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Evidence of strong dynamic core excitation in ^{19}C resonant break-up

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The resonant breakup of ^{19}C on protons measured at RIKEN [Y. Satou *et al.*, Phys. Lett. B **660**, 320 (2008)] is analyzed in terms of a valence-core model for ^{19}C that includes possible core excitations. The analysis of the angular distribution of a prominent peak appearing in the relative-energy spectrum could be well described with this model and is consistent with the previous assignment of $5/2^+$ for this state. Inclusion of core-excitation effects are found to be essential to giving the correct magnitude of the cross section for this state. By contrast, the calculation assuming an inert ^{18}C core is found to largely underestimate the data.

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Introduction. Current developments in radioactive beam facilities are permitting the production of neutron-rich nuclei which are both farther away from the stability line and heavier in mass. Among them, exotic structures, such as *haloes*, continue to receive special attention due to their remarkable properties. These nuclei are characterized by the presence of one or two weakly bound nucleons, which can thereby enable the exploration of distances far from the rest of the nucleus, usually referred to as the *core*. This decoupling of the valence particle(s) with respect to the tighter core permits us to study the structure and reactions of these systems in terms of few-body models.

In reactions involving halo nuclei, breakup channels are enhanced due to their small binding energy. In the case of elastic breakup, the standard formalisms for studying these reactions are the continuum-discretized coupled-channel (CDCC) method [1–4], the adiabatic approximation [5,6], and different semiclassical approximations [7,8]. Recently, it has become possible to solve AGS-Faddeev equations for specific cases [9,10].

In their standard formulations, the target and the constituent fragments of the projectile are considered to be inert and, therefore, possible excitations of them are ignored. The assumption of inert fragments is well justified for reactions with deuterons, where these formalisms were first applied [1]. It is expected to be a good approximation for the traditional two-neutron halo nuclei ^{6}He and ^{11}Li. However, in odd nuclei with a well-deformed core, such as in the ^{11}Be or ^{19}C cases, the inert-core approximation is less justified. For ^{11}Be, the archetype of a one-neutron halo nucleus, the single-particle picture based on a neutron orbiting a ^{10}Be(g.s.) core provides a rough description of the low-lying spectrum of this nucleus. The model has also permitted a reasonable description of nuclear reactions, assuming that the contributions of core-excited admixtures can be included in an effective way. For example, in transfer reactions this is usually done multiplying the inert-core result by the corresponding spectroscopic factor. Dynamic core excitations (DCE) occurring during the collision are effectively included in the effective core-target potentials.

However, there is evidence that this approximate model is not always accurate [11–13]. For example, recent calculations [14] have shown that in collisions of ^{11}Be with light targets, the explicit inclusion of the DCE mechanism gives rise to a sizable increase of the breakup cross section. This is particularly important for excitation energies around the low-lying $3/2^+$ resonance, where the effect is enhanced due to the dominant ^{10}Be(2^+) configuration for this resonance. Moreover, the admixture of different core states in the ^{11}Be states modifies the shape of the breakup angular distribution [12]. We expect that these effects will show up in other deformed weakly bound nuclei. This is the case of ^{19}C, where the core, ^{18}C, is well deformed and has a first excited 2^+state at 1.6 MeV. In addition, new halo candidates like ^{31}Ne and ^{37}Mg are within a well-established deformed region. Therefore, deviations from the naive inert-core-plus-valence particle are expected. We note that these dynamic core excitation effects have been also recently studied in the context of transfer reactions [15,16].

The success of few-body models describing halo phenomena suggests that the presence of a halo always implies a decoupling of its motion from the excitations of the core. As we mention here, there are several cases in the literature where the inclusion of core excitations and their interplay with excitations of the valence particle are mandatory to understanding the experimental data [12,17]. The novelty in the case we are discussing here, ^{19}C, is that the resonant breakup cross section is dominated almost entirely by the dynamic excitation of the core. This is so strong that it is able to overwhelm the role of the halo, as we will demonstrate in the following.

