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Probing preformed α particles in the ground state of nuclei

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In this Rapid Communication, we report on α-particle emission through the nuclear breakup in the reaction ^{40}Ca on a ^{40}Ca target at 50 A MeV. It is observed that, similar to nucleons, α particles can be emitted to the continuum with very specific angular distribution during the reaction. The α-particle properties seem to be compatible with an α cluster in the daughter nucleus that is perturbed and is emitted by the short-range nuclear attraction of the collision partner. A time-dependent theory that describes the α-particle wave-function evolution is able to qualitatively reproduce the observed angular distribution. This mechanism offers new possibilities for studying α-particle properties in the nuclear medium.

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Nuclei are complex self-bound systems formed by nucleons. Conjointly, to a mean-field picture in which nucleons can be regarded as independent particles, few nucleons might self-organize into compact objects, called clusters, inside the nucleus. The understanding of clustering in the nuclear medium is a central issue and has been the subject of extensive research. Clustering in $N = Z$ nuclei has a long-standing history (see discussion in Ref. [1]), and the recent antisymmetrized molecular dynamics calculation investigate the $\alpha + {}^{36}$Ar configuration of the ^{40}Ca nucleus [2] for which experimental results are presented here. The states based on α particles have also been observed in a $(d, {}^6\text{Li})$ experiment on ^{40}Ca, which led to the ground state (GS) and the first excited states, although these states were not shown in Ref. [3]. However, α clusters are not usually found very much in the GS but rather are observed as excited states close to the decay thresholds, which self-organize into clusters, as suggested by Ikeda *et al.* [4]. In particular, the Hoyle state (i.e., the 0_2^+ state at 7.65 MeV in ^{12}C) and other similar states in heavier $n\alpha$ nuclei, have attracted much renewed attention (see, e.g., Ref. [5]). In particular, the possibility to interpret specific states as the signature of α-particle condensates [6] is actually highly debated [7]. Other experiments have observed the emission of α particles but with different mechanisms, such as the decay of giant resonances [8] or the emission from the neck [9]. However, as will be discussed later, these mechanisms are observed at a much higher excitation energy ($E^*/A \simeq 2$ to 3 MeV/A) than here.

In this Rapid Communication, we report on sudden α-particle emission interpreted as the nuclear breakup, also called the towing mode, of the α cluster present in the GS of ^{40}Ca. This mechanism, first observed with neutrons and protons in the inelastic-scattering channels with stable beams [10] is an emission to the continuum caused by the nuclear potential of colliding nucleus. The time scale is much shorter here than for a regular evaporation as it is related to passing time of the projectile on the order of 10^{-22} s. The characteristics of this emission were reproduced with a dedicated time-dependent Schrödinger equation (TDSE) [11] technique as follows. As the emitter nucleus passes close to the collision partner, the short-range nuclear potential of the latter attracts the least-bound nucleons, which lead to the emission of particles at midrapidity. We have shown an excellent reproduction of the experimental properties with the model calculation, and we have demonstrated that this mechanism has several interesting aspects. The characteristics of the emission (angular and energy distributions) strongly depend on the initial quantum properties of the towed particle (angular momentum, extension of the wave function, and binding energy). These properties promote the towing mode as the tool of choice for inferring spectroscopic information of nucleons in nuclei as shown in Refs. [12–14] for ^{11}Be and ^{6}He.

In this present experiment, where the reaction ^{40}Ca on a ^{40}Ca target at 50 A MeV was measured, not only has the target breakup of one proton been observed [15], but also the breakup of an α particle has been observed [8] as we present in the following, which indicates the formation of an α cluster in the ^{40}Ca nucleus. The α cluster is emitted to the continuum

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because of the perturbation of the other nucleus with specific angular and energetic properties. A dedicated model, which initially describes the evolution of the α-particle wave function in the daughter nucleus for grazing impact parameters is able to qualitatively describe the observed behavior.

