Shape coexistence in ^{94}Zr studied via Coulomb excitation

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Abstract. In recent years, a number of both theoretical and experimental investigations have been performed focusing on the zirconium isotopic chain. In particular, state-of-the-art Monte Carlo shell-model calculations predict shape coexistence in these isotopes. In this context, the ^{94}Zr nucleus, which is believed to possess a nearly spherical ground state, is particularly interesting since the purported deformed structure is based on the low-lying 0^+_2 state, making it amenable for detailed study. In order to provide definitive conclusions on the shapes of the low-lying states, two complementary experiments to study ^{94}Zr by means of low-energy Coulomb excitation were performed. This data will allow the quadrupole moments of the $2^+_{1,2}$ levels to be extracted as well as for the deformation parameters of the $0^+_{1,2}$ states to be determined and, thus, definitive conclusions to be drawn on the role of shape coexistence in this nucleus for the first time.

The first experiment was performed at the INFN Legnaro National Laboratory with the GALILEO-SPIDER setup, which, for the first time, was coupled with 6 lanthanum bromide scintillators ($LaBr_3$:Ce) in order to maximize the γ-ray detection efficiency. The second experiment was performed at the Maier-Leibnitz Laboratory (MLL) in Munich and used a Q3D magnetic spectrograph to detect the scattered ^{12}C ions following Coulomb excitation of ^{94}Zr targets.

1 Introduction

The shape of the nucleus is one of its fundamental properties and is governed by the correlations present among the nucleons and evolves with their number. Some of the most dramatic cases of shape evolution in the ground states of nuclei are encountered along the Sr and Zr isotopic chains. ^{90}Zr, with a closed proton sub-shell at $Z = 40$ and a closed neutron shell at $N = 50$, behaves to a large extent like a doubly-magic nucleus. The neutron number $N = 56$ becomes an effective sub-shell closure at $Z = 40$, and ^{96}Zr also exhibits properties of a doubly-magic nucleus. With the addition of only four neutrons, however, the dramatic lowering of the first excited 2^+ state in ^{100}Zr is indicative of a sudden onset of deformation. Sudden shape changes may be interpreted as a result of an inversion of two distinct configurations associated with different nu-

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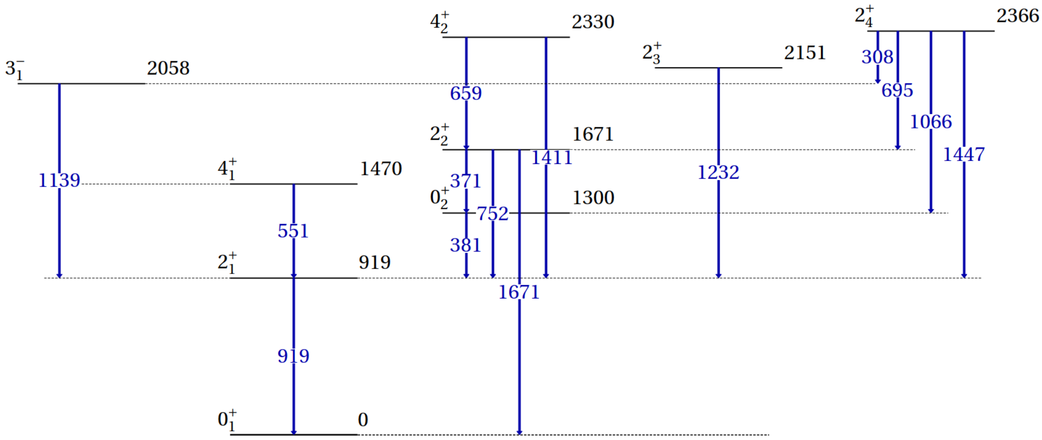

Figure 1. Level scheme for ^{94}Zr displaying the γ-ray transitions observed in the analysis performed to date for the ^{94}Zr+^{208}Pb Coulomb excitation experiment. The energies in keV for each transition are reported.

