Multiple Shape coexistence in ^{78}Se

AGATA + SPIDER + DANTE

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Abstract

Through this letter of intent, we propose to investigate the electromagnetic properties of the low-lying states in ^{78}Se, which is a promising candidate for the observation of multiple shape coexistence. This measurement will be done via a multi-step Coulomb excitation measurement with AGATA in conjunction with the particle detectors SPIDER and DANTE. The primary objective is to measure, with suitable accuracy, the diagonal and transition E2 matrix elements connecting the low-lying states. These matrix elements will be used to determine shape parameters on the basis of a rotational-invariant sum-rule analysis, thereby, providing considerable insight into the underlying collectivity and the inherent triaxial nature of the ground-state, gamma bands, and the other lower-lying excited 0^+ states. These newly determined shape parameters will shed light on the possible multiple shape coexistence phenomenon in the ^{78}Se nucleus. Four (4) days of beam on target are requested.

I. MOTIVATION

Nuclei in the A≈70-80 region exhibit a rich variety of shapes in their low-lying states, including spherical, prolate, oblate, and triaxial forms. Changes in nucleon number lead to phenomena such as shape transitions and coexistence. Several theoretical models [1–3] predict prolate-oblate shape coexistence within a narrow energy range of a few hundred keV. Precise measurements of excitation energies and transition rates provide sensitive tests of these models. The occurrence of low-lying excited 0^+ states in even-even Ge, Se, and Kr isotopes (see Fig.1) supports the existence of shape coexistence, further evidenced by strong ρ^2(E0) transitions [4, 5], indicating mixing between shapes. This coexistence stems from the interplay of shell effects and polarization, offering insights into nuclear structure evolution. In this context, a systematic study of the stable, even-mass Se isotopes [6, 7] have revealed large deformations in their ground-states which steadily decreases as one approaches $N = 50$. Lying within this transitional region, the even-even Se isotopes, hence, offer a unique testing ground for investigating the phenomena of shape transitions and shape coexistence.

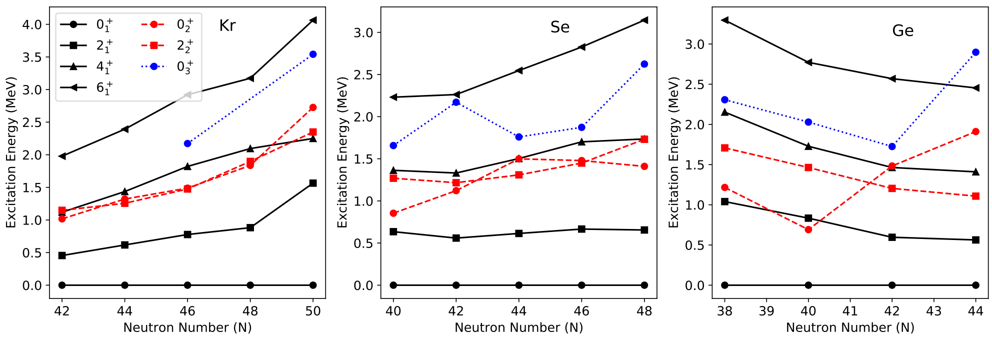

FIG. 1: Excitation energy as a function of neutron number (N) for the Kr, Se, and Ge nuclei, showing the ground-state band (black) along with the intruding 0_2^+, 2_2^+, and 0_3^+ states.