The experiment was performed at the GANIL facility, by bombarding a self-supported 0.2-mg/cm^2 natural Ca target with a 50-A MeV ^{40}Ca beam. The ejectiles were identified in the focal plane of the SPEG (Spectromètre à Perte d'Energie du Ganil) spectrometer [16], in coincidence with the light-charged particles detected in 240 CsI(Tl) detectors of the INDRA 4π array [17], which covers an angular range from 14° to 176° with respect to the beam direction. The projectiles were measured between $\theta_{\rm lab} = 0.5°$ and 5° by using the SPEG spectrometer with its standard detection system. Stripped cathode drift chambers were used for the position measurement in the focal plane [18]. Combined with the very thin target, they allowed for an excitation energy resolution of 350 keV (i.e., $\Delta p/p = 9 \times 10^{-5}$). The ejectiles were unambiguously identified in charge and mass through energy and time-of-flight measurements; and, in this Rapid Communication, we will only concentrate on the inelastic channel where the ejectiles are of the same nature as the ^{40}Ca projectile.

The identification of the particles was obtained by analyzing the fast and slow components of the CsI scintillator light and was fully reliable above particle kinetic energy of 4 MeV. Therefore, we have set a 4-MeV software energy threshold for the α particles. The light-particle energy calibration was performed by using the particle decay toward the GS of the daughter nucleus [15,19]. The obtained energy resolution for α particles is 1.1 MeV, hence, a 1.15-MeV energy resolution on the reconstructed missing energy (see the following).

We performed a measurement of the missing energy calculated as follows: $E_{\rm miss} = E^*_{\rm Ca} - E^{\rm CM}_\alpha - E_{\rm recoil}(^{36}{\rm Ar})$ where $E^*_{\rm Ca}$ is the initial excitation energy in ^{40}Ca obtained by the measurement of the inelastically scattered projectile detected after the SPEG spectrometer, $E^{\rm CM}_\alpha$ is the α-particle energy in the center-of-mass frame of the recoiling ^{40}Ca target, and $E_{\rm recoil}$ is the recoil energy of targetlike ^{36}Ar. The remaining excitation energy of ^{36}Ar is then $E^*_{^{36}{\rm Ar}} = E_{\rm miss} - Q_\alpha$ and is plotted in Fig. 1. We show the final states of ^{36}Ar after an α particle was removed from the target and was detected in two different angular regions (for an apparent excitation energy range between 20 and 50 MeV). Spectra (a) and (b) correspond to forward and backward emissions, respectively. Region (b) is selecting the evaporation of an excited ^{40}Ca target that will emit isotropically. Then, this statistical decay is also present in Fig. 1(a) with a strong feeding of several low-energy states of ^{36}Ar on top. On spectrum (a), we clearly recognize the 0^+ GS, the first 2^+ state at 1.97 MeV, and a second excited state around 4.4 MeV, which could not be separated from the surrounding states (see right panel of Fig. 1) but could possibly be assigned to the 4^+ state of ^{36}Ar. On spectrum (b), these states are much less populated. The difference observed between the forward and the backward α-particle emission is very similar to the anisotropy in nucleon emission measured previously in reaction ^{58}Ni(^{40}Ar, ^{40}Ar + p or n)^{57}X (see Ref. [10]), which is a clear signature of nuclear breakup, sometimes called the towing mode where the target, after its breakup, is left in its GS

