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Investigating the Structure of Deformed, Neutron-Rich, Odd-Odd Nuclei in the $A \approx 100$ Mass Region

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Abstract. The $A \approx 100$ mass region is a cornerstone of contemporary nuclear structure research, defined by a dramatic structural phase transition from spherical to strongly prolate-deformed shapes ($\beta_2 \approx 0.4$) that occurs sharply between neutron numbers $N = 58$ and $N = 60$. Investigating the odd-odd nuclei in this area, specifically the Nb ($Z = 41$) and Tc ($Z = 43$) isotopic chains, is particularly complex due to the demanding requirement of correctly modeling the proton-neutron (p-n) residual interaction and coupling. A historical deficiency of reliable experimental data, coupled with J^π assignments often based purely on theoretical models, has led to inconsistencies in the literature. To address this, we conducted specialized γ-ray and γ-conversion electron coincidence spectroscopy experiments utilizing the LOHENGRIN recoil mass spectrometer at the Institut Laue-Langevin. This technique is designed to determine transition multipolarities via internal conversion coefficients, providing the necessary experimental foundation for unambiguous J^π assignments. Our systematic study, targeting ^{100}Nb, ^{102}Tc, and ^{104}Nb, is aimed at challenging current theoretical understanding of deformation and *p-n* coupling far from stability. Preliminary analysis of ^{104}Tc data from the initial campaign reveals new candidate γ-ray transitions, confirming the need for fundamental revisions to the existing level schemes.

1 Introduction and Physical Motivation

The collective structure of nuclei in the neutron-rich $A \approx 100$ region is profoundly influenced by the filling of orbitals at the Fermi surface. The abrupt onset of deformation at $N = 60$ is often termed a 'Quantum Phase Transition' (QPT) [1]. This effect is largely driven by the strong attractive interaction between the proton $\pi g_{9/2}$ and neutron $\nu g_{7/2}$ orbitals. Large quadrupole-deformation parameters, approaching $\beta_2 \approx 0.4$, are commonly reported [2]. While neighboring Mo isotopes appear to be largely axially symmetric [3, 4], evidence for triaxiality ($\gamma \sim 30°$) has been measured in ^{110}Ru [5].

The incorporation of odd nucleons significantly complicates the nuclear mean field, often leading to shape coexistence and long-lived isomers [6]. For example, the $N = 59$ isotone, ^{98}Y, exhibits coexistence between a deformed 4^- isomer and a spherical 4^- state [7]. Furthermore, low-alignment $K^\pi = 1^+$ bands, sometimes referred to as "pairing-free" rotational bands, exist in odd-odd nuclides like ^{100}Y and ^{102}Nb [8, 9]. Studying these 1^+ bands alongside their 4^- Gallagher-Moszkowski (GM) doublets allows for systematic testing of p-n coupling rules far from stability [10].

The reliability of existing experimental level schemes of odd-odd nuclei in this mass region is a major concern. Past studies often relied on speculative or model-dependent J$^\pi$ assignments that have frequently changed. For example, ^{104}Nb is a prime case where J$^\pi$ assignments are poorly constrained [11–13]. Similarly, the proposed rotational band in ^{100}Nb is inconsistent with non-observation of expected γ-decay links [2, 14]. The low-spin structures of ^{102}Tc are derived from decades-old β-decay data suffering from contamination and highly uncertain J$^\pi$ inferences [15–18]. To resolve these inconsistencies, a systematic study demanding model-independent determination of transition multipolarities via Internal Conversion Coefficients (ICC's) is required.

