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The recent precise experimental determination of the monopole transition form factor from the ground state of ${}^4\text{He}$ to its 0_2^+ resonance via electron scattering has reinvigorated discussions about the nature of this first excited state of the α particle. The 0_2^+ state has been traditionally interpreted in the literature as the isoscalar monopole resonance (breathing mode) or, alternatively, as a particle-hole shell-model excitation. To better understand the nature of this state, which lies only ~ 410 keV above the proton emission threshold, we employ the coupled-channel representation of the no-core Gamow shell model. By considering the $[{}^3\text{H} + p]$, $[{}^3\text{He} + n]$, and $[{}^2\text{H} + {}^2\text{H}]$ reaction channels, we explain the excitation energy and monopole form factor of the 0_2^+ state. We argue that the continuum coupling strongly impacts the nature of this state, which carries characteristics of the proton decay threshold.

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Introduction.—The lowest excited state of the α particle is the 0_2^+ state at $E = 20.21$ MeV. Since 1966 [1] this state has been associated with a vibrational monopole (breathing) mode resulting from the $0s \rightarrow 1s$ particle-hole shell-model excitations [2–7]. It was noted, however, that two- and four-particle excitations from $0s$ to $0p$ shell could also account for the low-lying positive parity excited states, including 0_2^+ , hence the vibrational interpretation may not be strictly valid [8–10].

The 0_2^+ state lies 0.41 MeV above the proton decay threshold and hence it decays 100% by proton emission [11]. The $[{}^3\text{He} + n]$ decay threshold lies only 0.37 keV above, and the $[{}^2\text{H} + {}^2\text{H}]$ threshold lies 3.64 MeV higher [12]. Consequently, the theoretical description of the 0_2^+ state must consider the coupling to the nearby decay thresholds, i.e., it requires an open-quantum-system (OQS) framework.

An early description of nucleon reaction channels in ${}^4\text{He}$ was provided in Ref. [13] in terms of the continuum shell model. Excited states of ${}^4\text{He}$ were studied in Ref. [14] using variational R -matrix approach with realistic interactions. The four-body bound-state calculations of 0_2^+ interpreted this state as ${}^3\text{H} + p$ configuration [15], and provided a quantitative description of the monopole $0_1^+ \rightarrow 0_2^+$ form factor (for supporting discussion, see also Ref. [16]). In Refs. [17,18], the Lorentz integral transform approach, implicitly taking into account continuum effects, has been used to describe the 0_2^+ state and the monopole form factor.

The results turned out to be strongly dependent on the interaction used (see also discussion in Refs. [19,20]). The importance of the threshold structure on the properties of the 0_2^+ state was demonstrated in Ref. [21] in the framework of pionless effective field theory. Let us also mention significant literature on the microscopic description of four-nucleon scattering with realistic interactions using the Faddeev-Yakubovsky [22], hyperspherical harmonics [19,23], and Alt-Grassberger-Sandhas [24,25] frameworks, and recent *ab initio* no-core shell model (NCSM) studies combined with the resonating group method (RGM) [26]. All these approaches can take into account channel coupling effects in a fully microscopic way.

Recently, the A1 Collaboration at Mainz Microtron (MAMI) has carried out the precise measurement of the $0_1^+ \rightarrow 0_2^+$ transition via inelastic electron scattering [20]. The theoretical analysis carried out in their study confirmed the previous conclusions [17,18] that modern nuclear forces fail to reproduce the data. However, as noted in the accompanying viewpoint [27], a possible explanation could involve “the relationship between the form factor and the location of the 0_2^+ resonance.”

