Structure of ^{13}Be and ^{14}Be

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The ^{14}Be two-neutron halo nucleus is described within a two-neutron pairing model. In order to reproduce the measured two-neutron separation energy in ^{14}Be and the $d_{5/2}$ resonance in ^{13}Be at the measured energy of 2 MeV, one has to assume in ^{13}Be the inversion of $1p_{1/2}$ and $2s_{1/2}$ shells as in ^{11}Be and ^{10}Li. We thus predict the ground state of ^{13}Be to be a $1/2^-$ state unbound by about 0.3 MeV, instead of a $1/2^+$ state as usually accepted. [S0556-2813(99)05207-3]

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For some light nuclei on the neutron drip-line, the very weak binding of the valence neutron(s) leads to the formation of a low density distribution extending well beyond the core of the nucleus, the so-called nuclear halo. Strong interest has developed for the two-neutron halo systems, also known as ''Borromean'' haloes: the short-range interaction which binds the extended three-body system (core$+n+n$) is unable to bind the two-body subsystems (core$+n$ and $n+n$). Both experimental and theoretical efforts have been recently extended to the spectrum of the unbound core$+n$ system, as it determines the properties of the two-neutron halo. For example, this interdependence of the two systems has led to the prediction of a very weakly unbound $l=0$ resonance in ^{10}Li from the two-neutron separation energy and the low-energy dipole mode of ^{11}Li [1–4]. These predictions have been confirmed in a recent experiment [5]. As ^{11}Be, ^{10}Li exhibits an inversion of the $1p_{1/2}$ and $2s_{1/2}$ states compared to Hartree-Fock model. This inversion is due to strong correlations between the extra neutron and the core, which are introduced either as neutron-core vibration coupling effects on the Hartree-Fock neutron-core potential [6], or as a deformation of the neutron-core Woods-Saxon potential [8]. One may wonder if the same inversion properties hold in other nuclei having large neutron excess.

Particular effort is now focused on ^{14}Be, which has a small two-neutron separation energy $S_{2n}=1.34\pm0.11$ MeV [9] and is thus a candidate for a two-neutron halo structure. It can be described as a core of ^{12}Be plus two neutrons, while the core$+n$ system ^{13}Be is unbound. It is in that sense very similar to the description of ^{11}Li, modelized as a core of ^{9}Li plus two neutrons, while the core$+n$ system ^{10}Li is unbound. The size inferred from reaction cross sections, despite the big error bars, is much larger than that of the ^{12}Be core nucleus: $r^{\rm rms}_{^{14}\rm Be}=3.1\pm0.4$ fm and $r^{\rm rms}_{^{12}\rm Be}=2.57\pm0.05$ fm [10]. Two experiments have investigated the dissociation of ^{14}Be at intermediate energies: both the angular distribution of neutrons [11] and the momentum distributions of ^{12}Be fragments [12] exhibit narrow widths, as expected for a halo system. Little is known, however, about the detailed structure of the halo.

Following the Hartree-Fock approximation, the ^{12}Be core has $1s_{1/2}$, $1p_{3/2}$ and $1p_{1/2}$ filled shells, and the lowest energy state in ^{13}Be should be an s state. As a neutron halo system is favored when the last neutron is in an $l=0$ state, models assume that in ^{14}Be the lowest states for the two valence neutrons are $2s_{1/2}$ and $1d_{5/2}$ states. The first spectroscopy experiment on ^{13}Be used the reaction ^{13}C(^{14}C,^{14}O)^{13}Be and found a first level at 2.01 ± 0.05 MeV which, according to its width, was tentatively assigned to a $1d_{5/2}$ state; however, a lower-lying $2s_{1/2}$ state, if existing, could not be observed due to the too weak multinucleon transfer cross section to this neutron shell [13]. A second experiment was undertaken through the reaction $d(^{12}\mathrm{Be},p)$, finding the 2 MeV level but again failing in the investigation of the lower energy region [14]. Recently, an experiment using the multinucleon transfer reaction ^{14}C(^{11}B,^{12}N)^{13}Be has found the ground state of ^{13}Be unbound by 0.80 ± 0.09 MeV; the first excited state was found at 2.02 ± 0.10 MeV, and assigned to be a $1d_{5/2}$ state by comparing to the experimental spectrum of ^{11}Be measured with the same technique [15]. The ground-state parity could not be determined, the results being compatible with both $1/2^-$ and $1/2^+$ states [15].

