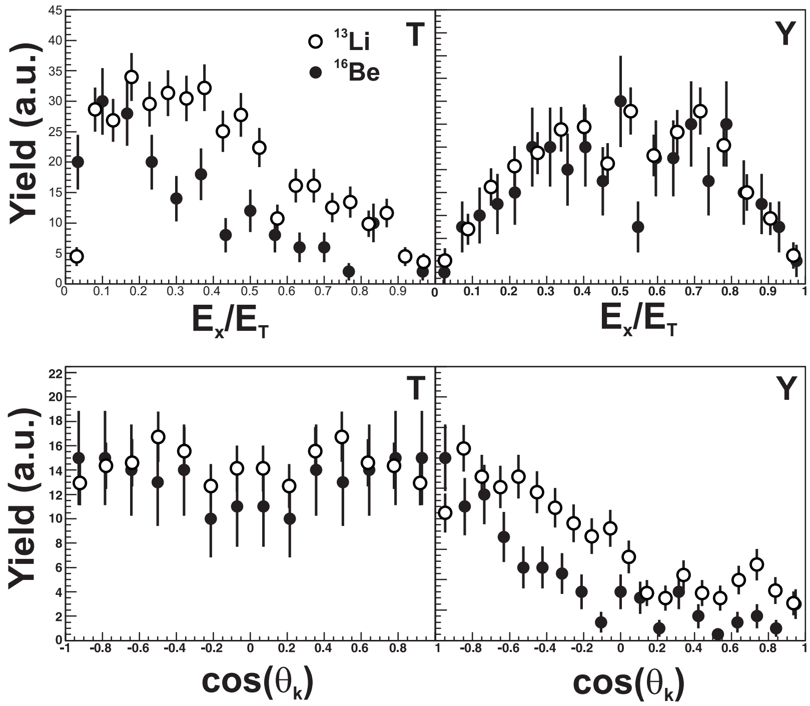

Figure 2. The relative energy (E_x/E_T) and angle ($\cos(\theta_k)$) as defined in the **T** and **Y** systems are shown for the experimentally measured decay of ^{13}Li (open circles) and ^{16}Be (closed circles).

two systems show a striking similarity with nearly identical features throughout the Jacobi coordinate plots. Of particular interest is the relative energy in the **T** system and $\cos(\theta_k)$ in the **Y** system which define the energy of the neutron-neutron system and the angle of each neutron relative to the neutron-core system, respectively. Therefore, these two observables are sensitive to the correlations between the neutrons. For both the ^{13}Li and ^{16}Be there is an enhancement in events with low E_x/E_T in the **T** system and for events with $\cos(\theta_k)$ near -1. These results indicate that the emitted neutrons are correlated in both energy and angle.

Further insight into the measured correlations can be garnered from the comparison with simulations of different decay modes. In Fig. 3, the experimental relative energy distribution from the **T** system, corresponding to the neutron-neutron energy, is shown in comparison to simulations for a 3-body phase-space [31, 32] and dineutron decay [14]. While the two simulations represent extreme cases, where the neutrons have no interaction (phase-space) and where the neutrons are emitted as a pair (dineutron), they can provide a general indication as to how the emission occurs. Both the ^{16}Be and ^{13}Li data are well reproduced by the dineutron decay, while the 3-body phase-space simulation significantly underpredicts the low energy portion of the distributions. The neutron-neutron energy from the dineutron simulation is governed by the nn scattering length (a_s). Simulations with the typical nn-scattering length of -18.7 fm and an increased value of -100 fm are shown. Particularly in the ^{16}Be case, the larger scattering length (increased neutron-neutron correlation) provides a better description of the data.

While the results demonstrate a strongly correlated emission of the neutrons, a full 3-body theoretical calculation is required to make the connection between the wavefunction of the unbound system and the correlation observed in the decay. It cannot be assumed that the observation of the dineutron-like decay is evidence of the existence of a dineutron in the ground state of the unbound system. However, theoretical calculation for dripline nuclei, such as ^{11}Li and ^{18}C [33, 34], as well as unbound nuclei, such as ^{26}O [35], do predict that the ground state wavefunction would contain a strong dineutron component.

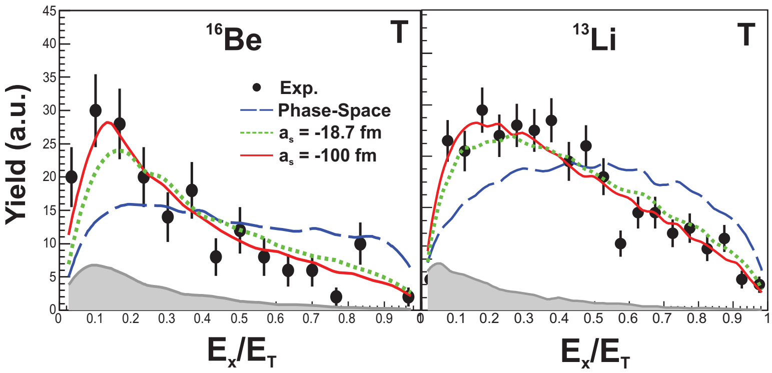

Figure 3. (Color online) Relative energy distribution, E_x/E_T, in the **T** system from the measured ^{16}Be and ^{13}Li decays. Simulations for the 3-body phase space and dineutron decay (represented by the nn-scattering length, a_s) are shown as the dashed and solid lines. The grey region represents the component of the distribution, determined from the dineutron simulation, that is from false two neutron hits.

