Shape coexistence in light Se isotopes: Evidence for oblate shape

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Lifetimes of states in the ground-state bands of ^{70}Se and ^{72}Se were measured using the recoil-distance Doppler shift method following the reactions ^{40}Ca(^{36}Ar,$\alpha 2p$)^{70}Se and ^{40}Ca(^{36}Ar,$4p$)^{72}Se. 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. Hartree-Fock-Bogolyubov-based configuration mixing calculations using the Gogny D1S interaction have been performed and compared to the new experimental results. Both experiment and theory find an oblate shape for the 2^+_1 state in ^{70}Se, resulting in a coherent description of the shape coexistence and shape evolution in the light Se isotopes.

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Atomic nuclei in the mass region $A \approx 70$ close to the $N = Z$ line are known to exhibit a variety of nuclear shapes. Large shell gaps exist at both prolate and oblate deformation for proton and neutron numbers 34 and 36, so that such shapes are expected to compete in particular in the neutron-deficient Se and Kr isotopes. 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 in particular the electric monopole strength between the 0^+_2 shape isomer and the ground state shows that the configuration mixing is strongest in ^{74}Kr [2], suggesting an inversion of the prolate and oblate configurations, and consequently 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 situation in the neutron-deficient Se isotopes is less clear. Several theoretical investigations predict a similar shape coexistence scenario as in Kr with oblate ground-state configurations for the Se isotopes near $N = Z$ [4, 10, 11]. An isomeric excited 0^+_2 state is known in ^{72}Se just above the 2^+_1 state [12]. The $B(E2)$ strength for the transitions in the yrast cascade of this nucleus is strongly decreasing towards the ground state [13], which can be attributed to a strong mixing between prolate and oblate configurations at low spin. This situation resembles that in ^{74}Kr, but is, on the other hand, very different from neighboring ^{70}Se. The lifetimes in ^{70}Se reported by Heese *et al.* [13] indicate a strong increase of the $B(E2)$ values towards the ground state. 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. In the case of ^{68}Se 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]. However, no excited 0^+_2 state could be identified, despite considerable experimental effort [14–16]. 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 [17]. This result cast doubt on the interpretation of oblate ground-state shape for ^{70}Se, since the strong transitional matrix element suggests a similar structure for the 2^+_1 and 0^+_1 states. 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, which represents at the same time evidence for the

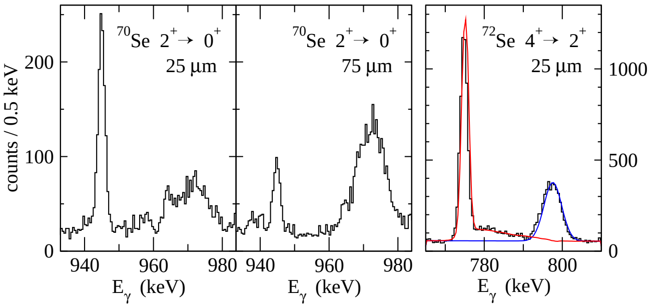

FIG. 1: (color online). Spectra showing the stopped and Doppler-shifted components observed in the forward detectors at 36° for the transitions and distances indicated. All spectra are gated on the shifted component of the transition directly feeding the state of interest. The simulated lineshape of 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.

strong link between the 2_1^+ state and the ground 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 [18]. The states were populated in the reactions ^{40}Ca(^{36}Ar,α2p)^{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 [19] 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 Au foil which was facing the beam. A thin Au layer of about 10 μg/cm^2 was evaporated onto the downstream side of the target to protect it from oxidation. The recoils had an average velocity of 10.73(3) μm/ps and were stopped in a Au stopper foil of 10 mg/cm^2 thickness. The Cologne Plunger device [20] was used to control the distance between the target and the stopper foils. Data was collected for 12 distances between 8 μm and 400 μm for an average of 10 hours 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. The γ rays were observed in the forwardmost ring of detectors at 36°, so that the γ rays emitted in flight are Doppler shifted to higher energies. 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

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 (see text). 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^2fm^4) exp.	$B(E2;\downarrow)$ (e^2fm^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

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 [18] following the procedure described in Ref. [21]. 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 lineshape profiles for various lifetimes of the respective states [22]. 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.

