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Study of α clusters in atomic nuclei through nuclear break-up

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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. It is theoretically predicted that it should manifest itself most strikingly for $N = Z$ nuclei close to the emission thresholds and has been studied extensively in this region. In this Proceedings of Science, we propose to study α-clusterization in the ground state of ^{40}Ca.

We have studied the nuclear break-up of ^{40}Ca when the ^{40}Ar projectile passes by. If α clusters are preformed in ^{40}Ca, they will be attracted by the nuclear potential of the projectile and be emitted on the same side. The experiment was performed at GANIL at 35 A.MeV using the SPEG spectrometer to detect the heavy projectile with accurate resolution. The MUST2 Silicon detectors were placed around the target to measure the emitted α and the EXL calorimeter prototype was used to identify the γ rays from the decay of the residual ^{36}Ar. A theoretical approach based on Time-Dependent Schrödinger Equation (TDSE) theory has been used to reproduce some experimental results like angular distributions. First results like excitation energy spectra or angular distributions compared to TDSE theory will be discussed.

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1. Motivations

A nucleus is a pure quantum object and its description is often puzzling. It can be roughly described as an homogeneous distribution of protons and neutrons. However, the chart of nuclides hides complex nuclear structures from the neutron drip line to the proton drip line across the valley of stability. For instance, halo nuclei like ^{11}Li or ^{6}He exhibit a radius much larger than that predicted by the Liquid Drop Model because one or two nucleons are weakly bound and their wave functions can extend very far away from the core [1]. There can be other complex structures such as clusters of nucleons like α. This idea was initiated by the discovery of alpha-decay of heavy nuclei. All of these nuclei may show α-clusterization on some states. One famous example is the well-known 0_2^+ Hoyle-state at 7.65 MeV in ^{12}C described as a $3-\alpha$ cluster structure. Hoyle *et al.* [2] predicted this cluster state to understand the carbon synthesis in stars through the triple-alpha process. During this nuclear mechanism, two alpha-particles fuse momentarily to form a ^{8}Be and then, before the system decays, a third α-particle is captured. Many experiments studied this peculiar state [3] with a very good agreement with theoretical predictions [4].
Furthermore, some light systems can be described in terms of the covalent exchange of neutrons between α clusters [5], resulting in so-called nuclear molecules, an example of which is the ^{10}Be nucleus, which has a $\alpha-n-n-\alpha$ structure or more complex the ^{30}Mg nucleus, which has a $\alpha-3n-^{16}O-3n-\alpha$ structure [6].

For most experiments, α clusters are not searched for in the ground state of the nucleus but rather observed in excited states close to the decay thresholds (the Hoyle state for instance) as suggested by Ikeda *et al.* [7]. In this Proceedings of Science, we report on sudden α particle emission described as the nuclear breakup, also called the Towing Mode, of the α cluster present in the ground state of the $N=Z$ ^{40}Ca stable nucleus. We are particularly interested by the $\alpha+^{36}Ar$ configuration of the ^{40}Ca.
The Towing-Mode, responsible for the emission of fast-moving neutrons and protons, was first observed in the inelastic-scattering channels with stable beams [8]. During this process, a nucleon (a cluster) is pulled out from the target by the projectile, and then is towed by the short-range nuclear potential of the latter. The main characteristic is that the nucleon (the cluster) is mainly emitted at large angle on the same side and in the same plane as the projectile. There is no transfer between the nucleon (the cluster) and projectile because the kinetic energy is important, and the nucleon (the cluster) is emitted into the continuum. The time scale is much shorter here than for a regular evaporation as it is related to the passing time of the projectile of the order of 10^{-22} s. The characteristics of this anisotropic emission were reproduced by a dedicated Time-Dependent Schrödinger Equation (TDSE) model [9]. This model shows that the angular and energy distributions depend on the initial quantum properties of the towed particle (angular momentum, extension of the wave function and binding energy). Thus, the Towing Mode is a powerful tool for inferring spectroscopic information of nucleons and clusters in nuclei [10, 11, 12].

