Rapid Communications

# Two-neutron halo structure of $^{31}$F

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(Received 25 July 2019; revised manuscript received 14 January 2020; accepted 11 February 2020; published 2 March 2020)

We apply the Gamow shell model to study $^{25-31}$F isotopes. As both internucleon correlations and continuum coupling are properly treated therein, the structure shape of $^{31}$F at large distance can be analyzed precisely. For this, one-nucleon densities, root-mean-square radii, and correlation densities are calculated in neutron-rich fluorine isotopes. It is then suggested that $^{31}$F exhibits a two-neutron halo structure, built from both continuum coupling and nucleon-nucleon correlations.

DOI: 10.1103/PhysRevC.101.031301

*Introduction.* Light exotic nuclei have been studied for several years using accelerators of the past generation [1,2]. Due to the use of radioactive ion beams, it has been possible to reach the neutron dripline up to $^{40}$Mg [3]. Contrary to well-bound nuclei, which are closed quantum systems, dripline nuclei are open quantum systems as they are either weakly bound or unbound with respect to particle emission. Furthermore, interesting phenomena appear at driplines, such as clusters in nuclei and halo structure [4]. Hence, the properties of dripline nuclei should be studied to understand the nuclear force, which acts differently in the valley of stability and driplines.

Several halo nuclei are known among $p$-shell nuclei, such as $^{6,8}$He [5,6], $^{11}$Be [7], and $^{11}$Li [8]. A few halos are also known in $sd$- and $sdpf$-shell nuclei, such as the one-neutron halos of $^{31}$Ne [9] and $^{37}$Mg [10] and the two-neutron halo of $^{22}$C [11]. The principal ingredient of halos is an important occupation of the $s$ and $p$ continua. Moreover, configuration mixing involving higher partial waves is also expected to be important for a proper description of halo nuclei. This is especially important for two-nucleon halo states. Theoretical calculations taking into account both these features are, thus, demanded to better understand halo structure.

The main models, including both internucleon correlations and continuum coupling in a complete fashion are the no-core shell model coupled with continuum (NCSMC) [12], the coupled-cluster (CC) model [13], and the Gamow shell model (GSM) [14–16]. However, due to the huge model space dimensions, the NCSMC model could be used to describe dripline nuclei of $A \approx 10$ nucleons at most [17]. Furthermore, only nuclei in the vicinity of closed-shell systems can be treated within the CC model [18]. Conversely, the GSM has been used to calculate weakly bound and resonance states of the $p$, $sd$, and $pf$ shell nuclei [19–22]. In particular, two-nucleon halos could be precisely described in the GSM framework [23]. Consequently, the GSM is an appropriate tool to precisely study neutron-rich nuclei and halo structure.

Fluorine isotopes have been synthesized up to the neutron dripline, which is reached with the loosely bound $^{31}$F isotope [24,25]. They form a very interesting ground for theoretical studies as they can provide information about the proton-neutron interaction at the dripline. Moreover, the ground state of $^{31}$F is suspected to be a neutron-halo state [26]. Hence, both proton-neutron and neutron-neutron correlations in the continuum would be present in a nuclear system extended in space, which will surely rise to interesting phenomena. Thus, it is the object of this Rapid Communication to study weakly bound fluorine isotopes and $^{31}$F in particular, with the GSM.

This Rapid Communication is written in the following way. The basic features of the GSM are first quickly stated. Then, the model space and Hamiltonians used in the calculation of fluorine isotopes will be presented. Afterwards, we will depict the ground-state energies of fluorine isotopes at the dripline as well as other observables of physical interest, such as one-nucleon density, root-mean-square (rms) radius, and correlation density. They will allow, in particular, to reveal the two-neutron halo structure in $^{31}$F.

*Model.* The GSM is a configuration interaction approach based on the use of the Berggren basis [27]. The Berggren basis possesses bound, resonance, and scattering states, generated by a finite-range potential, such as a Woods-Saxon (WS) potential,

$$\sum_n |n\rangle\langle n| + \int_{L^+} |k\rangle\langle k|\, dk = 1, \tag{1}$$

where $n$ runs over bound and resonance states and $L^+$ is a complex contour on the complex plane encompassing resonance states. The many-body basis used in the GSM consists of the Slater determinants built from the Berggren basis of

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Eq. (1). Consequently, continuum coupling is included at the basis level and internucleon correlations are exactly taken into account via configuration mixing. The GSM is then the tool of choice to study many-body halo and resonance states. Following the success of former GSM applications [19–22], we will consider a model consisting of valence protons and neutrons interacting with a Furutani-Horiuchi-Tamagaki (FHT) interaction [28,29] above an $^{24}$O core. The FHT interaction is a Gaussian-based residual interaction bearing central, spin-orbit, and tensor terms, whose coupling constants are denoted as $V_c^{\rm ST}$, $V_{\rm LS}^{\rm ST}$, and $V_T^{\rm ST}$, respectively, where $S = 0, 1$ and $T = 0, 1$ are the spin and isospin of the two nucleons, respectively. It has been already used in the context of the GSM to describe neutron-rich helium, lithium, and beryllium isotopes as well as radiative capture reactions in $A = 6$–$8$ nuclei [20,30,31]. The $^{24}$O core is mimicked by a Woods-Saxon potential.

