Triaxial-to-oblate shape transition at ^{68}Se in self-conjugate nuclei

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We report on the first measurement of the absolute transition strength B(E2;$0^+_1 \rightarrow 2^+_1$) in the self-conjugate nucleus ^{68}Se. The obtained value shows that ^{68}Se has similar properties than the triaxial ^{64}Ge and is at the edge of an onset of deformation towards the heavier nuclei ^{72}Kr and ^{76}Sr. The low-lying spectroscopy of self-conjugate nuclei in this mass region is correctly reproduced by beyond-mean-field calculations using the Gogny D1S interaction that predict a strong triaxiality in the ^{68}Se ground state with a positive quadrupole moment.

Mesoscopic systems ruled by quantum mechanics may exhibit sudden shape transitions by changing their number of constituants, as observed for semiconductor atomic clusters [1]. Atomic N = Z nuclei with $\sim$70 nucleons present large deformed single-particle shell gaps, at the Fermi level, at both elongated (prolate) and flattened (oblate) quadrupole deformations, leading to different stabilizing shapes. The ground-state deformation of these self-conjugate nuclei and its evolution with mass is driven by both the underlying single-particle properties, identical for protons and neutrons, and quantum mechanical long-range correlations.

The sign of the quadrupole deformation of the first 2^+ state is hardly reachable in these neutron-deficient nuclei and is experimentally known in very few cases, such as $^{74,76}_{36}$Kr [2] and $^{70}_{34}$Se [3]. The B(E2;$0^+_1 \rightarrow 2^+_1$) transition strength from the ground state (gs) to the first 2^+ excited state, quoted B(E2↑) in the following, remains a unique and reachable information to evaluate their collectivity at low excitation energy. The low-lying spectroscopy of the N = Z nucleus $^{64}_{32}$Ge, four nucleons away from ^{68}Se, shows strong similarities with predictions for a triaxial nucleus. Recently, its B(E2↑) transition strength has been measured and was found consistent with shell-model predictions for a triaxial shape [4]. In the case of the Selenium isotopes, it has been concluded from recent low-energy Coulomb-excitation and 2^+_1-lifetime [5] measurements, that ^{70}Se is oblate in its gs [3]. The moment of inertia extracted from the ground-state band of ^{68}Se is similar to the one of ^{70}Se and suggests a collective oblate deformation [6], but no direct information on the collectivity of the ^{68}Se gs has been measured yet. In the Krypton isotopes, a shape transition from a prolate-deformed gs in ^{76}Kr to an oblate shape in ^{72}Kr has been established [2, 7]. The N = Z nucleus ^{72}Kr is understood as having an almost pure oblate gs with very low mixing with the intrinsic prolate configuration. The absolute transition strength B(E2↑) of ^{72}Kr shows consistency with predictions of an oblate gs [8]. On the other hand, triaxiality has been suggested to be a key degree of freedom to understand the shape transition in light Krypton isotopes [9]. The importance of triaxiality in ^{68}Se, the transitional nucleus between the triaxial ^{64}Ge and the oblate ^{72}Kr, is still an open question.

Several theories have been employed to study the deformation of ^{68}Se at low excitation energy and their predictions for B(E2↑)'s vary from $\sim$0.2 to $\sim$2.5 times the experimental value for ^{64}Ge, leading to various interpretations of the collectivity of ^{68}Se [10–13]. It is therefore of importance to measure this quantity in ^{68}Se in order to bridge the picture of shape evolution along the N = Z line.

In this article, we report on the first measurement of the reduced transition probability B(E2;$0^+_1 \rightarrow 2^+_1$) in ^{68}Se obtained by intermediate-energy Coulomb excitation. We present new beyond-mean-field calculations using the Gogny D1S finite-range interaction, with no free parameter fitted in the region of interest, that highlight the shapes of self-conjugate nuclei in the region of interest.

