EPJ Web of Conferences **178**, 02013 (2018) https://doi.org/10.1051/epjconf/201817802013
CGS16

Nuclear shapes: Quest for triaxiality in ^{86}Ge and the shape of ^{98}Zr

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Abstract. The region of neutron-rich nuclei above the $N = 50$ magic neutron shell closure encompasses a rich variety of nuclear structure, especially shape-evolutionary phenomena. This can be attributed to the complexity of sub-shell closures, their appearance and disappearance in the region, such as the $N = 56$ sub shell or $Z = 40$ for protons. Structural effects reach from a shape phase transition in the Zr isotopes, over shape coexistence between spherical, prolate, and oblate shapes, to possibly rigid triaxial deformation. Recent experiments in this region and their main physics viewpoints are summarized.

1 Introduction

The mass $A \approx 100$ region above $N = 50$ is a region of the nuclear chart which is dominated by the occurrence of multiple major and sub-shell closures. That is, in particular, the $N = 50$ magic neutron shell itself, as well as the $Z = 40$ proton and the $N = 56$ and $N = 58$ neutron sub shells. Among the consequences of these sphericity-driving sub shells is a stabilization of spherical shapes in the ground states of the respective nuclei, and a fast transition toward deformation in the Zr isotopic chain as the sub-shell closures disappear due to changes in the ordering of effective single-particle energies and the early filling of higher-lying orbitals. It is, however, still an open question at what mass number in the Zr isotopic chain the phase transition from a spherical to a deformed ground-state structure occurs. It is known that spherical and deformed structures coexist at low energies in ^{94}Zr [1] and ^{96}Zr [2, 3], but it is not certain at which mass number those structures actually cross toward the ground-state deformed Zr isotopes above $A = 98$. We report on the first measurement of a stringent upper limit for the B(E2;$2^+_1 \to 0^+_1$) value of ^{98}Zr, which aids in the assignment of weak collectivity in its ground state.

Furthermore, the coexistence of prolate and oblate deformations has recently been suggested for Se isotopes in the mass $A \approx 90$ region [4]. These structures should cross each other, so a transition of the ground-state deformation from prolate to oblate shape would be

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expected. We performed isomer spectroscopy on ^{92,94}Se, which shows a significantly different decay behavior of the respective isomers, which may be a signature for this shape transition. Only two protons below the Se isotopes, namely, in ^{86}Ge, we identify ^{86}Ge as a candidate for displaying rigid ground-state triaxiality [5], a rare phenomenon which has, so far in medium-heavy nuclei, only been observed in its lighter isotope, ^{76}Ge [6].

2 Triaxial ^{86}Ge?

The occurrence of stable triaxiality in nuclei has attracted much attention in nuclear structure research, in terms of triaxial superdeformed bands and their wobbling modes (see, e.g., Ref [7]) or chirality (e.g., Ref. [8]). However, realizations of stabilized triaxiality in the ground state are rare and have heavily been discussed, and the only example in medium-heavy nuclei has recently been identified in ^{76}Ge [6] through the characteristic staggering in the γ band. Namely, in γ-soft nuclei, the 3^+_γ member of the odd-spin γ band is typically located closer to the 4^+_γ than to the 2^+_γ state [9]. In case of rigid triaxiality, the opposite is the case, in addition to the location of the γ band at rather low energies (around or below the 4^+_1 state), which is common for both, rigid and soft triaxial cases.

A recent experimental campaign at RIKEN-RIBF, aimed to locate first excited 2^+ states over a broad range of neutron-rich isotopes (SEASTAR) [10], in many cases quite complicated level schemes have been observed (see, e.g., [4, 11–14]), sometimes allowing to place the lowest members of the γ band. In ^{86}Ge, which was populated from a proton-knockout reaction on ^{87}As in the MINOS active LH_2 target [15], the observation of a low-energy γ-ray at 380 keV in the DALI2 array [16] allowed for the tentative placement of a (3^+_1) state at 1426(16)-keV excitation energy [5], closer to the 2^+_2 state at 1046(14) keV than to the 4^+_2 state at 1911(23) keV (compare Fig. 2 in [5]), in agreement with results from the shell model and from symmetry-conserving configuration mixing Gogny calculations.

3 Prolate-oblate shape transition in ^{92,94}Se

Calculations and recent RIKEN-RIBF data for neutron-rich Se isotopes [4] indicate the possibility for prolate-oblate shape coexistence and a transition from a prolate to an oblate ground-state minimum of the energy potential between ^{90}Se and ^{94}Se. Concurrently with the in-beam SEASTAR experiments we performed isomer spectroscopy using the EURICA array [17]. Isotopes were delivered through the BigRIPS and ZeroDegree separators to the location of EURICA, and energy and time information of delayed γ-ray transitions were recorded. In both, ^{92}Se and ^{94}Se, delayed transitions from an isomer with lifetime in the micro-second range have been observed. From considerations within the Nilsson scheme, an oblate configuration is most likely for those isomers, which would be in line with the observed lifetimes.

