Analyzing the halo nature of ^{31}F within a three-body approach

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In some exotic nuclei, the Pauli principle forces the progressively added valence nucleon(s) to penetrate the classically forbidden region outside an already saturated core, resulting in a longer then usual tail of the wave function. This enhances the matter radius of the nucleus and provides an extended density distribution. Such nuclei are called halo nuclei [1] and have been a hot topic of interest in the 'island of inversion' in recent times [2–6]. Characterized by small single particle orbital angular momentum configurations ($\ell = 0,\, 1$), they are weakly bound, with only one or two bound states below the breakup threshold. Hence, the role and the effects of the continuum become vital in their study. Techniques of continuum discretization are then required to explore the behavior of these nuclei and study their various observables to better understand their structure and reaction properties.

Of course, mimicking the continuum states and discretizing them is not trivial and researchers resort to either the binning procedure or the pseudostates (PS) approach. One such PS method of continuum discretization is the transformed harmonic oscillator (THO) method that makes the use of a harmonic oscillator (HO) basis to which an analytic local scale transformation (LST) has been applied [7, 8]. This transformation helps in changing its asymptotic behavior from a Gaussian to exponential form. For a three-body system, the Hamiltonian eigenstates within the hyperspherical formalism can be expanded as [6, 8],

$$\psi^{jm_j}(\rho,\Omega) = \frac{1}{\rho^{5/2}} \sum_{\beta} R^{j}_{\beta}(\rho)\mathcal{Y}^{jm_j}_{\beta}(\Omega), \qquad (1)$$

where $\rho^2 (= x^2 + y^2)$ is the hyperradius specified using the Jacobi coordinates $\{\boldsymbol{x}, \boldsymbol{y}\}$. β represents each of the channels of possible angular momenta coupling schemes that can result for the system. $R^{j}_{\beta}(\rho)$ are the hyperradial functions that can be expanded in a discrete basis through the THO basis, while $\mathcal{Y}^{jm_j}_{\beta}(\Omega)$ are hyperangular states of good angular momentum j, and which are constrained by fixing the hypermomentum operator K. It is noteworthy that the LST of the HO basis ensures that the continuum generated through the THO basis can be modulated to control the density of states above the breakup threshold, thus providing a flexible approach to mimic the spectral properties of the system. For more details on the formalism, please see Refs. [7, 8].

For the present case, we apply the THO method to study the dripline nucleus, ^{31}F, the last known bound system of the Fluorine isotopic chain [2]. Investigations have revealed it to be a Borromean nucleus, with its isotopic predecessor, ^{30}F being unbound [9]. We consider it as a composite system of a ^{29}F surrounded by two valence neutrons and scrutinize its halo character. Although ^{29}F is in itself a two neutron halo [5, 6], we consider it as an inert, spinless core for our analysis having a spin-parity of 0^+. We take the ground state two-neutron separation energy (S_{2n}) of ^{31}F to be 0.15 MeV and consider cases when the g.s. filling of neutrons to the ^{29}F core is according to the normal shell model ordering and when it is inverted [10], for the trends in the 'island of inversion' point to it having a strong contribution from the $2p_{3/2}$ state [11, 12].

Since it is a three-body system, we require three two-body potentials, i.e., ^{29}F+n, n+^{29}F and neutron-neutron (nn). The nn potential is given by the Gogny-Pires-Tourreil (GPT) interaction [13], while the core $+\, n$ interaction is modeled with central and spin-orbit terms as [14],

$$V_{(^{29}\mathrm{F}+n)} = -V_0\, g(r) + V_{ls} \lambda_\pi^2 \frac{1}{r}\frac{dg(r)}{dr}\, \vec{l}\cdot\vec{s}, \qquad (2)$$

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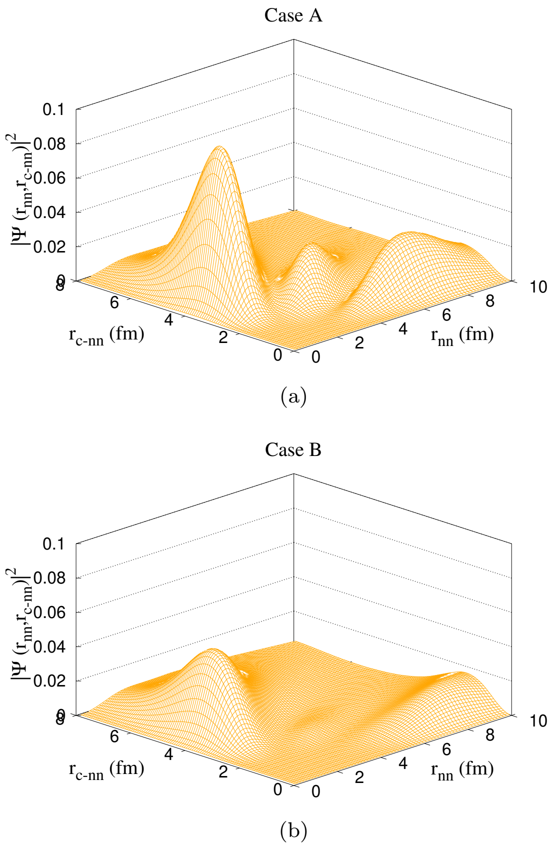

FIG. 1: The ground state probability density distribution (in units of fm^{-2}) of ^{31}F for the (a) normal shell model and (b) inverted scheme, as a function of r_{nn} and r_{c-nn}.

where $g(r)$ has the standard Woods-Saxon form, $g(r) = \left[1 + \exp\left(\frac{r-R_c}{a}\right)\right]^{-1}$. The potential depth V_0 is adjusted to fix the energies of different orbitals for the two-body subsystem ^{30}F. We fix the $d_{3/2}$, $f_{7/2}$ and $p_{3/2}$ levels at 0.11, 0.23 and 1.21 MeV, respectively, in compliance with the normal shell model ordering. This is our case A. We consider another case, B, where we see the *inverted* scheme by fixing 0.11, 1.22 and 2.00 MeV for the $p_{3/2}$, $f_{7/2}$ and $d_{3/2}$ orbitals, respectively [10]. We then add a phenomenological three-body potential through a Gaussian form [7] to reproduce the correct binding energy of ^{31}F.

Our results are shown in Fig. 1, where we compare the g.s. probability density distributions as a function of the *nn* distance, r_{nn} and the core - *nn* distance, r_{c-nn} for both cases A and B. It is seen that case A has three and higher rising peaks while case B has only two. This is due to the dominance of the $d_{3/2}$ orbital (higher ℓ) in the former case. In case B, the major contribution is from the $p_{3/2}$ state as it lies closest to the breakup threshold. The dineutron peaks (when r_{nn} is small) in this case gather about three times the probability density than the opposite cigar-like (when r_{nn} is large) peaks. The same ratio for case A is close to one, pointing to larger mixing of different parity states. This feature of a long and larger contribution from the density tail of the dineutron peaks is found in proven two-neutron halo nuclei [6, 7] and provides an extended matter radius with respect to the core [10].

Thus, ^{31}F, going also by the trends in the 'island of inversion', should be a two-neutron halo with a strong $2p_{3/2}$ contribution to its g.s. configuration. We encourage experiments to substantiate and put our predictions on a firmer footing.

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