Shape Coexistence in Light Se Isotopes: Evidence for Oblate Shapes

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(Received 17 December 2007; published 14 March 2008)

Lifetimes of states in the ground-state bands of ^{70}Se and ^{72}Se were measured using the recoil-distance Doppler shift method. The results deviate significantly from earlier measurements, requiring a revision of the conclusions drawn from a recent Coulomb excitation experiment concerning the shape of ^{70}Se. The new results lead to a coherent picture of shape coexistence in the neutron-deficient selenium and krypton isotopes. The coexistence and evolution of oblate and prolate shapes in this mass region is for the first time consistently described by new Hartree-Fock-Bogolyubov-based configuration-mixing calculations which were performed using the Gogny D1S interaction.

DOI: 10.1103/PhysRevLett.100.102502 PACS numbers: 21.10.Re, 21.10.Tg, 25.70.Hi, 27.50.+e

The nuclear shape is a very sensitive probe of the underlying nuclear structure and the interaction between the nucleons. Observables such as the electric quadrupole moment or the transition strength between excited nuclear states are hence important benchmarks for nuclear structure theory. Nuclei in the mass region $A \approx 70$ close to the $N = Z$ line are known to exhibit a variety of nuclear shapes, which can be attributed to large shell gaps at both prolate and oblate deformation for proton and neutron numbers 34 and 36. Coulomb excitation experiments have yielded the quadrupole moments for several low-lying states in ^{74}Kr and ^{76}Kr; their signs give firm evidence for the prolate character of the ground-state band coexisting with an excited oblate band built on a low-lying 0_2^+ state [1]. The analysis of the electromagnetic matrix elements and the properties of the 0_2^+ shape isomers [2] suggest an inversion of the prolate and oblate configurations with an oblate ground-state shape for ^{72}Kr. The relatively small $B(E2; 0_1^+ \rightarrow 2_1^+)$ value measured via intermediate-energy Coulomb excitation in ^{72}Kr [3] seems to support this interpretation. While many theoretical models predict the coexistence of prolate and oblate shapes [4–7], the inversion of oblate and prolate configurations in the light Kr isotopes is so far only correctly described by the so-called excited VAMPIR variational approach [8] and the Hartree-Fock-Bogoliubov (HFB) based configuration-mixing method using the Gogny D1S interaction, as described in Ref. [9].

The shape coexistence scenario in the neutron-deficient Se isotopes is less clear. Several theoretical investigations predict oblate ground-state configurations also for the Se isotopes near $N = Z$ [4,10,11]. The isotones ^{72}Se and ^{74}Kr show a similar structure with an isomeric excited 0_2^+ state just above the 2_1^+ state [12] and strongly decreasing $B(E2)$ strength for the transitions in the yrast cascade towards the ground state [13], which can be attributed to a strong mixing between prolate and oblate configurations at low spin. In neighboring ^{70}Se, on the other hand, a strong increase of the $B(E2)$ values was observed towards the ground state [13]. This behavior is very unusual, and the large $B(E2; 2_1^+ \rightarrow 0_1^+)$ value for ^{70}Se results in an unexplained discontinuity in the evolution of collectivity in the chain of Se isotopes. The best candidate for shape coexistence appears to be ^{68}Se, where two distinct rotational bands have been observed. The ground-state band has a lower moment of inertia and was interpreted as an oblate rotational band, while the excited band was found consistent with prolate shape [14]. The moments of inertia of the rotational structures observed in ^{68}Se and ^{70}Se show striking similarities [15], even though the presumed oblate rotation is not prevailing in ^{70}Se. Consequently, ^{70}Se was thought to show a rapid transition from oblate shape near the ground state to prolate shape at higher spins. A recent low-energy Coulomb excitation experiment with a ^{70}Se beam from REX-ISOLDE, however, found a negative diagonal $E2$ matrix element for the 2_1^+ state, indicating prolate shape for this state [16]. This result cast doubt on the existence of low-lying oblate states in ^{70}Se. As only the integral cross section was measured in the Coulomb excitation experiment, the result for the diagonal matrix element relies on the independently measured lifetime of the 2_1^+ state. This lifetime is hence a crucial parameter for the understanding of the shape coexistence in the light Se nuclei. In this Letter we report on a new lifetime measurement with improved precision, and we interpret the results in the light of new configuration-mixing calculations beyond the mean-field approach.

