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Lifetimes and Moments Measurements to Investigate the Structure of Midheavy Nuclei

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Abstract.
Mid–heavy nuclei 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 electromagnetic moments (μ,Q) 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. In recent studies [1, 2], the neutron–rich $^{144-146}\mathrm{Ba}$ isotopes have exhibited octupole degrees of freedom. Similar questions exist for the lighter $^{140}\mathrm{Ba}$ isotope, which is located at the onset of octupole collectivity. In addition, understanding the structure of heavier, even–even hafnium isotopes requires more data regarding shape coexistence and shape evolution. Preliminary results on lifetimes in this area pave the way to understand dynamical phenomena prior to studying more exotic species in the future.

KEY WORDS: ^{140}Ba, ^{180}Hf, lifetimes, octupole collectivity

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 ($A \sim 130 - 180$) belong to a part of the nuclear chart where protons and neutrons occupy different major shells. Compared to medium–weight nuclei (e.g. in the vicinity of Kr isotopes), where both protons and neutrons occupy similar orbitals in the fp shell giving rise to interesting phenomena [4], mid–heavy nuclei feature different Fermi energies for protons and neutrons and 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 into 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.

One special way to study the nuclear structure in mid–heavy nuclei is by means of the nuclear electromagnetic moments, in particular the magnetic dipole moment, μ and the electric quadrupole moment, Q. In the quantum picture both these observables are one–body operators, so they can scale up with the number of nucleons. The magnetic dipole moment has the unique ability to provide the wavefunction of a nuclear state in terms of its single–particle orbitals occupied by its constituents, protons and neutrons. As protons and neutrons have markedly different magnetic properties originating from their distinct spin contributions, the structure of any nuclear state is reflected on its magnetic moment. On the other hand, the electric quadrupole moment is directly related to the shape of the nucleus and its deformation. Q can be also related to the reduced matrix elements B(E2). That relation is model–dependent, however it provides the means to extract the shape evolution in a particular nucleus by measuring the lifetimes of states, which are connected to B(E2) values, see for example [5]. In addition, the intriguing phenomenon of shape coexistence is reportedly expected in mid–heavy nuclei providing additional motivation for detailed studies [6].

The present work reports on preliminary experimental results focusing on the nuclear structure of $^{140}\mathrm{Ba}$ with poorly known spectroscopic data, other than those of the ground–state, as well as $^{180}\mathrm{Hf}$, where the structure of a considerable number of observed non-band levels is unknown. In the following sections, the motivation to study each of these isotopes, the experimental approach and the first results of the ongoing analysis are presented in some detail. Lessons learnt and future research directions are also described in the concluding section.

The Case of $^{140}_{56}\mathrm{Ba}$

The $^{140}\mathrm{Ba}$ nucleus is an unstable nucleus ($t_{1/2} = 12.75$ d) located at the onset of octupole correlations. Two neighbouring isotopes, the neutron–rich $^{144,146}\mathrm{Ba}$

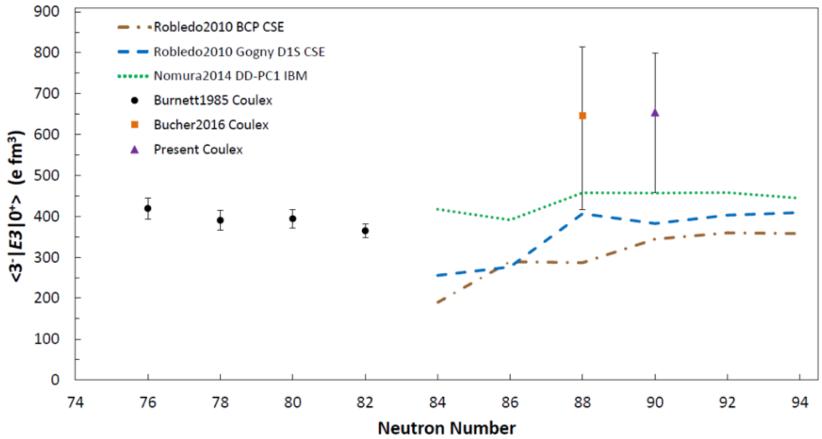

Figure 1. Experimental $B(E3)$ data for the barium isotopic chain. No data exist for ^{140,142}Ba. The figure has been adopted from [1, 2].

isotopes, have been recently studied experimentally in terms of their $B(E3)$ values [1, 2], using radioactive beams and Coulomb excitation. Despite some large uncertainties (see Figure 1) the respective $B(E3)$ values were found to deviate significantly from any theoretical prediction. As a consequence, the case of ^{140}Ba lays important questions on the onset and evolution of octupole correlations, as well as on the assessment of the degree of collectivity in the barium isotopic chain as a function of the neutron number.