A microscopic description of nuclear states close to the particle decay threshold requires the unitary formulation of the problem that would guarantee the flux conservation. As shown in Refs. [28,29], in the models that obey unitarity, the collective mixing of shell model eigenstates around the threshold gives rise to the appearance of the so-called

aligned state that shares many features of the decay channel. In fact, there exist many near-threshold resonances that exhibit a large degree of resemblance to the nearby reaction threshold (for illustrative recent examples, see Refs. [30,31]). Considering the above, it is indeed tempting to interpret the 0_2^+ excitation of the α particle as an eigenstate aligned with respect to the $[^3\text{H} + p]$ threshold. To this end, we employ the no-core Gamow shell model (GSM) [32,33] in the coupled-channel representation (NCGSM-CC) [34]. The unitary OQS formalism of the NCGSM-CC is very well suited for this task as it is based on realistic input and is capable of describing reaction channel coupling effects.

Coupled-channel representation of the no-core Gamow shell model.—Here we will briefly outline the essential steps in the calculation of the monopole form factor of the 0_2^+ resonance using the no-core NCGSM-CC formalism. More details about the NCGSM-CC approach can be found in the Supplemental Material [35].

In NCGSM-CC, the A -body state is decomposed into reaction channels defined as binary clusters (target T and projectile P) involving different numbers of neutrons and protons. The binary-cluster channel states are defined as:

$$|(c, r)_M^J\rangle = \hat{A}[|J_T^{(\text{int})}\rangle \otimes |r\ell J_P^{(\text{int})} j\rangle]_M^J \quad (1)$$

where the channel index c stands for different quantum numbers and mass partitions, \hat{A} is the intercluster antisymmetrizer that acts among the nucleons pertaining to different clusters with angular momenta J_T and J_P . The total angular momentum is $\mathbf{J} = \mathbf{j} + \mathbf{J}_T^{(\text{int})}$, where $\mathbf{j} = \boldsymbol{\ell} + \mathbf{J}_P^{(\text{int})}$.

All coordinates and angular quantum numbers in (1) are defined with respect to the center of mass (c.m.) of the target + projectile composite. Since the target state $|J_T^{(\text{int})}\rangle$ is intrinsic, it has no c.m. component. The projectile state $|r\ell J_P^{(\text{int})} j\rangle$ contains both the intrinsic wave function of the projectile $|J_P^{(\text{int})}\rangle$ and the relative wave function $|r\ell\rangle$, which can be identified with the projectile's c.m. motion in the asymptotic zone. By expanding the radial wave function $u_c(r)$ in the single-particle (s.p.) Berggren basis $u_n(r)$ [34,37] that involves resonant states and scattering continuum, one can derive the standard RGM expressions [34,36] for the Hamiltonian and norm kernels [35].

To handle the transformation from laboratory coordinates to c.m. and relative coordinates, it is convenient to use the harmonic oscillator (HO) basis. We emphasize that this procedure is consistent with the use of the Berggren expansion as the HO basis is used only to calculate the finite-range parts of NCGSM-CC potentials. The full NCGSM-CC coupled-channel Hamiltonian is diagonalized in the Berggren basis, so that the weakly bound and resonant eigenstates have proper asymptotic behavior.

In the first step, we calculate the ground states of target and projectile. These wave functions can be represented as

the products of the intrinsic wave functions $|J^{(\text{int})}\rangle$ and the c.m. HO wave functions $|0s_{\text{c.m.}}\rangle$ obtained by using the standard Lawson method [38]. To suppress the spurious c.m. component in the composite product states built from projectile and target states, an additional Talmi-Moshinsky-Brody [39–41] transformation has to be performed, see Ref. [35]. As this channel state is a linear combination of Slater determinants, the matrix elements of \hat{H} are straightforward to calculate. The numerical precision of the c.m. motion removal has been checked by explicitly acting on the channel state with the c.m. Hamiltonian; the resulting c.m. mode suppression is $\sim 10^{-11}$ or smaller.

The many-body matrix elements in NCGSM-CC are calculated using the Slater determinant expansion of the cluster wave functions. The RGM treatment of the non-orthogonality of channels is standard [34]. Note that the antisymmetry of channels, enforced by the antisymmetrizer in (1), is exactly taken into account through the Slater-determinant expansion of many-body target and projectile states.