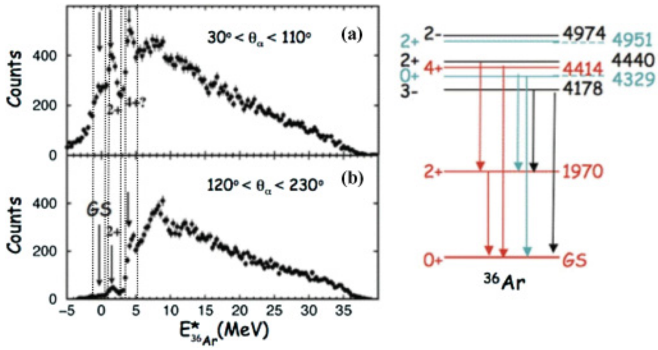

FIG. 1. (Color online) Missing energy spectrum of ^{36}Ar in the reaction ^{40}Ca(^{40}Ca, ^{40}Ca + α) for an excitation energy range between 20 and 50 MeV. (a) α particles are detected between 30° and 110°, (b) α particles are detected between 130° and 220° in the laboratory system, in the backward direction compared to the beam. The arrows show the GS, the 2^+ state, and a state around 4.4 MeV. The dashed lines are the upper and lower limits of the gates used to extract the angular distributions presented in Fig. 3. Lower and higher values for the gates were as follows: from -1.1 to 0.7 MeV to select most of the GS, from 1.1 to 2.9 MeV for the 2^+ state, and from 3.7 to 5.1 for state around 4 MeV. The right panel shows the level scheme of known states up to 4.974-MeV excitation energy in ^{36}Ar [20].

or with very small excitation energy. Because of this sudden nuclear breakup, the α particle is expelled from a cold nucleus, thus, the idea of a preformation in the GS of this nucleus.

This first evidence of a similar phenomenon with α particles motivates the precise understanding of this observation to provide a new tool for the study of α-particle properties in the nuclear medium. By extrapolating results obtained with nucleons, we do expect that the properties of the emitted particles depend significantly on the initial α-particle properties in the emitter (binding energy, quantum numbers, and wave-function extension). Here, we will follow the same strategy exactly as for single-nucleon emission and question if the observed anisotropy in α-angular distribution can be understood as the nuclear breakup of a preformed α-particle wave function.

The mechanism responsible for anisotropic distribution of α particles seems to feed different states of a band, which correspond to a deformed ^{36}Ar nucleus with a β of 0.256 [21] (see Fig. 1 right). The feeding of several states of ^{36}Ar can eventually be understood as follows. By assuming that the 0^+ GS of ^{40}Ca presents different configurations, which correspond to an α-particle wave function coupled to an ^{36}Ar core, eventually excited, we write a configuration as $[|\varphi_\alpha\rangle \otimes |(^{36}{\rm Ar})^*\rangle]_n$ where n labels the configuration, while φ_α and $|(^{36}{\rm Ar})^*\rangle$ denote a specific α-particle wave function and a specific state of ^{36}Ar, respectively. As the α particle is emitted, ^{36}Ar is left in the specific configuration $|(^{36}{\rm Ar})^*\rangle$ and can eventually decay through γ emission. By assuming that the α configurations present in the ^{40}Ca GS do not interfere with each other, the feeding of different states can directly be assigned to the independent contributions of each configuration. A complete understanding of the feeding process and/or the extraction of α-particle spectroscopic factors would require very good α-particle energy resolution as well as γ coincidence. Because of the absence of γ detection and insufficient energy resolution

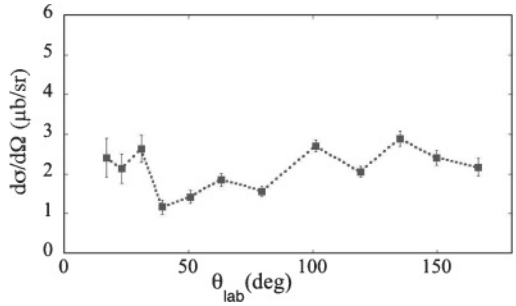

FIG. 2. Angular cross section of α particles when the region of excitation energy between 8 and 9 MeV is selected and only the decay of the target is expected.

(1.15 MeV) of the missing energy spectrum (Fig. 1), separation between the GS and the first 2^+ state and the states around 4 MeV in ^{36}Ar could not precisely be achieved. However, in spite of these limitations, the angular cross sections of the emitted α particles could be extracted. Here, the compatibility of the scenario described previously will be tested qualitatively on the angular distributions of the α particles associated with a particular state in ^{36}Ar against the experimental observation.