Lifetimes of low-lying states in ^{70}Se and ^{72}Se were measured at the Laboratori Nazionali di Legnaro using the recoil-distance Doppler shift method [17]. The states were populated in the reactions ^{40}Ca(^{36}Ar, $\alpha 2p$)^{70}Se and ^{40}Ca(^{36}Ar, $4p$)^{72}Se at a beam energy of 136 MeV. Gamma rays were detected with the GASP detector array [18] comprising 38 escape-suppressed Ge detectors arranged in seven rings with respect to the beam axis. The isotopically enriched ^{40}Ca target had a thickness of 0.5 mg/cm^2 and was evaporated onto a 2.0 mg/cm^2 gold foil which was facing the beam. The recoils had an average velocity of 10.73(3) μm/ps and were stopped in a gold stopper foil of 10 mg/cm^2 thickness. The Cologne plunger device [19] was used to control the distance between the target and the stopper foils. Data were collected for 12 distances between 8 and 400 μm for an average of 10 h per distance. Events with at least two prompt γ rays detected in coincidence were recorded and sorted offline into $\gamma - \gamma$ matrices for further analysis.

To illustrate the quality of the data, spectra of the $2_1^+ \rightarrow 0_1^+$ transition in ^{70}Se and the $4_1^+ \rightarrow 2_1^+$ transition in ^{72}Se are shown in Fig. 1 for different distances between target and stopper foil. Similar spectra were obtained for all detector rings and plunger distances and for other transitions in both ^{70}Se and ^{72}Se. In all cases a coincidence gate was placed on the shifted component of the transition directly feeding the state of interest, so that effects of unknown side feeding were eliminated. The lifetimes of the states were extracted from the intensities of the stopped and Doppler-shifted components as a function of the plunger distance using the differential decay-curve method [17] following the procedure described in Ref. [20]. Since the lifetimes are relatively short, the contribution from γ rays emitted during deceleration in the stopper foil had to be considered. An average stopping time of 1.45(18) ps was found in a Monte Carlo simulation of the stopping process, which was also used to produce a set of line shape profiles for various lifetimes of the respective states [21]. The effect of the finite stopping time was included in the analysis by correcting for the fraction of γ rays emitted during deceleration. The results are shown in Table I.

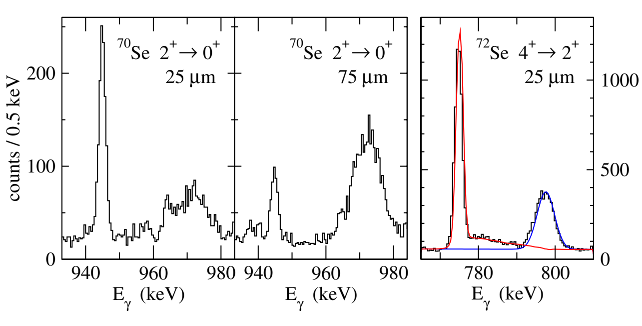

FIG. 1 (color online). Spectra showing the stopped and Doppler-shifted components observed in the forward detectors at 36° for the transitions and distances indicated. The simulated line shape of the stopped component (for a lifetime of 3.3 ps) and the Gaussian fit of the shifted component are shown for the transition in ^{72}Se.

While the new lifetimes for ^{72}Se are in reasonable agreement with the results of Heese *et al.* [13], the values for the 2_1^+ and 6_1^+ states in ^{70}Se deviate considerably. The most likely reason for this disagreement are effects from unknown side feeding in a singles measurement. It is interesting to note that significant deviations from older singles measurements were also observed in neighboring Kr isotopes [20], so that one might speculate about unusual feeding patterns in this mass region, which may not be correctly described by the feeding models employed in the older singles measurements. In the case of ^{70}Se, a delayed feeding component from the 13^- isomer with 2.3 ns lifetime [10] could have influenced the results of the previous measurement.

The experimental results in Table I are compared to HFB-based configuration-mixing calculations using the Gogny D1S interaction. The calculations contain no free parameters other than the globally derived parameters of the D1S nucleon-nucleon interaction [22,23]. The configuration mixing of the constrained HFB wave functions is calculated using the generator coordinate method with Gaussian overlap approximation. The five-dimensional generator coordinate comprises the collective quadrupole coordinates q_0 and q_2, which can be expressed in terms of the axial and triaxial deformation parameters β and γ, and the three Euler angles. It has been shown recently that the inclusion of the triaxial degree of freedom is crucial for the correct description of shape coexistence in the light Kr isotopes [1,24]. The procedure to calculate the energy spectra, reduced transition probabilities, and spectroscopic quadrupole moments is described in detail in Ref. [9].

TABLE I. Comparison of the new lifetimes with literature values. The resulting $B(E2)$ values and the energies of the states are compared to the theoretical calculations. The theoretical spectroscopic quadrupole moments are also given.

