

Decay spectroscopy in the neutron-rich Mo–Ru–Pd region

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Abstract. A leading challenge of nuclear-structure research is to understand the properties of nuclides of extreme isospin. Experiments at radioactive-ion-beam facilities, such as the Facility for Rare Isotope Beams in the US, may answer key questions that address diverse topics including fundamental nuclear physics, stellar nucleosynthesis and nuclear applications. The neutron-rich Mo–Ru–Pd ($Z = 42 - 46$) nuclides are hypothesised to exhibit triaxial-oblate deformation. We performed an experiment with the Facility for Rare Isotope Beams Decay Station initiator (FDSi) to study the structure and decay properties of nuclides in this region. Over 100 different nuclides have been identified in a preliminary analysis of the data. This work presents a first look at several examples between Rb ($Z = 37$) and Ag ($Z = 47$). Performance of the FDSi and methods developed to measure ground-state and excited-state lifetimes are presented, and plans for future work are also discussed.

1 Introduction

The neutron-rich region from zirconium to palladium has offered profound insights into the evolution of nuclear shapes with changing proton and/or neutron number [1–7]. While the dramatic shape phase transition between $N = 58$ and $N = 60$ has been known for many years [8], the radioactive and refractory nature of these elements has severely hindered experimental access to key nuclides of interest. With the advent of radioactive-ion-beam facilities such as the Facility for Rare Isotope Beams (FRIB), decay spectroscopy with high-quality beams in this region is now possible with isotopes approaching the neutron drip line. This opens up the possibility of performing a thorough investigation of key properties — including ground-

state shapes, half-lives, and excited-state lifetimes — for the first time in many cases.

There remains a significant lack of experimental data on oblate-triaxial nuclear shapes and their associated inertial dynamics. This gap presents a challenge in fully understanding the evolution of nuclear deformation, particularly in regions where axial asymmetry is expected to emerge. Among the most promising areas for observing such phenomena are the Os–Pt and neutron-rich Mo–Ru–Pd regions. In a comprehensive study, Wu *et al.* [9] investigated $^{186,188,190,192}\text{Os}$ and ^{194}Pt , identifying evidence consistent with a transition from prolate to oblate ground-state deformation. These findings support the interpretation of a shape transition occurring near neutron number $N \approx 116$, with ^{192}Os and ^{194}Pt lying at or just beyond the transition point. The neutron-rich Mo–Ru–Pd region also exhibits evidence of triaxial shapes [4–6]. Occupa-

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tion of the neutron $\nu h_{11/2}$ and proton $\pi g_{9/2}$ intruder orbitals is thought to strongly influence the ground-state shapes in these nuclei [10]. The presence of low-energy 2_2^+ states is consistent with triaxial deformation and has been interpreted as such in both experimental and theoretical studies.

Ground-state properties of very exotic Mo–Ru–Pd isotopes are expected to influence the rapid-neutron-capture process (r -process) in stellar nucleosynthesis [11]. The r -process is highly sensitive to β -decay half-lives, β -delayed neutron-emission probabilities, and ground-state and isomeric nuclear masses [12]; all of which are input parameters for r -process sensitivity models. As the onset of triaxiality has been predicted to significantly decrease ground-state masses [13], understanding nuclear shapes approaching the $N = 82$ shell closure is necessary to accurately describe r -process pathways.

The present work describes an experiment performed at FRIB in which over 100 rare isotopes, including very-neutron-rich isotopes of Mo, Ru and Pd, were delivered to the FRIB Decay Station initiator (FDSi) [14, 15]. To demonstrate the scope and quality of the data collected, preliminary β -delayed γ -ray spectra for ^{102}Zr and ^{103}Zr are presented here. Ground-state half-life determinations and a preliminary first 2^+ lifetime measurement for ^{110}Mo are also discussed. New ground-state shape determinations, new excited-state lifetimes, and improved β -decay lifetimes are all expected outcomes of future works. As our analysis continues, we expect discrete β -decay spectroscopy to give new insights into nuclear shapes and inertial dynamics in the $A > 100$ neutron-rich Mo–Ru–Pd region.

2 FRIB and the FDSi

FRIB is a next-generation radioactive-beam facility hosted at Michigan State University, USA. Having opened in 2022, FRIB research has already begun to shape our understanding of exotic nuclear structure [15–25]. At full power, it is expected to produce beams of approximately 80% of the isotopes predicted to exist for $Z < 93$ [26]. The linac accelerator is capable of delivering primary beams that range from ^{16}O to ^{238}U [27]. Secondary beams of rare isotopes are produced by the fragmentation of the primary beam on a primary target, and are separated and identified by the Advanced Rare Isotope Separator (ARIS) [28].