We first extracted the angular distribution for the region between 8 and 9 MeV where only the target emission is expected. This is shown in Fig. 2, and a rather flat behavior is observed. On the contrary, to isolate and to characterize the contribution of the different populated states through the towing-mode mechanism, the α-particle angular distributions were extracted by setting gates around the GS, the first 2^+ state, and the state about 4 MeV, by bearing in mind that this selection allows for some contribution from one state to the others because of the poor resolution we had experimentally. These gates are presented on the left spectra of Fig. 1 (vertical dashed lines), and the corresponding distributions are displayed in Fig. 3. For the state around 4 MeV, which has some contribution from evaporation as seen in Fig. 1(b), a subtraction was made from the 8-MeV to the 9-MeV region with a proper normalization that accounts for the contribution

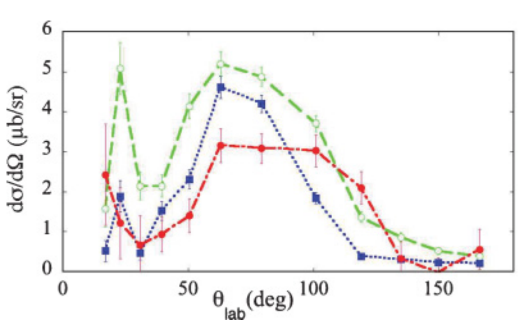

FIG. 3. (Color online) Angular cross sections of α particles when the three first states around $E^*_{^{36}\mathrm{Ar}} \simeq 0$ (blue dotted line), 2 (green dashed line), and 4 MeV (red dot-dashed line), respectively, in Fig. 1 are fed. For the latter state, a subtraction was made with the distribution obtained for the 8- to 9-MeV region.

of the target excitation contribution. A clear sensitivity of the angular distribution to the final state is observed in this figure.

Initially, to test if these distributions could be understood as the final product of an α particle in the ^{40}Ca and could be emitted to the continuum as the projectile passes by, our TDSE technique was applied to the emission of α's. In this model, an α-particle wave function, denoted by φ_α, is first initialized in a spherical symmetric potential by describing the core-α interaction. The potential of Ref. [22], which has been optimized for nuclei in the same mass region to reproduce nuclear structure spectra, $B(E_2)$ transition strength, α-decay widths, and elastic-scattering cross sections, is used here. Its nuclear part is given by

$$V(r) = V_0\left[\frac{\alpha}{(1+e^{(r-R_0)/a_0})} + \frac{1-\alpha}{(1+e^{(r-R_0)/a_0})^3}\right], \quad (1)$$

where the parameters are taken as $V_0 = -175.7$ MeV, $a_0 = 0.73$ fm, $\alpha = 0.3$, and $R_0 = 4.33$ fm and is complemented by a Coulomb repulsive potential. As stressed in Ref. [22], to approximately account for the Pauli blocking effect, which comes from the presence of nucleons in the core, only levels with $2n + L \geqslant 12$, with n and L, respectively, as the radial and angular quantum numbers, are considered. For ^{40}Ca, the first states that the α particle might occupy are the $6s$, $5d$, and $4g$ and have respective binding energies of 7.0, 6.4, and 5.5 MeV.

By starting from one of these α-particle wave functions, the corresponding nuclear breakup has been studied by solving the Schrödinger equation,

$$i\hbar\frac{d}{dt}\varphi_\alpha(\mathbf{r},t) = \left\{\frac{\mathbf{p}^2}{2m_\alpha} + V_{\alpha\,\mathrm{Ar}}[\mathbf{r}-\mathbf{R}_T(t)] + V_{\alpha\,\mathrm{Ca}}[\mathbf{r}-\mathbf{R}_P(t)]\right\}\varphi_\alpha(\mathbf{r},t), \quad (2)$$

where m_α is the mass of the α particle and $V_{\alpha\,\mathrm{Ar}}$ and $V_{\alpha\,\mathrm{Ca}}$ correspond to the target and the projectile mean-field potentials, respectively [both taken identical to Eq. (1)]. The target and projectile center-of-mass evolution $\mathbf{R}_T(t)$ and $\mathbf{R}_P(t)$ are chosen to describe a Coulomb trajectory for the passing ^{40}Ca projectile. The TDSE is solved on a three-dimensional mesh of size 259 in x and y (where y is the direction of the beam) and 199 in z with an r step and a time step of 0.2 fm and 1.22 fm/c, respectively.

Similar to the nucleon case, part of the wave function that was initially bound by the core is emitted to the continuum. From the wave function in momentum space, energetic and angular properties of emitted α can be calculated. Initially, the final angular distributions for an α-particle wave function in the $6s$, $5d$, and $4g$ states are shown in Fig. 4 for an impact parameter between 9.5 and 11.5 fm by taking the partial experimental coverage for the ejectile into account.

