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Exotic Clustering and Halo States in $^{12,14}\text{Be}$

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The nuclei ^{12}Be and ^{14}Be have been investigated using breakup reactions on p, ^{12}C and ^{208}Pb targets. The decay of ^{12}Be into two helium clusters ($^6\text{He}+^6\text{He}$ and $^4\text{He}+^8\text{He}$) was observed from a series of excited states between 10 and 25 MeV with spins in the range 4 to $8\hbar$, consistent with a deformed "molecular" structure. In the case of ^{14}Be , narrow forward peaked single-neutron angular distributions were observed for the breakup to ^{12}Be . Analysis of the associated neutron-neutron correlations indicate an RMS separation for the halo neutrons of around 5 fm.

1. Introduction

Clustering has long been known to play an important role in the structure of light nuclei [1]: ^8Be is, for example, well described within the framework of an $\alpha\alpha$ cluster model. This underlying cluster structure manifests itself in neighbouring nuclei, which may be described in terms of a two-centre shell model in which the valence nucleons occupy molecular type orbitals. In ^{10}Be , states close to the $\alpha + \alpha + 2n$ threshold can be described in terms of "covalent" bonding between the α -centres ($\alpha : 2n : \alpha$) [2]. For even larger neutron numbers more exotic clustering may occur. In particular, $\alpha\alpha + 4n$ related structures have been predicted in ^{12}Be in the region of 12 MeV excitation energy [3].

The heaviest particle stable Be isotope ^{14}Be ($S_{2n} = 1.34 \pm 0.11$ MeV) is Borromean and known to exhibit a two-neutron halo — that is clustering into a core (^{12}Be) and two valence nucleons forming an extended spatial distribution. In contrast to other halo systems ($^6,^8\text{He}$, ^{11}Li , ^{11}Be), the configuration of the valence neutrons is expected to contain a significant d-wave admixture. Additionally, ^{14}Be is the heaviest two-neutron halo nucleus currently known. The investigation of ^{14}Be thus provides an opportunity to study the evolution of halo systems with mass, angular momentum and binding energy.

2. Experiments and Results

The secondary beams of $^{12,14}\text{Be}$ ($\overline{E}_{^{12}\text{Be}} = 31.5$ MeV/nucleon, $i \approx 2 \cdot 10^4$ pps, $\overline{E}_{^{14}\text{Be}} = 41.3$ MeV/nucleon, $i \approx 10^2$ pps) were prepared via the fragmentation of an $^{18}\text{O}^{8+}$ beam (63

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Figure 1. Reconstructed ^{12}Be excitation energy spectra: (a) $^6\text{He}+^6\text{He}$ for proton and carbon recoils and $^8\text{He}+^4\text{He}$ for (b) carbon and (c) proton recoils.

MeV/nucleon, $2\mu\text{Ae}$) on a thick Be target using the LISE3 spectrometer. In the case of the ^{14}Be studies, measurements were carried out on secondary reaction targets of carbon and lead ($\overline{E}_{^{14}\text{Be}} = 35$ MeV/nucleon at target mid-point) in order to disentangle the effects of nuclear and Coulomb induced breakup. For the ^{12}Be measurements, ^{12}C and $(\text{CH}_2)_n$ target foils were used, with beam tracking and time-of-flight measurements provided by parallel plate avalanche counters. The breakup of the ^{12}Be nucleus into two helium fragments was detected using an array of ten Si-CsI telescopes placed around the beam axis. The silicon elements were two-dimensional position sensitive detectors, allowing the angles of the outgoing fragments to be determined to better than 0.5° . The telescopes provided for the identification of the $^4,^6,^8\text{He}$ nuclei of interest, and a measurement of the energies with a resolution of 1.5%.

For the ^{14}Be experiment the charged reaction products were detected using the Si-CsI array with one of the elements placed at zero degrees. Neutrons were detected using the 99 modules of the DEMON array. A staggered arrangement for the neutron detectors was chosen so as to maximize the coverage at forward angles whilst minimizing the effects of cross talk (both geometrically and in the off-line analysis).