Coulomb-excitation and g-factor measurements for some of the stable Se isotopes dates back to the mid-90s [7, 8]. The collective structure of the ^{76,80,82}Se isotopes were investigated and seen to exhibit features characteristic of anharmonic vibrational collective motion. However, the Se nuclei were only weakly excited to the 4^+ state and several important levels such as the 2_3^+ and 4_2^+ went unobserved. A more recent measurement for ^{76}Se [9] revealed significant triaxiality in the ground state, similar to the case of its isotone ^{76}Ge [10] which has also been seen to exhibit rigid triaxiality in its ground state. For the case of ^{78}Se, Ref. [11] reported large deformations of $\beta_{rms} = 0.27(2)$, 0.24(6), and 0.14(5) for the 0_1^+, 2_1^+, and 2_2^+ states, respectively. Moreover, a large asymmetry with $\gamma \approx 23$ - 28° was obtained from the analysis of the E2 matrix elements (ME). Our collaboration recently performed a study to explore the structure of ^{82}Se through a Coulomb excitation experiment using the AGATA array and SPIDER detector at Legnaro National Laboratory (Exp 24.008). In parallel, a new Coulomb-excitation study targeting shape coexistence in the odd-A nucleus ^{77}Se is being conducted at Argonne National Laboratory using the GRETINA array and CHICO-X. With ^{76}Se already studied and ^{77,82}Se under active investigation, we now turn our focus to ^{78}Se, which lies at the midpoint of this sequence. A detailed study of this nucleus offers a crucial opportunity to explore the evolution of nuclear shapes and the emergence of triaxiality and shape coexistence in this transitional region.

The earlier Coulomb-excitation study of ^{78}Se in Ref.[11] populated only five low-lying states — *viz,*, the $0_{1,2}^+$, $2_{1,2}^+$, and 4_1^+ levels. Several other excited states that could significantly influence the inferred ground-state deformation remained unobserved. While quadrupole shape invariants were extracted for the 0_1^+ and $2_{1,2}^+$ states, the absence of key E2 matrix elements from higher-lying excitations suggests that these invariants likely represent lower limits. With the superior efficiency and granularity of the AGATA array, we anticipate

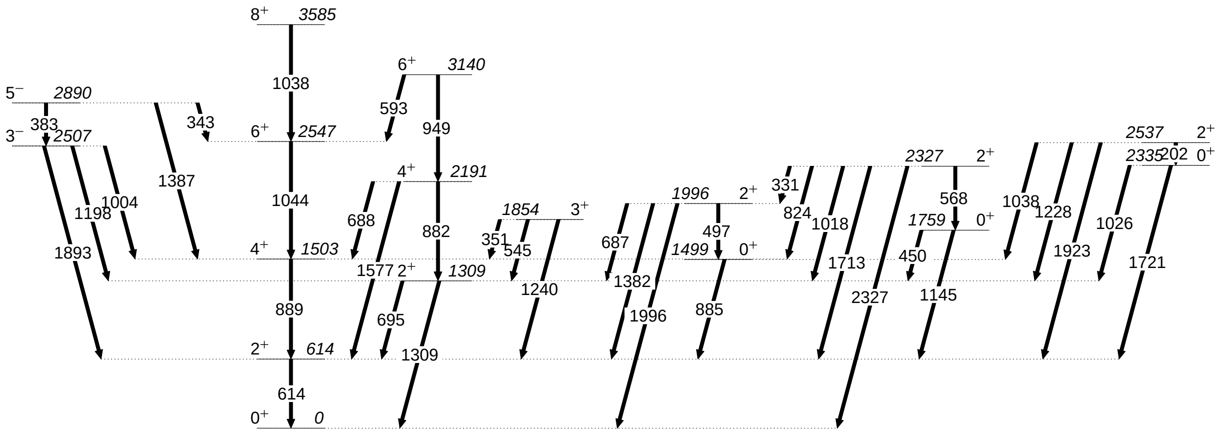

FIG. 2: The level scheme of ^{78}Se that has been adopted to perform GOSIA simulations for this proposal.

populating additional states beyond those seen in Ref.[11], including several low-lying excited 0^+ states. This may allow us to extract their deformation parameters and potentially uncover evidence for multiple shape coexistence.

II. GOALS OF THE PROPOSED EXPERIMENT

Given these gaps in experimental knowledge, we propose a multi-step Coulomb-excitation study of ^{78}Se to investigate the electromagnetic structure of its low-lying states with greater precision. Coulomb excitations, indeed, selectively populate collective low-lying states with cross sections that are related to the E2 transitional MEs and the spectroscopic quadrupole moments Q_s. Thus, by exploring the evolution of such differential cross sections as a function of the scattering angle, the nuclear shape of the ground and excited states can be determined in a model-independent way.