I^π	τ (ps) New	τ (ps) [13]	E_{ex} (keV) Exp.	E_{ex} (keV) Theo.	$B(E2;\downarrow)$ (e^2 fm^4) Exp.	$B(E2;\downarrow)$ (e^2 fm^4) Theo.	Q_S (e fm^2)
^{70}Se							
2_1^+	3.2(2)	1.5(3)	945	818	342(19)	549	+16
4_1^+	1.4(1)	1.4(3)	2038	1800	370(24)	955	+12
6_1^+	1.9(3)	3.9(9)	3002	2703	530(96)	1404	−35
^{72}Se							
2_1^+	4.2(3)	4.3(5)	862	742	405(25)	678	+6
4_1^+	3.3(2)	2.7(4)	1637	1660	882(50)	1277	−33
6_1^+	1.7(1)	2.3(2)	2467	2266	1220(76)	2123	−77

The $B(E2)$ transition strength in ^{72}Se strongly decreases from the 6_1^+ to the ground state. The same behavior has been observed in the light Kr isotopes, where it is understood by an increased mixing of oblate and prolate configurations for the low-spin states [20]. The overall collectivity is higher in the Kr isotopes, which can be attributed to the deformation-driving effect of the $g_{9/2}$ proton orbital. The collectivity in ^{70}Se is much smaller than in ^{72}Se (due to less occupation of the $g_{9/2}$ neutron orbital), but a similar trend is observed: the $6_1^+ \to 4_1^+$ transition is more collective than the transitions below, which are similar in strength. The configuration-mixing calculations reproduce the energies of the states very well; the theoretical $B(E2)$ values, however, are systematically too large. On the other hand, the systematic trend, i.e., the lower collectivity of ^{70}Se, and the reduction of the $B(E2)$ values towards the ground state is qualitatively reproduced by the calculations.

With the new values from the present measurement, the systematics of the $B(E2)$ values in the chain of light Se isotopes shows a smooth decreasing trend from the most collective isotopes ^{76}Se and ^{74}Se at midshell to a small value for ^{68}Se [25], resolving the unexplained staggering caused by the very large $B(E2)$ value previously assigned to ^{70}Se.

The revised lifetime of the 2_1^+ state in ^{70}Se has important consequences for the interpretation of the results obtained in the recent Coulomb excitation experiment [16]. This is illustrated in Fig. 2, which shows the $B(E2; 2_1^+ \to 0_1^+)$ value as a function of the spectroscopic quadrupole moment Q_s. The full sloping lines represent the 1σ limits obtained from the measured Coulomb excitation cross section, which is sensitive to the quadrupole moment via the reorientation effect [26]. The dashed horizontal lines mark the 1σ limit of the $B(E2)$ value based on the old lifetime measurement by Heese *et al.* [13]. Only negative values of Q_s are consistent with both the old lifetime and the Coulomb excitation measurements, and it was concluded that the shape associated with the 2_1^+ state in ^{70}Se is prolate [16]. The present lifetime measurement requires a revision of this conclusion. The 1σ limits for the $B(E2)$ value from the new measurement are shown by the full horizontal lines. The intersection of the areas of possible values clearly favors a positive value of the spectroscopic quadrupole moment, i.e., oblate shape. Even though the precision of the lifetime measurement is significantly improved, it does not yet permit a precise determination of the quadrupole moment due to the large uncertainty of the Coulomb excitation cross section and its relatively weak dependence on the quadrupole moment. A more stringent constraint would require a more precise Coulomb excitation experiment. While the theoretical $B(E2)$ value is too large, the calculation also favors a moderately oblate shape for the state, as indicated by the asterisk in Fig. 2.

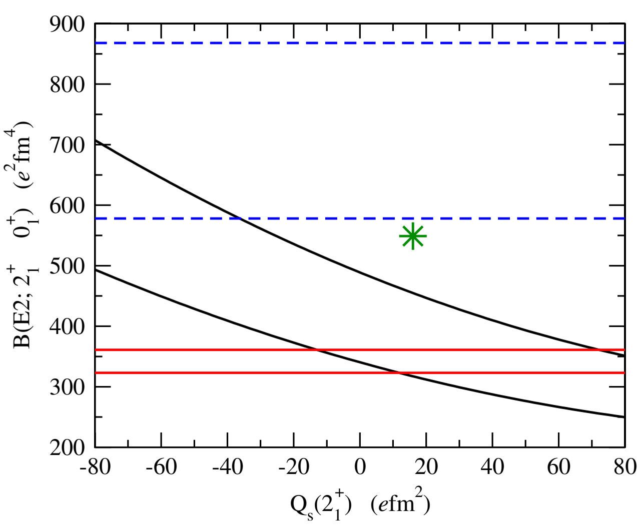

FIG. 2 (color online). $B(E2)$ value as a function of the spectroscopic quadrupole moment Q_s for the 2_1^+ state in ^{70}Se. The sloping lines indicate the 1σ range of values compatible with the Coulomb excitation measurement [16]. The horizontal solid (red) and dashed (blue) lines represent the 1σ ranges from the present and the earlier [13] lifetime measurements, respectively. The asterisk indicates the theoretical value.