The Hamiltonian is fitted to reproduce oxygen and fluorine isotopes at the neutron dripline. We included the ground-state energies and a few excited states of $^{25,26}$O and $^{25-31}$F in the fit. As a consequence, the features of fluorine isotopes at the dripline can be properly assessed. Fluorine isotopes with fewer neutrons, closer to the valley of stability, are well bound so that they do not need to be included in the GSM model space (see Ref. [32] for a study of well-bound fluorine isotopes with realistic interactions). The present formalism will also be used with an interaction issued from effective field theory (EFT) by fitting low-energy parameters on experimental data as performed in Ref. [33]. The latter approach will allow to compare two different Hamiltonians, on one hand, and provide with a theoretical approach similar to the one used with realistic Hamiltonians [34] on the other hand.

As the single-valence proton is well bound in neutron-rich fluorine isotopes, it is sufficient to use the $0d_{5/2}$ and $1s_{1/2}$ harmonic-oscillator (HO) basis states therein as proton valence states. The most important neutron partial waves, having a sizable coupling to the continuum, are $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$. Indeed, considering a WS potential mimicking the $^{24}$O core, the $0d_{3/2}$, $0f_{7/2}$, and $1p_{3/2}$ neutron states are close to the particle-emission threshold and bear a neutron-emission width of about 1 MeV or smaller. We checked that the $1p_{1/2}$ and $0f_{5/2}$ neutron states have very large widths of about 5 and 9 MeV, respectively, so that associated partial waves can be neglected. This situation is similar to that occurring in the halo ground state of $^6$He where the broad character of the $0p_{1/2}$ neutron state implies that $p_{1/2}$ contributions are negligible in the halo region [15,23].

The Berggren basis is generated by a WS potential bearing loosely bound $0d_{3/2}$, $0f_{7/2}$, and $1p_{3/2}$ neutron one-body states, whose associated Berggren basis contours are complex. We also restrict the model space by demanding two occupied neutron states, at most, in the continuum. It is, indeed, sufficient to have a precision of less than 0.1 keV for widths. The values of the optimized WS parameters are the diffuseness $d = 0.65$ fm, radius $R_0 = 3.663$ fm, the spin-orbit coupling $V_{\ell s} = 7.5$ MeV fm$^2$, and central depth $V_0$, which is equal to 65.659 MeV for protons (except for $\ell = 0$ using the EFT interaction where it is 67.659 MeV) and, for neutrons, is equal to 39.978 MeV for $\ell = 0$, 2–43.3 MeV for $\ell = 1$ and to 39.9 MeV for $\ell = 3$. The fitted parameters of the FHT interaction (see Table I) differ substantially from the values obtained in Ref. [20]. This mainly reflects their very different statistical uncertainties [20]. For example, $V_c^{11}$, $V_{\rm LS}^{11}$, and $V_T^{11}$, which are the most different in our calculation, exhibited the largest uncertainties in Ref. [20]. Conversely, $V_c^{00}$ and $V_c^{10}$, which were found to be well constrained in Ref. [20], did not deviate much from their initial value. $V_c^{01}$ and $V_T^{10}$ varied significantly compared to their fitted values of Ref. [20], even though they were found not to be poorly constrained therein. However, their change is much less important than for the most sloppy parameters, bearing $S = 1$ and $T = 1$ (see Table I and Ref. [20]). Hence, one can consider that the obtained values are consistent with those of Ref. [20]. The fit of the parameters of the EFT interaction is shown in Table II. The EFT parameters are separated in two parts: The first part is that of the LO parameters, denoted as $C_S^{0,1}, C_T^{0,1}$, which are spin independent and spin dependent, respectively, and where the isospin of the two nucleons, equal to 0,1, explicitly appears; the second part consists of the next-to-leading order parameters, denoted as $C_{1\ldots7}$ (see Ref. [35] for notation and definition of associated operators). Note that $C_S^0$ and $C_T^0$ reduce to a single constant so that we only fitted $C_S^0$ and arbitrarily put $C_T^0 = 0$. One can see that parameters are usually close to 1 as expected from the naturalness properties of low-energy constants [35]. Indeed, all nonzero constants are situated between 0.1 and 3 in absolute value with the sole exception of $C_2$, close to $10^{-3}$.