Despite the increased complexity, the study of core excitations constitutes a great opportunity to deepen our knowledge on these new structures. For example, it was shown in [12] that the presence of different core state admixtures has a sizable impact in the resonant breakup of halo nuclei. By analyzing these reactions one can extract information on the

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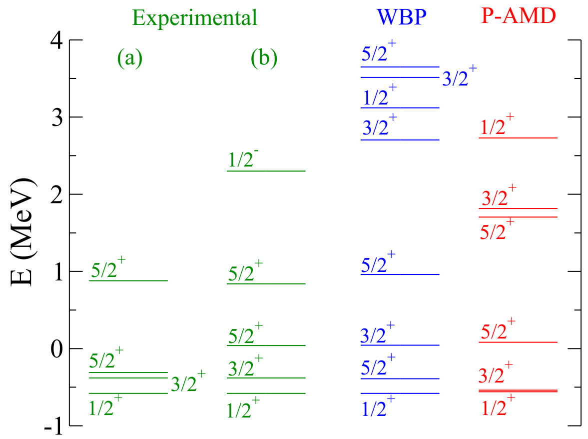

FIG. 1. Experimental (far left column) [29,33] and calculated spectrum of ^{19}C in a shell-model calculation with OXBASH using the WBP interaction [40,41] (middle right column), and within a semimicroscopic core-plus-valence-particle calculation (P-AMD, far right column) which takes into account core excitations as described in [34]. We include a second experimental spectrum (middle left column) due to the discrepancy raised by the latest knock-out experiments [30–32].

relative weights of the different core states in the spectra of the halo nucleus of interest. It also provides spectroscopic information on resonances which are weakly populated in transfer reactions, which is a more standard spectroscopic probe.

In the last few years, some of the traditional formalisms for studying breakup have been upgraded to include static and dynamic excitations of the core during the reaction process. This is the case of the no-recoil XDWBA [13], the XCDCC method [18,19], and a new formulation of the AGS-Faddeev equations [16,20]. Most of them focus on ^{11}Be as a benchmark. Here we focus on the less-known case of ^{19}C.

The ^{19}C nucleus has raised interest in connection with the disappearance of the $N = 14$ shell closure and the emergence of a subshell closure at $N = 16$ [21] and the possible shape-phase transition from prolate to oblate in the carbon isotopic chain [22,23]. ^{19}C is a halo nucleus [24] with a well-established spin $1/2^+$ ground state [25–27] and a neutron separation energy $\epsilon_B = 0.589$ MeV [28]. The situation is controversial for the rest of the low-lying spectrum. Two bound states, $3/2^+$ and $5/2^+$, with respect to neutron emission were proposed in Ref. [29] (see far left column in Fig. 1). Although this is supported by *sd* shell-model calculations (middle right column of Fig. 1), the existence of a bound $5/2^+$ state seems to be excluded according to knock-out experiments [30–32]. In addition, an unbound $5/2^+$ state was found at RIKEN in the breakup of ^{19}C on protons at 70 MeV/nucleon [33] and more recently in a one-neutron knockout reaction at 290 MeV/nucleon [32]. Semimicroscopic predictions and shell-model calculations suggest a strong overlap of this state with the 2^+ core excited state [34]. Nevertheless, both of them, and even *ab initio* coupled-cluster calculations, produce two $5/2^+$ states within the first 2 MeV of excitation energy.

The resonant breakup cross section found in Ref. [33] and associated with a $5/2^+$ state was previously analyzed in [35] within an inert-core AGS-Faddeev formalism using a realistic CD-Bonn interaction. Single-particle excitation was unable to explain the data by an order of magnitude, thus being a motivation to explore the role of core excitations in this nucleus.

In the following, we will analyze the data from Ref. [33] to clarify the nature of the measured $5/2^+$ unbound state. Following [34,36], we will describe the ^{19}C nucleus using a core-plus-valence-particle model, including core excitations, and compute the resonant breakup using the extended versions of the distorted-wave Born approximation (DWBA) [12,13] and the CDCC formalisms [18,19]. Through this analysis we will show how in this reaction the core excitation role is by far dominant. The importance of core excitations is much larger than in the previously analyzed case, ^{11}Be, due to the ^{18}C lower excitation energy and its larger deformation. Similar effects might be expected for more exotic halo candidates like the aforementioned ^{31}Ne and ^{37}Mg.

Structure and reaction formalisms. Further details of the core excitation model used in this work can be found in Refs. [12,13,19,36]. Here, only the main ingredients are briefly discussed. We consider the reaction of a two-body weakly bound projectile (^{19}C in our case) on a proton target. We describe the projectile in the weak-coupling limit, using a core+valence-particle model (^{18}C $+n$). For this model, a general projectile wave function with total angular momentum J and projection M can be expanded as

$$\Psi_{JM}(\vec{r},\xi) = \sum_{\alpha} \left[\varphi_\alpha(\vec{r}) \otimes \Phi_{IM_c}(\xi)\right]_{JM}, \tag{1}$$

where the functions $\varphi_\alpha(\vec{r})$ describe the relative motion between the valence particle and the core, and $\Phi_{IM_c}(\xi)$ are the core eigenstates with angular momentum I and projection M_c. ξ represents the core internal degrees of freedom. The index α denotes the set of quantum numbers $\{l,s,j,I\}$, with l,s, and j being the orbital angular momentum, the intrinsic spin of the valence particle, and their sum ($\vec{j} = \vec{l} + \vec{s}$), respectively. Any wave function will be the sum of different configurations (channels) labeled here with the index parameter α. Each channel will have a specific weight in each state of the composite nucleus. This weight can be regarded as a unit-normalized spectroscopic factor.