Results.—In the following, we apply the NCGSM-CC framework to the structure of the proton-unstable resonance 0_2^+ of ^4He and the related monopole transition form factor $F_{\text{rel}}(q^2)$. To this end, we study the channel occupation $\mathcal{R}e(a_c^2)$ corresponding to the NCGSM-CC wave function of the 0_2^+ state, where a_c^2 is the squared norm of the channel wave function. The channel occupation and its variation as a function of the energy $\Delta E_{\text{th}} = E - E_{\text{thr}}$ from the $[^3\text{H} + p]$ threshold provide insights into the microscopic structure of the 0_2^+ resonance.

The NCGSM Hamiltonian used is based on the $V_{\text{low-}k}$ [42] N^3LO interaction of Entem and Machleidt with $\Lambda = 1.9 \text{ fm}^{-1}$ [43]. A model space of $12\hbar\omega$ is used for the HO expansion of channel functions which is sufficiently large to provide a satisfactory description of both 0_1^+ and 0_2^+ states of ^4He . In our analysis, we consider three channels: $[^3\text{H} + p]$, $[^3\text{He} + n]$, and $[^2\text{H} + ^2\text{H}]$, corresponding to three different mass partitions of ^4He . The intrinsic wave functions of ^3H , ^3He and ^2H clusters are assumed to correspond to their ground states. The relative partial waves included in the basis are $s_{1/2}$ ($[^3\text{H} + p]$, $[^3\text{He} + n]$), and 3S_1 , 3D_1 ($[^2\text{H} + ^2\text{H}]$). The Berggren basis contours in the complex momentum plane are defined by the linear momenta $k = 0$, $k_{\text{peak}} = 0.2 - 0.19i$, $k_{\text{middle}} = 0.4 - 0.19i$, and $k_{\text{max}} = 3$ (all in fm^{-1}); they are discretized with 90 points, to which the poles $0s_{1/2}$, $1s_{1/2}$ ($[^3\text{H} + p]$, $[^3\text{He} + n]$), the three and two first resonant states of the 3S_1 and 3D_1 partial waves ($[^2\text{H} + ^2\text{H}]$) are added, respectively. This guarantees that the resonance 0_2^+ is properly described in the asymptotic zone. Since the ^3H , ^3He , and ^2H clusters are assumed to be in their positive-parity ground states, the $\ell = 1$ partial waves in projectile wave functions are not allowed.

The three-body part of the N^3LO interaction has been neglected. Based on our NCGSM calculations, the effect of

three-body forces on the binding energy is about 1.5 to 2 MeV. However, as discussed in Ref. [14], three body force has a very small effect on the spectrum above the proton decay threshold. Moreover, it is always necessary to modify the Hamiltonian by fixing the positions of particle-emission thresholds as it is impossible to reproduce binding energies up to a required precision of a few keV. In this way, the small energy shift due three-body force is phenomenologically accounted for. In all calculations we use the HO length of $b_{\text{HO}} = 1.8$ fm, as this value is optimal for the 0_2^+ state and close to optimum for the 0_1^+ ground state. For this choice of parameters, the energy of the 0_1^+ ground state is about -25 MeV with NCGSM-CC, which is sufficiently precise for our study.

The occupations $\mathcal{R}e(a_c^2)$ of proton, neutron, and deuteron channels are plotted in Fig. 1(a). Note that RGM-orthogonalized channels are used in order to simplify the interpretation [34]. This does not change asymptotic physical properties as the initial and RGM-orthogonalized channels are identical at large distances. Therefore, the channel label used in Fig. 1 properly characterizes the asymptotic behavior.

As shown in Fig. 1(a), the $[^3\text{H} + p]$ channel is dominant at $E < 320$ keV. For $\Delta E_{\text{thr}} \simeq 150$ keV, the percentage of the $[^3\text{H} + p]$ channel is $\sim 95\%$, whereas the weights of closed channels $[^3\text{He} + n]$ and $[^2\text{H} + ^2\text{H}]$ are very small.