The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL), at Michigan State University. A radioactive ^{68}Se beam was produced by fragmentation of a ^{78}Kr primary beam at 150 MeV/nucleon on a 329 mg/cm^2-thick ^{9}Be production target. The ^{68}Se secondary beam was purified to 12% with the A1900 separator [14]. The main contaminants were ^{67}As (41 %) and ^{66}Ge (30 %). The secondary beam was then sent on a 257 mg/cm^2-thick ^{197}Au target for Coulomb excitation. The energy of ^{68}Se was 92 MeV/nucleon at the secondary target, located at the pivot point of the S800 spectrometer and inside the SeGA segmented HPGe array [15]. For this experiment, SeGA was composed of 17 detectors positioned at 20 cm from

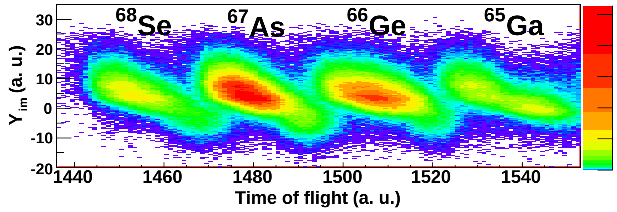

FIG. 1: (Color online) Identification of incoming particles (see text).

the target and arranged in a configuration consisting of two rings in a cylindrical symmetry around the beam axis : 7 detectors at 37° in the forward direction and 10 detectors at 90° relative to the beam direction. The SeGA photopeak efficiency was 2.49(2) % for a 1 MeV transition emitted at rest in the laboratory frame from the target position. The identification of incoming particles was performed on an event-by-event basis by a time-of-flight (TOF) measurement between two plastic scintillators located at the image point of the A1900 and at the object point of the S800 magnetic spectrometer [16]. A clear separation of incoming particles was performed by correlating the TOF measurement to a dispersion measurement (Y_{im}) from two position-sensitive detectors at the mid-plane of the S800 analysis beam line (see Fig. 1).

Downstream from the secondary target, the direct beam and inelastically scattered particles were transmitted to the S800 spectrometer focal plane that is composed of two cathode readout drift chambers (CRDCs) [17], an ionisation chamber and a plastic scintillator for trigger and timing. The beam intensity on the secondary target was limited to 6 kHz in order to minimize pileup in the drift chambers. Transmitted particles were identified via time-of-flight and energy loss. The CRDCs measured the positions and scattering angles in both dispersive and non-dispersive planes relative to the beam trajectory in the focal plane. The scattering angle off the secondary target was then obtained from a back-tracking method based on a fifth-order reconstruction polynomial obtained from a mapping of the S800 magnetic field. The angular acceptance of the S800 spectrometer is 3.5°. We estimated the uncertainty of the scattering angle of 0.1° in the laboratory frame, mainly due to the angular emitance of the incoming beam. For reference, we performed a similar Coulomb-excitation measurement with a ^{78}Kr stable beam.

The Doppler correction for gamma rays was performed considering the angles of hit segments for each event and the mean mid-target velocity. Doppler and non-Doppler corrected spectra in coincidence with particles scattered at angles up to 2.5° are shown in Fig. 2. Time gates on prompt events have been applied to reduce random coincidences. We measured the $2_1^+ \rightarrow 0_1^+$ transition at 854(2) keV, in agreement with the value of 854.3(2) keV

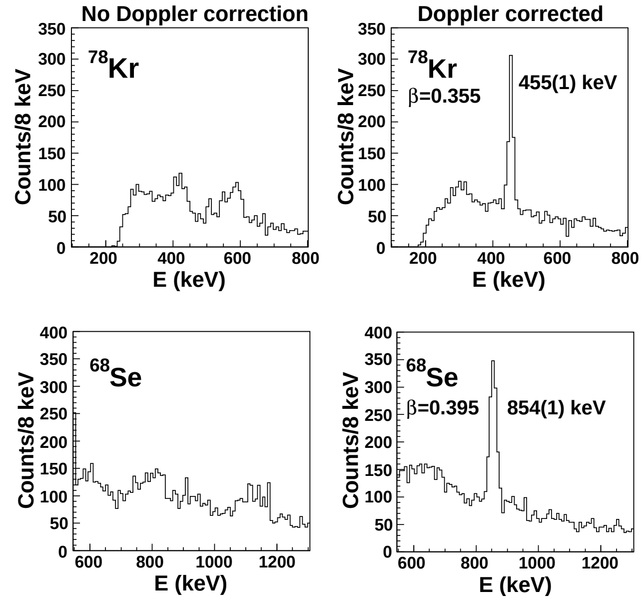

FIG. 2: De-excitation gamma spectra of ^{78}Kr (top) and ^{68}Se (bottom) with (right panel) and without (left panel) Doppler correction.