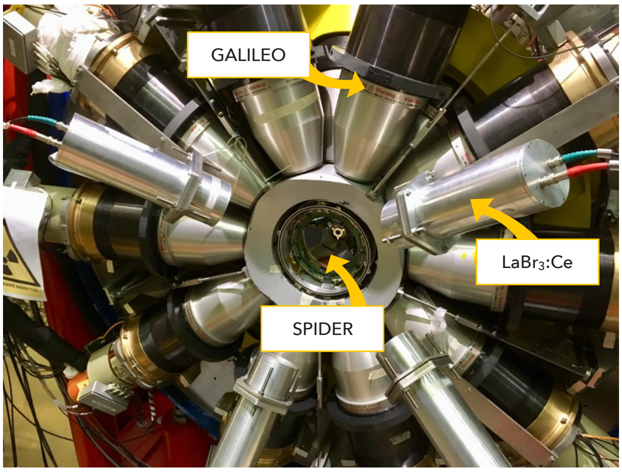

Figure 2. The experimental setup used for the ^{94}Zr Coulomb-excitation experiment at the INFN Legnaro National Laboratory. The GALILEO array, the SPIDER array and 6 Labr$_3$:Ce detectors are shown.

clear shapes, and the implication is that the distinct configurations should be present also in neighboring nuclei, although they may exist at high excitation energy. Thus, we may expect that the deformed configuration that forms the ground state for $N \geq 60$ persists in the lighter Zr isotopes. The first strong evidence for this was obtained for ^{94}Zr [1] where the observation of a $2_3^+ \rightarrow 0_2^+$ γ-ray branch, combined with a 2_3^+ level lifetime, enabled the determination of $B(E2; 2_3^+ \rightarrow 0_2^+) = 19 \pm 2$ W.u. indicative of a deformed collective structure. Recently, the even zirconium isotopes have been studied extensively in the framework of the Monte-Carlo Shell Model (MCSM) [2] that reproduces well the trends of the excitation energies and $B(E2)$ values. These calculations predict a spherical ground state and an oblate deformed structure for the 0_2^+ state for the ^{94}Zr isotope (see Fig. 1 of Ref. [2]).

The goal of the present study is to provide a definitive determination of the shapes involved for the 0_1^+ and 0_2^+ states, and for this purpose we employed Coulomb excitation which is the most direct method to study nuclear collectivity and shapes through the measurement of dynamic and static electromagnetic moments. Coulomb excitation selectively excites low-lying collective states with cross sections that are a direct measure of the electromagnetic matrix elements. When the beam energy is chosen to ensure that the nuclear surfaces are separated by a minimum of 5 fm [3], there is negligible contribution to the reaction process from nuclear forces and the matrix elements can be obtained in a model independent way.

2 Experimental details

A low-energy Coulomb excitation experiment was performed in 2018 at the INFN Legnaro National Laboratory using a 370-MeV beam of ^{94}Zr ions impinging on a 1 mg/cm^2 thick ^{208}Pb target. This beam energy was chosen as a compromise between compliance of the "safe-energy" criterion [3] and the necessity of maximising the population of high-lying states, allowing the excitation up to the 2_4^+ state. The level scheme of the ^{94}Zr states populated in this experiment is reported in Fig. 1. The γ rays emitted in the de-excitation of the excited states were detected by the GALILEO γ-ray array [4] and 6 large-volume $3'' \times 3''$ LaBr$_3$:Ce detectors [5], while the backscattered ^{94}Zr particles were detected with the SPIDER array [6] as shown in Fig. 2). The GALILEO γ-ray spectrometer (photo-peak efficiency ~2.1% and FWHM ~0.2% both at 1332.5 keV) consisted of 25 Compton-suppressed HPGe detectors arranged into 4 rings (at 152°, 129°, 119° and 90° with respect to the beam direction) while the SPIDER array for heavy-ion detection was composed of 7 segmented Si detectors each divided into 8 independent strips assembled in a cone-like shape. In order to enhance the sensitivity to the second-order effects, such as multi-step excitation or reorientation, SPIDER was positioned at backward angles in the GALILEO scattering chamber, covering the polar angular range from 123° to 161° in the laboratory frame. For the first time, LaBr$_3$:Ce detectors were coupled to the GALILEO-SPIDER installation in order to increase the