For ^{72}Se the new lifetimes are in reasonable agreement with the results of Heese *et al.* [13]. The lifetimes of the 2_1^+ and 6_1^+ states in ^{70}Se, however, deviate considerably from the literature values. It can only be speculated about the origin of this disagreement. To extract lifetimes from the γ singles spectra of the old measurement, where the density of transitions is much higher, is inevitably more difficult. The most likely reason for the 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 [21], 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 [23, 24]. 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, 25]. The procedure to calculate the energy spectra, reduced transition probabilities, and spectroscopic quadrupole moments is described in detail in Ref. [9].

The $B(E2)$ transition strength in ^{72}Se is strongly decreasing 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 [21]. 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 $6_1^+ \rightarrow 4_1^+$ 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 compared to ^{72}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 $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in the chain of light Se isotopes shows a smooth decreasing trend from the most collective isotopes ^{76}Se and ^{74}Se at mid-shell to a small value for ^{68}Se [16], 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 [17]. This is illustrated in Fig. 2, which shows the $B(E2; 2_1^+ \rightarrow 0_1^+)$ 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 [17]. 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

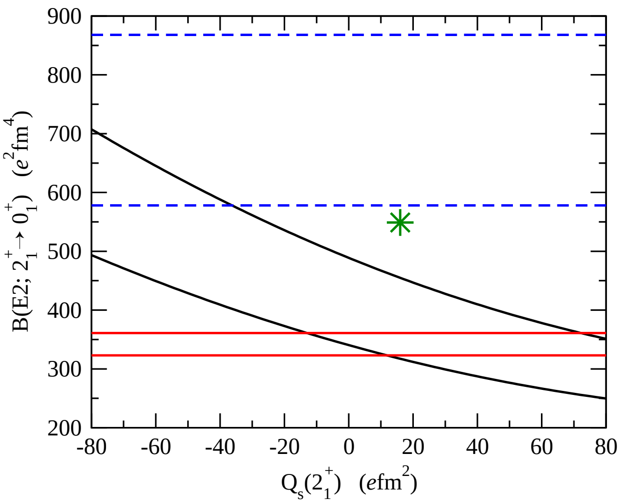

FIG. 2: (color online). $B(E2)$ value as a function of the spectroscopic quadrupole moment Q_s for the 2_1^+ state in ^{70}Se. The sloping lines indicate the 1σ range of values compatible with the Coulomb excitation measurement [17]. The horizontal solid (red) and dashed (blue) lines represent the 1σ ranges from the present and the earlier [13] lifetime measurements, respectively. The asterisk indicates the theoretical value.

determination of the quadrupole moment due to the relatively large error on 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.

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 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^+

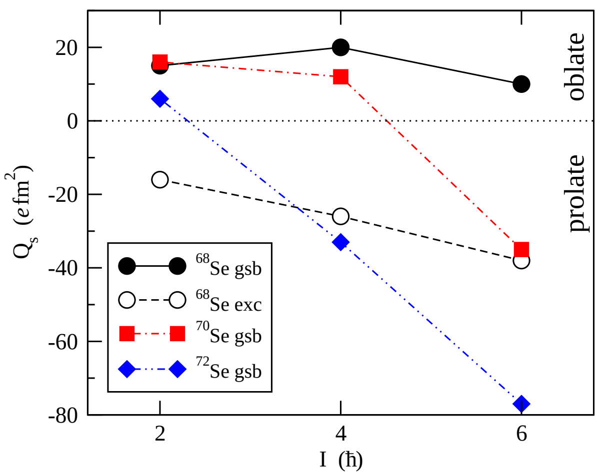

FIG. 3: (color online). Spectroscopic quadrupole moments obtained from the configuration-mixing calculations as a function of spin for the low-lying states in ^{68}Se, ^{70}Se, and ^{72}Se. Positive values correspond to oblate, negative values to prolate shapes.

state at 2.5 MeV excitation energy, which would explain why it has escaped observation so far. 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 [25].

