

Shell evolution and $E2$ collectivity: new spectroscopic information

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Abstract. We report here on the first evidence for shape coexistence caused by Type II Shell Evolution which is firmly based on the measurement of absolute $E2$ transition rates. The data have been obtained in high-resolution inelastic electron scattering spectroscopy of the nucleus ^{96}Zr at the Superconducting Darmstadt Linear electron Accelerator (S-DALINAC). The data are presented and discussed. The neutron sub-shell closure at neutron number $N = 56$ plays a crucial role for the occurrence of shape coexistence in $^{96,98}\text{Zr}$. We have studied the structure of exotic neutron-rich isotopes near the $N = 56$ neutron sub-shell closure using γ -ray spectroscopy and radioactive beams. We also present and discuss spectroscopic data on $^{84,86,88}\text{Ge}$ taken recently at RIBF, RIKEN. The new data suggest the hitherto unknown existence of a region of pronounced nuclear triaxiality in neutron-rich Ge isotopes.

1. Introduction

The way how the complex nuclear forces form atomic nuclei from their constituent protons and neutrons represents the core topic of nuclear structure research. The evolution of nuclear structure across the nuclear chart is dominated by the evolution of effective single-particle energies as a function of the numbers of protons and neutrons that make up the nuclei. Shell evolution has been realized as the reason for the disappearance of shell closures at magic numbers known from nuclei near the valley of stability and for the occurrence of new ones for exotic nuclides, in particular those with large neutron excess. The understanding of shell evolution has been pushed especially by the Tokyo group around T. Otsuka [1]. It is supported by vast experimental evidence in particular from the structure of neutron-rich nuclei that have become accessible due to new facilities for intense beams of radioactive ions.

Recently, the concept of *Type II Shell Evolution* has been introduced [2, 3]. It emphasizes, that the effective single-particle energies of nucleon orbitals systematically depend on the nucleonic configuration in each individual nuclear state due to the mutual interaction between the nucleons. This general mechanism can be particularly pronounced in key-nuclei with certain numbers of protons and neutrons, for which Type II Shell Evolution may lead to drastic nuclear structure effects such as even shape coexistence and first-order shape phase transitions.

The most rapid change of the shape of nuclear ground states in the nuclear chart occurs for the chain of Zirconium isotopes. While ^{96}Zr exhibits features of a doubly-closed shell nucleus, ^{100}Zr is already strongly deformed. In particular, the first excited state of the even-even nucleus ^{96}Zr is a $J^\pi = 0^+$ state instead of a 2^+ state. The 2_1^+ state has a high excitation energy of



1750 keV and the $B(E2; 2_1^+ \rightarrow 0_1^+) = 2.3(3)$ W.u. is non-collective. In contrast, in ^{100}Zr the 2_1^+ state lies at 213 keV and decays collectively to the ground state with an $E2$ strength of $B(E2; 2_1^+ \rightarrow 0_1^+) = 75(4)$ W.u. The corresponding shape phase transition has recently been shown to be due to shell evolution [4].

Therefore, the Zirconium isotopes provide a unique opportunity for investigating the mechanisms that dominate the formation of nuclear structure. In particular, the following general questions are intriguing: Is the shape-phase transition in the Zirconium isotopic chain of first or second order as a function of neutron number? If it is of first order, can we observe a region of shape coexistence in spherical Zirconium isotopes corresponding to the region between the spinodal point and the critical point of the quantum phase transition? Are the conditions for the occurrence of the quantum phase transition in Zirconium isotopes specific to this isotopic chain or can we observe traces of them in other nuclei in this mass region? We have performed nuclear spectroscopy experiments for contributing crucial data to answer these questions. In particular, we have studied inelastic electron scattering on ^{96}Zr and γ -ray spectroscopy on neutron-rich nuclides in the $A \approx 80 - 100$ mass region.

2. Electron-scattering experiment on ^{96}Zr

Inelastic electron scattering on the nuclide ^{96}Zr have been studied [5] at the Superconducting DArmstadt LINear electron ACcelerator (S-DALINAC) at TU Darmstadt using the Lintott high-resolution magnetic spectrometer. The electron-beam energies and observation angles have been set such that momentum transfers from 0.08 to 0.35 fm^{-1} were realized. Fig. 1 shows the relevant part of the level scheme of ^{96}Zr and corresponding electromagnetic transition strengths. The $E2$ strength in the deformed structure has been measured here for the first time.