A fundamental difference between ^{92}Se and ^{94}Se are the decay behaviors of the respective isomeric states. In ^{92}Se the decay takes place exclusively to the γ band, which is likely due to the lower K hindrance for this decay in comparison to a decay into the $K = 0$ ground state band. In ^{94}Se, however, the isomer decays exclusively into the ground-state band. This could be a signature of oblate deformation in the ground-state band of ^{94}Se, since in that case the decay of an oblate isomer should be less hindered due to a larger overlap of the isomer and the ground-state band wave functions.

4 The critical-point isotope ^{98}Zr

Another case of shape coexistence has been observed in the $^{96-100}$Zr isotopes, as mentioned above. In an experiment at the ATLAS/CARIBU [18] facility at Argonne National Laboratory we employed the combination of the GRETINA [19] and the CHICO2 [20] detectors with a ^{98}Zr beam to perform Coulomb excitation of ^{98}Zr on a ^{196}Pt target at a beam energy of 464 MeV. Unfortunately, the rare-isotope beam was dominated by contaminating ^{98}Mo, which resulted in a γ ray at 1230 keV from the de-excitation of the 3_1^- state of ^{98}Mo. A peak from the decay of the 2_1^+ state of ^{98}Zr was not observed, however, an upper limit of its intensity was obtained from the spectrum. In addition, the beam composition was measured at a decay station behind the experimental setup, yielding a rate of 152(64) pps ^{98}Zr in the beam, as well as rates for other components of the beam. With these values, and with the known excitation cross section of the 2_1^+ state of ^{196}Pt, it was possible to extract a stringent upper limit for the B(E2) excitation strength of the 2_1^+ state of ^{98}Zr. Along with an available lower limit [21] of about 1.8 W.u., and our upper limit of less than 20 W.u. for the B(E2;$2_1^+ \rightarrow 0_1^+$) value of ^{98}Zr, this isotope is not yet on the well-deformed side of the shape-phase transition towards ^{100}Zr with a B(E2;$2_1^+ \rightarrow 0_1^+$) value of about 75 W.u. Hence, ^{98}Zr is the closest to the spherical-deformed phase transtion in the Zr isotopes.

5 Summary

To conclude, we found evidence for three shape-evolutionary aspects in the $A \approx 100$ mass region above $N = 50$. Namely, these are the occurence of a spherical-deformed shape-phase transition in the Zr isotopes, where we identify ^{98}Zr as the transitional isotope, the coexistence of prolate and oblate shapes in the Se isotopes, where we find evidence that ^{94}Se is oblate in its ground-state band, and a first hint for triaxiality in the ground state of ^{86}Ge from the identification of a 3_1^+ state in the γ band. We acknowledge support from the German BMBF Grants 05P15RDFN1, 05P12RDFN8, and 05P15PKFNA, and ERC Grant MINOS-258567.

References

[1] A. Chakraborty *et al.*, Phys. Rev. Lett. **110**, 022504 (2013)
[2] C. Kremer *et al.*, Phys. Rev. Lett. **117**, 172503 (2016)
[3] T. Togashi *et al.*, Phys. Rev. Lett. **117**, 172502 (2016)
[4] S. Chen *et al.*, Phys. Rev. C **96**, 041302(R) (2017)
[5] M. Lettmann *et al.*, Phys. Rev. C **96**, 011301(R) (2017)
[6] Y. Toh *et al.*, Phys. Rev. C **87**, 041304(R) (2013)
[7] D.J. Hartley *et al.*, Phys. Rev. C **80**, 041304(R) (2009)
[8] T. Koike, K. Starosta, and I. Hamamoto, Phys. Rev. Lett. **93**, 172502 (2004)
[9] N.V. Zamfir and R.F. Casten, Phys. Lett. B **260**, 265 (1991)
[10] C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015)
[11] N. Paul *al.*, Phys. Rev. Lett. **118**, 032501 (2017)
[12] L. Olivier *et al.*, Phys. Rev. Lett. **119**, 192501 (2017)
[13] F. Flavigny *et al.*, Phys. Rev. Lett. **118**, 242501 (2017)
[14] C.M. Shand *et al.*, Phys. Lett. B **773**, 492 (2017)
[15] A. Obertelli *et al.*, Eur. Phys. J. A **50**, 8 (2014)
[16] S. Takeuchi *et al.*, Nucl. Instrum. Methods Phys. Res. A **763**, 596 (2014)
[17] P.-A. Söderström *et al.*, Nucl. Instrum. Methods Phys. Res. B **317**, 642 (2013)
[18] G. Savard *et al.*, Nucl. Instrum. Methods Phys. Res. B **376**, 246 (2016)
[19] S. Paschalis *et al.*, Nucl. Instrum. Methods Phys. Res. A **709**, 44 (2013)
[20] C.-Y. Wu *et al.*, Nucl. Instrum. Methods Phys. Res. A **814**, 6 (2016)
[21] S. Ansari *et al.*, Phys. Rev. C **96**, 054323 (2017)