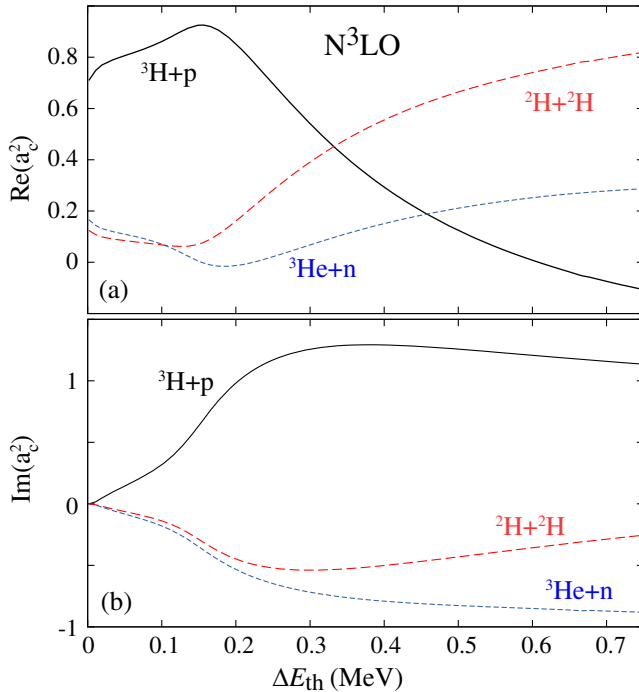


FIG. 1. Top: occupations $\mathcal{R}e(a_c^2)$ of orthogonalized proton (solid line), neutron (dashed line), and deuteron channels (long-dashed line) plotted as a function of the difference ΔE_{thr} between the energy of the 0_2^+ state and the proton threshold. Bottom: Corresponding imaginary channel occupations $\mathcal{I}m(a_c^2)$.

At the experimental value of $\Delta E_{\text{thr}} \approx 400$ keV, the $[^3\text{H} + p]$ channel occupation drops to 32% and the $[^2\text{H} + ^2\text{H}]$ channel becomes dominant. The neutron decay channel opens up at $\Delta E_{\text{thr}} \approx 0.78$ MeV. At this energy, the proton-channel amplitude is very small while the wave function is dominated by the deuteron-deuteron component. It is to be noted that in the complex-energy framework such as GSM, the squared wave-function amplitude $\mathcal{R}e(a_c^2)$ can be negative [44]. The statistical uncertainty of the $\mathcal{R}e(a_c^2)$ which, at the leading order, is associated with its imaginary part $\mathcal{I}m(a_c^2)$ [34,45] is shown in Fig. 1(b). A statistical uncertainty on $\mathcal{R}e(a_c^2)$ arises because of the different life times that the resonance 0_2^+ state can have in several experiments. Hence, as explained in Refs. [34,45,46], $\mathcal{R}e(a_c^2)$ is the average value of the corresponding occupation probability obtained in different measurements, while $\mathcal{I}m(a_c^2)$ can be related to the dispersion rate over time in the measurement, and hence represents its statistical uncertainty. The imaginary squared amplitudes are of the same order of magnitude as $\mathcal{R}e(a_c^2)$, except for a narrow region above the proton-emission threshold. Thus, there is a large statistical uncertainty on channel occupations in the energy region considered. This is consistent with the fact that the measured spectral function of the 0_2^+ state deviates from the Breit-Wigner profile [20], i.e., this state cannot be considered as quasistationary [46,47]. The NCGSM-CC predicts a large decay width, $\Gamma \approx 1200$ keV at $\Delta E_{\text{thr}} \approx 400$ keV. Consequently, the predicted 0_2^+ state is very broad. This means that it becomes difficult to relate the value of Γ , associated with the imaginary part of the complex energy of the 0_2^+ state with the lifetime, see Ref. [47].

We now consider the monopole transition form factor $|F_{\text{rel}}(q^2)|^2$, whose definition can be found in Refs. [15,35]. We include the effects of the intrinsic charge proton form factor and recoil terms (see Refs. [15,35] for details).

