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Shell Evolution and $E2$ Collectivity: New Spectroscopic Information

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Abstract. New spectroscopic information on electric quadrupole collectivity has recently been obtained. We report on our identification of a coexisting deformed structure in the quasi-doubly closed-shell nucleus ^{96}Zr from our measurement of a corresponding absolute $E2$ intraband transition strength in electron scattering reactions and its small mixing matrix element with the spherical ground state structure. The even-mass zirconium isotopes exhibit a first order quantum shape phase transition between neutron numbers 58 and 60. We have used photon scattering reactions for a first measurement of the $E2$ decay strength of the nuclear 1^+ scissors mode. Evidence for its 2^+ rotational excitation and its extraordinarily large rotational moment of inertia are presented.

1 Introduction

Nuclear collective motion and evolution of nuclear structure with the numbers, Z and N, of constituting nucleons have traditionally been at the core of the discussions at the International Symposia on Capture Gamma-Ray Spectroscopy and Related Topics. While our understanding has progressed considerably over the years, we are still witnessing the unveiling of hitherto unknown phenomena or the identification of new mechanisms that govern the evolution of nuclear structure.

One example is the occurrence of rapidly changing nuclear shapes as a function of nucleon number in a sequence of nuclides in the nuclear chart. While these so-called shape phase transitions have been known for a long time, high-quality data are needed in order to clarify the questions whether a particular shape phase transition exists due to a gradual evolution of one minimum in the nuclear potential energy surface to another, or whether the energies of separate minima exchange their order. The former corresponds to a situation where the nuclear potential energy as a function of deformation parameters evolves through a rather flat potential with large deformation fluctuations in the nuclear wave function at the transitional point [1]. The latter corresponds to a scenario where near the shape phase transitional point nuclear states with distinct deformation coexist at low excitation energies, a phenomenon called shape coexistence [2].

The evolution of nuclear single-particle energies due to the varying interaction between protons and neutrons has been identified [3] as a microscopic cause for the change in shell structure and for the occurrence of nuclear deformation along a sequence of nuclides. Recently, a quantitative mechanism has been formulated which relates the evolution of ground

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state deformation as a function of particle numbers to the structure of excited states in a single nucleus. This, so-called, *Type II Shell Evolution* (T2SE) has been held responsible for the occurrence of shape coexistence [4] in particular quasi-doubly magic nuclei such as ^{68}Ni or ^{96}Zr. The validation of the mechanism of T2SE based for the first time on the absolute measurement of the amount of quadrupole collectivity in both coexisting structures from our recent electron scattering experiment on ^{96}Zr [5] will be discussed. The phenomenon of T2SE is closely related to the proton-neutron interaction in the valence shells.

Another nuclear mode which is intimately linked to the proton-neutron interaction in the nuclear valence shell in an already deformed nucleus is the *Scissors Mode* [6]. While the scissors mode occurs due to nuclear quadrupole deformation, its $E2$ decay strength has still been unknown. We will report on our recent measurement [7] of the absolute $E2$ transition rate of the scissors mode into the ground state band using photon scattering reactions.

2 Shape coexistence in ^{96}Zr inferred from electron scattering

We report here on the first evidence for shape coexistence caused by T2SE which is firmly based on the measurement of absolute $E2$ transition rates. The data [5] have been obtained in high-resolution inelastic electron scattering spectroscopy of the nucleus ^{96}Zr at the Superconducting Darmstadt Linear electron Accelerator (S-DALINAC).