These calculations can be compared to the experimental angular distributions that leave the ^{36}Ar nucleus in its GS and the two observed excited states presented in Fig. 3. Although the core + α potential used in the calculation is very schematic, it is quite amazing to see the resemblance as for the widths between the three TDSE calculations of the $6s$, $5d$, and $4g$ wave functions and the experimental data gated on the three

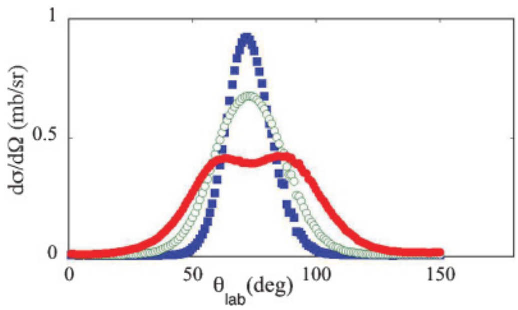

FIG. 4. (Color online) Calculated angular distributions for an α particle initially in 6s (blue squares), 5d (green open circles), and 4g (red dots) states in ^{40}Ca and performed with the TDSE calculation.

peaks at $E^*_{^{36}\mathrm{Ar}} \simeq 0$, 2, and 4 MeV, respectively, shown in Fig. 3. In particular, no adjustment was made to the nuclear potential nor was the possible deformation of the nucleus in which the α particle sits included. In addition, as stressed earlier, because of α-particle energy resolution, it is difficult to separate the different states, and some sizable contribution of the neighboring states could be present in the angular distribution extracted for a specific state.

The comparison of the calculated cross sections and the experimental results allowed us to extract rough spectroscopic factors (SFs) of 1.1%, 1.4%, and 0.9% as for the feeding of the GS, the 2^+, and the 4^+ states, respectively. This is to be compared with the shell-model calculation of Ref. [23], which gives a value of 4% for the GS.

However, a precise estimate of the SFs requires perfect knowledge of the model parameters and especially of the projectile potential, which is beyond the scope of this Rapid Communication.

Nevertheless, these findings are very encouraging: (i) They confirm the towing-mode scenario for the anisotropic emission of a recently observed α particle. (ii) It shows that experimental observation can be described by assuming a preformed α-particle wave function in the GS of ^{40}Ca. (iii) A qualitative description of the experiment is achieved by supposing different contributions, which come from different l values of the outgoing α particle.

Here, let us finally note that the mechanism under interest leads to large asymmetry between rates of α particles emitted in the forward and backward hemispheres. Similar asymmetry has been reported in Ref. [9] and has been attributed to midrapidity emission from a deformed projectilelike fragment. In that case, the asymmetry in the emission has also been interpreted by invoking the proximity effects of the target. However, it should be noted that the excitation energies reported in Ref. [9] ($E^*/A \simeq 2 - 3$ MeV/A) are much higher than the one considered here. The reconstruction of the missing energy spectrum (Fig. 1) indicates that the excitation energy is not more than $E^*/A = 0.12$ MeV/A. The experimental technique used here provides high selectivity on the properties of the emitter at low-excitation energy. While we do expect that the α-particle towing mode might also be present at higher excitation, the dependence of the internal structure of the emitter might be lost. Nevertheless, the transition from low- to high-excitation energy and the link with the mechanism reported in Ref. [9] should be addressed in the near future.

Experimental evidence was shown for the emission of α particles during the breakup of a ^{40}Ca target. A first comparison was made with a TDSE calculation by assuming a preformed α particle in the nucleus, and the general behavior of the measured distribution was reproduced. This finding opens new perspectives for the study of preformed α clusters in the nuclear medium. Similar to the nucleon case, α particles emitted through the nuclear breakup channel have properties that depend sensibly on the initial wave function (see, for instance, Fig. 4 for the quantum number dependence). By following the same strategy as in the nucleon case, one might, with dedicated experiments and improved calculations, be able to access preformed α-particle wave-function properties in the GS of the nuclei.

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