In the TDSE model, the target and the projectile nucleus are represented by a mean-field nuclear potential part and a Coulomb repulsive part. The nuclear potential has been optimized for nuclei in the same mass region to reproduce nuclear structure spectra, B(E2) transition strength,

α-decay widths, and elastic-scattering cross sections [13] and it is defined by:

$$V(r) = V_0 \left(\frac{\alpha}{1+e^{(r-R_0)/a_0}} + \frac{1-\alpha}{(1+e^{(r-R_0)/a_0})^3} \right) \tag{1.1}$$

where the parameters are summarized in table 1. Initially, in this model, an α particle wave func-

V_0 (MeV)	α	R_0 (fm)	a_0 (fm)
-175.2	0.3	4.33	0.73

Table 1: *Parameters of the nuclear part of the potential used to describe the target and the projectile.*

tion, denoted by $|\phi_\alpha\rangle$, is initialized in a symmetric spherical potential of the target defined by 1.1. Assuming that the total wave function of the ^{40}Ca in the 0^+ ground state $|\Psi_{^{40}Ca}\rangle$ has many configurations which describe:

- the mean-field picture in which nucleons can be regarded as independent particles $|\Phi\rangle$,
- the α clustering wave function coupled to an ^{36}Ar core wave function $|\psi_{^{36}Ar}\rangle$ eventually excited,

we can write the total wave function of the ^{40}Ca as:

$$|\Psi_{^{40}Ca}\rangle = |\Phi\rangle + \sum_{i=0}^{n} \lambda_i \left(|\phi_\alpha\rangle_i \otimes |\psi_{^{36}Ar}\rangle_i \right) \tag{1.2}$$

where i labels the configuration. When the α particle is emitted, the ^{36}Ar core is left in the specific configuration $|\psi_{^{36}Ar}\rangle_i$ and can eventually decay through γ emission. Assuming that the α configurations present in the ^{40}Ca ground state do not interfere with each other, the feeding of the different excited states of ^{36}Ar can be directly assigned to the independent contributions of each α cluster configuration. To take into account the Pauli blocking effect, which comes from the presence of nucleons in the ^{36}Ar core, the quantum numbers of the α particle wave function must satisfy the following equation [14]:

$$2N + L \geq 12 \tag{1.3}$$

with N and L, the radial and angular quantum numbers respectively. Thus, for ^{40}Ca, the first waves that α particles might occupy are the $6s$, $5d$, and $4g$. The depth of the potential is fixed so that the corresponding binding energies are 7.03, 6.47 and 5.47 MeV. Each α cluster wave function has been studied one-by-one by solving the TDSE in a 3D lattice (259 × 259 × 199 along x, the beam axis y and z respectively and with a time step of 0.24 fm/c and a lattice step of 0.2 fm):

$$i\hbar \frac{\partial}{\partial t} \phi_\alpha(\vec{r}, t) = \left(\frac{\vec{p}^{\,2}}{2m_\alpha} + V_{^{40}Ar}(\vec{r} - \vec{r_C}) + V_{^{40}Ca}(\vec{r} - \vec{r_P}) \right) \phi_\alpha(\vec{r}, t) \tag{1.4}$$

with m_α the α particle mass, $V_{^{40}Ar}$ and $V_{^{40}Ca}$ the mean-field potential of the target and the projectile respectively. The obtained angular distributions for an α-particle wave function in the $6s$, $5d$, and $4g$ states are shown in Fig. 1 for an impact parameter between 9.5 (grazing parameter) and 11.5

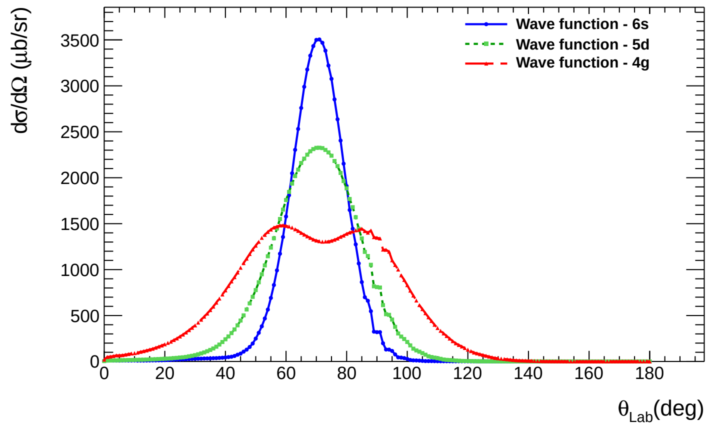

Figure 1: *Calculated angular distributions performed with the TDSE model for an α particle initially in 6s (blue line), 5d (green dashed line), and 4g (red dot-dashed line) states in the ground state of ^{40}Ca.*

fm. Finally, by comparison with experimental angular distributions, we are able to determine a spectroscopic factor for each α cluster configuration or in other words, the clusterization fraction of the ground state of the ^{40}Ca.
With this aim, we performed an experiment at GANIL in May 2011 using the SPEG energy loss spectrometer, the MUST2 Silicon detector and the prototype of the EXL calorimeter.