2.1. ^{12}Be Breakup

The Q-values for the reactions $^{12}\text{C}(^{12}\text{Be}, ^x\text{He}^y\text{He})^{12}\text{C}$ and $p(^{12}\text{Be}, ^x\text{He}^y\text{He})p$ were derived from the energies of the two helium nuclei and the energy of the undetected recoil inferred from the measured momenta of the beam particle and reaction products. In the case of the $(\text{CH}_2)_n$ target this technique was able to resolve the reactions taking place on the carbon and hydrogen. After selecting events identified with peaks in the Q-value spectra for the above reactions, the excitation energy (or invariant mass) of the ^{12}Be nucleus prior to decay was calculated as,

$$E_x = \frac{1}{2}\mu v_{\text{rel}}^2 + Q_{\text{bu}}$$

${}^6\text{He}+{}^6\text{He}$	E_x [MeV]	13.2	14.9	16.1		17.8 18.6 19.3	20.9	22.8
	J	4		6		6	8	
${}^8\text{He}+{}^4\text{He}$	E_x [MeV]	12.1 13.0 13.9	14.7		16.6		20.8	
	J	4						

Table 1

Excitation energies and deduced spins for states observed in the ${}^6\text{He}+{}^6\text{He}$ and ${}^8\text{He}+{}^4\text{He}$ decay channels [4]. The absolute uncertainty in the excitation energies is 0.5 MeV and the statistical uncertainty typically < 0.4 MeV.

Channel	$\sigma_{\text{telescope}}$ [mb]		Γ_n [MeV/c]	
	C	Pb	C	Pb
${}^{12}\text{Be}$	460 ± 40	2300 ± 400	—	—
${}^{12}\text{Be}+n$	—	—	78 ± 6	80 ± 1
${}^{11}\text{Be}$	85 ± 15	—	—	—
${}^{10}\text{Be}$	145 ± 20	—	—	—
${}^{10}\text{Be}+n$	—	—	120 ± 40	—

Table 2

Preliminary results for the breakup of ${}^{14}\text{Be}$ on C and Pb targets. The neutron angular distributions have been characterized in terms of a Lorentzian distribution.

where v_{rel} is the relative velocity of the two breakup fragments, μ the reduced mass and Q_{bu} the breakup Q-value — 10.11 MeV for ${}^6\text{He}+{}^6\text{He}$ and 8.95 MeV for the ${}^8\text{He}+{}^4\text{He}$ channel. The ${}^{12}\text{Be}$ excitation energy spectrum for decays into two ${}^6\text{He}$ nuclei is shown in figure 1a, where a number of states may be seen in the range $10 < E_x < 25$ MeV. Evidence is also seen for the same states in the ${}^8\text{He}+{}^4\text{He}$ decay channel (figures 1b,c). Angular correlations constructed for the breakup products suggest spin assignments from 4 to $8\hbar$ (Table 1). The resulting excitation energy-spin systematics exhibit the characteristics of a rotational band with a large moment of inertia ($\hbar^2/2I = 150\pm40$ keV) consistent with that of a deformed ${}^6\text{He}+{}^6\text{He}$ "molecule". Measurements of the associated partial decay widths are, however, required to confirm the identification with an $\alpha - 4n - \alpha$ structure. Further details may be found in ref. [4].

2.2. ${}^{14}\text{Be}$ Breakup

The ${}^{14}\text{Be}$ reaction cross sections derived from the telescope data confirm that the two-neutron removal channel is dominant (as seen in an earlier experiment [5]), while the single-neutron angular distributions exhibit the narrow, forward peaked form characteristic of a halo (Table 2). Interestingly the widths of the distributions for the two targets are very similar and thus may suggest, as in the case of ${}^{10,11}\text{Li}$ [6], the existence of a very low-lying state in ${}^{13}\text{Be}$. The analysis of the ${}^{12}\text{Be}+n$ invariant mass spectrum, presently underway, should shed further light on this conjecture. The ${}^{12}\text{Be}+n+n$ invariant mass spectrum is being investigated in parallel with the objective of extracting the low-lying

Figure 2. Two-neutron correlation function for neutrons arising from the dissociation of ^{14}Be . The solid line is a fit assuming a Gaussian source [7].

dipole strength function, $dB(E1)/dE_x$. Preliminary results indicate a significant amount of strength in the region of ~ 1 MeV. Additionally, no velocity shift is observed at the present stage of analysis between the outgoing core and neutrons.

The neutron-neutron structure of the halo has been explored using intensity interferometry. Importantly it has been found that the usual procedures applied for constructing the associated correlation function are not valid for halo neutrons. Using a new iterative technique an estimate of the neutron-neutron separation has been derived from the measured $^{12}\text{Be} + n + n$ coincidences [7]. An RMS value of 5.4 ± 1.0 fm was found assuming a Gaussian source.

The ensemble of results arising from these analyses are expected, when compared with realistic three-body models, to provide important insights into the halo structure of ^{14}Be .

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