With the assumption of a $d_{5/2}$ resonance at 2 MeV and an s resonance at lower energy, the ^{14}Be ground state has been calculated with a two-neutron pairing model [16], a three-body Faddeev approach [17] and a three-body generator coordinate method [18]. All these calculations arrive at the same conclusion: with the $d_{5/2}$ resonance at 2 MeV, the s neutron state in ^{13}Be needs to be bound to get the correct binding energy of ^{14}Be. As we know that ^{13}Be is unbound, the only alternative in order to obtain the binding energy of ^{14}Be is to lower the $d_{5/2}$ resonance energy, which is also in contradiction with existing experimental data.

We describe ^{14}Be as a core of ^{12}Be plus two neutrons with the pairing model used in Ref. [3]. We take the neutron-core interaction of the form

$$V_{n\text{-core}}(r)=V_{\rm WS}(r)+16a^2\alpha_n\left(\frac{df(r)}{dr}\right)^2, \tag{1}$$

where $V_{\rm WS}$ is a Woods-Saxon potential with spin-orbit force and a symmetry term taking into account the neutron excess. The parameters of this average potential are kept the same for all studied nuclei. In the second term of Eq. (1), $f(r)$ is the Fermi form factor of $V_{\rm WS}$ with the diffusivity parameter a. This term has been suggested by a microscopic calculation of the contribution of the neutron-core vibration couplings to the mean one-body potential. It has been shown that the

TABLE I. The ^{14}Be two-neutron separation energy and the rms radii defined in the text are calculated with different assumptions on the single-neutron energies ϵ in ^{13}Be (energies are in MeV and distances in fm). The $r^{\rm rms}_{^{12}\rm Be}$ is assumed to be 2.57 fm [10].

$\epsilon(1p_{1/2})$	$\epsilon(2s_{1/2})$	$\epsilon(1d_{5/2})$	S_{2n}	$r^{\rm rms}_{^{14}\rm Be}$	$\langle\rho^2\rangle^{1/2}$	$\langle\lambda^2\rangle^{1/2}$
−3.05	0.09	2	0.31	3.45	9.3	5.0
−3.05	−0.09	2	0.79	3.32	8.7	4.6
−3.05	0.09	1.38	1.02	3.02	7.1	3.8
0.12	−3.15	2	1.62	2.91	6.4	3.3
0.29	−3.15	2	1.29	2.93	6.5	3.4
0.34	−3.15	2	1.20	2.94	6.5	3.4
Measured values:		2.02 ± 0.10[a]	1.34 ± 0.11[b]	3.1 ± 0.4[c]	5.4 ± 1.0[d]	

[a]From Ref. [15].
[b]From Ref. [9].
[c]From Ref. [10].
[d]From Ref. [21].

strength of the coupling term α_n depends on the core and on the neutron state considered [6,7]. The α_n are considered as parameters, fitted for e core and each neutron state on the experimental neutron energies in the core$+n$ system. The V_{nn} interaction of [3] is of zero range and density dependent. It has been adjusted at once in order to obtain the binding energy of ^{14}C. Then the states of two-valence-neutron nuclei are calculated by diagonalizing the two-neutron Hamiltonian over a subspace including all neutron states up to 4 MeV.

We have applied the model, with the same interactions $V_{\rm WS}$ and V_{nn}, to the $N=10$ nuclei ^{16}C and ^{14}Be. The results for ^{16}C, a test of the model for the description of $N=10$ nuclei, are in good agreement with experimental data: $S_{2n}=5.41$ MeV to be compared to $S_{2n}=5.47\pm0.14$ MeV. We also get two more bound 0^+ states at 2.8 and 5.2 MeV excitation energies. It is interesting to mention that a plausible 0^+ state has been found experimentally at 3.03 MeV [19]. We apply this model to ^{14}Be assuming that the $d_{5/2}$ resonance is at 2 MeV. By varying the energy of a low s resonance, we obtain for S_{2n} the results listed in the upper part of Table I. These results are qualitatively the same than those obtained in previous works: the experimental binding energy of ^{14}Be can only be obtained by, either binding the $2s_{1/2}$ state in ^{13}Be, either lowering the energy of the $d_{5/2}$ resonance. In both cases we are in contradiction with the experimental informations on ^{13}Be.

Since this model, without free parameters, was able to describe halo or nonhalo nuclei with $N=8$–10, we wonder if some of the starting assumptions about the core$+n$ system were wrong. Let us reconsider the description of ^{13}Be. The n-^{12}Be potential should be able to reproduce the whole neutron spectrum in a core of ^{12}Be, occupied and unoccupied states. The occupied states correspond to one-neutron states in ^{13}Be, whereas the unoccupied states correspond to ^{11}Be viewed as a neutron hole in a core of ^{12}Be. The ^{11}Be ground state is $1/2^+$, which implies that the last filled shell in ^{12}Be should be $2s_{1/2}$ and not $1p_{1/2}$ as always assumed. The first unoccupied state is thus $1p_{1/2}$. The ground state of ^{13}Be would therefore be a $1/2^-$ state.