2. Description of the setup

During the experiment, an ^{40}Ar beam at 35 MeV/A was impinged onto 0.2 mg.cm^{-2} self-supported natural ^{40}Ca target.

The SPEG energy loss spectrometer ("Spectromètre à Perte d'Énergie du Ganil" [15]) identified in its focal plane the heavy ejectile (cf. Fig. 2). SPEG is covering 4.88 msr and measured the kinematical properties of the projectile between 1° and 5° in the laboratory frame. It was in coincidence with the Double Sided Silicon Stripped Detector MUST2 [16] used to detect the light-charged particles. The 8 telescopes covered 3.56 sr of 4π solid angle. Five of them (T1 to T4 and T6) were placed between 30° and 170° in the laboratory frame, on the right side of the target to identify the α particles from Towing-Mode (cf. Fig. 2). Because of an electronics problem, the telescopes T1, T3 and T4 were not working properly. This issue will be shown on the experimental angular distributions.

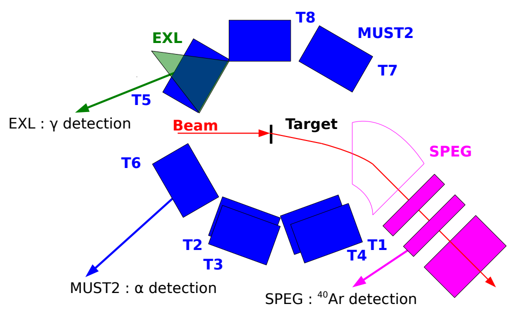

Figure 2: *Schematic view of the experimental setup.*

To study only the inelastic channel, the ^{40}Ar ejectile was identified with the ionization chamber and the plastic scintillators of SPEG. Thus, the ejectiles were unambiguously identified in charge and mass through energy and Time-Of-Flight (TOF) measurements. Two stripped-cathode drift chambers were used to reconstruct the ejectile position in the focal plane proportional to the target excitation energy. This standard detection provides a good excitation energy resolution: 460 keV (FWHM) at 1400 MeV. The identification of the light particles (protons, deuterons, tritons, ^{3}He and α) was obtained by analyzing the TOF$-$Energy and the $\Delta E - E$ matrix correlations from MUST2 with a resolution FWHM of 47.10 keV at 5.8 MeV. The 18 CsI crystals of the EXL calorimeter prototype were placed at 110 mm from the target inside the interaction chamber and measured the γ rays from the decay of the ^{36}Ar with a resolution FWHM of 246 keV at 2.6 MeV. Taking into account the target effects, the energy straggling and the dispersion of the beam onto the target, the resolution of the experiment was 1.01 MeV.

3. Data analysis

To study α clustering in ^{40}Ca, we studied its nuclear break-up:

$$\begin{aligned} ^{40}\mathrm{Ar} + ^{40}\mathrm{Ca} &\longrightarrow {}^{40}\mathrm{Ar} + ^{36}\mathrm{Ar}^* + \alpha \\ ^{36}\mathrm{Ar}^* &\xrightarrow{\gamma} {}^{36}\mathrm{Ar} \end{aligned}$$

After selecting nuclei of interest in SPEG and MUST2, we use the missing energy method to calculate the ^{36}Ar excitation energy:

$$E_{^{36}Ar,ex} = E_{^{40}Ca,ex} - T_{\alpha}^{CM} - T_{^{36}Ar}^{CM} - Q_{\alpha} \tag{3.1}$$

where $E_{^{40}Ca,ex}$ is the initial excitation energy in ^{40}Ca obtained by the measurement of the inelastically scattered projectile detected after the SPEG spectrometer, T_{α}^{CM} is the α particle kinetic energy in the center-of-mass frame of the recoiling ^{40}Ca target and $T_{^{36}Ar}^{CM}$ is the kinetic energy of target-like ^{36}Ar calculated using the impulsion conservation. The ^{36}Ar excitation energy is plotted in Fig. 3 for ^{40}Ca excitation energy range greater than 15 MeV and for the two following angular ranges:

- α particles detected between 30° and 120° in the laboratory frame corresponding to the T1 to T4 MUST2 telescopes (the Towing-Mode dominant angles),
- α particles between 130° and 170° in the laboratory system corresponding to the T6 MUST2 telescope.