*Results.* The binding energies of fluorine isotopes are presented in Fig. 1. Along with the GSM calculations performed with the FHT and EFT interactions and experimental data, results issued from other theoretical calculations employing the HO basis, i.e., MPBT based on a bound HF basis in an $sdpf$-cross-shell-model space [37,38], and the IMSRG method utilized in a $sd$- or $pf$-single-shell VS [39,40] with bound HF basis states as well are depicted. $^{25}$F has been fixed

TABLE I. Optimized parameters of the FHT interaction. The parameters of the FHT interaction consist of central ($V_c^{\rm ST}$), spin-orbit ($V_{\rm LS}^{\rm ST}$), and tensor ($V_T^{\rm ST}$) parts (see Ref. [20] for definitions). They depend on the spin $S = 0, 1$ and isospin $T = 0, 1$ of the two nucleons, respectively.

| Parameter | $V_c^{11}$ | $V_c^{10}$ | $V_c^{00}$ | $V_c^{01}$ | $V_{\rm LS}^{11}$ | $V_T^{11}$ | $V_T^{10}$ |
|---|---|---|---|---|---|---|---|
| Value | −59.9 | −5.4 | −24.3 | −0.07 | 9.5 | 29.9 | 1.02 |

TABLE II. Optimized parameters of the EFT interaction at leading order (LO) and next-to-leading order (NLO). They are given in natural units. The $C_S^{0,1}$, $C_T^{0,1}$, and $C_{1\ldots7}$ notations are taken from Ref. [35]. Parameters at leading order ($C_S^{0,1}, C_T^{0,1}$) explicitly depend on the isospin $T = 0, 1$ of the two nucleons.

| LO constant | $C_S^0$ | $C_S^1$ | $C_T^0$ | $C_T^1$ | | | |
|---|---|---|---|---|---|---|---|
| LO value | −0.12 | −2.27 | 0 | −0.73 | | | |
| NLO constant | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ |
| NLO value | 0.20 | 0.001 | 0.25 | 0.10 | 0.25 | −0.52 | 0.17 |

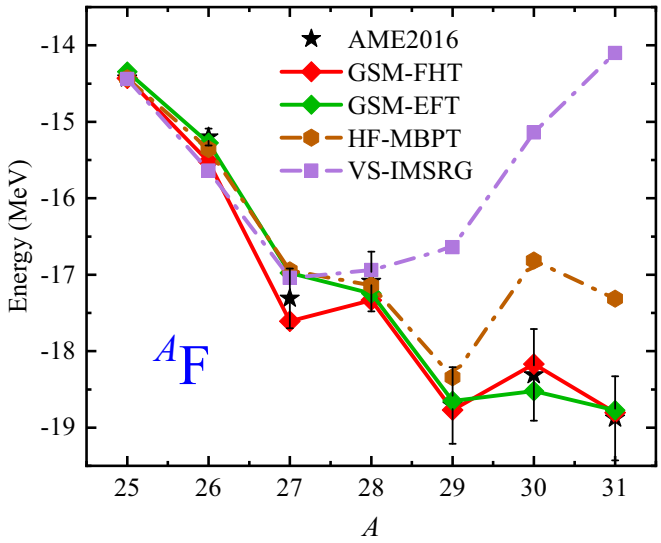


FIG. 1. Binding energies of $^{25-31}$F in MeV with respect to the $^{24}$O core calculated within different theoretical frameworks and compared to experimental data [36]. Besides the GSM calculations using FHT and EFT interactions of this Rapid Communication, calculations utilizing the HO basis, hence, without continuum coupling, are presented with the Hartree-Fock–many-body perturbation theory method (HF-MBPT) and valence-space–in-medium similarity renormalization-group (VS-IMSRG) frameworks.

