The Halo of $^{14}$Be

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Abstract

The two-neutron halo nucleus $^{14}$Be has been investigated in a kinematically complete measurement of the fragments ($^{12}$Be and neutrons) produced in dissociation at 35 MeV/nucleon on C and Pb targets. Two-neutron removal cross-sections, neutron angular distributions and invariant mass spectra characteristic of a halo were observed and the electromagnetic (EMD) contributions deduced. Comparison with three-body model predictions indicate that the halo wavefunction contains a large $\nu(2s_{1/2})^2$ admixture. The EMD invariant mass spectrum exhibited a relatively narrow structure near threshold ($E_{\text{decay}} = 1.8 \pm 0.1$ MeV, $\Gamma = 0.8 \pm 0.4$ MeV) consistent with a soft-dipole excitation.

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The size and distribution of matter in the nucleus have long played a central role in nuclear physics. Indeed, such gross properties reflect the combined effects of many fundamental aspects of nuclei. For the stable nuclei, measurements employing conventional probes, such as high energy electron and hadron scattering, have shown that the neutron and proton distributions exhibit essentially identical radii [1]. In contrast, for some light nuclei far from stability, which combine a large neutron excess with very weak binding, large differences have been found. Such “halo” systems are well described by a core, resembling a normal nucleus, surrounded by an extended valence neutron density distribution [2].

In general terms the halo may be regarded as a threshold phenomenon whereby the loosely bound valence neutrons tunnel with significant probability into the classically forbidden region outside the core potential. Within a simple quasideuteron description, the extent of the halo is governed by the separation energy and reduced mass of the system [3]. Under more realistic considerations the development of the halo is also influenced by the centrifugal barrier [4]. In the cases of $^{6,8}$He, $^{11}$Be, and $^{11}$Li, which have been investigated experimentally in considerable detail, the valence neutrons occupy the $2s_{1/2}$ and/or $1p_{3/2,1/2}$ single-particle orbitals. In $^{14}$Be the configuration of the halo neutrons would, in a naïve shell model prescription, be $\nu(d_{5/2})^2$. Sophisticated models suggest, however, that a $\nu(s_{1/2})^2$ admixture is also present [5-8]. Unfortunately, a paucity of experimental data [9-11] has precluded the elucidation of the structure of $^{14}$Be beyond the matter radius [12-15]. Compared to the other halo systems, the comparatively strong binding of the valence neutrons in $^{14}$Be ($S_{2n}=1.34\pm0.11\text{MeV}$ [6,7]) combined with the $\nu(d_{5/2})^2$ component may provide a new window on continuum excitations, including the long sought-after Soft-Dipole Resonance (SDR) [18,19].

The goal of the present study was thus to explore the halo structure and continuum excitations of the two-neutron halo nucleus $^{14}$Be. The tool chosen was a kinematically complete measurement of the fragments ($^{12}$Be and two neutrons) from the dissociation of an intermediate energy beam of $^{14}$Be on C and Pb targets. Such a measurement allowed the two-neutron removal cross sections, neutron angular distributions and invariant mass
spectra to be extracted (the results of an analysis of the neutron-neutron correlations have been presented elsewhere \[20\]). The use of C and Pb targets permitted the electromagnetic component of the dissociation (EMD) to be deduced.

The $^{14}$Be beam (∼130 pps) was prepared using the LISE3 spectrometer and a 63 MeV/nucleon $^{18}$O primary beam bombarding a thick Be production target. The mean energy of the beam at the mid-point of the secondary breakup targets was 35 MeV/nucleon. The energy spread in the beam was 10% and was compensated for by a time-of-flight (TOF) measurement over a 24 m flight-path between a parallel-plate avalanche counter (PPAC) located at the first focus of the spectrometer and the beam identification Si-detector. The beam particles were tracked onto the breakup targets (C 275 mg/cm$^2$, Pb 570 mg/cm$^2$) using two position sensitive PPAC’s (resolution FWHM ≈ 1-2 mm). Owing to the mixed nature of the secondary beam (50 % $^{14}$Be) the incoming ions were identified on a particle-by-particle basis using the TOF information combined with the energy loss derived from a Si-detector (300 µm) located just upstream of the target. The charged fragments from breakup were identified using a large area (5×5 cm$^2$) position sensitive (FWHM ≈ 0.5 mm) Si-CsI telescope (Si 500 µm, CsI 2.5 cm) centred at zero degrees and located 11.4 cm downstream of the target. The energy response of the telescope (FWHM = 1.5%) was calibrated using various mixed secondary beams containing $^{12}$Be with energies straddling that expected for $^{12}$Be fragments arising from the dissociation of $^{14}$Be. In order to account for events arising from reactions in the telescope, data was also acquired without a reaction target with the beam energy reduced by the amount corresponding to the energy loss in the C and Pb targets.