Figure 1 shows a spectrum of electrons scattered off a self-supporting metal target enriched to 57.4% in the isotope ^{96}Zr which otherwise has a natural abundance of only 2.8%. The target also contained other isotopes of zirconium including 9.2% of the isotope ^{90}Zr. The spectrum around 2.2 MeV contains a signal from the 2^+_2 state of ^{96}Zr at an excitation energy of 2226 keV and a signal from the 2^+_1 state of ^{90}Zr at 2186 keV with a known excitation strength of $B(E2; 0^+_1 \rightarrow 2^+_1) = 660\ e^2\text{fm}^4$. Data were taken at quadratic momentum transfers $q^2 \in [0.09, 0.35]$ fm^{-2}. An analysis of the peak areas for the excitation of the 2^+_2 state of ^{96}Zr was done relative to the peak areas of other 2^+ excitations with previously known $E2$ excitation strengths, such as the 2^+_1 states of ^{90}Zr and ^{96}Zr.

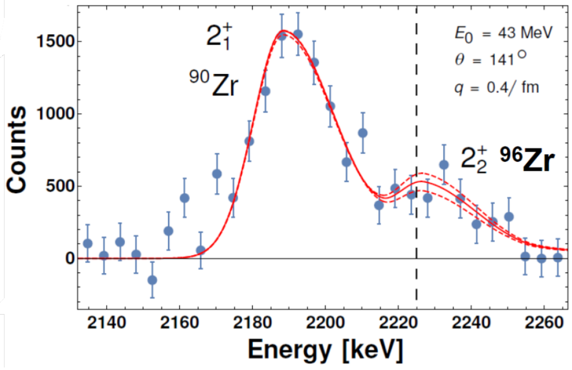

Figure 1. Region of interest of an energy-loss spectrum of electrons scattered off a metal zirconium target at the S-DALINAC. The incident electron energy amounts to 43 MeV. The polar scattering angle of the electrons is 141°. The scattering reaction yields a momentum transfer of 0.4 fm^{-1}. Spectra were taken with a total energy resolution of about 25 keV. Adapted from Ref. [5].

This resulted in the assignment of the $E2$ transition strength from the 2^+_2 state of ^{96}Zr to its ground state with a value of $B(E2; 2^+_2 \rightarrow 0^+_1) = 7(2)\ e^2\text{fm}^4 = 0.26^{+9}_{-7}$ W.u. [5]. This $E2$ strength is an order of magnitude smaller than the already small value of 2.3 W.u. for the $2^+_1 \rightarrow 0^+_1$ transition [8], and it is 140 times smaller than the $E2$ decay strength of the 2^+_2 state to the first excited 0^+_2 state. The latter has a collective character with a transition strength of $B(E2; 2^+_2 \rightarrow 0^+_2) = 36$ W.u. as can be inferred from the excitation cross section measured here in combination with previously known γ-decay branching ratios in ^{96}Zr [8]. The absolute transition rates clearly indicate the 0_1^+ and 2_1^+ states of ^{96}Zr belonging to a non-collective spherical structure and the 0_2^+ and 2_2^+ states forming a deformed rotational sequence of levels. The tiny $E2$ rate between them indicates very small mixing of these structures coexisting at low excitation energies in the level scheme of ^{96}Zr with considerably different shapes.

3 Type II Shell Evolution in ^{96}Zr

Large-scale shell model calculations performed by the Tokyo group [9] are able to reproduce the experimental findings very well. The occurrence of coexisting weakly collective and deformed states is understood in terms of T2SE. The ground state of ^{96}Zr reflects the quasi-doubly magic character at proton number $Z = 40$ and neutron number $N = 56$ with considerable energy gaps between the occupied pf-shell and the $1g_{9/2}$ intruder orbital for protons and between the occupied $n(2d_{5/2})$ orbital for neutrons and the upper part of the 50-82 neutron major shell. The 2_1^+ state's wave function is dominated by a $n(2d_{5/2} \rightarrow 3s_{1/2})$ single neutron excitation.

