Experimental Investigations of Nuclear Structure around $A = 180$

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Abstract. Mid-heavy nuclei with $A \sim 140 - 180$ offer unique opportunities to study the collective and single-particle aspects of nuclear structure. This mass regime is a dynamic area where protons and neutrons generally occupy different orbitals, giving rise to complex structures with a wide variety of shapes, shape evolution and shape coexistence. To that end, measurements of nuclear lifetimes and transition matrix elements can be invaluable. Recent experimental activities of the NuSTRAP group in Athens have focused on γ -spectroscopy studies employing the ROSPHERE array in Magurele, Romania. A brief overview is reported.

KEY WORDS: mid-heavy nuclei, lifetimes, plunger, ROSPHERE.

1 Introduction

The entire nuclear landscape is formed due to the existence of two competing forces: the nuclear attraction and the Coulomb repulsion. As general as this statement might sound, it is the interplay of those two forces, which can stabilize or destabilize groups of nucleons so as to form the ≈ 3500 isotopes known today.

The lack of a rigorous mathematical description of the aggregate nuclear field is a major drawback in describing the effects of the interplay on nuclear structure and has been at the forefront of nuclear studies for several decades. As one moves through different areas of the nuclear chart, the number of degrees of freedom that need be included in theoretical modeling grows exponentially with mass. Experimental data are necessary to improve theoretical description.

The mid-heavy nuclei ($A \sim 140 - 180$) belong to a part of the nuclear chart where protons and neutrons occupy different major shells. Compared to medium-mass nuclei, that is nuclei in the fp shell, where both protons and neutrons occupy similar orbitals giving rise to interesting phenomena, protons and neutrons in mid-heavy nuclei occupy different Fermi levels and feature a larger variety of spins. The advent of radioactive beams together with the rise of interest for nuclear processes in stellar environments have recently put the region of mid-heavy nuclei under scrutiny. The structure of exotic species in this mass regime is largely unknown, where spectroscopic data are scarce, even for isotopes a few nucleons away from the valley of stability, thus making any information on lifetimes, transition rates, wavefunctions or even production cross sections quite important for understanding the occurrence of dynamical phenomena.

To that end, recent work by the NuSTRAP Group in Athens in collaboration with international colleagues has been focused on investigating nuclear structure properties of a few neutron-rich isotopes in $A \sim 140 - 180$ delivering an experimental program at the 9 MV Tandem Accelerator Lab at IFIN-HH in Magurele, Romania. Collective properties have been examined by performing lifetime measurements in various states, where no or very limited data exist in literature. The main focus is on observables related to nuclear shapes, nuclear deformations and other interesting phenomena, such as shape coexistence.

The present paper reports work on the ^{140}Ba , $^{152-154}\text{Gd}$, ^{180}Hf and Yb isotopes. Results, lessons learnt and future research steps are described in the following sections.

2 Experiments and Results

2.1 Experimental Setups and Methods

All experiments reported in this work have been carried out at the 9 MV Tandem Accelerator Laboratory at IFIN-HH, Romania. Beams were produced at various energies depending on the optimal conditions required for each experiment. Targets have been manufactured at the radiochemistry lab of the same Institution by either vacuum evaporation (e.g. ^{138}Ba targets) or foil rolling (e.g. ^{181}Ta targets).

The ROSPHERE Array [1] was used to record emitted γ rays following the de-

Figure 1. (Color online) The γ -ray detection array ROSPHERE employed in this work (picture modified from Ref. [1]).

excitation of states populated during the reactions (Figure 1). The array was used in two different configurations; either with 5 rings (loaded with 25 HPGe+BGO shields) or with 3 rings (15 HPGe+BGO shields) and 10 LaBr₃(Ce) scintillators. The former configuration is generally preferred when angular correlations are studied, while the latter offers the opportunity to measure lifetimes of excited states with the in-beam Fast Electronic Scintillation Timing (FEST) Method, taking advantage of the excellent time resolution of the LaBr₃(Ce) scintillators. For transfer reaction experiments with Yb isotopes (see §2.4), a solar-cell particle detector, SORCERER [2], was employed to enable selection of reaction channels in the recorded data.