The neutrons emitted at forward angles were detected using the 99 elements of the DéMoN array \[21\]. The array covered angles between $+13^\circ$ and $-40^\circ$ in the horizontal plane and $\pm 14^\circ$ in the vertical with the modules arranged in a staggered configuration at distances between 2.5 and 6.5 m from the target \[21\]. Such a geometry provided for a relatively high two-neutron detection efficiency (1.5%) whilst reducing the rate of cross-talk — both intrinsically and via the use of an off-line rejection algorithm — to negligible levels \[21,22\]. A threshold of 15 MeV on the neutron energy was applied in the off-line analysis.
to eliminate contamination from the small number of evaporation neutrons arising from the target.

The results obtained for the two-neutron removal cross sections, $\sigma_{-2n}$ ($^{12}\text{Be}$ identified in the telescope), the single-neutron angular distributions, $d\sigma/d\Omega$ ($^{12}\text{Be}$ and neutron), and the associated angle integrated (0-40°) cross sections, $\sigma_n$, are displayed in table I and figure 1a. In addition, the average neutron multiplicities have been derived ($\langle m_n \rangle = \sigma_n/\sigma_{-2n}$) and are also listed. The single-neutron angular distributions are well characterised by a Lorentzian lineshape [9,22] and the corresponding momentum width parameters, $\Gamma_n$, have been tabulated. The large neutron removal cross sections and relatively narrow neutron distributions, while not as pronounced as for $^{11}\text{Li}$ [9], clearly indicate the halo character of $^{14}\text{Be}$. The present results improve considerably on the earlier measurements of Riisager et al. [9] which suffered from poor statistics (no angular distribution could be constructed for a heavy target) and were restricted to a limited angular range.

The multiplicities obtained for the two targets are instructive in terms of the reaction mechanisms leading to dissociation [23]. For a light target, unless the halo neutrons are highly spatially correlated, the reaction is expected to proceed via single-neutron removal (absorption or diffraction) followed by the in-flight decay of $^{13}\text{Be}$. As approximately equal contributions are expected for absorption and diffraction [23], the average neutron multiplicity should be 1.5, in accordance with that measured here (table I). This scenario is also supported by the single-neutron angular distribution for the C target which is well reproduced assuming passage via a low-lying resonance in $^{13}\text{Be}$ [22,24]. In the case of a heavy target, nuclear and Coulomb dissociation are present. Given that Coulomb dissociation should be associated with a multiplicity of 2, the average multiplicity for dissociation on Pb should be between 1.5 and 2, as observed.

The enhanced cross section for dissociation on the Pb target is indicative of a large EMD contribution. Assuming that the nuclear–Coulomb interference is small, the C target data (which arises essentially from nuclear induced reactions) may be scaled to estimate the nuclear contribution to breakup on Pb [13,22]. Assuming a root-mean-square radius of 3.2
fm for $^{14}\text{Be}$ [14,15], $\sigma_{2n}^{\text{nuc}}(Pb) = 0.85\pm0.07$ b and, consequently, $\sigma_{2n}^{\text{EMD}}(Pb) = 1.45\pm0.40$ b. The latter can be compared to the value of $0.47\pm0.15$ b measured at 800 MeV/nucleon [19]. Importantly, for halo nuclei, the EMD cross section is dominated by the E1 component [25,26]. An enhancement with decreasing beam energy is thus expected, owing to the large amount of dipole strength near threshold (see below) coupled with the weighting of the virtual photon spectrum to low photon energies [27].