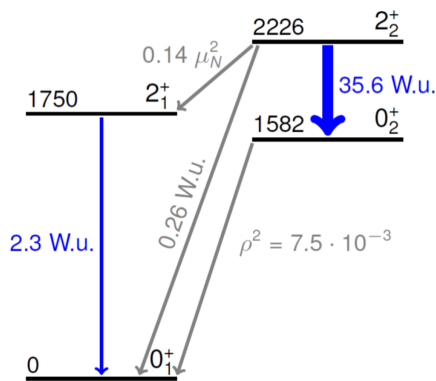


Figure 1. Partial level scheme of ^{96}Zr . The electromagnetic decay rates of the 2_2^+ state were measured [5] in this work. The $E2$ transition strength between the excited 2_2^+ and 0_2^+ states is an order of magnitude larger than the one from the 2_1^+ state to the ground state and two orders of magnitude larger than the one from the 2_2^+ state to the ground state.

A typical part of the data is shown in Fig. 2. In particular, the 2_2^+ state of ^{96}Zr at an excitation energy of 2.226 MeV has been observed. Its electromagnetic excitation strength from the ground state has been measured relative to the excitation of the 2_1^+ state with a known excitation strength of $B(E2; 0_1^+ \rightarrow 2_1^+) = 0.030(4) e^2 b^2$ [6] with the method described in Refs. [7, 8]. Together with the pre-existing information on the γ -decay intensities this measurement provides first information on the $E2$ strength within the deformed sequence of states built on top of the first excited 0^+ state of ^{96}Zr . Moreover, the $E2$ decay strength from the 2_2^+ state to the ground state is small. It amounts to less than 1% of the intra-band transition strength in the deformed structure and indicates very weak mixing between the spherical ground state and the coexisting deformed first-excited state and hence a high potential barrier between spherical and deformed configurations at low energies.

The coexistence of spherical and deformed structures of ^{96}Zr at low excitation energies can be attributed to the mechanism of type II shell evolution [4]. The ground state exhibits a