Secondary beams can be delivered to the FRIB Decay Station initiator (FDSi): an assembly of high-sensitivity detectors, specifically designed for decay spectroscopy with low-intensity, rare-isotope beams. The experimental arrangement is centred around a YSO (yttrium orthosilicate, Y_2SiO_5) scintillator implantation detector [29]. To the left of the implant detector, relative to the beam axis, is the DEcay Germaninum Array initiator (DEGAi) [26]; a hemisphere of tapered large-volume HPGe clover and fast-timing LaBr_3 detectors. Opposite to this hemisphere are the 88 neutron time-of-flight detectors, collectively referred to as the Neutron (Xn) Tracking array initiator (NEXTi/VANDLE) [26, 30, 31]. A timing scintillator and Si PIN detector were placed within ARIS at Detector Box

3 (DB3), and a second timing scintillator was placed further downstream within the FDSi in the diagnostic cross in front of the implantation detector. A photograph of the FDSi is shown in Fig. 1, where the beam axis has been drawn for reference.

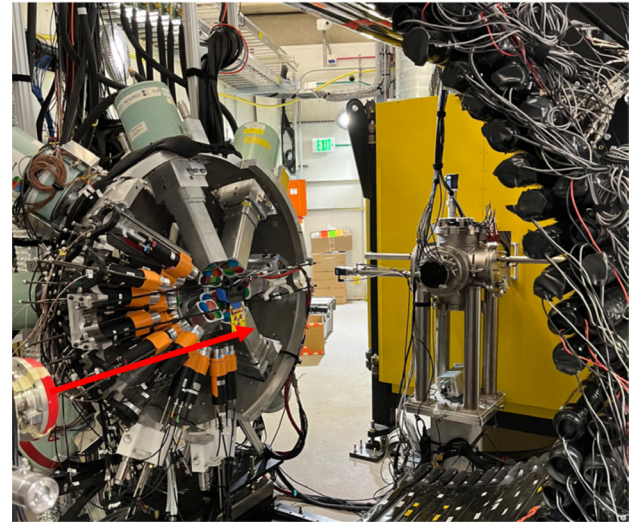


Figure 1. A photograph of the FDSi with an arrow indicating the beam axis. DEGAi is to the left of the beam axis, and NEXTi/VANDLE to the right. The YSO scintillator implantation detector is positioned within the small black box at the centre of DEGAi.

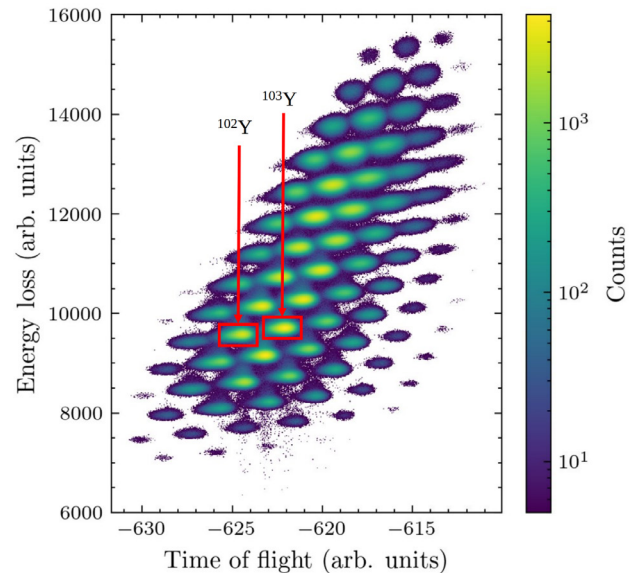


Figure 2. Particle identification (PID) plot of nuclides implanted during the experiment. Differences in energy loss of each nuclide provides separation in Z ; an uncalibrated time-of-flight measurement is sufficient to distinguish the isotopes. The ^{102}Y and ^{103}Y implant groups have been labelled.

