First evidence for low lying s-wave strength in ^{13}Be

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The particle-unbound nucleus ^{13}Be was populated in fragmentation reactions using the method of sequential-neutron-decay-spectroscopy at 0°. The observed central peak in the relative velocity spectrum is most likely first evidence for low lying s-wave strength with a scattering length of $a_s < -10$ fm. This virtual state as the ground state of ^{13}Be would make it unbound with respect to ^{12}Be and a neutron by <200 keV.

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The observation of low lying s-wave strength in neutron-rich nuclei along and beyond the drip line play a crucial role in the description of halo nuclei. The s-wave ground state in ^{10}Li is necessary in order to describe the two-neutron halo nucleus ^{11}Li [1,2]. Low lying s-wave strength in these nuclei is also crucial for the discovery of Efimov states [3–5]. Some marginally bound three-body systems can have one or even several bound excited states. These excited Efimov states will be near to the three-body threshold and of large spatial dimensions, for nuclear systems possibly on the order of 100 fm [6]. One possible candidate for the observation of the elusive Efimov states could be ^{14}Be [4]. It is also another two-neutron halo nucleus where the understanding of its structure depends on the presence of an s-wave ground state in ^{13}Be [7–9]. ^{14}Be is bound by only 1.34 ± 0.11 MeV [10] and the sub-system ^{13}Be is unbound. Several theoretical calculations predicted a $2s_{1/2}$ ground instead of the $1d_{5/2}$ state [11–14]. A microscopic cluster model predicted ^{13}Be to be even slightly bound [12] although the results are consistent with a very low lying unbound state within the uncertainty of the calculations [13]. From the systematics of $N=9$ nuclei it is expected that the $2s_{1/2}$ state, which is already the ground state in ^{15}C [15–17], lies 2 MeV below the $1d_{5/2}$ state in ^{13}Be. This would position the s-state very close to the neutron binding energy [18].

The first measurements indicating that ^{13}Be is actually unbound were made about 30 years ago [19,20], although the latter paper indicated that ^{14}Be was also unbound. The "non-existence" of ^{13}Be was verified in 1973 [21]. An unbound state in ^{13}Be at 1.8(5)MeV relative to the neutron separation threshold was detected in the reaction ^{14}C(^{7}Li,^{8}B)^{13}Be, however, with limited statistics [18,22]. Subsequent measurements reported states at 2.01(5) MeV [11] in the reaction ^{13}C(^{14}C,^{14}O)^{13}Be which was tentatively assigned to be a $5/2^+$ state. This state was confirmed in a radioactive beam experiment using the inverse kinematic reaction d(^{12}Be,p)^{13}Be [23]. A broad low lying s-wave state would have been difficult to observe in these experiments [11,23]. However, a recent experiment using the reaction ^{14}C(^{11}B,^{12}N)^{13}Be observed in addition to the state at 2 MeV a broad ($\Gamma = 1$ MeV) state at 800(90) keV [24]. The limited resolution of the experiment did not allow the determination of the parity of this state.

For the search for low lying s-wave strength in ^{13}Be, we utilized the method of sequential neutron decay spectroscopy (SNDS) [25] which was first applied to study ground state decays in ^{10}Li [26]. An 80A MeV ^{18}O beam was fragmented on a 94 mg/cm^2 thick ^{9}Be target. Neutrons at 0° were detected in coincidence with charged fragments of charge-to-mass ratio of 3, which were deflected with the quadrupole-dipole magnet combination. The neutron-fragment relative velocity which is directly related to the decay energy of the system was calculated from the fragment energy and the time of flight measured between the fragment and the neutron. Details about the experimental setup and analysis can be found in Ref. [27] and preliminary results for ^{13}Be were presented in Ref. [28].

Figure 1 shows the relative velocity spectrum of neutrons in coincidence with ^{12}Be. It shows a fairly sharp central peak on top of a broad background similar to the spectrum observed for ^{10}Li [27] which indicates a state in ^{13}Be with a very small decay energy.