For the first angular range, we clearly see a strong population of the ground and first excited states compared to the statistical isotropic decay of the ^{40}Ca target expected when selecting the second angular range. In both spectra, we clearly recognize the 0^+ ground state and the first 2^+ state at 1.97 MeV. Because of the 1.01 MeV resolution of the experiment, we cannot properly separate the ^{36}Ar states in the region between 4.2 MeV and 5.0 MeV (cf. Fig. 4). Nevertheless, using the EXL calorimeter, we can measure the γ transitions between a non-assigned second excited state and the first excited state. Thus, using a triple coincidence between SPEG, MUST2 and EXL, we can assign the second excited state in Fig. 3 as either the 4^+ excited state at 4.414 MeV or the 2^+ at 4.440 MeV.

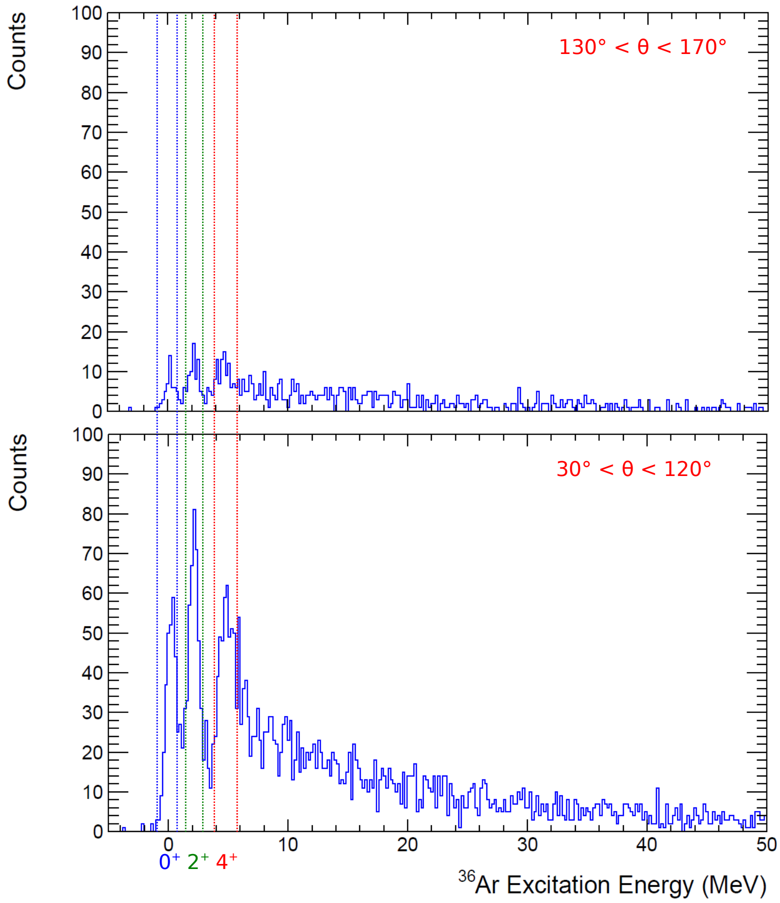

Figure 3: *Missing energy spectrum of ^{36}Ar for a ^{40}Ca excitation energy range greater than 15 MeV and - (bottom) for α particles detected between 30° and 120° in the laboratory system corresponding to T1 to T4 MUST2 - (top) for α particles detected between 130° and 170° in the laboratory system corresponding to the T6 MUST2. The blue gate represents the 0^+ ground state at 142 keV, the green one the 2^+ excited state at 2.1 MeV and the red one the 4^+ state around 4.75 MeV. The upper and lower limits of the gates used to extract the angular distributions are:* $[-0.84;1.02]$ *MeV to select most of the GS,* $[1.39;2.80]$ *MeV for the 2^+ state and* $[3.64;5.57]$ *MeV for 4^+ state.*

4. Results and discussions

The statistical emission is normalized and subtracted for the extraction of experimental angular distributions. The difference observed between the forward and the backward α particle emission is a clear signature of the Towing-Mode nuclear breakup. Indeed, the target, after its breakup, is left in its GS or with a very small excitation energy. As described above, the nuclear breakup is very short in time so that the α particle is emitted from a cold nucleus, hence the preformation in the GS of the nucleus is preserved.

