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Search for 0^+ states in ^{42}Ca

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Summary. — A series of experiments were performed at the *Institut Laue-Langevin* high-power reactor facility. The FIPPS γ-ray spectrometer was used to perform complete low-spin spectroscopy of ^{42,43,44,45}Ca isotopes in order to investigate the arise of shape coexistence in the Ca isotopic chain between the $N = 20$ and $N = 28$ shell closures. This article discusses some preliminary results on the even-even ^{42}Ca nucleus and the search for excited 0^+ states. The current study added 10 new levels and 109 new transitions to the existing γ decay scheme. Angular distribution analyses were also carried out for a number of transitions to determine the spin-parity of selected new levels.

1. – Introduction

The shape of a nucleus results from the complex interaction among the nucleonic constituents, therefore its study can provide valuable information on the nuclear force. Spherical, prolate and oblate nuclear shapes have been observed in different regions of the nuclear chart, and the evolution of the nuclear shape has also been reported along isotopic chains as a function of the excitation energy. In some cases, two or more shapes can appear within the same nucleus at energies lying close to each other and we refer to this phenomenon as shape coexistence [1-3]. In this context, the nuclear mass region with $A \sim 40$ is particularly relevant, being the meeting point of several theoretical approaches that can be used to predict nuclear structure properties, *e.g.*, Density Functional theories, *ab initio* methods and large-scale shell model calculation [4-6]. Therefore, high-precision experimental data from this mass region are highly needed as a benchmark for different theoretical methods, in particular in connection with the study of nuclear shape coexistence phenomena.

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At the *Institut Laue-Langevin* in Grenoble (France), a series of neutron-capture experiments were performed on the even-even ^{42,44}Ca and the odd-even ^{43,45}Ca isotopes. These experiments, together with the work on ^{41,47,49}Ca recently published by our collaboration [7], aim to investigate the evolution of nuclear structure across the $Z = 20$ isotopic chain towards the neutron-rich part of the nuclear chart. In this article we discuss the case of ^{42}Ca and we focus on the search for low-lying 0^+ states, some already reported by Williams *et al.* in (t,p) reaction studies [8], since they could be a hint of shape coexistence in even-even nuclei [1-3].

2. – Experimental setup and analysis

The experiments discussed in this work were carried out at the *Institut Laue-Langevin* (ILL) high-power nuclear reactor [9]. The isotopes of interest were populated by (n, γ) reactions with a thermal-neutron pencil-like beam with an intensity of 10^8 n cm^{-2} s^{-1}. In the case of ^{42}Ca, the beam was impinging on a 600 μg ^{41}Ca radioactive target with an activity of 2 MBq, while for ^{43,44,45}Ca three $CaCO_3$ rare powdered targets were used comprising 200 mg of ^{42}Ca, 20 mg of ^{43}Ca and 100 mg of ^{44}Ca, respectively. Gamma rays produced by the reactions were detected by the FIssion Product Prompt γ-ray Spectrometer (FIPPS) [10], placed at the end of the H22 neutron beam line. FIPPS is a γ-ray spectrometer made of 32 HPGe clover detectors equipped with BGO scintillators for Compton suppression, positioned on a circular frame around the scattering chamber. In the ^{42}Ca experiment, FIPPS was also coupled with 16 $LaBr_3$:Ce scintillators meant to be used for lifetime measurements with fast-timing techniques [11].

Prior to this work, only one neutron-capture experiment was performed to study ^{42}Ca in the late '80s at the Los Alamos Omega Reactor, by Kikstra *et al.* [12]. In that case, only a few γ-ray transitions were placed in the decay scheme since only one single Ge(Li) detector was used. More recently, Hadyńska *et al.* demonstrated the existence of a super-deformed band lying over the first excited 0^+ at 1837 keV [13], while Williams *et al.*, in (t,p) studies, reported the observation of three other 0^+ states located in the 5.8–6.5 MeV excitation energy region, that still need to be characterized [8].

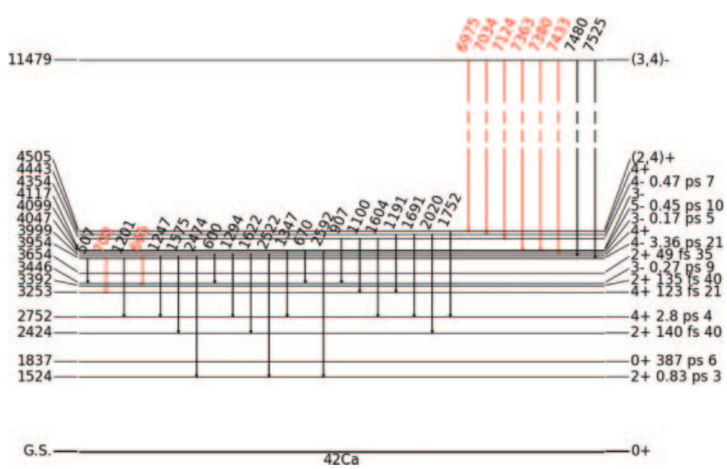

Fig. 1. – Partial decay scheme of ^{42}Ca from our experiment. The neutron-capture state is located at 11479 keV, with spin-parity $(3^-, 4^-)$. Newly found transitions are reported in red.