2 Experimental Methodology and Setup

The robust determination of J^π values hinges on measuring the multipolarities of low-energy transitions, typically requiring high-statistics conversion electron data. Two dedicated campaigns were conducted at the LOHENGRIN recoil mass spectrometer at the Institut Laue-Langevin (ILL), Grenoble. The $A \approx 100$ isotopes were produced

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from neutron-induced fission of a ^{239}Pu target (for the $A = 104$ chain) and a ^{235}U target (for the $A = 100$ and $A = 102$ chains). Fission produces a variety of nuclei with different masses and different ionic charge states, as the products undergo both stripping and electron capture while leaving the target. Electric and magnetic fields can be used to alter the fragment trajectories, enabling selective separation of the nuclei of interest based on their mass-to-charge (A/q) ratio and kinetic-energy-to-charge (E_k/q) ratio. An ionisation chamber in the focal plane of LOHENGRIN provides an independent determination of the fragment energy and thus mass. After separation, the selected fission products are implanted into a Mylar foil, from which their decay properties can be studied using the surrounding detector array.

The first experimental campaign, conducted in 2023, employed ^{239}Pu and ^{235}U targets and focused on populating nuclei in the $A \approx 104$ region, including ^{104}Tc. The second campaign, carried out in 2025, used a ^{235}U target and was specifically designed to investigate the $N = 59$ isotones in the $A = 100$ and $A = 102$ mass chains, i.e. ^{100}Nb and ^{102}Tc.

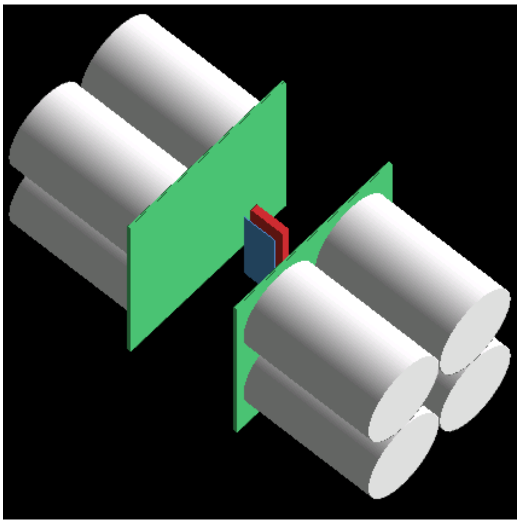

Fig. 1. Geant4 model showing the experimental configuration with two beta-tagged (plastic scintillators in green) HPGe Clover detectors (white) perpendicular to the plane of the Mylar implantation foil (blue). A Si(Li) electron detector with two independently read out segments (red) is placed close to the foil. This configuration was adopted in the 2025 LOHENGRIN run after comparing detector efficiencies for all other possible configurations.

2.1 Detector Configuration and Optimization

The detector array utilized mass-separated fission fragments implanted into a Mylar foil stopper. The configuration for the 2025 run (Fig. 1) was optimized using Geant4 simulations to maximize detection efficiency, especially for conversion electrons. The setup consisted of two Clover HPGe detectors for γ-ray detection and one segmented Si(Li) electron detector (with two galvanically separated segments) placed closely behind the Mylar foil. Plastic scintillators were placed in front of the Clovers, functioning as β-taggers which can be used as coincidence or veto to suppress background in the Si(Li) or Ge spectra respectively and improve spectral purity.

2.2 Analytical Techniques

The data were analysed using the ROOT [19, 20] framework.

The core analytical methodology involves sorting the data into 2-D matrices (γ-γ, γ-electron and electron-electron). Gating on coincident γ-rays enables the identification of decay cascades and the establishment of level schemes. The simultaneous detection of γ-rays and conversion electrons allows for the experimental determination of ICC's. ICC's provide the definitive measure of transition multipolarity via comparison with the expected ICC's for different multipolarities [21], thereby enabling reliable J$^\pi$ assignments. The experiment involved runs at a given mass A but different ionic charge-states q. Comparison of spectra at different q for the same mass allows us to differentiate contaminants in the spectra that have the same A/q ratio as the isotopes of interest. Furthermore, the experiment also included a set of measurements where the incident ion beam was chopped alternately on and off for 30 s each to assign γ-rays based on their grow-in and decay behaviour.

3 Preliminary Work and Discussion

The data presented in this section originate from the two recent experimental campaigns at LOHENGRIN. While the comprehensive analysis of the full dataset is currently underway, the findings presented here are preliminary results derived primarily from initial coincidence sorting.

