SEARCH FOR SHAPE COEXISTENCE IN SELENIUM ISOTOPES AROUND $N = 50$*

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Received 28 November 2023, accepted 12 March 2024, published online 24 April 2024

In the present contribution, the experimental investigation of the possible occurrence of the shape coexistence phenomenon in the ^{83}Se ($Z = 34$, $N = 49$) and ^{84}Se ($Z = 34$, $N = 50$) isotopes is presented. The aim of the experiment was to identify excited states which may be associated with different deformed shapes, *i.e.*, spherical, oblate, and prolate. The structure of both nuclei was studied by using γ-ray spectroscopy techniques, and the states and transitions of interest were investigated in detail through lifetime measurements and angular correlations.

DOI:10.5506/APhysPolBSupp.17.3-A5

1. Introduction

The shape coexistence phenomenon in atomic nuclei is associated with the presence of eigenstates possessing different shapes in the intrinsic frame that occur at similar excitation energies [1, 2]. It can be represented through the Potential Energy Surface (PES), *i.e.*, the potential energy of the nucleus

* Presented at the XXXVII Mazurian Lakes Conference on Physics, Piaski, Poland, 3–9 September, 2023.

as a function of its deformation parameters. The deepest minimum of the PES represents the ground state of the system, while other local minima may be associated with different shapes [1–5]. In the present contribution, the ^{83}Se ($N = 49$) and ^{84}Se ($N = 50$) isotopes are investigated. Concerning the even–even ^{84}Se nucleus, 0^+ excited states are possible candidates to be the band-head of deformed structures. Prior works on this nucleus, using (t, p) reactions, proposed six 0^+ excited states, located at the excitation energies of 1967(3), 2244(7), 2654(4), 2716(10), 2740(11), and 4106(17) keV [6, 7]. No γ-ray decays depopulating these 0^+ states were observed before the present experiment. The aim of the experiment was to study the 0^+ states exploiting a sub-Coulomb-barrier two-neutron-transfer reaction at the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH, Bucharest, Romania), and to measure their γ-ray decay for the first time. Moreover, lifetimes were also measured using different experimental techniques. In a second experiment, the ^{83}Se nucleus was populated at the Institut Laue-Langevin (ILL, Grenoble, France), using the neutron-capture reaction, for which very little information was available in the literature [8]. In this nucleus, an indication of shape coexistence in ^{83}Se already existed due to the presence of the isomeric 582 keV, $5/2^+$ state ($T_{1/2} = 3.6 \pm 0.6$ ns) [9], with a retarded E2 γ-ray transition towards the ground state. In this work, the γ rays depopulating the $3/2^+$ state at 1100 keV were studied through angular correlations, providing information on the structure of this state which might belong to the same deformed band of the $5/2^+$ state, built on the $1/2^+$ state at 540 keV.

2. Experiments and results

The ^{84}Se nucleus was populated at the IFIN-HH facility by a sub-Coulomb-barrier two-neutron-transfer reaction, ^{82}Se(^{18}O,^{16}O)^{84}Se, with a beam energy of 43.5 MeV. For the γ-ray detection, the HPGe ROSPHERE array was employed. The array was arranged in a spherical geometry composed of five rings, placed at 37°, 70°, 90°, 110°, and 143° angles with respect to the beam axis. Each ring can accommodate five detectors equipped with their BGO anti-Compton shields. Two out of the six 0^+ states, previously observed at 2244 and 2654 keV, were populated in the present reaction. By requiring a coincidence with the 1454 keV, $2_1^+ \rightarrow 0_1^+$ transition of ^{84}Se, it was possible to observe for the first time their γ-ray decay to the 2_1^+ state (with energies $E_\gamma = 790$ and 1200 keV, respectively). No evidence was found for the population of the other 0^+ states reported in the literature, even for the lowest one, tentatively located at 1967(3) keV by the (t, p) study of Ref. [7]. In this case, no clear trace of γ decay was observed in the $2_1^+ \rightarrow 0_1^+$ gated spectrum, therefore, no firm conclusion on the existence of such 0^+ excitation could be drawn.