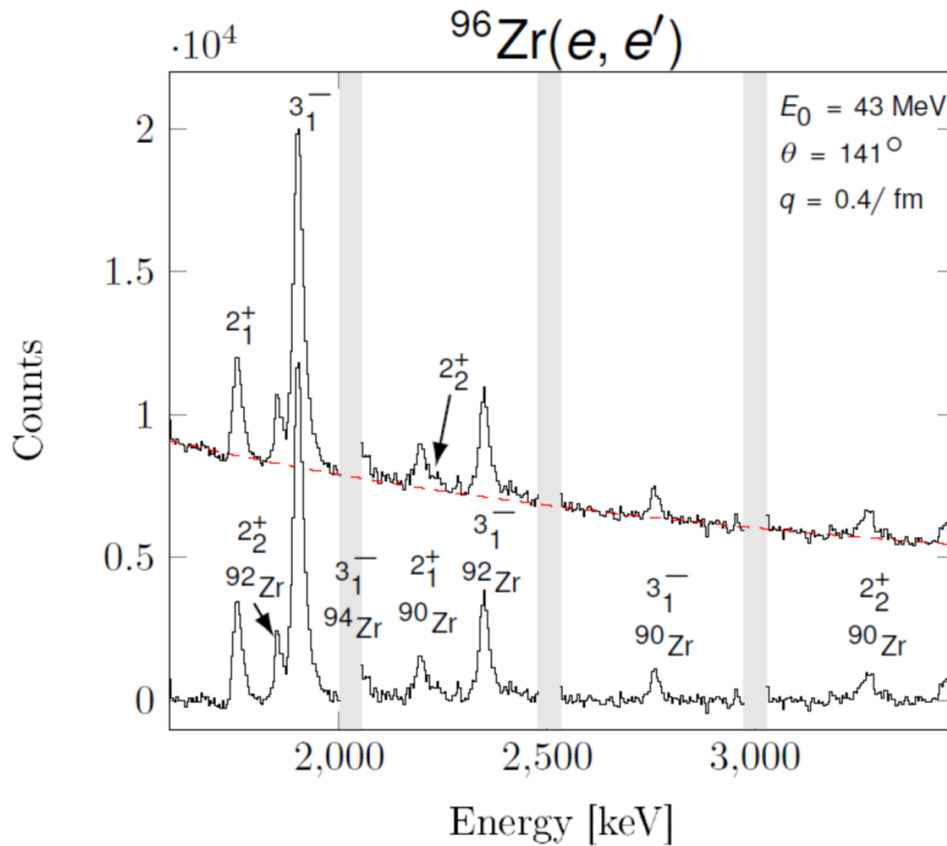


Figure 2. Summed and efficiency corrected energy-loss spectrum of the $^{96}\text{Zr}(e, e')$ electron-scattering reaction with a beam energy of 43 MeV on a sample of Zirconium metal enriched in the isotope ^{96}Zr to 57% observed at a polar angle of $\vartheta = 141^\circ$. The radiative tail of the elastic line has been subtracted in the spectrum at the bottom. Gray areas correspond to inactive segments of the detector system. At 2.226 MeV a signal from the 2_2^+ state of ^{96}Zr is observed. See [5].

doubly closed-shell configuration with almost full occupancies of the proton $\pi(fp)$ -shell and the neutron $\nu(d_{5/2})$ orbital and pronounced shell gaps for $Z=40$ and $N=56$. In contrast to that, the occupancy of the $\nu(d_{5/2})$ orbital is considerably reduced in the excited deformed structure. This leads to a modification of the effective proton single-particle energies due to the effects of the tensor force of the nucleon-nucleon interaction such that the $Z=40$ shell gap is significantly reduced and the $\pi(g_{9/2})$ proton orbital is occupied by about 4 protons. This, in turn, modifies the effective neutron single-particle energies due to the tensor force such that the $\nu(g_{7/2}, d_{3/2}, h_{11/2})$ orbitals are lowered in energy, the $\nu(d_{5/2})$ orbital is lifted, and the shell gap for $N=56$ is reduced facilitating the excitation of neutrons from the $\nu(d_{5/2})$ orbital to other orbitals. This is a self-reinforcing mechanism and the nuclear wave functions of the deformed states are spread out over several single-particle orbitals indicative of collectivity and deformation. The coexisting spherical and deformed structures of ^{96}Zr represent the first case of type II shell evolution, the observation of which is firmly based on the measurement of absolute transition rates [5].

3. Coulomb excitation of ^{98}Zr and evolution of $E2$ strength in the Zirconium isotopic chain

Information on the $E2$ excitation strength of the neighboring neutron-rich radioactive isotope ^{98}Zr does not exist to date. We have attempted a Coulomb-excitation experiment with a beam of radioactive ^{98}Zr ions delivered by the CARIBU facility at the ANL. The experiment took advantage of the powerful combination of the position-sensitive GRETINA array [9] consisting at the time of 4 quad modules in combination with the CHICO2 detector [10], to identify the beam-like recoils and fix the kinematics. Unfortunately, the yield of ^{98}Zr ions was too small and the contamination of the beam with $A=98$ isobars was too strong at the time of the experiment for us being able to see an in-beam excitation of ^{98}Zr . However, the superior Doppler correction making use of GRETINA and CHICO2 allowed to separate the expected transition energy of the 2_1^+ state of ^{98}Zr at 1223 keV from a contaminant transition ($3_1^- \rightarrow 2_1^+$) at 1230 keV from the main component of the beam, ^{98}Mo . Analysis of the background count rate at the position of the expected peak for the $2_1^+ \rightarrow 0_1^+$ transition in ^{98}Zr provided an upper limit for its intensity. This converts into an upper limit for the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value with a strength smaller than 16 W.u. The new experimental information is included in Fig. 3 showing the evolution of $E2$ transition rates in heavy Zirconium isotopes and corresponding large-scale shell model calculations as taken from Ref. [4]. In particular, the new data points on $^{96,98}\text{Zr}$ support the interpretation of a smooth evolution of deformed structures in Zirconium isotopes, a region of shape coexistence for $^{94-98}\text{Zr}$ and a first-order ground state shape phase transition between ^{98}Zr and ^{100}Zr .