From the totality of experimental and theoretical results found in the light Se nuclei, a consistent picture seems to emerge in which oblate shapes become more and more favored near the ground state as one approaches ^{68}Se, which remains the best example for coexistence between oblate and prolate configurations. The conclusions drawn from the Coulomb excitation of ^{70}Se, which were contradicting this picture, have to be revised based on the new lifetime measurement. Further experimental evidence for the shape coexistence scenario could come from multi-step Coulomb excitation experiments in ^{70}Se and in particular in ^{68}Se.

In summary, the lifetimes of low-lying states in ^{70}Se and ^{72}Se were re-measured with high precision using the RDDS technique. The results show considerable discrepancies with the literature values. In particular the deviating lifetime of the 2^+_1 state in ^{70}Se requires a revision of the conclusions drawn from the recent Coulomb excitation experiment. 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 is increasing with neutron number, so that prolate shapes are prevailing more and more in the heavier isotopes.

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[1] E. Clément *et al.*, Phys. Rev. C **75**, 054313 (2007).
[2] E. Bouchez *et al.*, Phys. Rev. Lett. **90**, 082502 (2003).
[3] A. Gade *et al.*, Phys. Rev. Lett. **95**, 022502 (2005).
[4] W. Nazarewicz *et al.*, Nucl. Phys. **A 435**, 397 (1985).
[5] P. Bonche *et al.*, Nucl. Phys. **A 443**, 39 (1985).
[6] M. Yamagami, K. Matsuyanagi, M. Matsuo, Nucl. Phys. **A 693**, 579 (2001).
[7] M. Bender, P. Bonche, P.-H. Heenen, Phys. Rev. C **74**, 024312 (2006).
[8] A. Petrovici, K.W. Schmid, A. Faessler, Nucl. Phys. **A 665**, 333 (2000).
[9] J. Libert, M. Girod, J.-P. Delaroche, Phys. Rev. C **60**, 054301 (1999).
[10] T. Mylaeus *et al.*, J. Phys G. **15**, L135 (1989).
[11] A. Petrovici, K.W. Schmid, A. Faessler, Nucl. Phys. **A 728**, 396 (2003).
[12] J.E. Draper, N.S.P. King, and W.G. Wyckoff, Phys. Rev. C **9**, 948 (1974).
[13] J. Heese *et al.*, Z. Phys. **A 325**, 45 (1986).
[14] S.M. Fischer *et al.*, Phys. Rev. Lett. **84**, 4064 (2000).
[15] S.M. Fischer, C.J. Lister, D.P. Balamuth, Phys. Rev. C **67**, 064318 (2003).
[16] E. Clément *et al.*, submitted to Nucl. Instr. Meth. A.
[17] A.M. Hurst *et al.*, Phys. Rev. Lett. **98**, 072501 (2007).
[18] A. Dewald *et al.*, Z. Phys. **A 334**, 163 (1989).
[19] D. Bazzacco, in International Conference on Nuclear Structure at High Angular Momentum, Ottawa 1992, AECL Report 10613, Vol. 2, p. 376.
[20] A. Dewald, in Ancillary Detectors and Devices for Euroball, ed. H. Grawe, GSI and the Euroball Ancillary Group, Darmstadt, 1998, p. 70.
[21] A. Görgen *et al.*, Eur. Phys. J. A **26**, 153 (2005).
[22] P. Petkov *et al.*, Nucl. Instr. and Meth. **A 431**, 208 (1999).
[23] J. Dechargé and D. Gogny, Phys. Rev. C **21**, 1568 (1980).
[24] J.-F. Berger, M. Girod, and D. Gogny, Comput. Phys. Commun. **63**, 365 (1991).
[25] M. Girod *et al.*, to be published.
[26] K. Alder and A. Winther, *Electromagnetic Excitation, Theory of Coulomb Excitation with Heavy Ions*, (North-Holland, Amsterdam, 1975).