The two observed 0^+ states, located at 2244 and 2654 keV, were then investigated through lifetime measurements. A first measurement with a thick ^{82}Se target (6 mg/cm^2) was performed to investigate the line shape of γ rays depopulating the 0^+ states (2244 and 2654 keV), exploiting the different angular position of the ROSPHERE detectors. In Fig. 1, it is possible to observe no difference between the lineshapes at 37° and at 143°, compared to the ring at 90°, suggesting lifetimes longer than ~ 1 ps.

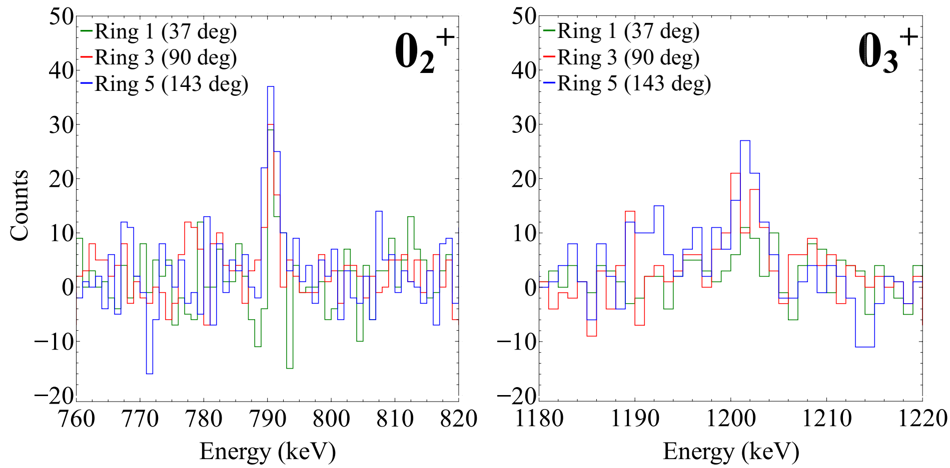

Fig. 1. Portion of the γ-ray energy spectra of ^{84}Se, as measured by ring 1, 3, and 5 of ROSPHERE, showing the $0^+_{2,3} \rightarrow 2^+_1$ transitions of energy 790 (left) and 1200 keV (right), depopulating the 0^+ states located at 2244 and 2654 keV, respectively. The spectra are gated on the 1454 keV, $2^+_1 \rightarrow 0^+_1$ transition.

In order to obtain a finite value for the lifetime of the states of interest, a second experiment at the IFIN-HH was performed, exploiting the same sub-Coulomb-barrier two-neutron-transfer reaction and the plunger technique. From the analysis, it was possible to extract the finite half-life of the third 0^+ state, of $T_{1/2} = 3.2 \pm 0.6$ ps, corresponding to a reduced transition probability of $B(\mathrm{E2}) = 3.3 \pm 0.6$ W.u. Concerning the second 0^+, the analysis pointed to a lifetime of several hundreds of ps (not measurable with the plunger technique), suggesting a possible strong hindrance of the 790 keV transition. For this reason, a third experiment at the IFIN-HH was performed, to measure the lifetime of the third 0^+ state with the $\mathrm{LaBr_3}$ scintillators and fast-timing methods. The experiment was successfully performed and the analysis is ongoing. The ^{83}Se nucleus was populated at the ILL laboratory by a neutron-capture reaction, $^{82}\mathrm{Se}(n,\gamma)$. The γ rays from the reaction were measured with the FIPPS array, composed of eight HPGe clover detectors, each equipped with three BGO anti-Compton shields, and five HPGe clover detectors coming from the IFIN-HH, each equipped with a single BGO anti-Compton shield. The highly enriched ^{82}Se target (95%) was provided by the CUPID Collaboration of Laboratori Nazionali del Gran Sasso [10]. Significant spectroscopy work was done to expand the decay scheme of this nucleus, finding in total 28 new primary γ rays (only two were previously observed in Ref. [8], *i.e.*, the 5587.07(25.4) and 4343.0(4.2) keV transitions), 16 new levels, and 89 new secondary γ-ray transitions. The intensity balance analysis to confirm the levels and decay pattern is currently ongoing. Preliminary angular correlation measurements and mixing ratio evaluations were performed for the 518 and 561 keV transitions depopulating the $3/2^+$ state at 1100 keV and feeding the $5/2^+$ and $1/2^+$ states, respectively, in order to infer the multipolarity of the transitions. The experimental angular correlation coefficients were obtained using the fit function