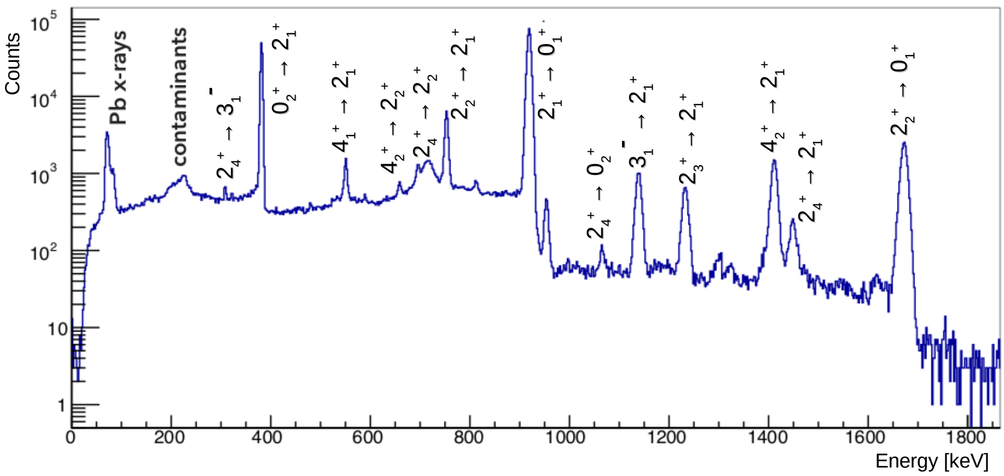

Figure 3. Spectrum of Doppler-corrected γ-ray energies measured by the GALILEO array with events in coincidence with backscattered ^{94}Zr ions detected by SPIDER for the ^{94}Zr+^{208}Pb Coulomb excitation reaction.

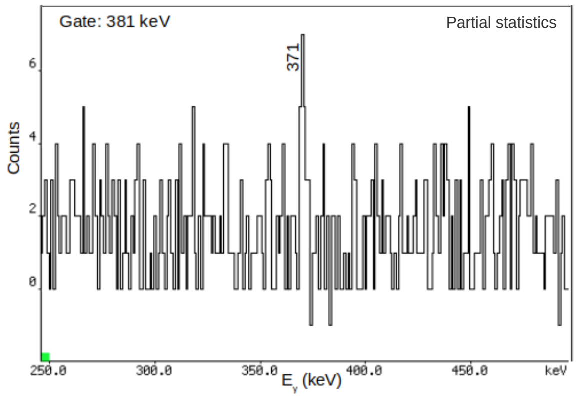

Figure 4. Confirmation for the existence of the de-exciting 371 keV transition, obtained by gating on the $0_2^+ \rightarrow 2_1^+$ transition at 381 keV in $\gamma-\gamma$–particle coincidence matrix.

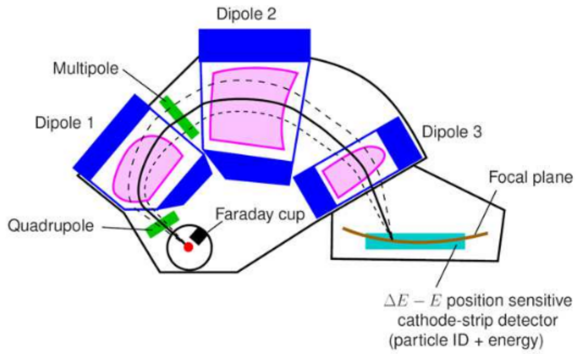

Figure 5. Schematic view of the Q3D spectrometer at the MLL.

efficiency for high-energy γ-ray detection [7]. The coincidence between γ rays and particles allows for the reconstruction of the event kinematics and to perform an event-by-event Doppler correction of detected γ-ray energies. A preliminary Doppler-corrected γ-ray energy spectrum, obtained by selecting the coincidence of events registered in GALILEO and SPIDER, is reported in Fig. 3.

3 On-going analysis

As indicated in Fig. 1, γ rays depopulating the purported shape-coexisting 2_2^+ level are observed. Shown in Fig. 4 is a partial γ-ray spectrum obtained with a coincidence condition set on the 381 keV $0_2^+ \rightarrow 2_1^+$ γ ray. A peak at 371 keV is clearly visible in this spectrum, confirming the result of Ref. [1].

The electromagnetic matrix elements will be extracted from the experimental data using the GOSIA code [8]. This code performs a fitting procedure to the experimental γ-yields (76 in this experiment) with the matrix elements as free parameters. Additional experimental spectroscopic data such as lifetimes, branching ratios and $E2/M1$ multipole mixing ratios, taken from Ref. [9], are also included in the analysis. The transitions needed to obtain the spectroscopic quadrupole moments of the $2_{1,2}^+$ states are clearly observed and, applying the quadrupole sum rules method [10], we will extract the deformation parameters of the ground state and the 0_2^+ state. As shown in Fig. 3, the transitions that involve the 3^- state are also observed. These transitions are necessary to reliably determine the $B(E3; 3_1^- \rightarrow 0_1^+)$ value.