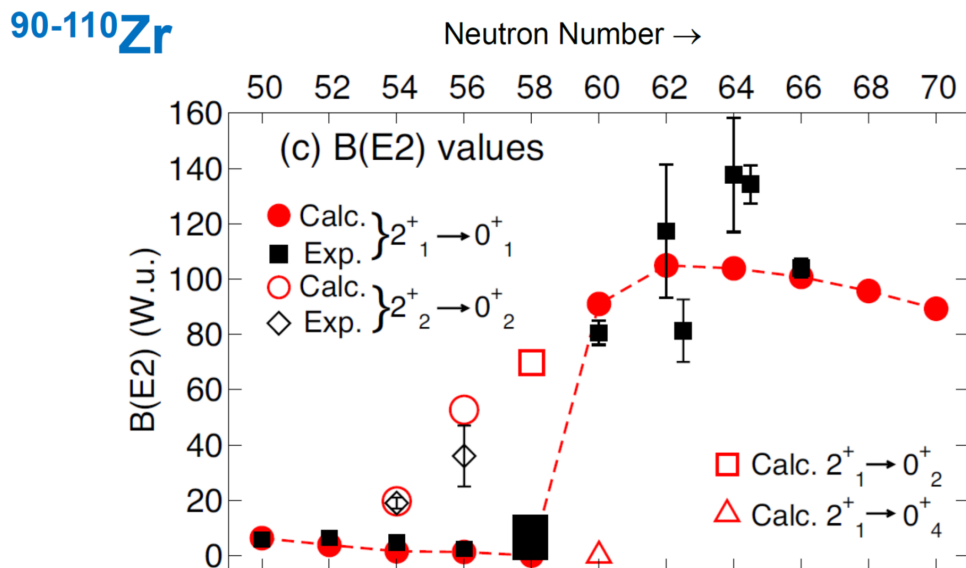


Figure 3. Evolution of $E2$ transition rates in Zirconium isotopes over the shape-phase transition at $^{98,100}\text{Zr}$ as a function of neutron number. See [4, 5]. The new data on $^{96,98}\text{Zr}$ support the conclusion that a coexisting deformed structure in the lighter-mass Zirconium isotopes evolve gradually into the deformed ground-state structure of the heavier mass isotopes.

4. Spectroscopy at the $N = 56$ sub-shell closure at the neutron-rich extremes

The occupancy of the $\nu(d_{5/2})$ neutron orbital has been recognized as the driving ingredient for the type II shell evolution in the Zirconium chain of isotopes. It is interesting to study the structure near $N=56$ for even more neutron-rich isotopes. However, spectroscopic information is scarce. We have recently studied [11] neutron-rich Germanium isotopes in γ -ray spectroscopy

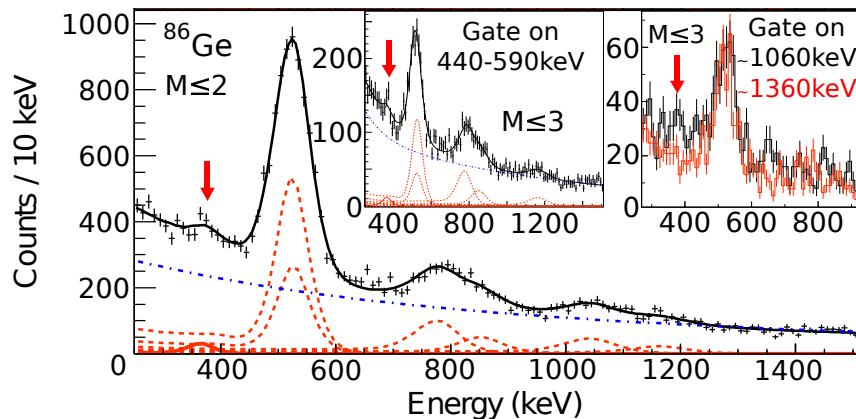


Figure 4. Single and coincidence spectra of ^{86}Ge from the $^{87}\text{As}(p, 2p)$ reaction observed with an array of NaI detectors superimposed with the fit of the whole spectrum (black solid line). The respective background (blue dash-dotted line) and simulated response functions for each transition (red dotted and solid lines) are shown. The insets show spectra after gating on the energy region for the $2_{1,2}^+$ transition and a neighboring region (red). The multiplicity cutoff M is chosen to optimize the peak-to-background ratio and available statistics. The red arrows emphasize the 380-keV tentatively assigned $(3_1^+) \rightarrow (2_2^+)$ transition [11].

experiments at the Radioactive-Ion Beam Facility (RIBF) at RIKEN, Tokyo, Japan. Excited states of $^{84,86,88}\text{Ge}$ were populated by (p, pn) or $(p, 2p)$ reactions of beams of odd-mass Ge or As ions, from in-flight fission of a primary ^{238}U beam, on a liquid-hydrogen target. It was the first time that γ -ray spectroscopy of the exotic isotope ^{88}Ge at neutron number $N=56$ has been successfully performed and first information on γ transitions in ^{88}Ge has been obtained [11].