The spectroscopic quadrupole moments for the low-lying states in ^{70}Se and ^{72}Se obtained in the calculations are given in Table I, and they are plotted in Fig. 3 as a function of spin. In addition, calculations were also performed for ^{68}Se, and the resulting quadrupole moments are included in Fig. 3. The agreement between the calculated and experimental excitation energies of the states in ^{68}Se is equally satisfying as for ^{70}Se and ^{72}Se. The 2_1^+ states of all three Se isotopes can be associated with oblate shapes of moderate deformation. The ground-state band in ^{72}Se evolves quickly into a highly collective prolate rotational

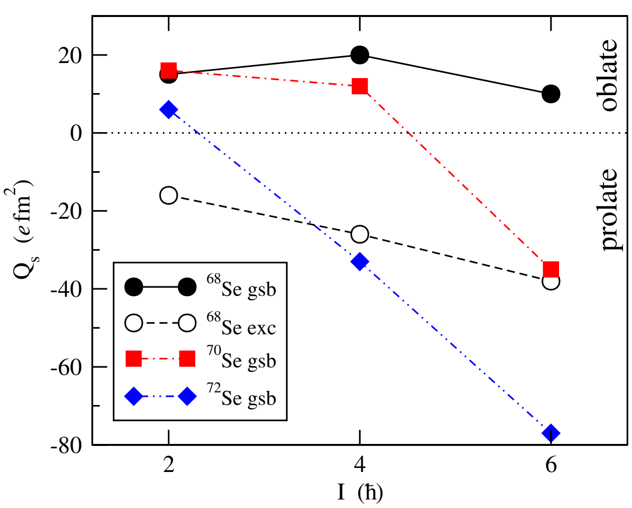

FIG. 3 (color online). Spectroscopic quadrupole moments obtained from the configuration-mixing calculations as a function of spin for the low-lying states in ^{68}Se, ^{70}Se, and ^{72}Se.

band. This is consistent with the rapid increase of the $B(E2)$ with spin, found both experimentally and theoretically. The ground-state band in ^{70}Se, on the other hand, stays oblate up to the 4_1^+ state and turns prolate only with the 6_1^+ state. This is consistent with the relatively small experimental $B(E2; 4_1^+ \rightarrow 2_1^+)$ and $B(E2; 2_1^+ \rightarrow 0_1^+)$ values, and the lower overall collectivity found in ^{70}Se. Finally, in ^{68}Se the ground-state band stays oblate, as already concluded by Fischer *et al.* from its low moment of inertia [14]. The quadrupole moments of the states in the excited band in ^{68}Se are negative, confirming the previous interpretation of shape coexistence in this nucleus. It is interesting to note in this context that the calculations find the lowest excited 0_2^+ state at 2.5 MeV excitation energy, which would explain why it has escaped observation so far, despite considerable experimental effort [14,15,25]. It also shows that the picture of two rotational bands built on oblate and prolate 0^+ states is too simplistic to describe the shape coexistence scenario in this mass region. This has already been pointed out based on the experimental results in the light Kr isotopes, which show not only a complex mixing of prolate and oblate shapes, but also mixing between rotational and vibrational states [1]. It has also become evident that triaxial shapes play a crucial role in this mass region; a correct description of the shape coexistence is only achieved if the triaxial degree of freedom is included in the beyond-mean-field calculations [24].

From the totality of experimental and theoretical results found in the light Se and Kr nuclei, a consistent picture seems to emerge in which oblate shapes become more and more favored near the ground state as one approaches $N = Z$. In the chain of Se isotopes ^{68}Se remains the best example for coexistence between oblate and prolate configurations. The conclusions drawn from the Coulomb excitation of ^{70}Se, which contradicted this picture, have to be revised based on the new lifetime measurement. The shape coexistence in ^{70}Se and ^{72}Se is, however, more delicate than in ^{68}Se or in the Kr isotopes, as the coexisting shapes do not prevail in collective bands to higher spin. Further experimental evidence for the shape coexistence scenario could come from multistep Coulomb excitation experiments.

In summary, a new RDDS lifetime measurement in ^{70}Se and ^{72}Se revealed considerable discrepancies with the literature values, requiring a revision of the conclusions drawn from the recent Coulomb excitation experiment on the shape of ^{70}Se. HFB-based configuration-mixing calculations have been performed through solving a five-dimensional, microscopic collective Hamiltonian. The calculated energies are in rather good agreement with the experimental results, while the $B(E2)$ values are systematically too large. The calculations support the interpretation of an oblate rotational ground-state band in ^{68}Se. Both theoretical and experimental results indicate that the energy of the oblate configuration increases with neutron number, so that prolate shapes are prevailing more and more in the heavier isotopes.

This work was partly supported by the European Community FP6—Structuring the ERA—Integrated Infrastructure Initiative—Contract EURONS No. RII3-CT-2004-506065.

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