Once the structure model is defined, for the reaction calculations one needs also the optical potential V_{pT} representing the interaction of the projectile p with the target T. Within the assumed three-body reaction model, this interaction will be the sum of the interactions of the different projectile constituents (core + valence) with the target, i.e.,

$$V_{pT} = V_{vT}(\vec{R_{vT}}) + V_{cT}(\vec{R_{cT}},\xi). \tag{2}$$

V_{vT} and V_{cT} are evaluated at the energy per nucleon of the incident projectile. This interaction enters in the reaction calculation through the coupling potentials or form factors which read

$$\langle \Psi^f_{JM} | V_{vT}(\vec{R_{vT}}) + V_{cT}(\vec{R_{cT}},\xi) | \Psi^i_{J'M'} \rangle. \tag{3}$$

Note that this V_{cT} depends on, in addition to the relative coordinates, the core internal degrees of freedom ξ. In this way, the core-target interaction is able to excite the core states during the reaction process. This implies the connection and exploration of wave function parts not accessible through the *normal* valence particle excitation, which is the aspect we intend to exploit with this kind of analysis. This process is normally called *dynamic* core excitation (DCE) to distinguish it from the *static* effect of these excitations in the projectile structure. In other words, static effects are connected to the weights of the different contributions in the wave functions of the projectile Ψ_{JM}, whereas dynamic effects are related to V_{cT}. Standard few-body models neglect this dependence of V_{cT} on ξ, thereby omitting the dynamical excitation of the core.

We will use here two different frameworks which are the appropriate generalizations of the DWBA and CDCC formalisms for breakup reactions including both static and dynamical core excitations. The main difference between the XDWBA and XCDCC approaches is that in the former, the breakup is treated to first order and the relative motion of the projectile and target is described by appropriate distorted waves, whereas in the CDCC formalism the breakup is treated to all orders, and the functions describing the projectile-target relative motion are obtained by solving a system of coupled equations. Additionally, in the XDWBA method used here, we make a *no-recoil approximation*, in which the core-target coordinate is approximated by the projectile-target coordinate [13]. These two approximations are expected to be well justified in the present case [37]. In addition to simplifying the reaction problem, the appealing feature of the XDWBA formalism is that it permits a separation of the scattering amplitude into two terms: one corresponding to the excitation of the valence particle and the other one associated with the core excitation. We will take advantage of this separation to evaluate the relative importance of the two processes: (i) the traditional elastic breakup due to the excitation of the weakly bound neutron and (ii) the breakup due to the dynamical core excitation where the valence neutron is just a spectator.

Results. We apply the XDWBA and XCDCC frameworks to the resonant breakup of ^{19}C on protons at 70 MeV/nucleon. This reaction was measured at RIKEN by Satou *et al.* [33]. In this experiment they found a prominent peak in the energy distribution of the breakup cross section at $E_x = 1.46 \pm 0.10$ MeV. In [33] a microscopic DWBA study using transition densities calculated from a shell-model calculation was performed for the corresponding angular distribution, and the peak was associated with a resonance with spin and parity $5/2^+$. However, different structure models have predicted two $5/2^+$ resonances and there is a long-standing controversy regarding the possibility of having a $5/2^+$ bound state, as suggested by Elekes *et al.* [29].

In the present calculations, we will consider the recently developed semimicroscopic particle-core model for ^{19}C [34], in which the diagonal and off-diagonal neutron-core couplings are obtained by folding the effective Jeukenne-Lejeune-Mahaux (JLM) interaction [38] with microscopic central and transition densities of ^{18}C, calculated with antisymmetrized molecular dynamics (AMD) [39]. For simplicity, only the 0^+ and 2^+ states of the core are considered, and the orbital angular momentum of the halo neutron is restricted to $\ell = 0,2$. A phenomenological spin-orbit potential with standard parameters is also added. The wave functions and energies of the system are then obtained by diagonalizing this Hamiltonian in a transformed harmonic oscillator (THO) basis. With a suitable choice of the basis, the resonance states are well characterized by a single eigenstate. Further details can be found in Ref. [34]. The resulting low-lying spectrum is depicted in the last column of Fig. 1. Despite its simplicity, the model succeeds in reproducing the doublet of bound states $1/2^+$ and $3/2^+$. It also predicts two unbound $5/2^+$ resonances. This is in disagreement with the observations of Ref. [29], but is consistent with the observation of Ref. [31] and with the conclusions of Ref. [30]. However, none of these two states has an energy consistent with the peak observed by Satou *et al.* [33]. Consequently, it is not possible to assign the peak observed by them to one of our $5/2^+$ states based solely on their energies. Thus, in the reaction calculations we have considered both resonances as potential candidates for this peak.