3.1 Preliminary Analysis of ^{104}Tc

Preliminary analysis of the 2023 LOHENGRIN campaign focused on the odd-odd nuclide ^{104}Tc ($Z = 43$, $N = 61$). By gating on the known 69.7-keV transition of ^{104}Tc [22], spectra confirmed 29 known transitions and revealed 13 new candidate γ-ray transitions (Fig. 2). This suggests that there are gaps in the adopted level scheme of ^{104}Tc.

Resolving the structure of ^{104}Tc is essential for anchoring systematic knowledge in the $A = 104$ chain. The structure of the neighboring nuclide, ^{104}Nb, remains speculative, with its $J^\pi = 1^+$ ground-state assignment being tentative due to reliance on assumptions regarding low-energy-transition multipolarities. The next step in this analysis involves using the γ-electron coincidence data to experimentally determine ICCs and transition multipolarities for both known and new transitions, providing the definitive J^π assignments required to stabilize these level schemes.

3.2 Preliminary γ-Conversion Electron Spectroscopy of ^{102}Mo

To test the γ-ray-conversion electron coincidence analysis methodology, part of the $A = 102$ data from the 2023

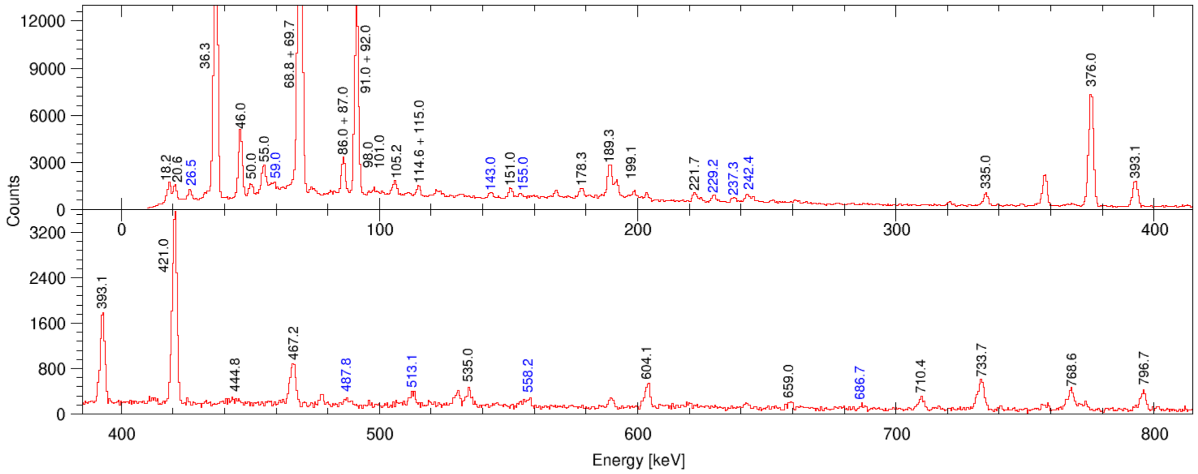

Fig. 2. Gamma-ray coincidence spectrum gated on the 69.7 keV ground-state decay in ^{104}Tc. Identified transitions are labelled by their energy. Transitions shown in black are known [22], new transitions are shown in blue.