4. Entrance-channel effects in population of ^{10}He

Recently, Grigorenko *et al.* suggested that the measured energy of a neutron unbound state energy can be "shifted" relative to the true energy of the state in cases where the state is populated from halo nuclei [36–39]. The argument is that the time-scale for the population and decay of a broad unbound state is so short that a component of the initial extended wavefunction of the halo projectile is observed in the outgoing channel. Therefore, the measured decay energy spectrum is modified due to the entrance channel wavefunction. If this theory can be verified, it would have profound impact on previous and future measurements of unbound neutron-rich nuclei populated from halo nuclei.

The two-neutron unbound ^{10}He nucleus has become the "test case" for this theory since it has been populated and measured using different reaction mechanisms, as shown in Fig. 4, and has a large resonance width ($\Gamma \sim$1.8 MeV). The determination of the ground-state energy of ^{10}He has sparked some controversy due to inconsistent experimental measurements. At the JINR in Dubna, the missing mass spectrum of ^{10}He was measured using a ^{8}He(t, p) transfer reaction by Golovkov in 2009 [37] and an updated measurement was completed by Sidorchuk in 2012 [38]. The results of these experiments (shown as solid stars in Fig. 4) indicate a ^{10}He ground state resonance above 2 MeV. In contrast, the GSI-LAND group measured the ^{10}He invariant mass using a 1-proton knockout from ^{11}Li and reported a g.s. resonance energy of 1.54 MeV [40]. This measurement along with other ^{11}Li$(-p)$ experiments are shown in Fig. 4 as open circles. An extended discussion of the different measurements can be found in Ref. [15]. A large discrepancy of about 500 keV remains between the transfer reaction measurements and the one-proton knockout reactions from ^{11}Li. This discrepancy was reconciled through the theoretical calculations of Grigorenko and Zhukov, which showed that the observed peak in the ^{10}He spectrum depends on the reaction mechanism and source size or wavefunction of the projectile [36]. Thus, the observed energy spectrum from the ^{11}Li$(-p)$ is shifted down in energy, while the mechanism of the transfer reaction does not perturb the observed energy spectrum.

The MoNA collaboration measured the ^{10}He ground state resonance using a ^{14}Be$(-2p2n)$ reaction and proposed that this would not exhibit a shifted energy spectrum due to the more complex $2p2n$-removal reaction [15]. Therefore, the ^{10}He g.s. measured from the ^{14}Be($-2p2n$) reaction should be around 2 MeV if the predictions of Grigorenko and transfer reaction measurements were correct. Instead, the ^{10}He g.s. measured from the ^{14}Be($-2p2n$) was observed at 1.6 MeV (see Fig. 4). This suggests that the measured unbound resonance was not dependent on the reaction mechanism or incoming wavefunction. However, new theoretical calculations have shown that the halo component of the ^{14}Be nucleus, even in a $2p2n$-removal, could also create a shift in the ^{10}He energy spectrum [39]. Thus, the situation is not resolved as to whether the observed decay energy spectra of neutron unbound nuclei, specifically ^{10}He, can be modified by unique reaction mechanisms involving halo nuclei. It is worth noting that Fortune proposed another explanation for differences observed in the ^{10}He g.s. measurements based on the prediction that ^{10}He has two low-energy 0^+ states [41]. Fortune suggests that the differences in the measured g.s. energies could be due to different relative populations of the ground and excited 0^+ states which would be dependent on the p and sd components of the projectile wavefunctions. Further investigation of this open question is needed.

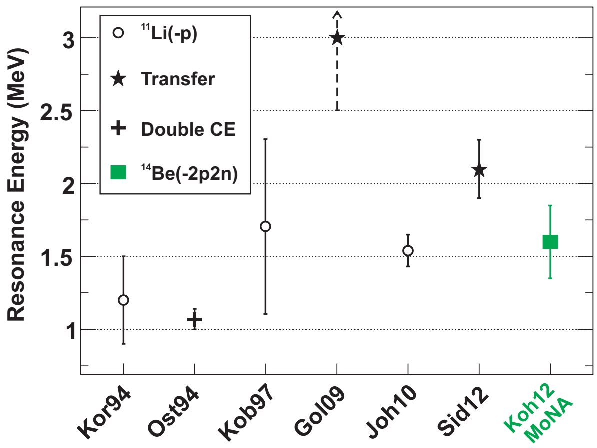

Figure 4. (Color online) Compilation of experimental measurements of the ^{10}He ground state resonance. The reaction mechanism used to populate ^{10}He is described in the legend. The associated references for each entry are: Kor94 [42], Ost94 [43], Kob97 [44], Gol09 [37], Joh10 [40, 45], Sid12 [38], and Koh12 [15].