The calculated weights, within the present semimicroscopic model, for the main components in the ^{19}C ground-state wave function and in the two $5/2^+$ low-lying resonances considered here are listed in Table I. For the ground state, the major component is $|0^+ \otimes s_{1/2}\rangle$, i.e., a neutron in the $2s_{1/2}$ orbit with the core in its ground state: ^{18}C(0^+). The situation for the two $5/2^+$ resonances is the opposite: the larger weights are associated with the excited state of the core ^{18}C(2^+). This fact already suggests a non-negligible role of core excitations in the present resonant breakup. In both resonances the component with ^{18}C in its ground state, $|0^+ \otimes d_{5/2}\rangle$, is just around 25% of the total wave function. A fuller discussion and a comparison of these weights with shell-model calculations and experimental values can be found in [34].

For both the XDWBA and XCDCC calculations, valence-target and core-target interactions are also needed. For the p-^{18}C interaction we construct folding potentials using the JLM nucleon-nucleon interaction [38]. This procedure has been able to reproduce the elastic and inelastic scattering of protons on ^{10}Be and ^{12}Be [42], after some suitable renormalization of the real and imaginary parts. The renormalization factors depend also on the assumed range parameter for the JLM interaction (t). We adopt here the original value $t = 1.4$ fm, for which renormalization factors of 1.2 and 0.8 have been prescribed for the real and imaginary parts, respectively.

For the n-p potential, we use the simple Gaussian potential of Refs. [11,13], whose parameters were adjusted to reproduce the breakup in the ^{11}Be + p reaction obtained with a Faddeev calculation with the more realistic p-n CD-Bonn potential.

TABLE I. Weights of the different configurations for the ground state and the two $5/2^+$ resonances in ^{19}C, according to the semimicroscopic particle-plus-core model described in the text [34].

	$\|0^+ \otimes (\ell s)j\rangle$	$\|2^+ \otimes s_{1/2}\rangle$	$\|2^+ \otimes d_{3/2}\rangle$	$\|2^+ \otimes d_{5/2}\rangle$
$1/2^+_1$	0.529		0.035	0.436
$5/2^+_1$	0.276	0.721	0.000	0.003
$5/2^+_2$	0.200	0.142	0.002	0.657

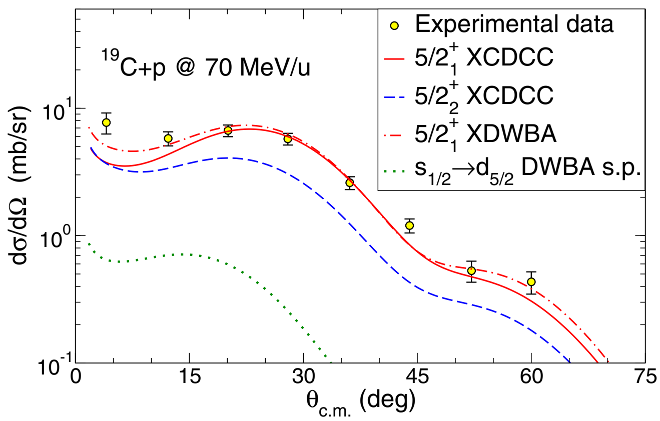

FIG. 2. Angular distribution of the resonant breakup of ^{19}C on protons at 70 MeV/nucleon. The solid red line and the dashed blue line correspond to the XCDCC calculation for the first and the second $5/2^+$ resonance of the P-AMD model [34] respectively. The dotted dashed line corresponds to a XDWBA calculation for the first $5/2^+$ resonance. The dotted line corresponds to an inert-core DWBA calculation where ground state and resonance are considered to be pure $s_{1/2}$ and $d_{5/2}$ states respectively. Experimental data are from Ref. [33].