For ^{86}Ge six new γ transitions were identified [11] and placed in the level scheme together with the only previously known 527-keV $2_1^+ \rightarrow 0_1^+$ transition. Fig. 4 shows a γ -ray spectrum from ^{86}Ge . The data suggest pronounced triaxiality of ^{86}Ge . Namely, a 380-keV transition, observed with better than 95% confidence [11], is in agreement with predictions from shell model and SCCM calculations, and would correspond to a transition from a relatively low-lying 3^+ state to the 2_2^+ state. A corresponding staggering parameter, which is a measure of the triaxial rigidity [12, 13], of $S(4) = 0.20(4)$ can be deduced. As such, data support the model predictions of a triaxial potential minimum about 30° , with a degree of rigidity larger than that in ^{76}Ge with $S(4) = 0.091(2)$ which was recently established [14]. This pronounced triaxial shape together with its comparatively high rigidity makes ^{86}Ge an intriguing test ground for further studies of triaxial nuclear deformation.

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References

- [1] Otsuka T, Suzuki T, Fujimoto R, Grawe H and Akaishi Y 2005 *Phys. Rev. Lett.* **95** 232502
- [2] Tsunoda Y, Otsuka T, Shimizu N, Honma M and Utsuno Y 2014 *Phys. Rev. C* **89** 031301
- [3] Otsuka T and Tsunoda Y 2016 *J. Phys. G* **43** 024009
- [4] Togashi T, Tsunoda Y, Otsuka T and N. Shimizu N 2016 *Phys. Rev. Lett.* **117** 172502
- [5] Kremer K, Aslanidou S, Bassauer S, Hilcker M, Krugmann A, von Neumann-Cosel P, Otsuka T, Pietralla N, Ponomarev V Yu, Shimizu N, Singer M, Steinhilber G, Togashi T, Tsunoda Y, Werner V and Zweidinger M 2016 First measurement of collectivity of coexisting shapes based on type II shell evolution: The case of ^{96}Zr *Phys. Rev. Lett.* **117** 172503
- [6] Kumbartzki G, Benczer-Koller N, Holden J, Jakob G, Mertzimekis T J, Taylor M J, Speidel K-H, Ernst R, Stuchbery A E, Beausang C W and Krücken R 2003 *Phys. Lett. B* **562** 193
- [7] Scheikh Obeid A, Burda O, Chernykh M, Krugmann A, von Neumann-Cosel P, Pietralla N, Poltoratska I, Ponomarev V Yu and Walz C 2013 *Phys. Rev. C* **87** 014337
- [8] Scheikh Obeid A, Aslanidou A, Birkhan J, Krugmann A, von Neumann-Cosel P, Pietralla N, Poltoratska I and Ponomarev V Yu 2014 *Phys. Rev. C* **89** 037301
- [9] Paschalis S, Lee I Y, Macchiavelli A O, Campbell C M, Cromaz M, Gros S, Pavan J, Qian J, Clark R M, Crawford H L, Doering D, Fallon P, Lionberger C, Loew T, Petri M, Stezelberger T, Zimmermann S, Radford D C, Lagergren K, Weisshaar D, Winkler R, Glasmacher T, Anderson J T and Beausang C W 2013 *Nucl. Instr. and Meth. in Phys. Res. A* **709** 44 - 55
- [10] Wu C Y, Cline D, Hayes A, Flight R S, Melchionna A M, Zhou C, Lee I Y, Swan D, Fox R and Anderson J T 2016 *Nucl. Instr. and Meth. in Phys. Res. A* **814** 6 - 11
- [11] Lettmann M, Werner V, Pietralla N, Doornenbal P, Obertelli A, Rodriguez T R, Sieja K *et al.* 2017 Triaxiality of neutron-rich $^{84,86,88}\text{Ge}$ from low-energy nuclear spectra *Phys. Rev. C* **96** 011301(R)
- [12] Zamfir N V and Casten R F 1991 *Phys. Lett. B* **260** 265
- [13] McCutchan E A, Bonatsos D, Zamfir N V and Casten R F 2007 *Phys. Rev. C* **76** 024306(R)
- [14] Toh Y, Chiara C J, McCutchan E A, Walters W B, Janssens R V F, Carpenter M P, Zhu S, Broda R, Fornal B, Kay B P *et al.* 2013 *Phys. Rev. C* **87** 041304(R)