Lifetimes of the lower–lying states in ^{140}Ba are generally unknown, with the sole exception of the first 2^+ state [3]. It is clear that even lower/upper limits of lifetime measurements can have an impact on understanding the nuclear structure in ^{140}Ba. This is particularly relevant for the negative parity band (Figure 2), which suggests the occurrence of octupole degrees of freedom. From a technical point of view, there is a certain degree of difficulty in populating the side–band states via Coulomb excitation, which favors E2 excitations strongly. Thus, a 2n–transfer reaction was chosen instead to populate states during the experiment. The advantage from using such a reaction is two–fold in the present case, as ^{140}Ba can be populated directly from a stable isotope target (^{138}Ba). Chemically, barium is very reactive with air, thus making target–manufacturing a real challenge, if one needs to preserve target integrity and stoichiometry.

In addition, cross section data related to the production of ^{140}Ba via the 2n–transfer reaction at energies near and below the Coulomb barrier do not exist for the case of bombardment with heavy ions, such as ^{18}O. Such experimental data can be proven useful for populating neutron–rich nuclei near the neutron dripline.

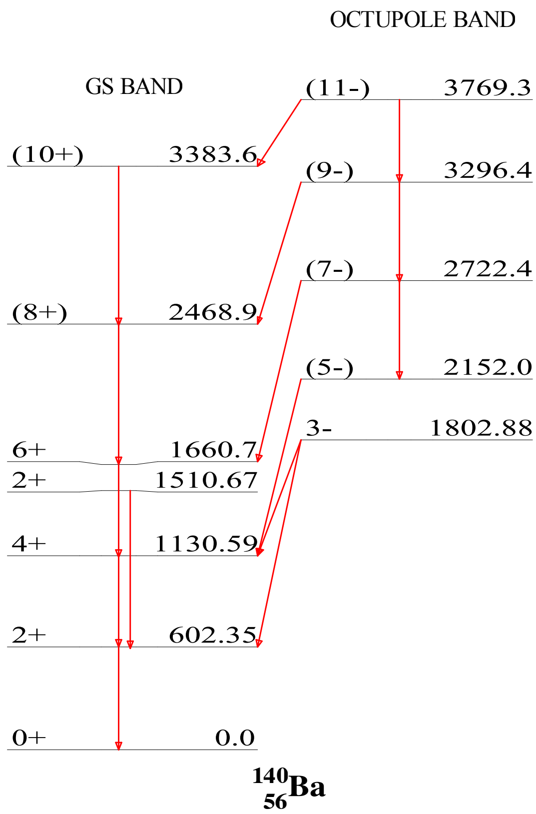

Figure 2. A partial level scheme of ^{140}Ba (source [7]).

The Case of $^{180}_{72}$Hf

^{180}Hf is a stable nucleus with an extensive level scheme known from earlier studies [8]. The ground state band features a typical rotational spectrum and lifetimes of its states are known up to spin 12^+. An interesting feature of the nuclear structure is a negative parity band and a few K–isomers, such as the K=4 8^- at 1141.6 MeV with halflife of 5.53 h, that acts as the bandhead of another rotational band. Questions about its structure arise from the fact that several non–band members exist with no data present in literature, and no information on shapes and deformations. The recently developed proxy-SU(3) model [9, 10] predicts ^{180}Hf to be a nucleus with shape coexistence, but this requires experimental confirmation. Lifetimes and quadrupole moments can provide useful information to that end, therefore a dedicated study is highly desired.

2 Experimental Details

Two separate three–day long experiments were carried out at the 9 MV Tandem Accelerator Laboratory IFIN–HH in Magurele, Romania using the the RoSPHERE array.

In the first experiment, the 2n–transfer reaction $^{138}\mathrm{Ba}(^{18}\mathrm{O},^{16}\mathrm{O})^{140}\mathrm{Ba}$ was employed at four energies just below the Coulomb barrier (61, 63, 65 and 67 MeV). The target was made with a "sandwich–like" structure after an elaborate procedure that placed 2 mg/cm^2 of barium between a thick Au backing of 4.88 mg/cm^2, and an evaporated 0.5 mg/cm^2 Au layer at the front. RoSPHERE was loaded with 15 HPGe detectors and 10 $LaBr_3$ scintillators (the latter were not used).