5. Evidence of two-neutron radioactivity in ^{26}O

The ground state of the two-neutron unbound ^{26}O was measured for the first time at the NSCL using a one-proton knockout reaction from a ^{27}F beam. The ground state decay energy was constrained to be less than 200 keV [16]. Further experimental results from GSI-LAND have constrained this value to <120 keV [46]. Theoretical predictions had indicated that if ^{26}O had a purely $[d^2]$ configuration that the lifetime for such a low decay energy could be on the order of picoseconds [47]. This suggested that ^{26}O could provide the first case for the discovery of two-neutron radioactivity.

A new technique to determine the half-life was developed, termed Decay in Target (DiT), in which the relative velocity between the ^{24}O fragment and two neutrons was used as a probe for the distance the ^{26}O fragment traveled within the target [48]. Assuming a more typical unbound system, the decay should occur immediately ($\sim 10^{-21}$s), as shown in the top of Fig. 5(a). If the ^{26}O has a finite lifetime then the ^{26}O would traverse through part of the target before decaying (bottom of Fig. 5(a)). Therefore, the relative velocity between the ^{24}O and two neutrons should be dependent on the lifetime of ^{26}O. The relative velocity spectrum (V_{rel}) is shown in Fig. 5(b) compared with simulations for how the shape and location of the distribution would change as a function of lifetime. The results indicate that a 0 ps decay time is not the best fit. The distribution is shifted away from $V_{rel} = 0$ and is better reproduced by a lifetime around 4 ps. An unbinned maximum likelihood technique was employed to determine the statistical significance of the results [21, 49] and the reported lifetime of ^{26}O was $4.5^{+1.1}_{-1.5}$ $(stat.) \pm 3(sys.)$ ps. This represents the first evidence for new mode of radioactive decay: two-neutron radioactivity.

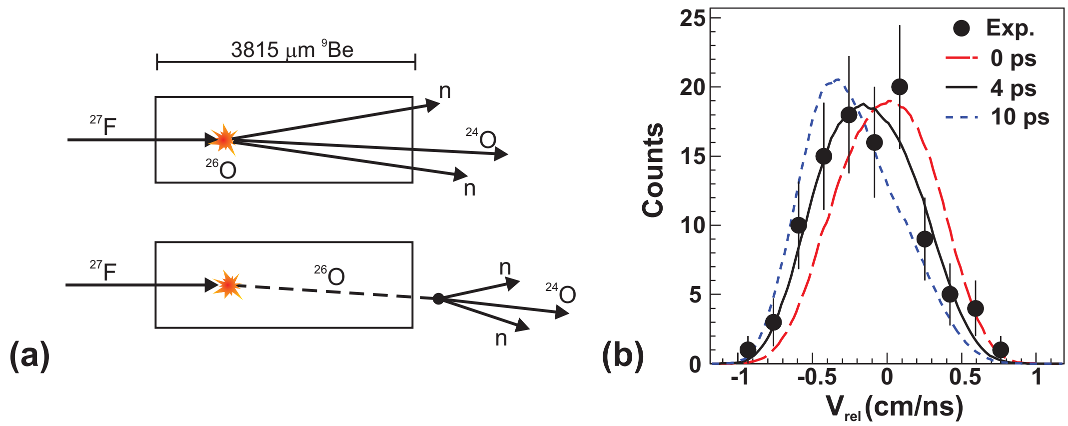

Figure 5. (Color online) (a) Illustration of the DiT technique. (b) Relative velocity spectrum for the ^{24}O fragment and two-neutrons from the decay of the ^{26}O ground state.

6. Conclusions

The exploration of neutron unbound systems beyond the dripline provides access to nuclear matter with neutron excess and, therefore, new phenomena can occur and be studied. The recent two-neutron decay studies of the MoNA collaboration have examined the 3-body decay correlations resulting from the two-neutron emission from the ground states of ^{16}Be and ^{13}Li, the predicted entrance-channel effects of populating neutron unbound systems from halo nuclei in population of ^{10}He from ^{14}Be, and the possibility for two-neutron radioactivity within the ^{26}O system. In all cases further investigation is required to gain a more complete understanding of the results. For example, full 3-body decay calculations are strongly encouraged which would allow for improved understanding of the strong neutron-neutron correlations observed in the decays of ^{16}Be and ^{13}Li. In particular, this would offer the opportunity to possibly connect the observed correlations to information about the ground state wavefunction of these systems. It will also be extremely important in the future to remeasure the ^{26}O lifetime with higher statistics to confirm the existence of two-neutron radioactivity.

Acknowledgements

The authors gratefully acknowledge the support of the NSCL operations staff for providing a high quality beam. This work was supported by the National Science Foundation under Grant No. PHY11-02511.

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