The wave functions of the deformed 0_2^+ and 2_2^+ states are characterized by a considerable population of the $p(1g_{9/2})$ proton orbital. This results in a vanishing of the $N = 56$ sub-shell gap because of the increased binding of the $n(2d_{3/2}, 1g_{7/2})$ neutron orbitals with $j = l - 1/2$ due to the monopole part of the nucleon-nucleon tensor interaction as well as of the $n(1h_{11/2})$ high-l orbital. Consequently, more neutrons are occupying the $j = l - 1/2$ neutron orbitals that induce an increased binding of the $p(1g_{9/2})$ $j = l + 1/2$ proton orbital and hence a reduction of the $Z = 40$ sub-shell gap for protons in turn facilitating its occupation. This mechanism is self-reinforcing and, thus, robustly results in a nuclear wave function which differs significantly from that of the closed-shell ground state. It is characterized by a more even spread of neutrons and protons over the $Z = 28 - 50$ proton orbitals and the $N = 50 - 82$ neutron orbitals indicative of nuclear deformation. The nucleus ^{96}Zr features quantum states that either do populate significantly the $p(1g_{9/2})$ proton orbital and are deformed or that do not and are spherical [5].

The barrier between these configurations is high and prevents significant mixing between them. A simple two-structure mixing scheme provides a quantitative estimate for the rather small mixing matrix element, $V_{\text{mix}} = 76$ keV, between the spherical and deformed configurations [5]. They form the 0_1^+ ground state and the first excited 0_2^+ state, respectively, with a mixture between them of less then 1%. This can be concluded quantitatively from the fact that the inter-structural $B(E2; 2_2^+ \rightarrow 0_1^+)$ value measured in this work is two orders of magnitude smaller than the $B(E2; 2_2^+ \rightarrow 0_2^+)$ value within the collective structure. A small mixing matrix element between configurations with different deformations is indicative of a high barrier between their corresponding minima in the potential energy surfaces. The situation encountered in ^{96}Zr with a spherical ground state, a deformed excited 0_2^+ state at low excitation energy, and a high potential barrier between them, resembles to a considerable extent the situation studied previously by Leviatan in the theoretical context of partial dynamical symmetries [10]. The high barrier between the spherical and deformed structures and their energetic evolution as a function of neutron number provides the main ingredients for the occurrence of a first order quantum shape phase transition in the sequence of zirconium isotopes beyond $N = 56$.

The addition of neutrons beyond $N = 56$ results in an increasing occupation of $j = l - 1/2$ neutron orbitals already in the ground state, and a corresponding reduction of the $Z = 40$ proton shell gap. The deformed configuration decreases in energy and eventually becomes the ground state. This mechanism is responsible for the extraordinarily sharp shape phase transition between the isotopes ^{98}Zr with still spherical ground state and ^{100}Zr with a collective quadrupole deformed ground state. The latter can be concluded from the large $B(E2; 2_1^+ \rightarrow 0_1^+) = 75(4)$ W.u. value known for ^{100}Zr [11]. The spherical character of ^{98}Zr is inferred from the high excitation energy of its 2_1^+ state at 1.2 MeV [12]. Unfortunately, an absolute value for a vibrational small $B(E2; 2_1^+ \rightarrow 0_1^+)$ transition strength for ^{98}Zr is still missing in the literature. To that end we have recently studied Coulomb excitation of a beam of ^{252}Cf-fission fragments of mass 98 from which we can determine a decisive upper limit for the $B(E2; 2_1^+ \rightarrow 0_1^+) < 11$ W.u. for the $E2$ transition strength of ^{98}Zr. The data will be published elsewhere [13]. They indicate the transitional character of ^{98}Zr at neutron number 58 in contrast to its deformed rotational even-even neighbor ^{100}Zr with 60 neutrons.

The prime example for a first order nuclear shape phase transition in the sequence of zirconium nuclei between neutron numbers $N = 58$ and 60 is understood microscopically in terms of the details of the proton-neutron interaction leading to quadrupole deformation. An example of an excitation mode of deformed nuclei based on the proton-neutron degree of freedom is the $J^\pi = 1^+$ nuclear scissors mode. In the last section of this contribution we present our measurement [7] of its $E2$ decay strength.