A precise determination of the transition and diagonal MEs for states within the ground-state and "gamma" bands will, hence, help in assessing the accuracy of the existing model predictions as well as establishing the possible triaxiality and shape coexistence in ^{78}Se. Furthermore, these measurements will offer direct insights into the E2 properties, contributing valuable information about shape evolution along the stable Se isotopic chain. The proposed measurement aims to exploit the high-intensity stable-ion beams provided by the Tandem+ALPI accelerator complex for a Coulomb-excitation study of the electromagnetic properties of the low-lying states in ^{78}Se. Based on our experience with previous Coulomb-excitation measurements, we expect to be able to determine the Q_s values for several low-lying states in ^{78}Se. We also expect to populate several states (such as the 4^+_2, $6^+_{1,2}$, 3^+_1, and $2^+_{3,4}$ to mention a few) in addition to those that were identified in Ref. [11], allowing us to determine not only the quadrupole invariants (β_2, γ) but also their variance (which provides information about the "softness" of the nuclear shape). Through this measurement, we hence, expect to present a more complete picture of the underlying structure and possible multiple shape coexistence in ^{78}Se.

The data will be used to achieve the following specific objectives:

1. Precise measurement of both transitional and diagonal MEs (e.g., Q_s for the $2^+_{1,2}$ and $4^+_{1,2}$ states). This will enable the determination of reduced transition probabilities, $B(E2)$, providing crucial insights into the electromagnetic properties of the underlying states.

2. Accurate determination of β_2 and γ deformations for not only the ground state, but also the next three excited 0^+ states in ^{78}Se. Additionally, determining the variance $\delta\beta_2$ to elucidate the predicted "softness" of the ground state and wherever possible, for the other 0^+ states.
3. Determination of the quadrupole deformation for the $2^+_{1,2}$ and $4^+_{1,2}$ states in ^{78}Se.
4. Evaluation of the extent of shape mixing between the multiple coexisting structures of ^{78}Se using the measured $E2$ MEs.

III. EXPERIMENTAL DETAILS

The electromagnetic properties of the low-lying states in ^{78}Se will be investigated via a multi-step Coulomb-excitation measurement utilizing two different beam energies. In the first step, a 305-MeV ^{78}Se beam will impinge onto a 0.5-mg/cm^2 ^{208}Pb target and for the second step, using the same beam-target combination, the beam energy will be reduced to 270 MeV. These energies fulfill the Cline's safe distance criterion [12], and the target thickness is limited to avoid excessive Doppler broadening of γ–ray lines due to energy loss. Building on the experience gained from previous experiments, the beam current will be limited to 0.5 pnA.

The emitted γ rays will be detected by the AGATA array (ϵ_γ = 4.5% at 1.332 MeV), while the scattered Se ions will be detected with the particle detector SPIDER at backward angles, where the probability of multi-step excitation and the sensitivity to Q_s and signs of MEs are maximized. At forward angles, we aim to use the DANTE particle detector to increase the angular coverage for particle detection and gain further sensitivity to quadrupole moments and ME signs. The employment of both AGATA and SPIDER are crucial for the goals of this experiment: the unique position sensitivity and detection efficiency of these arrays will allow us to reach unprecedented Doppler-correction capabilities and to exploit $\gamma-\gamma-$particle coincidence analysis to search for new, weak transitions and disentangle lines with close energies (e.g., the 889 keV $4^+_1 \rightarrow 2^+_1$ and the 885 keV $0^+_2 \rightarrow 2^+_1$ transitions). Furthermore, the large angular coverage of SPIDER at backward angles (123° - 161°) will enable determination of many transitional MEs, particularly for those excited states whose spectroscopic information is partial or scarce.

Using two beam energies - 305 and 270 MeV, will increase sensitivity to second-order effects such as relative signs of matrix elements and spectroscopic quadrupole moments due to the difference in the expected excitation patterns, as also seen in the rate estimates given in Table I. Moreover, the doubly-magic character of the target ^{208}Pb ensures that only the 2614-keV state is populated, limiting overlaps with γ-ray transitions of interest arising from beam excitation. The results obtained from the Coulomb excitation of ^{78}Se on the ^{208}Pb target at a lower beam energy of 270 MeV will be used as constraints when repeating the measurement at the higher beam energy of 305 MeV, which is expected to lead to a more complex spectrum.