3 Experiment

A 20-kW primary beam of ^{238}U was accelerated to 177 MeV/u, the highest power uranium beam so far achieved

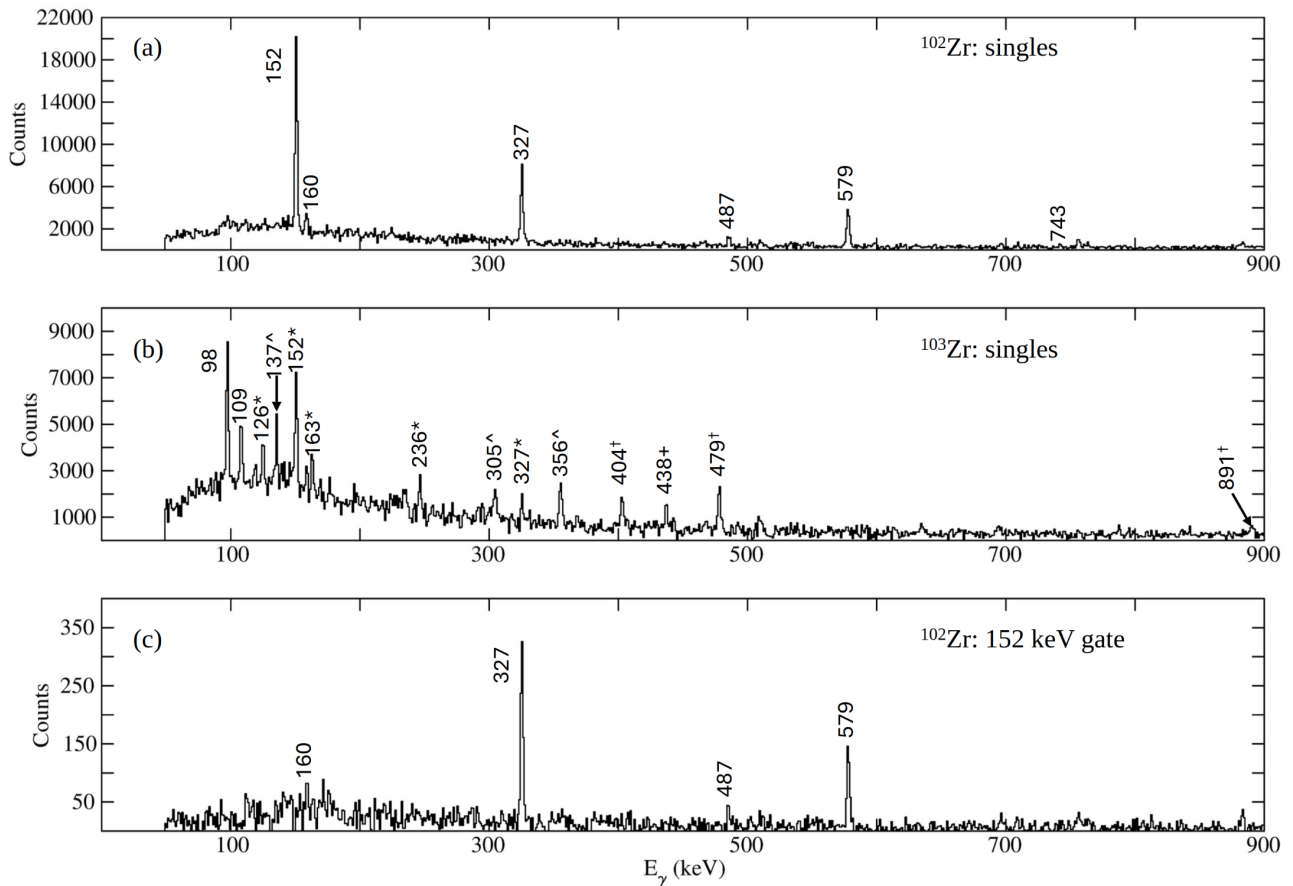


Figure 3. (a), (b) Beta-delayed γ -ray singles spectra for the (a) ^{102}Y and (b) ^{103}Y implant groups, where ^{102}Zr and ^{103}Zr are the primary decay products, respectively. (c) Beta-delayed γ -ray spectra for the ^{102}Y implant group, where ^{102}Zr is the primary decay product, gated on the 152-keV $2_1^+ \rightarrow 0_{g.s.}^+$ transition in ^{102}Zr . Contaminant γ rays from subsequent β -decays in the chain or from β -delayed neutron emission are marked with *, as yet unidentified γ rays are marked with \wedge , and tentatively assigned new γ rays are marked with \dagger .

at FRIB. The ^{238}U was fragmented on a primary ^{12}C foil target, and a secondary cocktail beam of neutron-rich nuclei was selected by the ARIS and delivered to the FDSi. The time of flight (ToF) of the nuclides was determined by the time difference between the ARIS and FDSi timing scintillators.