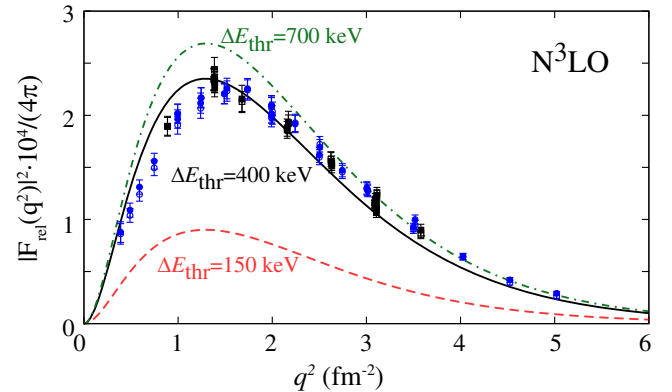


FIG. 2. Monopole transition form factor $|F_{\text{rel}}(q^2)|^2$ obtained with N^3LO for the excitation of the ground state 0_1^+ to the excited 0_2^+ state of ^4He as a function of q^2 for three values of $\Delta E_{\text{thr}} = 150, 400,$ and 700 keV. For the experimental data, see Ref. [20].

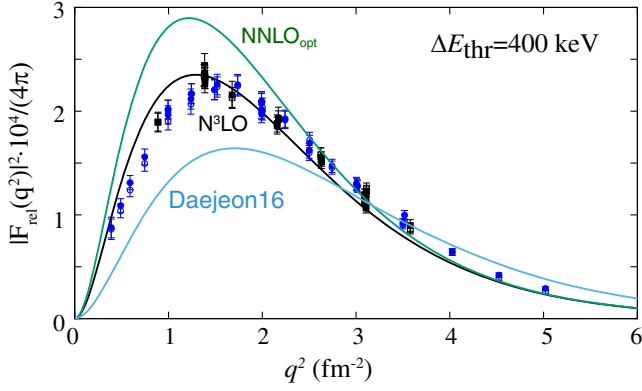


FIG. 3. Monopole transition form factor for the $0_1^+ \rightarrow 0_2^+$ excitation of ${}^4\text{He}$ at $\Delta E_{\text{thr}} = 400$ keV obtained with three interactions: N^3LO [42], NNLO_{opt} [49], and Daejeon16 [50].

Neutron finite-size effects are neglected as neutron form factor and meson exchange terms are small [15,48]. The monopole form factor $|F_{\text{rel}}(q^2)|^2$ is shown in Fig. 2 at $\Delta E_{\text{thr}} = 150, 400,$ and 700 keV. The 400 keV value corresponds to the experimental position of the 0_2^+ resonance. It is seen that (i) the calculated magnitude of $|F_{\text{rel}}(q^2)|^2$ strongly depends on the energy distance from the proton threshold, and (ii) the NCGSM-CC calculation at the experimental value of ΔE_{thr} reproduces experiment fairly well. It should be noted that the occupation of the channels $[{}^3\text{H} + p]$ and $[{}^2\text{H} + {}^2\text{H}]$ is comparable at $\Delta E_{\text{thr}} = 400$ keV, suggesting a complicated continuum structure of the 0_2^+ resonance. Moreover, the dispersion