4 $E2$ strength of the Scissors Mode inferred from photon scattering

While the formation of the nuclear scissors mode originates from the nuclear quadrupole deformation its dominant decay mode is enhanced $M1$ transitions due to its isovector character. In fact, the $E2$ decay strength of the scissors mode of deformed nuclei has been unknown until recently. We have measured now the (small) $E2$ decay strength of the $J^\pi = 1^+$ band head of the scissors mode to the ground state band by γ-ray polarimetry in Nuclear Resonance Fluorescence [7]. Photon beams of the HIγS facility were scattered off a Gd_2O_3 target

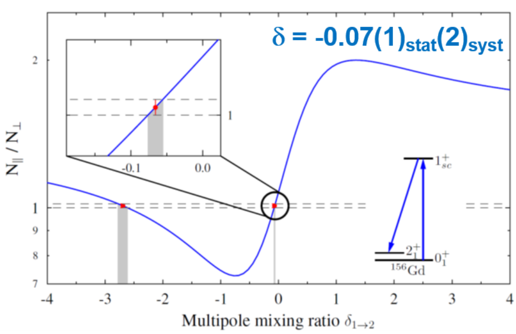

Figure 2. Measurement of the $E2/M1$ mixing ratio δ of the $1^+ \rightarrow 2_1^+$ transition of the main fragment of the scissors mode of ^{156}Gd from azimuthal angular correlations in photon scattering reactions at the High Intensity γ-ray Source at the Duke Free Electron Laser Laboratory. Adapted from Ref. [7].

which contained 10 g of Gadolinium with an enrichment of 93.79(3)% in the isotope ^{156}Gd. The azimuthal intensity distribution of the scattered γ radiation about the axis of the incident horizontally polarized γ-ray beam was measured at a polar angle of 135°. The ratio of count rates in the horizontal polarization plane and perpendicular to it was measured such that a finite $E2/M1$ mixing ratio δ, the square of which is equal to the ratio of $E2$ and $M1$ decay intensities, could be determined [7] for the $1_{sc}^+ \rightarrow 2_1^+$ transition. The measured $E2$ intensity corresponds to an electric quadrupole transition strength of $B(E2; 1_{sc}^+ \rightarrow 2_1^+) = 0.037(26)$ W.u. Within the framework of the interacting boson model, the $1_{sc}^+ \rightarrow 2_1^+$ transition corresponds to a transition between a mixed-symmetry state with F-spin quantum number $F = F_{max} - 1$ and the ground state band of proton-neutron symmetric states with F-spin quantum number $F = F_{max} = N/2$ where $N = N_\pi + N_\nu$ is the total number of proton and neutron bosons. This first measurement of an F-vector $E2$ transition rate in deformed nuclei provides direct evidence for the small F-vector quadrupole boson charge in deformed nuclei [7] conjectured already 30 years ago [14].

The data also provide evidence for the rotational excitation of the $K = 1$ scissors mode with spin quantum number $J = 2$. That 2_{sc}^+ state has been identified [7] on the basis of a reduced excitation strength $B(E2; 0^+_1 \rightarrow 2^+_{sc})$ corresponding within uncertainties to the intrinsic $E2$ transition matrix element between the $J^\pi = 1^+$ scissors mode state and the ground state band discussed above. The energy difference $E(2^+_{sc}) - E(1^+_{sc}) = 19(1)$ keV provides first experimental evidence for the rotational moment of inertia of the scissors mode. It turns out to be very large even exceeding the rigid-body value for the ground state band of ^{156}Gd by about 50% if the alternative of an extraordinarily large signature splitting is neglected. Whether the scissors mode band in deformed nuclei is subject to extraordinarily large signature splitting or whether its moment of inertia is extraordinarily large can only be answered by a future observation of the next higher rotational excitation of the scissors mode band, the 3^+_{sc} state. Its observation might be possible in high-resolution electron scattering spectroscopy by direct $M3$ excitation in inelastic (e, e') reactions.

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