Beam particles were stopped in the implantation detector, which was used to record the implant events and subsequent β decays. Mass and charge separation of individual nuclide species was achieved from their ToF (A), and their energy loss in the Si PIN detector in DB3 (Z). Over 100 nuclides were identified in the particle-identification spectrum shown in Fig. 2, where the ^{102}Y and ^{103}Y implant groups have been labelled. 11 HPGe detectors, covering $\theta = 20 - 129$ deg at $r = 10.67, 14.48, \text{ and } 19.05$ cm, were used to precisely measure γ -ray energies. 15 LaBr₃ detectors, most of which were positioned at $\theta > 129$ deg, were used to measure gamma-ray timings. The positions of these detectors can be seen in Fig. 1.

4 Decay Spectroscopy with the HPGe Clover Array

The low-lying excited states of nuclei often provide the first insights into their ground-state shapes. In even-even

nuclei, the energy of the first 2^+ state and $4_1^+/2_1^+$ energy ratio often give first insights into the structure of a newly discovered nuclide, particularly if the $4_1^+/2_1^+$ value approaches the ‘rotational limit’. In this region, prolate deformation is expected to dominate. However, other features — such as the location of the second 2^+ state — can indicate triaxiality. A combination of γ -ray singles and coincidence measurements is a common tool in nuclear spectroscopy to confirm the locations of these key states.

The γ -ray singles spectra for ^{102}Zr and ^{103}Zr are shown in Fig. 3 (a) and (b), respectively. The FWHM energy resolution of the singles spectra is 1.83(2) keV at 128.2(2) keV and 2.19(2) keV at 874.3(2) keV. Software gates were applied to the implant groups identified as ^{102}Y and ^{103}Y . Spectra of β -gated clover-energy events correlated with each implant group show γ rays associated with each member of the associated decay chain. In many cases, additional chains from β -delayed neutron emission are also present. In Fig. 3, known γ rays associated with the primary decay products (^{102}Zr [32] and ^{103}Zr [33]) are labelled by their energies.

Observation of the 743-keV transition (Fig. 3 (a)) is indicative of the high-spin isomer in ^{102}Y being produced in the fragmentation reaction and transported to the collection point. A γ -ray coincidence spectrum (Fig. 3 (c)),

gated on the known first 2^+ state in ^{102}Zr , reveals the transitions that feed into this state, directly or indirectly. The 327-keV, $4^+ \rightarrow 2^+$ transition in ^{102}Zr is prominent, as are several other transitions that are labelled by their energies. In the ^{103}Zr singles spectrum (Fig. 3 (b)), the 109-keV γ ray from the $7/2^- \rightarrow 5/2^-$ transition is present; however, little else is known of this nucleus. Presence of the 152-keV and 327-keV γ rays in this spectrum indicate a significant β -delayed neutron branch, which is consistent with the adopted value of $B_{1n}(^{103}\text{Y}) = 8\%$ [33]. Deeper analysis of this more complex spectrum may yield further information on the structure of this nuclide.

The data can also be used to measure ground-state half-lives. Beta-decay rates are an important input in r -process sensitivity studies [12, 34] and many values in this region are poorly constrained through limited numbers of experiments and large uncertainties. Methods to determine ground-state half-lives from such data are currently being developed in-line with that described by Ong *et al.* [35], with simultaneous fitting of Bateman equations to encapsulate the decay series.