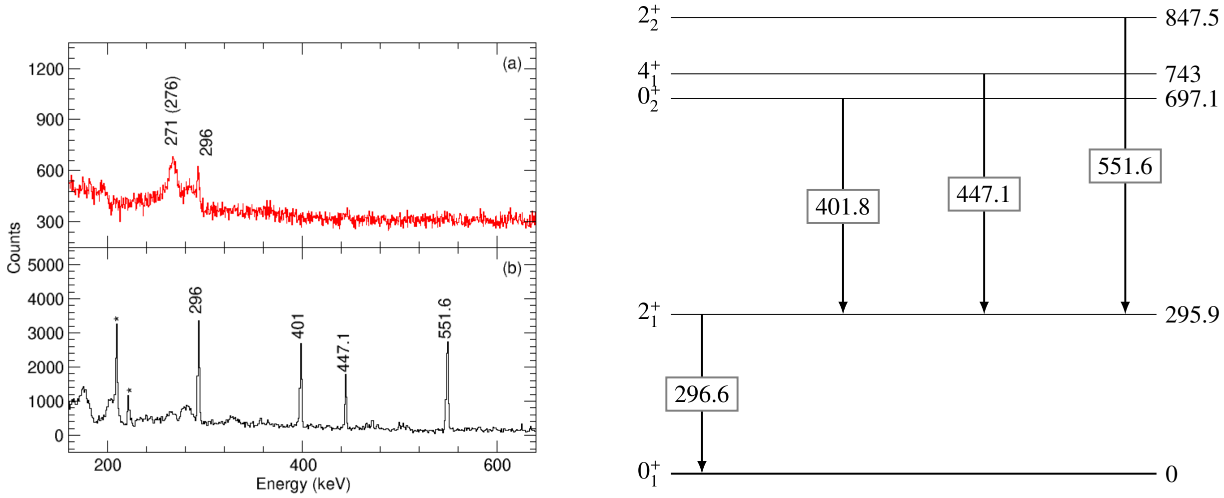

Fig. 3. Panels (a) and (b) show a background-subtracted electron coincidence spectrum gated on the 401 keV γ-ray and a background-subtracted γ-ray coincidence spectrum gated on the 276 keV conversion electron, respectively. Partial level scheme for ^{102}Mo (based on ref. [23]) is shown on the right for reference. Contamination from ^{102}Tc decay is marked with '$*$'.

LOHENGRIN run were sorted into γ-electron matrices and coincidence gates were applied (Fig. 3). The energy of the conversion electron for the 296-keV transition is 276 keV [21]; however, this peak is observed at 271 keV (see Fig. 3 panel (a)) due to energy loss of the electrons in the implantation foil. Additionally, the 296 keV γ-ray is also observed in this spectrum, due to the Si(Li) detector's sensitivity to γ-rays. Gating on the 271-keV conversion electron yields panel (b) of Fig. 3, and the strong, coincident γ-rays in the cascade are identified. These observations show that it is feasible to extract information about the internal conversion transitions using this detector setup and analysis method. After calibration of the detectors for efficiencies, it would be possible to ascertain the ICC's of these transitions.

3.3 Context and Future Analysis for $A = 100$ and $N = 59$ Isotones

The $A = 100$ data collected in the 2025 run has yielded singles spectra showing multiple unidentified lines, confirming the potential for significant expansion of the existing level schemes for specific isotopes like ^{100}Nb (Fig. 4).

The nucleus ^{100}Nb ($Z = 41$, $N = 59$) is an important test case. The existence of a 2.99-s isomer (tentatively assigned $J^\pi \approx 5^+$) and a proposed rotational $K^\pi = 1^+$ ground-state band derived from prompt fission is inconsistent with observed decay patterns (e.g., missing γ-transitions between the isomer and yrast states) [2, 14]. Similarly, the published level scheme for the $N = 59$ isotone ^{102}Tc ($Z = 43$) is severely limited and unreliable, relying on old β-decay studies with inferred J^π values based on assumptions and questionable transfer-reaction data [15–18].