A plunger device was mounted to enable the Recoil Distance Doppler Shift (RDDS) Method in an experiment aimed to measure lifetimes in ¹⁸⁰Hf (§2.5). In the other cases, the Doppler Shift Attenuation Method (DSAM) and the FEST method were used to measure lifetimes. The employed method was selected after assessing existing information (if any) for the isotopes under investigation, as well as the experimental conditions (target thickness etc.).

2.2 $^{140}_{56}\text{Ba}$

The unstable ^{140}Ba nucleus with a ground-state $t_{1/2} = 12.75$ d is situated at the onset of octupole correlations. Two of its heavier isotopes, the neutron-rich $^{144,146}\text{Ba}$, have been studied experimentally in terms of their $B(E3)$ values [3, 4], showing enhanced octupole collectivity. ^{140}Ba is an important nucleus to assess the degree of collectivity in the barium isotopic chain as a function of the neutron number.

An experiment targeted spectroscopy and lifetime measurements in ^{140}Ba , especially in the negative parity band, because an existence of an isomer offers a strong hint for octupole collectivity. The $^{138}\text{Ba}(^{18}\text{O}, ^{16}\text{O})^{140}\text{Ba}$ reaction (2n-transfer) was used to populate various states in a dedicated test run that had three main objectives: (i) overcome challenging targetry, as barium oxidizes rapidly in contact with air, (ii) use the Doppler-Shift Attenuation Method (DSAM) to deduce lifetimes, (iii) investigate the production yields at energy near the Coulomb barrier as the reaction was never used before, and determine cross sections, if possible.

The construction of the target was successful albeit extreme caution was required to avoid oxidation that could result in large elastic reaction cross sections due to accumulation of oxygen atoms. The short run (≈ 21 h of beam on target) did not allow for sufficient statistics to have decisive lifetime measurements with DSAM. Despite no clear forward/backward Doppler shifts have been observed in the spectra (see Figure 2), the kinematics involved in combination with the range of lifetimes DSAM is sensitive to (≤ 1 ps) suggested an upper limit for

Figure 2. (Color online) Forward/backward spectra for the 528 and 530 γ -ray peaks in ^{140}Ba . No Doppler effects are observed.

the states up to 8^+ in the ground-state band of ^{140}Ba . In addition, production cross section data for the particular reaction have been deduced, relative to the strong fusion–evaporation channels populated in the same experiment.

The full experimental details and the results can be found in the published work by A. Chalil *et al.* [5].

2.3 $^{152-154}_{64}\text{Gd}$

Fusion evaporation reactions were strongly populated in the same experiment with ^{140}Ba providing an additional data set. The $^{152-154}\text{Gd}$ isotopes are interesting cases, as they lie in the transitional region from vibrational to rotational collectivity and their study can offer valuable understanding for the mechanisms being responsible for this transition.

Figure 3. (Color online) Partial level scheme of ^{152}Gd reconstructed from the raw experimental data.

The Gd isotopes have been populated with sufficient statistics and various bands are present in the data (Figure 3). From the analysis, various branching ratios have been determined, some for the first time in literature, such as:

- For the ^{152}Gd 4_2^+ level ($E_{level} = 1282$ keV)
 0.47(5) for the transition $4_2^+ \rightarrow 4_1^+$
 0.53(7) for the transition $4_2^+ \rightarrow 2_2^+$
 compare to values in literature: 0.512(15) and 0.452(14), respectively [6]
- For the ^{152}Gd 7_1^- level ($E_{level} = 1880$ keV)
 0.42(16) for the transition $7_1^- \rightarrow 5_1^-$

0.58(19) for the transition $7_1^- \rightarrow 6_1^+$

This is a new result.

- For the ^{153}Gd $23/2^+$ level ($E_{level} = 1436.5$ keV)
0.59(22) for the transition $23/2^+ \rightarrow 19/2^+$
0.41(25) for the transition $23/2^+ \rightarrow 21/2^+$
compare to values in literature: 0.53(4) and 0.36(3), respectively [6]

This work is still in progress.

2.4 $^{178}_{70}\text{Yb}$

The Yb isotopes ($Z = 70$) around mass 170 are known to exhibit distinct rotational properties in their ground state bands and can be populated to very high spins. According to Heyde and Woods [7], Yb isotopes are located inside the borders of an island of shape coexistence. Additionally, recent proxy-SU(3) calculations [8] suggest that such phenomena should be present in the even-even neutron-rich Yb isotopes. In particular, ^{178}Yb , which is completely unknown in terms of lifetimes of excited states (Figure 4), offers a strong motivation to investigate.