5 Fast-Timing with the LaBr₃ Array

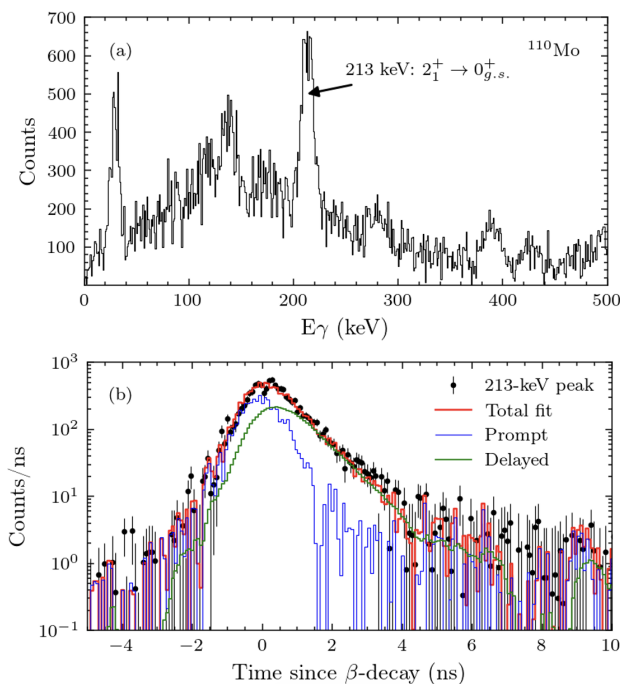


Figure 4. (a) Time-random background subtracted LaBr₃ γ -ray spectrum for the ^{110}Nb implant group, where ^{110}Mo is the primary decay product. (b) Time spectrum of the 213-keV $2^+ \rightarrow 0^+_{g.s.}$ transition in ^{110}Mo as recorded by the LaBr₃ array. The 213-keV peak has been fitted by a sum of delayed and prompt components. The two components have been scaled relative to the peak and background counts in the LaBr₃ γ -ray spectrum.

The reduced transition probabilities, $B(E2; 2^+ \rightarrow 0^+_{g.s.})$, often provide further insights into ground-state shapes for even-even nuclei [36]. $B(E2; 2^+ \rightarrow 0^+_{g.s.})$ values can be extracted from $2^+ \rightarrow 0^+_{g.s.}$ lifetime measurements using

the standard relation cited in [37]. Methods to measure excited-state lifetimes from the LaBr₃ data collected in this experiment are currently being developed.

The time-random background subtracted γ -ray energy spectrum of the LaBr₃ array for ^{110}Mo is shown in Fig. 4 (a). A preliminary lifetime determination for the 213-keV $2^+ \rightarrow 0^+_{g.s.}$ transition in ^{110}Mo is presented in Fig. 4 (b). The prompt component was empirically determined by gating from 230 to 280 keV and has a FWHM of 1.3(1) ns. The prompt gate was selected such that it closely neighbored the upper range of the peak gate (199 to 227 keV) to minimise time-walk relative to the peak signal, and to avoid including Compton scattered γ rays originating from the delayed γ -rays from the $2^+ \rightarrow 0^+_{g.s.}$ transition.

The delayed component was modelled as a discrete convolution of the empirical prompt component with an exponential decay. The total fitted model is a sum of the prompt and delayed components, and the fitted lifetime can be extracted from the exponential in the delayed component. Errors in the model, stemming from the uncertainties associated with the empirical prompt, were accounted for in the χ^2 minimisation. The systematic uncertainty associated with the choice of prompt gate was also estimated by characterising the time-walk of the prompt signal and analysing how the fitted lifetime varied with the choice of prompt gate.

Our preliminary value of $\tau = 0.77(8)$ ns is consistent with the adopted value of 0.84(4) ns [4]; however, there is still significant work required to finalise the analysis method, including confirming that the upper background is indeed prompt. Having identified numerous $2^+ \rightarrow 0^+_{g.s.}$ transitions in other even-even nuclei with similar statistics as ^{110}Mo within this experiment's dataset, the early agreement presented here suggests good prospects for our lifetime determination technique to further constrain known values and measure others for the first time.

6 Conclusion

Over 100 nuclei were identified as part of this experiment, with the unique FRIB beams and FDSi expected to facilitate a thorough investigation into properties such as ground-state shapes through measured half-lives and excited-state lifetimes for nuclei in the $A > 100$ neutron-rich Mo–Ru–Pd region. Here, we discussed data collection techniques, preliminary experimental methods and tentative results to illustrate the scope of data collected. Example β -delayed γ -ray spectra for ^{102}Zr and ^{103}Zr were presented, with future analysis potentially providing new insights into the structure of ^{103}Zr . Fitting methods for both ground-state and excited-state lifetimes are in development, with a preliminary result of $\tau = 0.77(8)$ ns for the 213-keV $2^+ \rightarrow 0^+_{g.s.}$ transition in ^{110}Mo being consistent with the adopted value. This is promising for constraining known values and measuring others. Our immediate future efforts will focus on ^{118}Ru and $^{120,122}\text{Pd}$ to search for triaxial deformation in this promising neutron-rich Mo–Ru–Pd region.

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