We have recalculated the ground-state properties of ^{14}Be within this new picture of the neutron spectrum. We fix the $2s_{1/2}$ occupied state at -3.15 MeV, according to the experimental one-neutron separation energy in ^{12}Be, the $d_{5/2}$ resonance at the measured value of 2 MeV, and vary the energy of a $p_{1/2}$ resonance in order to reproduce the two-neutron separation energy in ^{14}Be. The results are also reported in Table I. A good agreement with experimental data is found for a $p_{1/2}$ resonance at 0.29 MeV, leading to $S_{2n}=1.29$ MeV to be compared to 1.34 ± 0.11 MeV. Therefore, our model predicts a $1/2^-$ ground state for ^{13}Be. We conclude that the inversion of $1/2^-$–$1/2^+$ neutron shells found in ^{11}Be and ^{10}Li takes also place in ^{13}Be. The wave function has 25% of $(d_{5/2})^2$ and 45% of $(p_{1/2})^2$.

This is on one side consistent with the $1/2^+$ ground state of ^{11}Be described as a neutron hole in the ^{12}Be core, as discussed above. On the other side, the origin of the inversion of the neutron $1/2^+$ and $1/2^-$ shells in ^{11}Be is caused by the strong coupling between the neutron and the 2^+ vibrational state in ^{10}Be at 3.37 MeV with a $B(E2;0^+\rightarrow2^+)=52\ e^2\ {\rm fm}^4$. The ^{12}Be has its first 2^+ state at a lower energy of 2.1 MeV, but no measurement of the $B(E2)$ is available for this nucleus. Following the global systematics defined by Raman *et al.* [20], where $B(E2;0^+\rightarrow2^+)$ is proportional to $1/E(2^+)$, the $B(E2)$ of ^{12}Be should be larger than that of ^{10}Be. This induces an increase of collectivity for the ^{12}Be core. Therefore, one expects even larger coupling effects in the $n+{}^{12}$Be system. This is confirmed when looking at the α_n strengths in the potential of Eq. (1) for the same neutron s state in the three nuclei, ^{11}Be, ^{10}Li, and ^{13}Be: we find larger absolute values of the strength (larger collectivity) for smaller excitation energies of the 2^+ in the core, $\alpha_n=-10.55$, -12.22, -23.33 and $E(2^+)=3.37$, 2.7, 2.1 MeV, respectively.

In Table I are also given the rms radii of ^{14}Be calculated by varying either the position of the $2s_{1/2}$ or the $1p_{1/2}$ state. They are somewhat smaller than the measured radius in the last three cases, but still compatible with the large experimental uncertainties. We also calculate the rms distance between the two neutrons $\langle\rho^2\rangle^{1/2}$ and between the two center-of-mass of the core and of the two-neutron system $\langle\lambda^2\rangle^{1/2}$. In a recent experiment, where the technique of two-neutron intensity interferometry has been applied to the dissociation of ^{14}Be, a rms distance between the two halo-neutrons of 5.4 $\pm$1.0 fm has been extracted [21]. Even though our values are all somewhat larger, we find a reasonable agreement for the cases where the $2s$ shell is occupied in ^{13}Be. As in ^{11}Li, we find that $\langle\rho^2\rangle^{1/2}$ is much larger than $\langle\lambda^2\rangle^{1/2}$. The radius of ^{14}Be is 3 fm with the radius of the two-neutron halo of 4.5 fm. The halo is not as pronounced as it is in ^{11}Li or ^{11}Be, as expected from the work of Riisager *et al.* [22] who show that $l=1$ states are less favored than $l=0$ states to build a halo.

As a summary, we have shown that only if the ground state of ^{13}Be is a $1/2^-$ state, unbound by about 0.3 MeV, our two-neutron pairing model can explain the known properties of ^{14}Be: the two-neutron separation energy, the rms radius of the system, and the rms distance between the two halo neutrons. This inversion of the neutron $1/2^+$ and $1/2^-$ shells, as in the other two known cases ^{11}Be and ^{10}Li, can be explained as due to the strong coupling between the neutron and the 2^+ vibrational state in the core. In the case of ^{13}Be this coupling is expected to be even larger, as the 2^+ in ^{12}Be is lower than in the other two cases (^{10}Be and ^{9}Li).

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