In our case, the use of a multiple-detectors array like FIPPS allowed us to exploit the γ-γ coincidence technique to reconstruct the complex level and decay scheme of ^{42}Ca at low spin, resulting in the addition of 10 new levels and 109 new transitions. Figure 1 shows a partial decay scheme of ^{42}Ca obtained from our work, highlighting some of the new transitions (red arrows) identified during the experiment. Despite the effectiveness of the γ-γ coincidence technique here employed, the only 0^+ state identified in our reaction is the first excited 0^+_2 state at 1837 keV, already characterized and associated with a highly deformed triaxial-prolate shape by Hadyńska-Klek *et al.* [13]. We did not observe, instead, the three 0^+ levels reported by the (t,p) studies of Williams *et al.*, [8] at the excitation energy of 5863(10), 6015(9) and 6518(8) keV, respectively. The direct population of 0^+ states from the Sn neutron-capture level of ^{42}Ca, with spin/parity $(3^-,4^-)$, is highly suppressed due to gamma-ray selection rules for such a large spin difference. Therefore, 0^+ states may only be observed through a subsequent $S_n \rightarrow 2^+ \rightarrow 0^+$ cascade. In general, the gamma-ray decay from the neutron-capture state is dominated by high-energy E1 transitions which, in the present nucleus, can lead to the population of 2^+ states. However, only a few of them were found in the 6–11 MeV energy region and no further decay transitions to the aforementioned 0^+ states were observed.

In our analysis, we also investigated the spin-parity of some new levels by performing an angular correlation analysis of selected pairs of gamma rays. Figure 2 shows the results of this analysis for an already-known case, here used as a benchmark. In panel (a), a zoomed area of the γ-γ coincidence matrix is shown, focusing on the coincidence peak between the 1729 keV $4^+_2 \rightarrow 2^+_1$ and the 1524 keV $2^+_1 \rightarrow 0^+_{g.s.}$ transitions. In

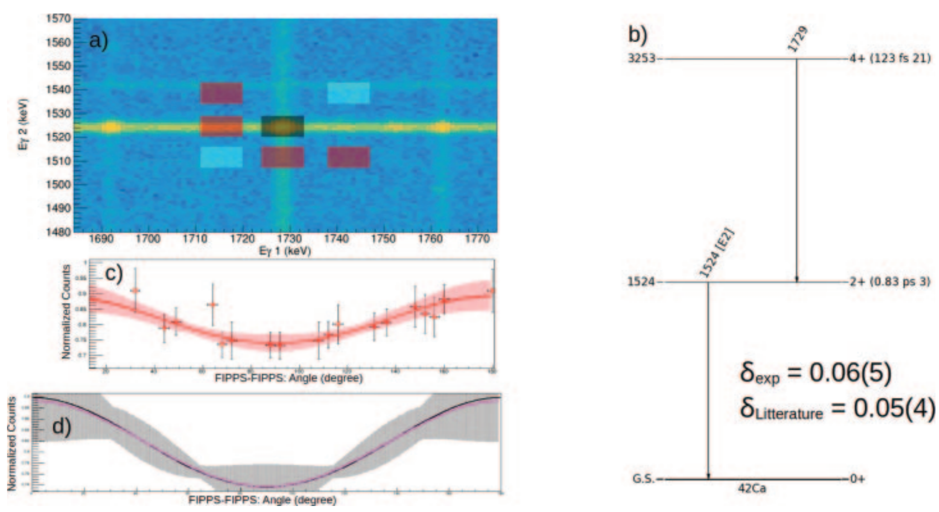

Fig. 2. – Angular correlation analysis for the 1729-1524 keV pair of transitions associated with the $4^+_2 \rightarrow 2^+_1 \rightarrow 0^+_{g.s.}$ cascade. In this case, the δ mixing value for the $4^+_2 \rightarrow 2^+_1$ transition, already present in the literature [14], is here used as a benchmark for our analysis technique. Panel (a) shows a zoomed area of the γ-γ coincidence matrix with the coincidence peak of interest. Panel (b) shows the decay scheme for the two-transitions cascade together with the δ mixing value for the $4^+_2 \rightarrow 2^+_1$ transition, obtained in our analysis and reported in the literature. Panel (c) shows the angular distribution experimental points and the fitted distribution (red line) with its error bar (shadowed red area). Panel (d) displays the fitted angular distribution curve and its error bar (shadowed grey area) superimposed with the distribution obtained using the literature value for the mixing ratio (purple line).

panel (b), the decay scheme involving the two transitions of interest is displayed, and the values of the mixing ratio δ for the $4^+_2 \rightarrow 2^+_1$ transition from our experiment and from the literature [14] are given. In panel (c), the experimental angular distributions (scattered points) are superimposed with the fitted angular distribution (red line) and its error (shadowed red area). Finally, in panel (d), the superposition of the fitted angular distribution curve plus its error (shadowed grey area) and the one obtained with the mixing ratio from the literature (purple line) [14] is depicted. A good agreement is found between the δ mixing ratio of the $4^+_2 \rightarrow 2^+_1$ transition reported in the literature and the one obtained from our analysis.

3. – Conclusions

Four neutron capture experiments were performed at the *Institut Laue-Langevin* to investigate the structure of Ca isotopes between the $N = 20$ and $N = 28$ shell closures and the appearance of shape-coexistence phenomena. The use of the FIPPS γ-ray spectrometer allowed us to significantly expand the existing ^{42}Ca γ-decay scheme, here discussed. Due to the (3^-,4^-) spin-parity value of the capture state, only the first excited 0^+ state could be observed through a sequential decay via a 2^+ state. Moreover, the angular correlations studies between γ rays did not prove the presence of other 0^+ states populated in our reaction. In the future, $LaBr_3$ scintillator will be used to measure the lifetimes of some of the observed states and the same analysis here presented will be performed in the remaining Ca isotopes with $A = 43$, 44, 45, in particular in ^{44}Ca where excited 0^+ states will be searched for and characterized by γ-ray angular correlations.

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