Assuming that the neutron angular distribution arising from nuclear dissociation on Pb is identical to that measured for the C target, the single-neutron angular distribution for EMD has been constructed (figure 1b) and the corresponding integrated cross section and average multiplicity derived (table I). Interestingly, the angular distribution remains narrow and forward peaked whilst the multiplicity is consistent with the value of 2 expected for EMD, confirming the validity of the methods used to estimate the contribution arising from nuclear breakup.

The invariant mass spectra, reconstructed from the measured momenta of the beam and fragments ($^{12}\text{Be}$ and two neutrons) from breakup, are displayed in figure 2a and b for the C and Pb targets. The EMD spectrum (figure 2c) has been deduced, as described above, following subtraction of the estimated nuclear contribution to reactions on Pb. As for the spectra obtained with the C and Pb targets, the EMD spectrum exhibits enhanced strength around 2 MeV decay energy ($E_{\text{decay}}$). Given the complex nature of the response function of the present setup, a detailed Monte Carlo simulation, including the influence of all nonactive materials, was developed based on the GEANT package [22]. The results shown in figure 2 were obtained following the descriptions for dissociation on C and Pb outlined earlier. In the case of the nuclear induced reactions a single low-lying state in $^{13}\text{Be}$ ($E_0 = 0.5$ MeV, $\Gamma_0 = 0.5 \pm 0.4$ MeV) was assumed to be populated following the diffraction of one of the halo neutrons [22,28]. The EMD was simulated under the assumption that the energy sharing between the $^{12}\text{Be}$ and the two neutrons was governed by 3-body phase space. As shown in figure 2c, the observed EMD decay energy spectrum could be reproduced using a Breit-Wigner lineshape with a resonance decay energy of $E_0 = 1.8 \pm 0.1$ MeV and
width $\Gamma_0 = 0.8 \pm 0.4$ MeV. Furthermore, the corresponding simulations of the single-neutron angular distributions were in good agreement with those observed for reactions on C and Pb, as well as that deduced for EMD \cite{22}.

As noted above, the EMD of halo nuclei is essentially E1 in character. An analytical estimate for the E1 strength for two-neutron halo nuclei has been derived in a simple 3-body model based on Yukawa wavefunctions \cite{29}, whereby the maximum occurs for $E_{\text{decay}} = 6/5S_{\text{eff}}$, where $S_{\text{eff}} \approx 1.5S_{2n}$. Whilst agreeing well with the available results for $^{11}$Li, a maximum is predicted for $^{14}$Be at $E_{\text{decay}} \approx 2.4$ MeV, somewhat above that observed here.

Thompson and Zhukov have examined $^{14}$Be within the framework of a more realistic 3-body model in which the $^{12}$Be core is treated as inert \cite{7} and a number of trial wavefunctions developed. Based on the binding energy and matter radius \cite{14,15} of $^{14}$Be, together with the known d-wave resonance at 2.01 MeV in $^{13}$Be \cite{30}, two $^{14}$Be wavefunctions are favoured (both of which require an s-wave state near threshold in $^{13}$Be as suggested by recent experiments \cite{28,31,32}): the so-called D4 wavefunction – 86% $\nu(2s_{1/2})^2$ and 10% $\nu(1d_{5/2})^2$; and C7 – 29% $\nu(2s_{1/2})^2$ and 67% $\nu(1d_{5/2})^2$. The EMD decay energy spectra calculated for these wavefunctions for breakup at 35 MeV/nucleon on Pb \cite{7} are compared in figure 3 with that of the empirical Breit-Wigner deduced from the present measurements. The corresponding integrated two-neutron removal cross sections are 1.05 b (D4) and 0.395 b (C7) \cite{7}, compared to the measured value of 1.45$\pm$0.40 b. Although the strength is predicted to be concentrated at a somewhat lower energy than that observed, a large $\nu(2s_{1/2})^2$ admixture to the valence neutrons wavefunction is favoured. Such a result is supported by the total reaction cross section measurement of Suzuki \textit{et al.} \cite{15} and is also in line with Lagrange mesh calculations of the $^{14}$Be ground state (76% $\nu(2s_{1/2})^2$, 18% $\nu(1d_{5/2})^2$) \cite{18}. It should be noted that the treatment of the core as inert precludes, ab initio, the existence of any simple negative parity resonances in $^{14}$Be.