It is worth mentioning that the Coulomb-excitation measurement of ^{82}Se (Exp 038, Proposal No. 24.008) was recently performed at INFN-LNL employing the AGATA+SPIDER+DANTE setup in experimental conditions similar to those discussed in the current proposal. The success of the measurement of ^{82}Se also guarantees the feasibility of this proposal.

IV. RATE ESTIMATES AND BEAM-TIME REQUEST

Taking into account the features of the experimental setup and the level scheme of ^{78}Se (Fig. 2), the expected γ-ray yields were simulated using the GOSIA code. The results of

TABLE I: Number of counts estimated for the γ-ray transitions of ^{78}Se as displayed in the level scheme of Fig 2. The columns marked with a '-' indicate that the yields of those γ transitions are too low to be observed.

E_γ (keV)	E_{beam} = 305 MeV		E_{beam} = 270 MeV	
	Counts [1/day] (DANTE)	Counts [1/day] (SPIDER)	Counts [1/day] (DANTE)	Counts [1/day] (SPIDER)
614	4.90E+08	1.38E+08	4.07E+08	1.39E+08
889	3.60E+07	1.78E+07	1.62E+07	8.96E+06
695	6.98E+06	9.65E+06	3.25E+06	4.98E+06
1309	4.25E+06	6.48E+06	1.99E+06	3.37E+06
1721	2.27E+06	4.64E+06	5.26E+05	1.81E+06
882	1.40E+06	2.45E+06	3.70E+05	6.99E+05
1044	1.52E+06	2.40E+06	3.18E+05	4.63E+05
2537	1.69E+06	2.24E+06	3.89E+05	7.93E+05
688	5.96E+05	1.04E+06	1.58E+05	2.97E+05
1026	3.12E+05	6.38E+05	7.23E+04	2.49E+05
1577	1.00E+05	1.76E+05	2.66E+04	5.02E+04
885	5.14E+04	1.37E+05	2.20E+04	7.40E+04
949	5.44E+04	1.28E+05	7.55E+03	1.74E+04
1038	4.84E+04	1.17E+05	4.80E+03	1.03E+04
593	3.77E+04	8.70E+04	5.22E+03	1.18E+04
1145	2.00E+04	8.15E+04	4.78E+03	2.72E+04
1996	3.56E+04	4.21E+04	1.02E+04	1.28E+04
1240	1.58E+05	4.00E+04	3.84E+04	1.32E+04
545	1.04E+05	3.75E+04	2.54E+04	1.24E+04
687	3.06E+04	3.12E+04	8.63E+03	9.47E+03
1382	2.55E+04	2.94E+04	7.32E+03	8.97E+03
1198	7.95E+04	2.29E+04	1.96E+04	6.87E+03
1713	7.52E+04	1.58E+04	1.65E+04	6.77E+03
1923	1.27E+04	1.19E+04	2.86E+03	4.19E+03
1387	1.12E+04	8.55E+03	1.94E+03	1.52E+03
497	6.74E+03	7.97E+03	1.93E+03	2.43E+03
1004	1.76E+04	5.21E+03	4.35E+03	1.56E+03
383	5.74E+03	4.68E+03	-	-
1228	4.45E+03	4.17E+03	1.00E+03	1.47E+03
450	-	4.01E+03	-	1.34E+03
1893	1.14E+04	3.29E+03	2.81E+03	-
343	2.74E+03	2.11E+03	-	-
1018	8.14E+03	1.73E+03	1.76E+03	-
351	6.04E+03	1.62E+03	1.47E+03	-
2327	7.25E+03	1.57E+03	1.56E+03	-
568	3.65E+03	-	-	-
331	2.89E+03	-	-	-
824	2.58E+03	-	-	-
2507	1.02E+03	-	-	-

this calculation are listed in Table I. Considering the ambitious goals of the experiment and the estimated yields provided by GOSIA, we ask the following:

- **Beam:** ^{78}Se at 305 and 270 MeV, 0.5 pnA
- **Target:** ^{208}Pb (0.5 mg/cm^2), self-supporting
- **Experimental Setup:** AGATA + SPIDER + DANTE
- **Beam time:** 4 (2 + 2) days

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