$$W(\theta) = A_0(1 + A_{22}Q_2P_2(\cos\theta) + A_{44}Q_4P_4(\cos\theta))\,, \tag{1}$$

where the Q value represents the attenuation coefficient taking into account the geometric configuration of the detectors and were calculated via the Monte-Carlo simulation [11]. The δ mixing-ratio value was then measured minimizing a χ^2 function depending on the experimental A_{22} and A_{44} coefficients and the theoretical $A_{22}(\delta)$ and $A_{44}(\delta)$ coefficients. For the 518 keV decay (assumed to be an M1+E2 transition) measurement, the 518–583 keV coincidence was exploited (for the $3/2^+ \to 5/2^+ \to 9/2^+$ cascade, see Fig. 2) due to the known pure E2 nature of the 583 keV transition. The results are reported in Fig. 3 [11], where a clear minimum is present. Moreover, the 4715–518 keV coincidence (for the $1/2^+ \to 3/2^+ \to 5/2^+$ cascade, see Fig. 2) was also taken into account, assuming the primary 4715 keV to be a pure M1 transition. The results are also reported in Fig. 3. Considering the

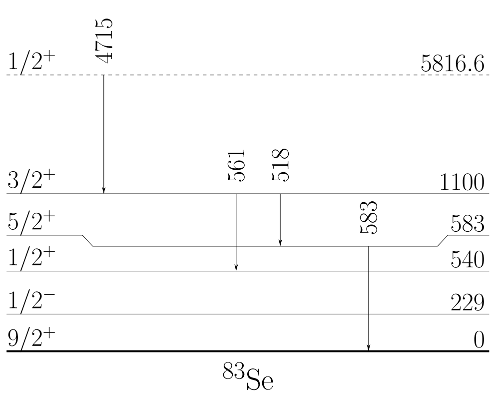

Fig. 2. Partial decay scheme of ^{83}Se. The transitions reported are those used for the angular correlation analysis.

agreement between the measured δ values in the two cases, the final mixing ratio for the 518 keV transition was obtained by the weighted average, giving $\delta = -0.13 \pm 0.03$ [11]. Concerning the 561 keV transition (assumed to be a M1+E2 transition), angular correlation studies were performed considering the 4715–561 keV coincidence (for the $1/2^+ \rightarrow 3/2^+ \rightarrow 1/2^+$ cascade, see Fig. 2). Also in this case, the primary 4715 keV transition was assumed to be a pure M1. The preliminary result is $\delta = 0.40^{+0.06}_{-0.06}$ [11]. The obtained results for the 518 and 561 keV decays, together with the half-life of the 1100 keV, $3/2^+$ state ($T_{1/2} \sim 300$ fs), measured at Laboratori Nazionali di Legnaro [12], point to a strong collectivity of the band built on the 540 keV $1/2^+$ level. Further studies are currently ongoing in order to finalize the analysis and extend the angular-correlation investigation to other pairs of intense γ rays.