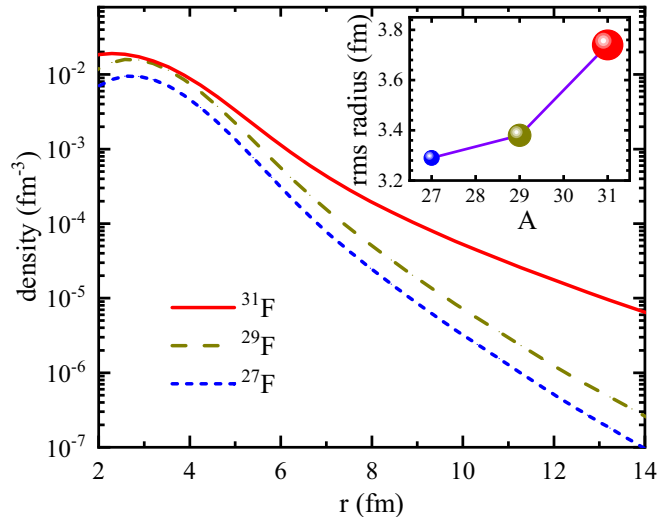


FIG. 2. One-nucleon densities (in fm$^{-3}$) of the bound $^{27,29,31}$F isotopes calculated with the GSM using the EFT interaction in the valence space as a function of $r$ (in femtometers), respectively, depicted by short-dashed, long-dashed, and solid lines. The rms radii of these isotopes are shown in the inset.

to its experimental energy in all used models in Fig. 1. One can immediately see that all methods reproduce the ground state energies of $^{25-28}$F isotopes, situated in the well-bound region, and start differing after $^{29}$F, hence, when one reaches the neutron dripline. This is particularly visible in VS-IMSRG where the neglect of both multishell and continuum couplings at the neutron dripline generates a 4- to 5-MeV error in $^{30,31}$F. Conversely, the cross-shell couplings generated by the *sd* and *pf* shells are included in HF-MBPT. Thus, HF-MBPT predicts proper binding energies up to $^{29}$F. Due to the lack of continuum coupling, however, the binding energies of $^{30,31}$F are about 1 MeV away from experimental error bars. One cannot make accurate predictions about a possible halo structure therein.

On the contrary, a GSM using a WS potential with FHT and EFT interactions correctly provides with binding energies up to $^{31}$F. Moreover, the odd-even staggering encountered from $^{28}$F, typical of the presence of a strong proton-neutron interaction, is well reproduced with $^{30}$F being unbound and $^{31}$F being loosely bound. The $\chi^2$ deviation obtained with the FHT interaction is about 300 keV, which is comparable to the value of 250 keV of Ref. [20], whereas that provided by EFT is about 170 keV. Note that the slightly different $\chi^2$ deviations obtained with the FHT and EFT interactions are, in fact, equivalent due to the large experimental error bars present in $^{29-31}$F, on the order of 1 MeV. We can then expect both interactions to provide with sensible observables other than energies, such as one-nucleon densities, rms radii, and correlation densities, which we will consider in the following.

One will investigate the asymptote of the $^{31}$F ground-state wave function. Its two-neutron separation energy is about 170 keV [25] so that is sufficiently small to sustain a halo. It is, indeed, our assumption that the many-body wave function of $^{31}$F is principally made of a $^{29}$F subsystem and of two loosely bound valence neutrons mainly situated in the $p_{3/2}$ partial wave. Consequently, $^{31}$F would bear a two-neutron halo, similar to that present in $^{6}$He. In order to verify this assumption, we calculated the one-nucleon densities and neutron rms radii of the neutron-bound $^{27,29,31}$F isotopes with the EFT interaction (see Fig. 2). Indeed, a halo clearly develops in the asymptotic region of $^{31}$F. On one hand, the one-nucleon density of $^{31}$F very slowly decreases on the real axis and is about one to two orders of magnitude larger than those of $^{27,29}$F in the asymptotic region. On the other hand, the neutron rms radius of $^{31}$F does not follow the trend present in $^{27,29}$F as it sharply increases by about 0.4 fm when the increase from $^{27}$F to $^{29}$F is about 0.1 fm. Results have been checked to be nearly identical when using the FHT interaction.

It is clear that $^{31}$F is very extended in space compared to $^{27,29}$F. One-nucleon density and the neutron rms radius are, nevertheless, not sufficient to make definite statements about the possible two-neutron halo of $^{31}$F. Consequently, we calculated the correlation densities of $^{27,29,31}$F. The correlation density definition is standard [23],

$$\rho(r,\theta_{12}) = \langle\Psi|\frac{\delta(r-r_1')}{rr_1'}\frac{\delta(r-r_2')}{rr_2'}\delta(\theta_{12}-\theta_{12}')|\Psi\rangle, \quad (2)$$

where $r = r_1 = r_2$ is the distance between the core center of mass and the two nucleons, denoted as 1 and 2, $\theta_{12}$ is the angle between the two nucleons relative to the core center of the mass, and $|\Psi\rangle$ is the nuclear wave function, integrated over the space coordinates of the nucleons $r_1'$, $r_2'$, and $\theta_{12}'$. The Jacobian induced by the angular dependence is implicitly included in $\rho(r,\theta_{12})$, similar to the definition of Ref. [23]. However, we added divisions by $rr_1'$ and $rr_2'$ in Eq. (2) compared to the