measured by J. M. Fischer *et al.* [6]. We did not observe any other transition in ^{68}Se that could let us to assume any significant feeding from high-lying states. Note that ^{68}Se must impinge the secondary target is in its gs since no isomeric state of life time greater than 1μs has been previously observed in ^{68}Se produced by fragmentation of ^{78}Kr [18].

The Coulomb-excitation cross section to populate excited states is obtained from the number of photopeak events in SeGA, corrected for the photopeak efficiency of the array, absorption in the target and for theoretical Coulomb-excitation gamma-ray angular distributions [19]. The ratio of measured counts in the two angular rings, N(90°)/N(37°)=0.73(2) in the case of ^{68}Se, is close to the 0.66 ratio expected from theory, proving that the gamma angular distribution is adequatly taken into account. The number of incoming ^{68}Se particles on the secondary target is directly measured in the S800 focal plane with an uncertainty of 5%. All uncertainties described above have been added in quadrature. The extraction of the B(E2↑) transition strength from the Coulomb-excitation cross section is performed using the semi-classical theory of A. Winther and K. Alder for relativistic Coulomb excitation [20] and relates the classical impact parameter of the collision and the scattering angle of the beam-like particle. In order to restrict the data to purely Coulomb excitation and exclude nuclear excitation, one considers only "safe" angles for the scattered particles. The method has been shown to provide reliable results [21]. In the following, we consid-

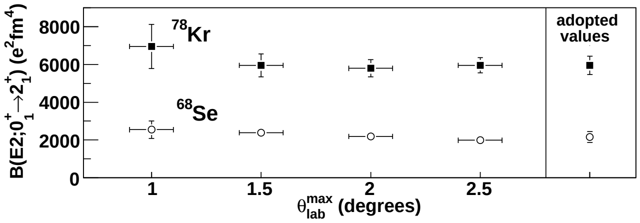

FIG. 3: Extracted B(E2↑) values for ^{78}Kr and ^{68}Se as a function of the maximum scattering angle θ_{lab}^{max} in the laboratory frame. Only statistical uncertainties are presented for $\sigma(\theta < \theta_{lab}^{max})$.

ered the definition of W. W. Wilcke *et al.* [22] for the nuclear-interaction impact parameter. In the case of ^{68}Se interacting with ^{197}Au, the nuclear-interaction impact-parameter is R =13.9 fm. In the Alder-Winther theory, for an incident energy of 92 (73) MeV/nucleon at the entrance (exit) of the target, this limit impact parameter corresponds to a scattering angle of 2.5° (3.1°) in the laboratory frame. We therefore restricted ourselves to scattering angles lower than θ_{lab}^{max}=2.5° in the laboratory frame, which correspond to a mean impact parameter of 15.8 fm for the mid-target energy, above the nuclear interaction radius. In the case of ^{78}Kr, we also consider scattering angles up to 2.5°, corresponding to trajectories of impact parameter larger than 19.3 fm, above the nuclear-interaction radius of 14.1 fm. To further validate our approach, we performed the analysis for different θ_{lab}^{max} ranging from 1° to 2.5° with 0.5° steps, and calculated the B(E2↑) transition strength that reproduces the experimental integrated cross section $\sigma(\theta \leq \theta_{lab}^{max})$. For all θ_{lab}^{max}, we obtain consistent values as shown in Fig. 3. For instance, in the case of ^{68}Se, the angle-integrated Coulomb excitation cross sections $\sigma(\theta \leq 1°)$= 83(15) mb and $\sigma(\theta \leq 2.5°)$= 367(26) mb give a B(E2↑) transition strength of 2544(469) e^{2}fm^4 and 1982(140) e^{2}fm^4, respectively. We adopted the values that best reproduce measurements at all θ_{lab}^{max}. In the case of ^{78}Kr, the obtained transition strength of 5951(481)e^{2}fm^4 is in agreement with the tabulated value of 6330(390) e^{2}fm^4 [23]. The transition strength in ^{68}Se is found to be 2158(290) e^{2}fm^4. Interestingly, this value is similar to the B(E2↑)=2050(300) e^{2}fm^4 in ^{64}Ge and 2.5 times lower than that of ^{72}Kr, measured at 4997(647) e^{2}fm^4. This sudden increase of transition strength from ^{68}Se to ^{72}Kr indicates a strong onset of collectivity from Z = 34 to Z = 36 along the line of self-conjugate nuclei. The similar transition strength between ^{64}Ge and ^{68}Se, associated to their very close low-lying state spectroscopy (the excitation energies of their 2_1^+, 2_2^+ and 4_1^+ states are equal within 90 keV), further establishes the similarity of these two nuclei at low excitation energy.