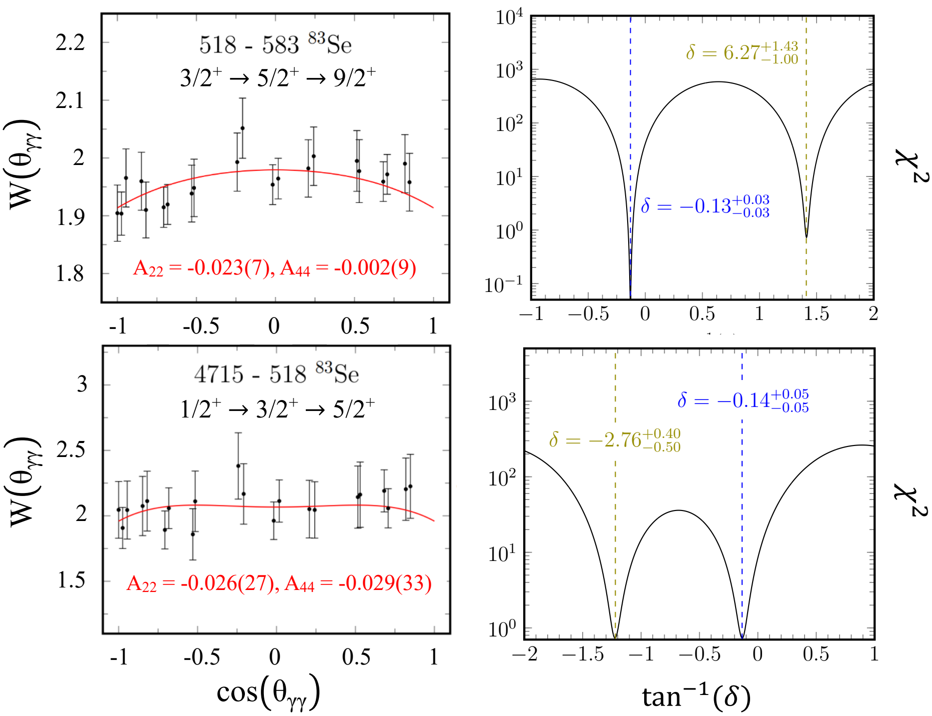

Fig. 3. Left: angular correlation for the 518–583 keV and 4715–518 keV transitions. Right: χ^2 function for the 518 keV transition mixing ratio evaluation. The δ values which minimize the function are reported. The picture is adapted from Ref. [11].

3. Conclusion

In this work, the shape coexistence phenomenon was investigated in the ^{83}Se and ^{84}Se nuclei around the $N = 50$ neutron shell closure, by considering results from a two-neutron sub-barrier transfer reaction and a neutron-capture experiment, performed at the IFIN-HH and ILL, respectively. The transfer reaction, employed to populate ^{84}Se, allowed to observe for the first time the γ-ray transitions from the de-excitation of two 0^+ states at 2244 and 2654 keV. Exploiting a thick ^{82}Se target, lifetime measurements for the 0^+ excited states were performed using the DSAM technique. The analysis provided the lower limit $\tau = 1$ ps for the lifetimes of both 0^+ states. On the other hand, a subsequent plunger technique provided a finite half-life value for the 0_3^+ ($T_{1/2} = 3.2 \pm 0.6$ ps) and showed a very long lifetime of the 0_2^+ state, indicating a hindered $0_2^+ \rightarrow 2_1^+$ transition. The ^{83}Se was populated by neutron capture and its decay scheme was significantly expanded (28 new primary γ rays, 16 new levels, and 89 new secondary γ rays). Angular correlation and mixing ratio evaluation were performed for the 518 and 561 keV transitions, in order to investigate the collective character of the possible deformed band built on the 540 keV, $1/2^+$ state. Preliminary results point to a strong collectivity of the band. Future comparisons of the experimental results with the Monte Carlo Shell Model predictions will allow to interpret the experimental findings and provide a microscopic description of the shape coexistence in the Se isotopes around $N = 50$.

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