SEARCHING FOR SHAPE COEXISTENCE IN ^{42}Ca*

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Four neutron capture experiments were carried out at the Institut Laue–Langevin (ILL), Grenoble, with the FIPPS γ-ray spectrometer, with the aim of performing a complete low-spin spectroscopy study of ^{42,43,44,45}Ca isotopes. The goal of the project is to investigate the structure of Ca isotopes in the $A \sim 40$–48 mass region, focusing in particular on shape coexistence phenomena. Preliminary results on ^{42}Ca are discussed here, for which more than 10 new levels and 100 new transitions were found. Angular correlation analysis was also carried out based on newly found transitions, in order to pin down the spin-parity values for a number of new levels.

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1. Introduction

In atomic nuclei, the phenomenon where two or more distinct shapes of the same nucleus are found at similar energies is referred to as shape coexistence. Several remarkable examples have been found, over decades of investigation across the Segrè Chart [1–4], from heavy nuclei in the neutron-deficient Pb region [5], all the way down to lighter, medium-mass systems such as Cd, Zr, and Ni [6–8]. Along with theoretical predictions, experimental data provide valuable information which helps shed light on the microscopic nature of shape coexistence driven by nucleon correlations.

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In this context, the $A \sim 40$ mass region represents a perfect testing ground for such a purpose. Here, different theoretical approaches such as *ab-initio* methods, large-scale shell model calculations, and Density Functional Theory can be tested and compared with results from different types of experiments [9–11]. Our project aims at performing an almost complete low-spin spectroscopy of the even–even ^{42,44}Ca and the odd–even ^{43,45}Ca isotopes, populated by neutron capture reactions. Together with already published results on ^{41,47,49}Ca [12], the new data will allow us to further investigate the evolution of the structure of semi-magic Ca isotopes in between the $N = 20$ and $N = 28$ neutron shell closures, when going towards the neutron-rich side of the nuclear chart.

In this contribution, we focus on ^{42}Ca. This is a particularly interesting case in the context of shape-coexistence studies, since evidence for a strongly-deformed rotational band has been found, built on the excited 0^+ state located at 1837 keV excitation energy [13, 14]. We also remind that an highly-deformed structure, extending to high spins, was observed in ^{40}Ca as well [15], further supporting the scenario of shape coexistence in Ca nuclei around $A = 40$.

2. Experiments and data analysis

The experiments were performed at the nuclear reactor of the Institut Laue–Langevin (ILL) in Grenoble, France [16], currently the most intense continuous neutron source for research purposes. The reactor produces an outgoing neutron flux of 1.5×10^{15} n cm^{-2} s^{-1} delivered to more than 40 experimental setups. The FIssion Product Prompt gamma-ray Spectrometer (FIPPS) [17], used in the present experiments, was placed at the end of the H22 beamline, receiving a pencil-like neutron beam, with a flux of 1×10^8 n cm^{-2} s^{-1} after collimation.

The FIPPS array is a spectrometer used for γ-ray detection, consisting of 8 HPGe clover detectors, for a total of 32 crystals, equipped with BGO scintillators used for the Compton suppression, arranged in a circular frame around the scattering chamber (see Fig. 1). It is designed to be coupled to other detectors, such as additional HPGe detectors or $LaBr_3$ scintillators, the latter typically employed for lifetime measurements with fast-timing techniques [18]. In this work, a series of experiments were carried out to study the ^{41,42,43,44}Ca(n,γ) neutron-capture reactions with the FIPPS array. For the ^{41}Ca(n,γ) measurement, populating ^{42}Ca here discussed in detail, the spectrometer was also coupled to 16 $LaBr_3$ scintillators. In this experiment, a 600 μg ^{41}Ca radioactive target with an activity of ≈ 2 MBq was used. This is the first neutron-capture study on such a radioactive target, which also employs a high-resolution composite spectrometer; the former experiment being made in the 1980s with a single Ge(Li) detector [19].