In order to improve the precision of the analysis, we have extended our studies by performing single-step Coulomb-excitation studies at the Maier-Leibnitz Laboratory (MLL) in Munich [11]. Beams of 45 MeV of ^{12}C ions

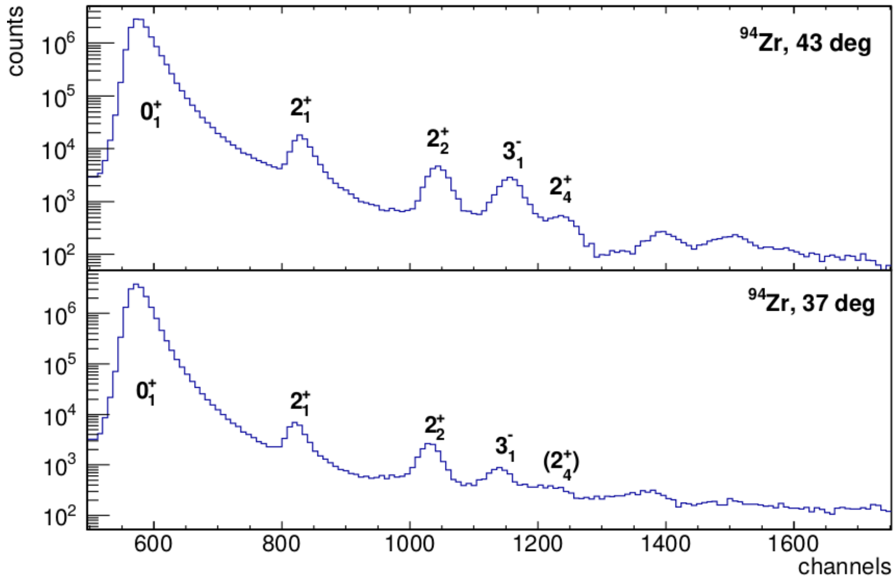

Figure 6. Spectrum of momentum-analysed ^{12}C ions detected at the focal plane of the Q3D spectrograph at angles of 43° (upper part) and 37° (lower part).

up to 100 pnA impinged on a ^{94}Zr target approximately 50 μb/cm^2 thickness. The scattered ^{12}C ions were momentum analysed using a Q3D magnetic spectrograph (a schematic of the apparatus is shown in Fig. 5), at angles of 34°, 37°, 41°, and 43°. Shown in Fig.6 are the ^{12}C spectra observed at angles of 37° and 43°, and clearly show peaks associated with the 2_1^+, 2_2^+, 3_1^-, and 2_4^+ states. Also present in each spectrum is the peak due to the elastically scattered ^{12}C ions. The ratio of the inelastic-to-elastic peak areas yield the excitation probabilities that are directly related to the $B(E\lambda; 0_1^+ \rightarrow I^\pi)$ values that serve as valuable additional constraints for the detailed GOSIA analysis of the γ-ray data, significantly aiding in the extraction of spectroscopic quadrupole moments.

4 Conclusion and further perspectives

We have performed complementary experiments using the Coulomb excitation of ^{94}Zr with ^{12}C and ^{208}Pb using a magnetic spectrograph for the former and a large-scale γ-ray detector array and particle detectors for the latter. From these experiments, we anticipate we can extract precise values for the quadrupole moments of the $2_{1,2}^+$, and through an invariant analysis the deformations parameters for the 0_1^+ and 0_2^+ states that can be directly compared with theoretical calculations.

We aim to extend this investigation to the closed neutron sub-shell nucleus ^{96}Zr. For this isotope, the MCSM calculations predicted spherical shapes for both the ground and 2_1^+ states, coexisting with triaxial shapes for both the 0_2^+ and 2_2^+ states. We have recently proposed a Coulomb-excitation experiment employing a ^{96}Zr target using the GALILEO + SPIDER + LaBr$_3$:Ce experimental setup at the Legnaro National Laboratory, while complementary data from ^{12}C scattering using the Q3D at the MLL have already been obtained.

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