The experimental angular distributions, shown in Fig. 5, were extracted using the three different gates defined in Fig. 3 to characterize the contribution of the different populated states through the Towing-Mode mechanism. The efficiency of the failing telescopes is very low in the angular

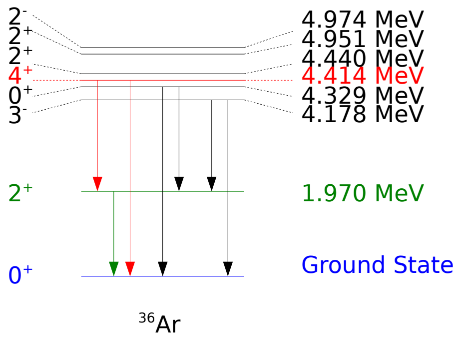

Figure 4: *^{36}Ar level scheme of known-states up to 4.974 MeV excitation energy.*

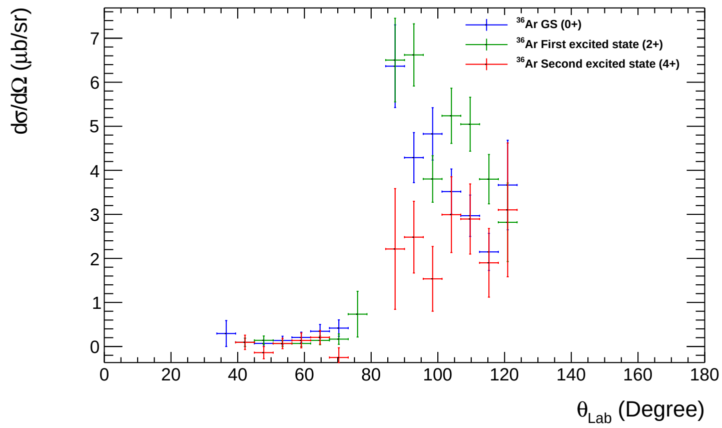

Figure 5: *Angular distributions of α particles from Towing-Mode: 0^+ in blue dots, 2^+ in green dots and 4^+ in red dots. For the latter state, a subtraction of statistical decay of the target was made with the distribution obtained for the ^{36}Ar excitation energy between 6 and 7.93 MeV. We see the dysfunction of T1, T3 and T4 MUST2 Telescope in the angular region between 30° and 80°. The statistical error bars are represented.*

region between 30° and 80°. However, the three different distributions show clearly a different behavior in the angular region between 80° and 130°. For the 4^+ state, the target decay contribution was subtracted from the ^{36}Ar excitation energy region between 6 and 7.93 MeV with an absolute normalization. The TDSE model describes a schematic $\alpha-$core potential and because of the poor angular distribution statistic (cf. Fig. 5), the comparison between experimental results and theoretical calculations (cf. Fig. 1) is difficult. However, using the previous work of the reference [12], the widths and the amplitudes of these calculations might indicate that the 6s wave function may be assigned to the 0^+ ground state of the ^{36}Ar, 5d to the 2^+ excited state and 4g to the 4^+ state. However, the extraction of spectroscopic factors is very complicated due to the fact that several detectors were not functioning properly.
Nevertheless, these results are encouraging because:

- the anisotropic emission of α clusters preformed in the ground state ^{40}Ca was understood by the Towing-Mode mechanism,

- the shapes of the experimental angular distributions reproduced qualitatively with a rather good agreement with theoretical calculations may show that there are at least three kinds of clusters configurations in ground state of ^{40}Ca resulting from the angular distributions of the outgoing α particle.

5. Conclusions and perspectives

The Towing-Mode nuclear break-up, responsible for the anisotropic emission of α particle, is a good spectroscopic tool to study cluster structure in nuclei. The very short duration of this nuclear mechanism shows that the outgoing particle is preformed in the nucleus. The experimental angular distributions qualitatively reproduce the TDSE calculations. These evidences may be understood as a preformed α cluster in the ground state of the $N = Z$ ^{40}Ca.

To complete these results, spectroscopic factors is tentatively extracted for each α cluster configuration in the ground state of the ^{40}Ca. The study of clusterization of the $N \neq Z$ ^{40}Ar is under analysis. Finally, we will compare the different clusterization fractions in the ^{40}Ca and the ^{40}Ar to have a better comprehension of the cluster structure in nuclei.

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