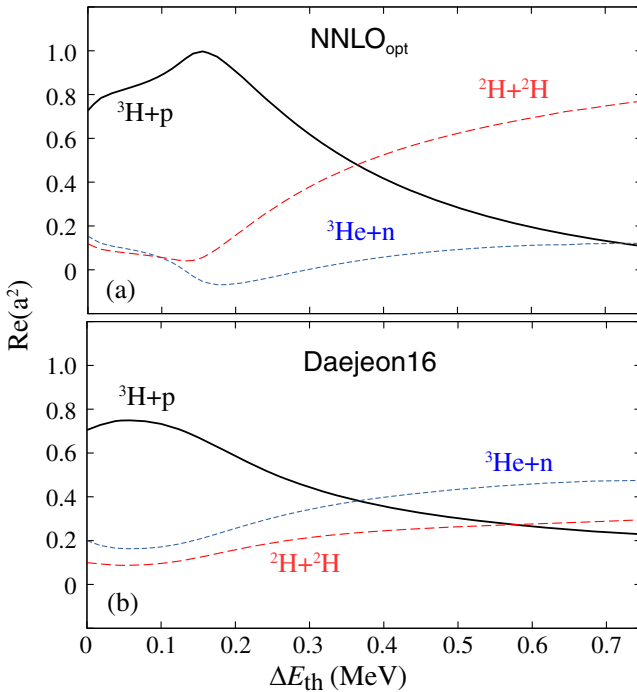


FIG. 4. Similar as Fig. 1(a) but for (a) NNLO_{opt} and (b) Daejeon16.

of the $[{}^3\text{H} + p]$ channel occupation is maximal at this energy.

In order to check the sensitivity of predictions to the choice of interaction, we carried out calculations with NNLO_{opt} [49] and Daejeon16 [50] forces (see Fig. 3). The form factors obtained with NNLO_{opt} and N^3LO interactions are fairly similar, with the NNLO_{opt} prediction slightly overshooting the data at $q^2 \approx 1.2$ fm 2 . The form factor obtained with Daejeon16 is lower in this region of q^2 .

The NNLO_{opt} and Daejeon16 occupations $\text{Re}(a_c^2)$ of orthogonalized channels are shown in Fig. 4. One can see that the difference of the occupations of the channels $[{}^3\text{H} + p]$ and $[{}^3\text{He} + n]$ at $\Delta E_{\text{thr}} = 400$, keV follows the increase of the monopole form factor.

Conclusions.—In this Letter, stimulated by the recent experimental study [20], we developed the OQS NCGSM-CC framework to understand the structure of the proton-decaying 0_2^+ excited of the α particle. Particular attention has been paid to the proper removal of the spurious c.m. modes when constructing the channel wave functions. Our model based on the N^3LO chiral interaction reproduces the binding energies of 0_1^+ and 0_2^+ states, a broad resonance character of the 0_2^+ state, and the measured monopole form factor.

We predict a rather complex character of the 0_2^+ state that involves a strong continuum coupling between the $[{}^3\text{H} + p]$, $[{}^3\text{He} + n]$, and $[{}^2\text{H} + {}^2\text{H}]$ decay channels. The best agreement with the measured form factor is obtained at the experimental energy ΔE_{thr} . We also predict a rather strong dependence of $|F_{\text{rel}}(q^2)|^2$ on the energy distance from the proton threshold, i.e., we answer the question raised in Ref. [27] affirmatively. In this respect, the 0_2^+ state should not be viewed in terms of a breathing oscillation or the $0s \rightarrow 1s$ particle-hole excitation, but rather interpreted as a threshold-aligned broad resonance whose structure is dominated by the interplay of the open channel $[{}^3\text{H} + p]$ and closed channels $[{}^3\text{He} + n]$ and $[{}^2\text{H} + {}^2\text{H}]$. Based on our N^3LO results, the explicit reproduction of competing particle-emission thresholds is important for the theoretical understanding of the 0_2^+ state.

But the position of the 0_2^+ state relative to the thresholds is not the full story. Calculations performed with other interactions, namely, NNLO_{opt} and Daejeon16, have shown some interaction dependence of the wave function decomposition and hence the monopole form factor. This suggests that—when it comes to theoretical description—the monopole form factor is a fairly sensitive and demanding observable: it is controlled by several factors, such as interaction, threshold positions, and resonance energy. Consequently, this quantity is not ideal when it comes to constraining nuclear interaction.

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- details on the NCGSM-CC Hamiltonian and RGM equations; the basis-generating potential of NCGSM-CC equations, the suppression of c.m. motion in reaction channels using the harmonic oscillator basis; and the monopole form factor calculations; it includes Refs. [15,34,36].
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Correction: A typographical error in the first affiliation has been fixed.