The calculated breakup angular distributions for the two $5/2^+$ resonances predicted by our structure model are shown in Fig. 2. The first $5/2^+$ resonance is the one that best reproduces the experimental data. However, the second resonance gives a similar angular distribution and even the sum of both would be consistent with the data. As shown in Ref. [12], the magnitude and shape of the resonant breakup is sensitive to the weights of the different configurations of each state. Unfortunately, in this case, both resonances are mainly based in the 2^+ core excited state and, therefore, there is not a clear difference between both choices. Furthermore, in this case the population of both resonances was found to be almost exclusively due to the core excitation mechanism. To illustrate this effect, we include in Fig. 2 a standard inert-core DWBA calculation where the ground state and the $5/2^+$ resonant state are represented by pure $s_{1/2}$ and $d_{5/2}$ single-particle configurations orbiting an inert ^{18}C core, respectively. The result of this calculation is given by the dotted line in Fig. 2. It is clearly seen that the resulting angular distribution significantly underestimates the magnitude of the data, and fails to reproduce the shape too. The same conclusion was achieved in Ref. [35] where a AGS-Faddeev calculation, using a more realistic *p-n* interaction (CD-Bonn), but ignoring core excitations, was also found to provide too small a breakup cross section. This result clearly shows that the observed resonant peak is not consistent with a simple $2s_{1/2} \to 1d_{5/2}$ transition and evidences the dominance of the core excitation mechanism in the present case, resulting from the large ^{18}C(2^+) component in both resonances (cf. Table I). The DCE mechanism is much larger than that found in the ^{11}Be $+ p$ case, in which the valence and core excitations have been found to be of similar magnitude.

Additionally, XDWBA and XCDCC calculations for the first $5/2^+$ resonance have been performed. Both calculations give almost identical results as expected at intermediate energies. This agreement shows that the process is a one-step excitation, which in this case is almost entirely a dynamical core excitation.

A final comment is in order related to the agreement between the semimicroscopic calculations presented here in Fig. 2 and the fully microscopic calculations presented in Ref. [33]. These two approaches give very similar results, thus indicating that the microscopic description of ^{19}C is able to reproduce the collective nature of the core excitations. However, in such a description it is very difficult to isolate and identify the underlying core structures responsible for the resonances. In our semimicroscopic approach this can be easily done as presented in Table I. More importantly, the reaction frameworks used here are able to consider and distinguish the contribution of valence and core excitations to the total cross section. This allows us to predict quantitatively the contribution to the resonances of ^{18}C ground state and excited states, an observable that can be compared directly with the experimental yields.

Conclusions. We have investigated the role of core excitations in the resonant breakup of ^{19}C on a proton target. For that, we have considered a two-body model for ^{19}C and performed XCDCC and XDWBA calculations that include the possibility of core (^{18}C) excitations in the structure of the projectile as well as in the reaction dynamics.

We have compared our results with the experimental data measured by Satou and collaborators [33] for this reaction, at an incident energy of 70 MeV/nucleon, corresponding to the angular distribution for a resonant state in ^{19}C, which was identified with the second $5/2^+$ state predicted by *sd* shell-model calculations.

Our structure calculations, based on a particle-plus-core model of ^{19}C, predict two $5/2^+$ low-lying resonances, but none of them at the energy of the peak observed in [33]. Furthermore, the corresponding angular distributions are both compatible with the shape and magnitude of the experimental one, thus precluding an unambiguous identification of the experimental peak with one or another. This result is understood as a consequence of the similar structure for the two resonances. Both resonances are mainly based on the first 2^+ state of the core. Therefore, it is clearly seen in the present analysis that the dynamic excitation of the core is the main mechanism responsible for the peak observed in the breakup with protons. Moreover, we have shown that the pure valence excitation mechanism, assuming a $2s_{1/2} \to 1d_{5/2}$ single-particle transition, gives a negligible contribution here. This is the first case where we have identified that the core excitation mechanism dominates overwhelmingly.

The present results are in contrast with the naive picture of halo nuclei where the weakly bound neutron is completely decoupled from the rest of the nucleons inside the core, which could be considered as a frozen object. We had previously found cases where single-particle excitations of the valence particle and dynamic excitations of the core compete on equal footing, leading to an interesting interplay of both processes [12]. However, the dynamic excitation of the core in ^{19}C is so strong that it is the core that plays the main role in the breakup reaction of a halo nucleus.

As a final remark, we would like to insist on the importance of the effects of core excitations in reactions with halo nuclei. The cores of the new and heavier halo candidates, like ^{31}Ne and ^{37}Mg, will present more and more complex structures since they will be more exotic. This will make the analysis of the forthcoming experiments more involved. According to Ref. [19], core excitation effects will be smaller for heavier targets. However, low-lying quadrupole resonances as low as the one recently found in Ref. [32] may have a non-negligible impact in Coulomb dissociation experiments like those reported in Ref. [27] and will need further exploration. Taking into account possible core excitation effects will be mandatory for a better understanding and a correct analysis of the experimental data.

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