The 2n-transfer reactions of an ^{18}O projectile with a natural Yb target populated various states, including those of interest in ^{178}Yb . Coincident spectra have been used to avoid the complications arising from the products of the nuclear reactions on the numerous stable isotopes in the natural target (^{176}Yb is a mere 13% of the total abundance). This resulted in a complicated analysis. A serious hindrance is caused by the fact that the 2_1^+ and 4_1^+ states in ^{170}Yb , ^{176}Yb and

Figure 4. (Color online) The full level scheme of ^{178}Yb . No lifetimes of excited states are known [6].

^{178}Yb have very similar energies, exceeding the resolution of the spectrometer. Consequently, gates on higher transitions (i.e. 6_1^+) bring down the statistics, but offer a solution for lifetime measurements in the neutron-rich ^{178}Yb . As the investigation is still in progress at both experimental and theoretical level (see also the paper by A. Zyriliou *et al.* in this Proceedings volume), the main lesson learnt is that an enriched or an isotopic target must be used to overcome the aforementioned difficulties in the analysis.

2.5 $^{180}_{72}\text{Hf}$

The stable ^{180}Hf has a well-established level scheme featuring a rotational spectrum ground state band with known lifetimes for states with spin up to 12^+ . The existence of a negative parity band and a few K -isomers, such as the $K = 8$ with 8^- at 1141.6 MeV, are interesting nuclear structure characteristics, with no data currently existing in literature, and no information on shapes and deformations. Similarly to the isotone ^{178}Yb , ^{180}Hf is predicted to exhibit shape coexistence. However, experimental confirmation is needed. Lifetimes and quadrupole moments can provide useful information on this front.

A recent experiment at IFIN-HH used a ^{11}B beam impinging on a natural Ta target was used to populate states in ^{180}Hf . To measure lifetimes, the Recoil-Distance Doppler Shift method (RDDS) was employed with a plunger device

Figure 5. (Color online) A close up of the plunger device used in the experiment for ^{180}Hf . Six target–stopper distances have been used to measure the lifetimes of states under investigation.

mounted in the center of the ROSPHERE array (Figure 5). The ROSPHERE array was loaded with 25 HPGe detectors distributed over five (5) rings. Six distances (15-250 μm) between the target (Ta) and the stopper (Au) foils have been used. The SORCERER solar-cell array enabled the selection of reaction channels based on the particles emitted in each one of them, significantly cleaning the data.

As the analysis is ongoing (see full details in the paper by P. Vasileiou *et al.* in the same Proceedings volume), experimental results are still considered preliminary. At present, the validation of the instrument (ROSPHERE+SORCERER+plunger) has confirmed a literature value for the lifetime of the 6_1^+ state in the ground-state band, which can be used to pin down any systematic effects, plunger offsets etc. Further work is on the way.

3 Conclusions and Future Work

The present work provides an overview of experimental activities at IFIN-HH, focusing on spectroscopic studies and lifetime measurements to provide information on nuclear structure in the mass region $A \sim 140 - 180$. Preliminary results exist for all isotopes studied, as mentioned earlier.

Besides published results for ^{140}Ba , the main conclusion is that an experiment at a RIB facility is probably most appropriate to populate states and enable lifetime measurements, as the targetry in combination with the overall low cross sections of the 2n-transfer reactions played an important role.

Similarly, an enriched target seems to be necessary for a future experiment to study ^{178}Yb . Despite the limited beam time in the test run, several states have been populated in the experiment. Provided that contributions from the lighter Yb isotopes are eliminated, sufficient statistics for states in ^{178}Yb are expected to allow for lifetime measurements and provide input for the shape dynamics in this nucleus.

Work in $^{152-154}\text{Gd}$ is a step before completion and is expected to provide various new information on multipolarities and branching ratios of states, that are currently missing from literature.

Finally, the analysis of the data recorded during the plunger experiment is at an early stage and is expected to provide more information on ^{180}Hf in the near future. Theoretical work with various models is also in progress.

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