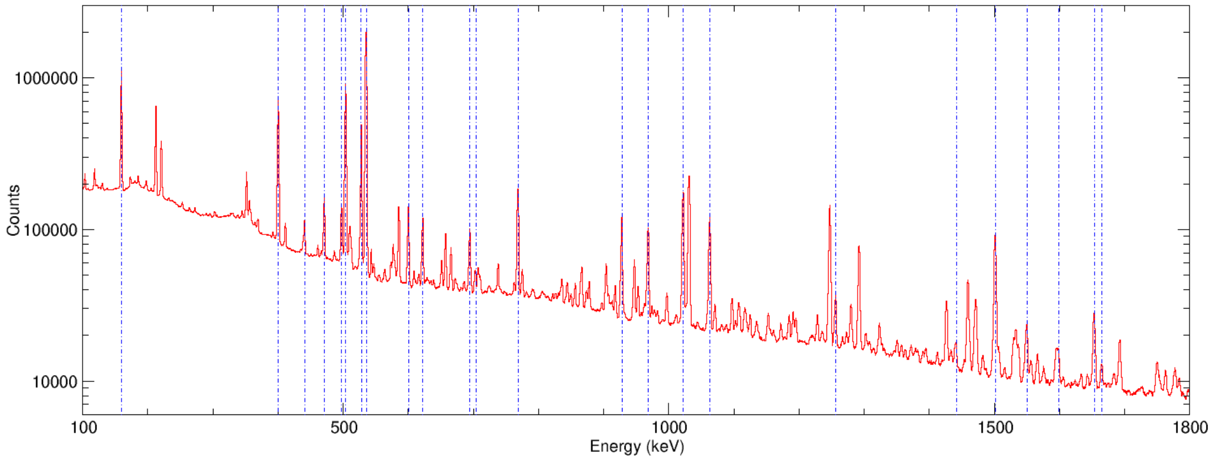

Fig. 4. Representative spectrum with a part of the singles data of $A = 100$ nuclei obtained with LOHENGRIN in 2025. Strong, known transitions from ^{100}Zr and ^{100}Nb (other $A = 100$ nuclei were also compared) are marked with blue lines. The unmarked strong lines are potentially new decays. Contamination (e.g., from other mass isotopes) is also present due to LOHENGRIN mass and charge state settings.

The goal of the ongoing analysis is to overcome these ambiguities through systematic study of the $N = 59$ isotones and neighboring nuclei. High-quality γ-electron coincidence data from the recent LOHENGRIN runs are crucial for extracting the ICC values needed to assign reliable J^π values to low-lying states in ^{100}Nb and ^{102}Tc.

3.4 Theoretical Implications

The determination of accurate J^π values will directly impact the evaluation of complex theoretical phenomena in this region. The large quadrupole deformation is structurally sensitive to the proton and neutron orbitals involved [12]. The structure of Nb isotopes is influenced by intruder orbitals $\pi 1/2^+$, which play an important role in explaining isomeric decay and shape evolution toward nearly axially symmetric shapes in bandheads, contrasting with partially triaxial ground states.

Furthermore, the consistency of these odd-odd nuclei structures with the Gallagher-Moszkowski coupling rules requires empirical verification. The high-precision spectroscopic information derived from this project will provide the essential data needed to benchmark modern nuclear structure models against triaxiality predictions [5] and complex *p*-*n* coupling mechanisms in the highly deformed $A \approx 100$ region.

4 Summary and Outlook

The two experimental campaigns utilizing the LOHENGRIN facility have secured extensive, high-quality data targeting the poorly understood odd-odd nuclei in the highly deformed $A \approx 100$ region. Preliminary analysis of the 2023 dataset revealed new candidate γ-ray transitions in ^{104}Tc, indicating the need to revise the currently adopted level schemes. Likewise, the $A = 100$ singles spectra obtained from the 2025 campaign exhibit multiple previously unidentified decay lines, demonstrating the strong potential for major expansion and refinement of the level schemes for ^{100}Nb and ^{102}Tc.

Looking ahead, the immediate priority is the comprehensive analysis of the full LOHENGRIN datasets. This next stage will focus on detailed γ-ray–electron coincidence analysis to extract reliable internal conversion coefficients (ICCs) and establish the multipolarities of key low-energy transitions. A further objective is the construction of accurate, internally consistent level schemes and the assignment of definitive J^π values across the $A = 100$, $A = 102$, and $A = 104$ isotopic chains. The results will subsequently be prepared for publication and integrated with existing theoretical nuclear-structure models. Collectively, this experimental groundwork will resolve long-standing inconsistencies in the literature and will allow rigorous testing of theoretical predictions concerning deformation and proton–neutron coupling in this structurally critical region of the nuclear chart.

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