The result of a simulation including the detector geometry and efficiencies of the decay of a $d_{5/2}$ state at 2 MeV is shown as the dashed curve. It clearly does not account for the central peak. Although the data show hints of an enhancement in the region of the calculated peak, it is not statistically significant because the efficiency for large decay energies is small. In order to fit the central peak we analyze the data assuming the presence of a low-lying s wave in ^{13}Be following the description of the potential scattering model of Refs. [27,29,30]. This method is essentially equivalent to the approach of Ref. [31]. Figure 1(a) shows the results of a calculation with a scattering length of $a_s = -20$ fm which corresponds to an approximate energy of the virtual state of ~ 60 keV. In addition to the s wave the total fit includes the d state at 2 MeV and a simulated Gaussian-shaped background. From the fit to the data an upper limit of $a_s < -10$ fm corresponding to an apparent peak energy of <200 keV can be extracted. This value is consistent with the prediction of Ref. [8] where "a $1/2^-$ state unbound by about 0.3 MeV" was necessary in order to describe the two-neutron halo nucleus ^{14}Be. Since the data is only consistent

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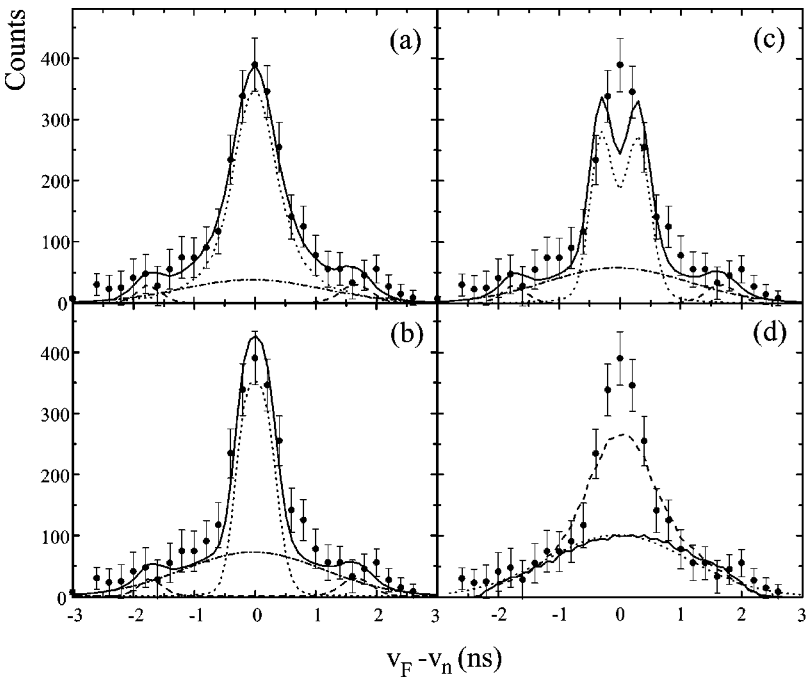

FIG. 1. Relative velocity spectrum from the decay of ^{13}Be. The solid lines in (a)–(c) correspond to fits including a $d_{5/2}$ state at 2 MeV (dashed) and an estimated background (dot-dashed). In addition, the main contribution (dotted) to the fit are a virtual $s_{1/2}$ with a scattering length of $a_s=-20$ fm (a), a $p_{1/2}$ state at 50 keV (b), and a $p_{1/2}$ state at 100 keV (c). Part (d) shows a virtual $s_{1/2}$ with a scattering length of $a_s=-5$ fm (dashed) and results of a calculations with no final state interaction [$a_s=0$ fm (solid)]. The 0 fm calculation is essentially identical to the assumed background (dotted).

with the presence of the d state at 2 MeV, but it is not necessary to fit the data, it is not possible to extract a relative population ratio of the two states. In the breakup of ^{18}O ($N=10$) to ^{13}Be ($N=9$) only one neutron is stripped in addition to four protons. The last two neutrons in ^{18}O are in the sd shell with 20 and 80 % in an s and d state, respectively. Assuming the presence of the d state yields ratios that are consistent with these estimates.