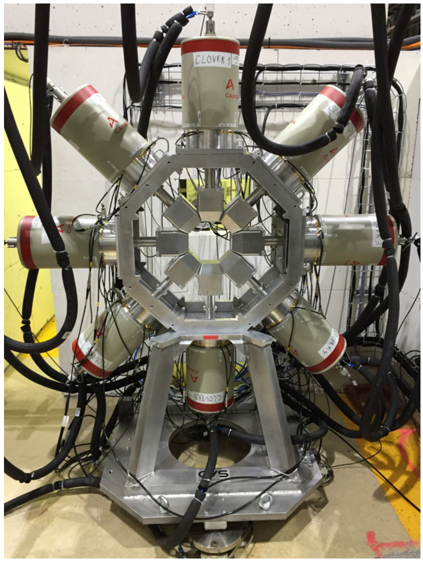

Fig. 1. Picture of the FIPPS array showing the 8 clover detectors mounted on the circular frame around the scattering chamber [17].

The use of a multi-detector array allowed us to investigate the structure of ^{42}Ca using γ–γ coincidence techniques. As a result, we were able to clearly identify γ-ray cascades belonging to the nucleus of interest and disentangle them from γ rays originating from neutron-capture reactions on target contaminants. As an example, Fig. 2 shows two projections of the γ–γ coincidence matrix gated on the $2^+_1 \rightarrow 0^+_{\mathrm{GS}}$ transition at 1524 keV (left panels) and the 7525 keV primary transition, connecting the S_n capture state to the 4^- state at 3954 keV (right panel). When a gate is applied to a specific transition on one axis of the γ–γ matrix, the projected spectrum on the other axis contains those events that happen to be in time coincidence with the gating transition. In this work, two γ rays are considered in coincidence if their time-stamps difference falls within 400 ns. This procedure allowed us to significantly expand the level and γ-decay scheme of ^{42}Ca, adding more than 10 new excited levels and more than 100 γ transitions, never observed before this work. Partial results are reported in Fig. 3, with new primary γ rays depopulating the neutron-capture state, as well as new states, shown in red/gray. Moreover, the neutron-capture energy was evaluated by considering all the possible decay patterns, giving $S_n = (11\,479.38 \pm 0.01)$ keV. We note that our result is outside the error bars of the $S_n = (11\,480.66 \pm 0.09)$ keV value reported in the literature [19].

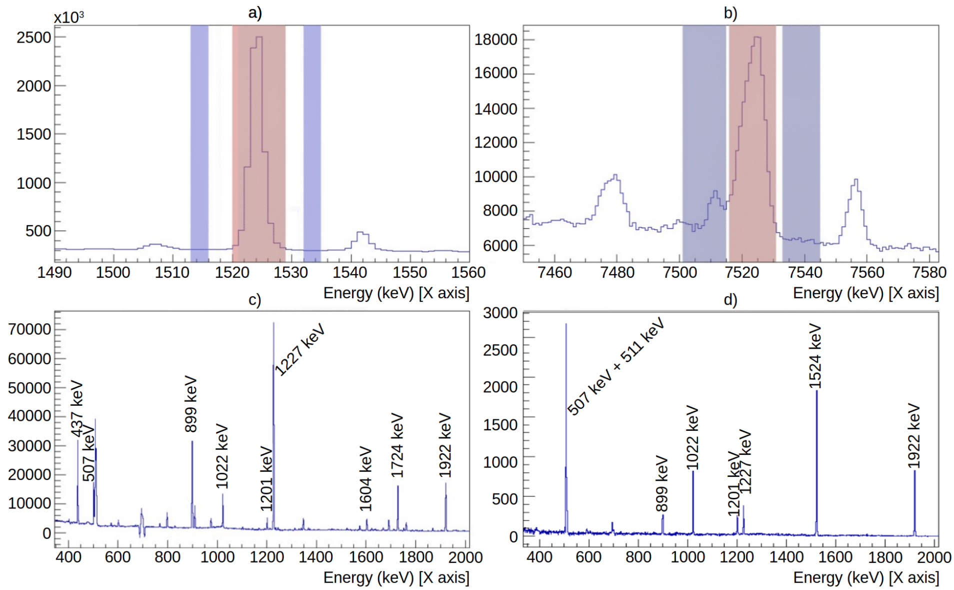

Fig. 2. (Color online) Total projection of the γ–γ matrix with a gate imposed on the 1524 keV transition (a) and 7525 keV primary transition (b). The red/light gray area indicates the peak gate, while the blue/dark gray areas refer to the background regions. (c)–(d) Projections obtained with the above-mentioned gates, showing γ rays measured in coincidence.