TABLE I: Excitation energy of 2_1^+(keV) and reduced-transition probability B(E2↑) (e^{2}fm^4) of ^{68}Se and ^{78}Kr.

Nucleus		this work	Ref. [23]
^{68}Se	E(2_1^+)	854(2)	854.2(3)
	B(E2;$0_1^+ \rightarrow 2_1^+$)	2158(290)	-
^{78}Kr	E(2_1^+)	454(1)	455.04(3)
	B(E2;$0_1^+ \rightarrow 2_1^+$)	5951(481)	6330(390)

To further investigate this significant structure change beyond ^{68}Se and the similarities with ^{64}Ge, we calculated the wave functions of N = Z nuclei from ^{60}Zn to ^{76}Sr in a microscopic Hartree-Fock-Bogoliubov (HFB)-based formalism using the finite-range Gogny D1S effective nucleon-nucleon interaction [24, 25]. To derive low-lying collective states, the Generator Coordinate Method (GCM) with the Gaussian Overlap approximation (GOA) have been employed. The nuclear wave function is described as a mixing of constrained HFB wave functions of different deformations. In this work, we considered five collective degrees of freedom, allowing all quadrupole deformations. The calculations are performed with a self-consistent cranked moment of inertia at spin zero. This formalism has already been shown to reproduce the shape transition from prolate deformation in ^{76}Kr to oblate deformation in ^{72}Kr, giving a good agreement with experimental excitation energies and transition strengths [9]. Our calculations for the excitation energy of the first excited 2^+ state in ^{60}Zn, ^{64}Ge, ^{68}Se, ^{72}Kr and ^{76}Sr and the corresponding B(E2↑) transition strength show a strong increase of the collectivity towards the heaviest nuclei (see Fig. 4). The agreement with existing data is very good. We predict that the transition strength is B(E2↑)=2820 e^{2}fm^4 for ^{68}Se, with a positive quadrupole moment of +15 efm^2, and should

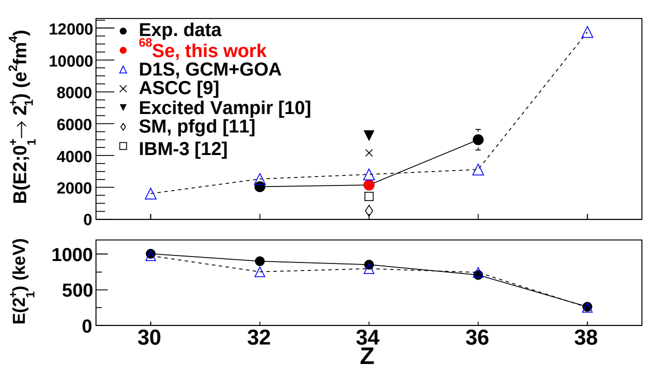

FIG. 4: (Color online) (top) Experimental B(E2↑) transition strength of self-conjugate nuclei (filled circles). The measured value in this work for ^{68}Se is compared to predictions from different theories. Our beyond-mean-field calculations are indicated by blue triangles. (bottom) Experimental and theoretical excitation energy of the 2_1^+ states. Lines are drawn to guide the eyes.