Descouvemont has explored $^{13,14}$Be within a microscopic cluster ($^{12}$Be+n+n) model in which the core is active \cite{33}. In the case of $^{13}$Be an s-wave state is predicted very close to threshold, whilst the energy of the d-wave resonance is well reproduced. Significantly,
a strong E1 transition \[ B(E1) \approx 1.2 e^2 \text{ fm}^2 \] centred at \( E_{\text{decay}} = 1.5 \) MeV is predicted in \(^{14}\text{Be}\), very close to the structure observed experimentally. Analysis of the corresponding energy surface suggests, however, that this transition is not associated with a true resonance \(^{33}\). Calculations of the form of the associated continuum energy spectrum would be of considerable interest. Further support for the predictions of this model exists in the observation in a heavy-ion double charge-exchange reaction of a probable \( 2^+ \) state in \(^{14}\text{Be}\) at \( E_{\text{decay}} = 0.25 \pm 0.06 \) MeV \(^{34}\), compared to a calculated value of 0.5 MeV.

It is interesting to note that the width of the structure seen in the present experiment would correspond, in the case of a true E1 resonance, to a mean lifetime \( (1/\Gamma) \) of some 250±120 fm/c. This may be compared to a simple \( \hbar \omega (E_x = S_{2n} + E_0 = 3.14 \pm 0.15 \) MeV) collective mode oscillation period of \( \sim 400 \) fm/c, suggesting again the nonresonant nature of the observed transition.

In conclusion, the first kinematically complete breakup reaction study of \(^{14}\text{Be}\) has been reported. Two-neutron removal cross sections, neutron angular distributions and invariant mass spectra characteristic of a halo were measured. The EMD observables indicate that the configuration of the halo neutrons contains a large \( \nu (2s_{1/2})^2 \) component. The relatively narrow structure observed near threshold in the EMD invariant mass spectrum is consistent with a soft-dipole excitation. Exploration of the continuum excitations beyond those probed here \( (E_{\text{decay}} > 5 \) MeV) would thus be of particular interest. Additionally, spectroscopic studies of \(^{13}\text{Be}\) and a determination of the \( \beta_2 \) of \(^{12}\text{Be}\), which are essential to developing more refined models describing \(^{14}\text{Be}\), are needed. Finally, in light of the present results, it would be highly desirable to explore the \(^{14}\text{Be}\) continuum via other means, including inelastic scattering and surface dominated probes such as transfer or charge exchange.

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FIGURE CAPTIONS

**Figure 1:** (a) Single-neutron angular distributions for dissociation on C (open) and Pb (solid points). The results for C have been scaled by a factor of 1.8 so as to represent the nuclear contribution to dissociation on Pb (see text). (b) Deduced EMD single-neutron angular distribution for reactions on Pb.

**Figure 2:** Reconstructed $^{14}$Be decay energy spectra for dissociation on (a) C, (b) Pb and (c) that deduced for EMD on Pb. The histogrammes correspond to the results of simulations (see text).

**Figure 3:** Comparison of the EMD decay energy spectra for the 3-body wavefunctions D4 and C7 [7] with that deduced from the present experiment – $E_0 = 1.8$ MeV and $\Gamma_0 = 0.8$ MeV (shaded region). The later has been normalised to an integrated cross section of $1.45 \pm 0.40$ b.
TABLE I. Measured cross sections, average neutron multiplicities and neutron distribution momentum widths for the dissociation of $^{14}$Be at 35 MeV/nucleon.

|       | $\sigma_{-2n}$ [b] | $\sigma_n$ [b] | $\overline{m}_n$ | $\Gamma_n$ [MeV/c] |
|-------|-------------------|----------------|------------------|-------------------|
| C     | 0.46±0.04         | 0.75±0.10      | 1.6±0.3          | 75±3              |
| Pb    | 2.3±0.4           | 4.0±0.3        | 1.7±0.2          | 77±4              |
| Pb(EMD) | 1.45±0.40       | 2.7±0.4        | 1.9±0.6          | 87±6              |
$\frac{d\sigma}{dE_{\text{decay}}} \text{ [mb/MeV]}$