The geometry of the FIPPS array allowed us to perform γ-ray angular correlations as well in order to constrain the multipolarity of the transitions and possibly determine the spin and parity of the excited states. Figure 4 shows a benchmark example of this technique for the $2^+_3 \rightarrow 2^+_1 \rightarrow 0^+_{\mathrm{GS}}$ cascade. The study of the angular correlation of this 1869–1524 keV cascade allowed us to extract the $\delta = (1.4 \pm 0.6)$ mixing ratio for the 1869 keV transition, which compares well with the $\delta = (1.7 \pm 0.4)$ value reported in the literature [20].

We note that from our preliminary analysis of ^{42}Ca data, we were not able to identify any other excited 0^+ state, apart from the already known one located at 1837 keV, which could be associated with a different intrinsic shape. This may be caused by a lack of populated 2^+ states that would allow decay paths from the neutron-capture level S_n ($J^\pi = 3^-, 4^-$) to possible 0^+ states.

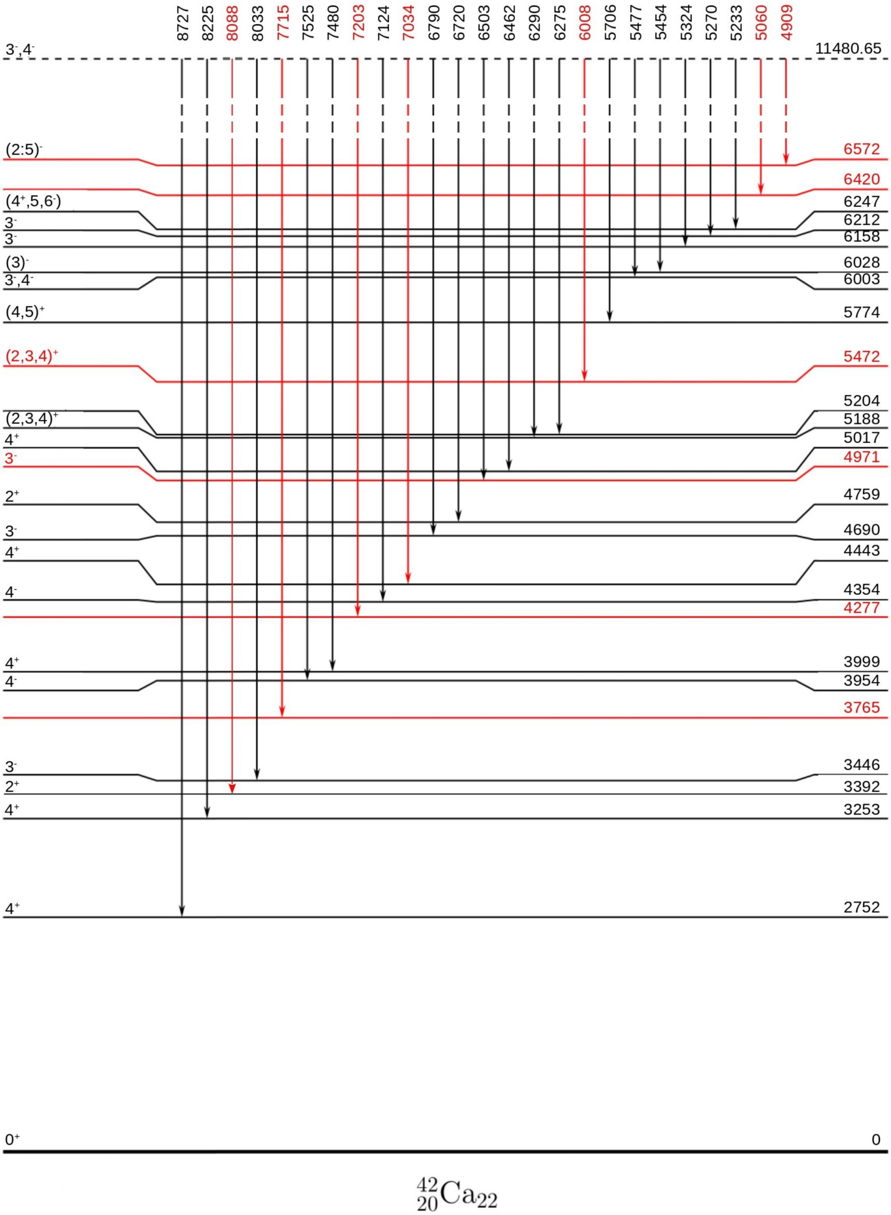

Fig. 3. (Color online) Partial level scheme showing primary γ-ray transitions depopulating the neutron-capture state S_n. New transitions and levels are marked in red/gray.

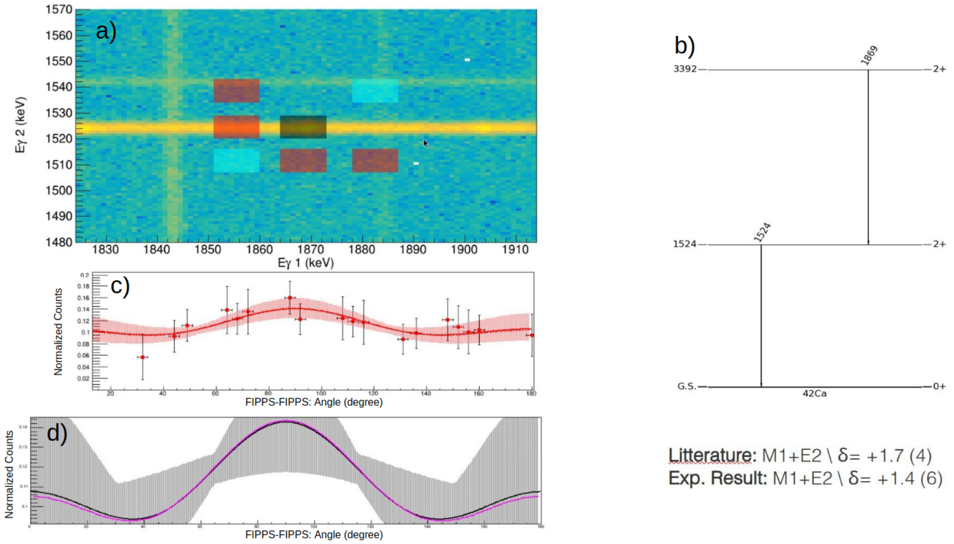

Fig. 4. (Color online) Example of angular correlation between the 1869 keV and 1524 keV transitions. (a) Zoomed area with the coincidence peak formed by the two γ rays of interest. (b) Partial level scheme relevant to this example. (c) Experimental points of the angular distribution superimposed with the angular distribution curve with its error (shadowed area). (d) Experimental angular distribution (black line) with its error (shadowed area) and the one obtained with the mixing ratio reported by the literature.

3. Conclusions and perspectives

A series of experiments were performed at the Institut Laue–Langevin to investigate the structure of Ca isotopes using neutron-capture reactions and the FIPPS spectrometer. The first results on ^{42}Ca allowed us to substantially expand its level and γ-decay scheme through γ–γ coincidence techniques. Angular correlations between γ rays were successfully tested on known transitions and will be used to characterise new γ rays and excited states found in this work. The aim is to understand better the structure of ^{42}Ca, focusing also on shape-coexistence phenomena. In the future, $LaBr_3$ scintillator, present in the experimental setup, may also be used to measure lifetimes with fast-timing techniques. The analysis presented here is planned to be performed on the other Ca isotopes populated in this series of experiments.

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