Figures 1(b) and 1(c) illustrate that it is unlikely that the spectral shape corresponds to $l\neq 0$ states. The fit shown in panel (b) includes a p state at 50 keV in addition to the background and the 2 MeV d state. Although it describes the data reasonably well the fit is worse compared to the s-state fit shown in panel (a). An even smaller decay energy for the p state would clearly be too narrow in order to describe the data. A larger decay energy leads to a splitting of the central peak into two peaks as shown in panel (c) for a p state with a resonance energy of 100 keV. Thus, the data could in principle be described by a fit with the resonance energy of a p or d state at 50 ± 10 keV. The width of such a state would be <10 keV. However, if the central peak would correspond to such a narrow low energy p or d state it most certainly would have been observed in the transfer reaction experiments.

Another potential interpretation of the central peak in the data could be the decay to bound excited states in ^{12}Be. The present method only measures relative decay energies and thus cannot distinguish between excited state to excited state decays and ground state to ground state decays. Figure 2 shows the level scheme of ^{13}Be relative to ^{12}Be$+n$. The 5/2 state could decay to the bound excited state in ^{12}Be at 2.10(5) MeV, which then subsequently will decay by γ-ray emission. Although the energy is above the 5/2 state [2.01(5) MeV] they overlap within the uncertainties and a very low-energy transition could be possible.

This scenario is unlikely because the branching ratio to the ground state is expected to be much larger. In a simple shell model the 5/2 state consists predominantly of a single particle $d_{5/2}$ configuration which decays essentially 100% to the ground state of ^{12}Be. However, it has recently been shown that the $N=8$ neutron shell breaks down and this simple picture of a closed shell ground state is not valid [32,33]. Nevertheless, the present data would require a $>75\%$ decay branch to the 2^+ in order to account for the central peak with only marginal indication of the 2 MeV decay to the ground state.

Finally, the 800 keV state [24] shown in Fig. 2 has to be discussed. In Ref. [24] it is speculated that this state corresponds to a 1/2 state, with no determination of the parity. The current data is not sensitive to the presence of a $p_{1/2}$ state at this energy. Although the fit does not require a state at this energy (~ 0.9 cm/ns), a small contribution cannot be ruled out.

In contrast, a $s_{1/2}$ state at 800 keV is not consistent with the present data. The relative velocity spectrum of such a state at 800 keV, corresponding to a scattering length of approximately -5 fm is shown as the dashed line in Fig. 1(d). This calculation is clearly too broad compared to the data. Figure 1(d) shows also the results of a calculation with a scattering length of 0 fm (solid) which is equivalent to no

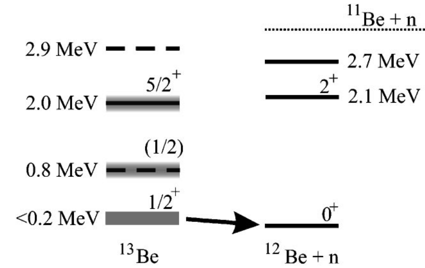

FIG. 2. Level scheme of ^{13}Be relative to ^{12}Be$+n$. The newly observed $s_{1/2}$ state is shown as a broad band below 200 keV.

final state interaction. It is essentially identical to the Gaussian shaped background (dotted) which justifies the use of this background approximation. A more detailed discussion of the justification for the background can be found in Ref. [30].

In conclusion, we found first evidence for low-lying *s* wave strength in the neutron unbound nucleus ^{13}Be from the fragmentation of ^{18}O. The upper limit of a scattering length of $a_s < -10$ fm suggests a virtual state very close to the threshold. This observation validates the need for strong *s*-wave contribution for the ground state of the two-neutron halo nucleus ^{14}Be and may warrant the search for Efimov states in this nucleus.

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