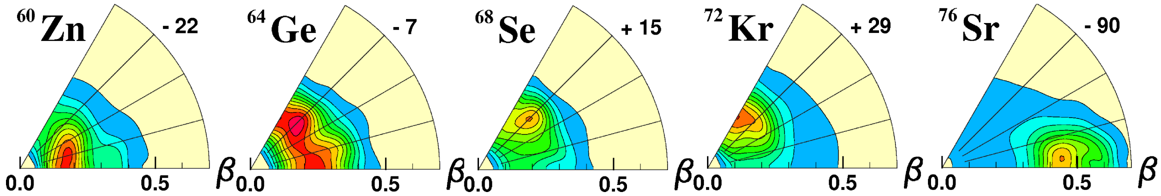

FIG. 5: (Color online) Probability density for the collective wave functions of the 2_1^+ state of ^{60}Zn, ^{64}Ge, ^{68}Se, ^{72}Kr and ^{76}Sr in the β-γ triaxial plane. The corresponding spectroscopic quadrupole moment is given in $e\,\mathrm{fm}^2$ for each case.

reach B(E2↑)=11750 e^2fm^4 in ^{76}Sr with a large prolate shape and a quadrupole moment of -92 efm^2 in agreement with conclusions from its beta-decay strength distribution [26]. Several other predictions for the transition strength B(E2↑) of ^{68}Se from different models have been published. For the sake of comparison, they are also indicated in Fig. 4. All considered models predict ^{68}Se to be oblate in its gs. Our calculation shows a smoother increase of collectivity from ^{68}Se to ^{72}Kr than found experimentally. This onset of collectivity can be understood from the wave function of the first 2^+ state in these nuclei shown in Fig. 5: our calculations show a moderately prolate-deformed ^{60}Zn and a clear γ unstability ^{64}Ge, in agreement with experiment [4]. This γ unstability largely remains in ^{68}Se with a probability density for the 2_1^+ wave function peaked at β=0.25 and γ=45°. We observe a clear change in ^{72}Kr for which the wave function is peaked on an axial symmetric oblate shape. A strong structure modification is observed from ^{72}Kr to ^{76}Sr, predicted to be prolate with a large mean deformation of β=0.4. This increase of collectivity along the N = Z line can be partly understood through the mean-field deformed single-particle shell gaps restricted to axial symmetry, defined by *pf* and *g* orbits, and identical for protons and neutrons, at both prolate and oblate deformations for N = Z = 30-38 (see Fig. 5 of reference [9]). Indeed, whereas prolate and oblate single-particle shell gaps are found at $\beta \sim \pm 0.3$ for N = Z= 30-34, gaps at much larger $\beta \sim \pm 0.5$ are found in ^{72}Kr. At N = Z = 38, the situation is even more extreme with a large prolate gap of 3 MeV at $\beta \sim 0.6$. The collectivity evolution in self-conjugate nuclei around ^{68}Se, in addition to the importance of considering all quadrupole degrees of freedom, is very sensitive to the single-particle $f_{5/2}pg_{9/2}$ shell properties of effective interactions.

We have measured for the first time the transition strength B(E2;$0_1^+ \rightarrow 2_1^+$) in ^{68}Se by intermediate-energy Coulomb excitation. The obtained value of 2158(290) e^2fm^4 is close to that of ^{64}Ge and significantly lower than in ^{72}Kr. We have studied the collectivity in self-conjugate nuclei from ^{60}Zn to ^{76}Sr through a parameter-free beyond-mean-field approach using the Gogny D1S interaction within a GCM+GOA formalism including all quadrupole degrees of freedom. Calculations, in agreement with existing data, show that these nuclei exhibit a large variety of ground-state shapes from prolate in ^{60}Zn, triaxial in ^{64}Ge, oblate in ^{72}Kr and prolate in ^{76}Sr. ^{68}Se appears to be a transition nucleus between the γ-soft ^{64}Ge and the oblate ^{72}Kr, with a triaxial behavior and a tendency towards oblate deformation in its ground state.

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