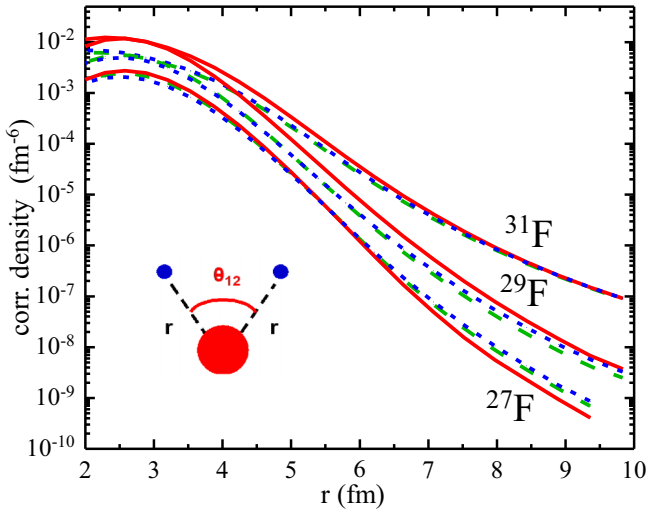


FIG. 3. Correlation densities (in fm$^{-6}$) of the bound $^{27,29,31}$F isotopes calculated with the GSM using the EFT interaction as a function of $r$ (in femtometers). The long-dashed, solid, and short-dashed lines correspond to three values of the $\theta_{12}$ angle between the two nucleons, that is, 32.75°, 96.88°, and 147.24°, respectively.

definition of Ref. [23] to allow for a direct comparison with the one-body density. We show $\rho(r, \theta_{12})$ for three different $\theta_{12}$ angles, equal to 32.75°, 96.88°, and 147.24° (see Fig. 3). We have checked that $\rho(r, \theta_{12})$ has a similar behavior for other angles at long distances. We can now analyze two-nucleon correlations in the wave function of $^{31}$F at long distances. Indeed, $\rho(r, \theta_{12})$ shows the same pattern as the one-body density. Although it falls off rapidly in the asymptotic region for $^{27,29}$F, its decrease for $^{31}$F is much slower as for the one-nucleon density (see Figs. 2 and 3). As the proton part of the $^{31}$F wave function is very localized, the asymptotic regions are mainly generated from two delocalized neutrons. The correlation densities calculated with the EFT and FHT interactions have been checked to be qualitatively similar. Thus, the asymptotic wave function of $^{31}$F is dominated by a halo of two neutrons, situated above a $^{29}$F well-bound core. Moreover, $p_{3/2}$ one-body states are almost always present in the neutron configurations of the wave function of $^{31}$F where configurations containing $p_{3/2}$, $d_{3/2}$, and $f_{7/2}$ neutron one-body states play an important role. Thus, all configurations contribute to build a complex two-neutron halo in $^{31}$F.

*Conclusion.* Nuclei at driplines exhibit unique phenomena arising from the proximity of the continuum region and internucleon correlations. One of the most important of them is the halo structure where one or two nucleons extend very far away from the nuclear region. It was the object of this Rapid Communication to demonstrate the two-neutron halo character of $^{31}$F. Indeed, besides its small two-neutron separation energy, it is an odd-even nucleus so that both proton-neutron and neutron-neutron interactions participate in halo formation in $^{31}$F. By fitting the neutron-rich oxygen and fluorine isotopes with effective Hamiltonians, it has been possible to generate many-body wave functions recapturing the essential features of $^{25-31}$F. Consequently, the shape of $^{31}$F at long distances could be investigated by considering the rms radius, one-nucleon density, and correlation density, which clearly revealed a two-neutron halo structure in the wave function of $^{31}$F. This phenomenon has been noted using two different effective interactions. As a consequence, it is very likely that $^{31}$F is a two-neutron halo nucleus. The study of nuclei at driplines in the $sdpf$ region is, thus, expected to present unique features where the radial extension of many-body wave functions and interactions between both protons and neutrons are intertwined.

*Acknowledgments.* This work has been supported by the National Natural Science Foundation of China under Grants No. 11435014, No. 11835001, No. 11921006, No. 11847203, and No. 11975282; the National Key R&D Program of China under Grant No. 2018YFA0404401; and the CUSTIPEN (China-US Theory Institute for Physics with Exotic Nuclei) funded by the US Department of Energy, Office of Science under Grant No. de-sc0009971. We acknowledge the High-Performance Computing Platform of Peking University for providing computational resources.

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