The second experiment used a thick 5 mg/cm^2 $^{nat}\mathrm{Ta}$ foil to produce $^{180}\mathrm{Hf}$ via the charge–pickup reaction $^{181}\mathrm{Ta}(^{11}\mathrm{B},^{12}\mathrm{C})^{180}\mathrm{Hf}$ at a beam energy of 47 MeV. Following de–excitation, emitted γ rays were recorded by 25 HPGe distributed over (five) 5 rings.

3 Results and Discussion

In the first experiment, the beam energies of 61 and 63 MeV resulted in very low statistics for the 2n–transfer reaction, while the maximum energy of 67 MeV was sufficient to trigger strong, competing reaction channels that dominated the recorded spectra. The 65 MeV energy was a convenient choice that avoided the aforementioned drawbacks. A typical spectrum of $^{140}\mathrm{Ba}$ is shown in Figure 3. At this energy setting, the levels in the ground–state band were populated up to 8^+. Unfortunately, levels in the side band, in particular those that are potentially the best indicators for studying quadrupole and octupole collectivity (see 0_2^+ and 3_1^- in Figure 2) have not been populated sufficiently during the total 21 hours of data collection.

An attempt to measure lifetimes in $^{140}\mathrm{Ba}$ in the g.s. band was performed with the Doppler–Shift Attenuation Method (DSAM). Forward–backward lineshapes were searched in the 37–143° ring spectra, without much success. Given the limitations of DSAM, a lower lifetime limit can be safely set to ≈ 1 ps.

Further analysis of the $^{140}\mathrm{Ba}$ data focused on the production cross sections. Relative cross sections of the 2n–transfer reaction have been measured with respect to the competing fusion–evaporation channel $^{138}\mathrm{Ba}(^{18}\mathrm{O},4\mathrm{n})^{154}\mathrm{Gd}$. The results of this part of the analysis are reported elsewhere [11].

In the second experiment, approximately three (3) full days of experimental data were collected. The focus on this experiment was on both the ground state band, which has unknown lifetimes, but also on the negative parity band that has an isomeric state as a bandhead ($J^\pi = 4^-$, $t_{1/2} = 0.57$ μs). This part of the analysis is ongoing and has already offered interesting results on the $^{180}\mathrm{Hf}$ nuclear structure. A focus on $\gamma - \gamma$ angular correlations has already shown sufficient

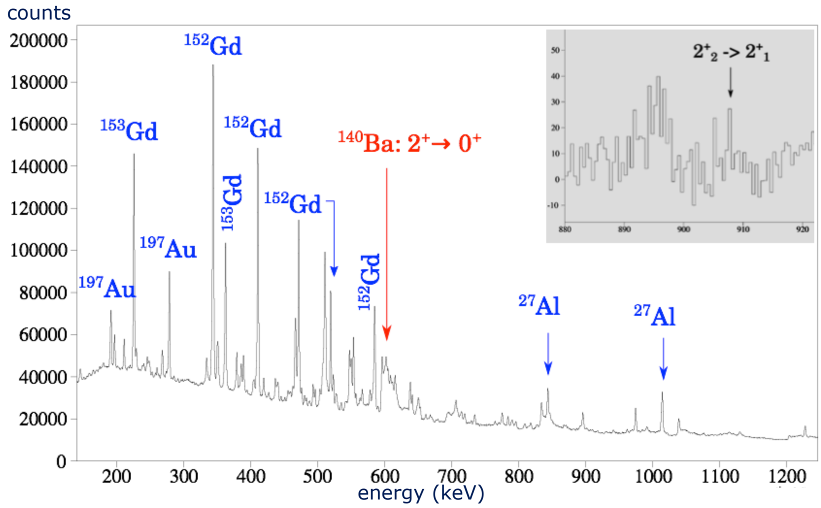

Figure 3. A total statistics spectrum of ^{140}Ba in the forward ring. The $2^+_1 \rightarrow 0^+_{gs}$ transition is marked. The inset marks the $2^+_2 \rightarrow 2^+_1$ transition.

statistics to suggest or re-examine spin/parity assignments and offers the opportunity to study the unknown structure of non–band levels depopulated from γ transitions as shown in Figure 4, where the 1821 non–band state is depopulated by a γ transition of 447 keV.

4 Conclusions and Future Work

The present work reports on two different test experiments focusing on mid–heavy nuclei: the lighter, unstable ^{140}Ba and the heavier, but stable, ^{180}Hf, respectively. In the latter experiment, the suspected occurrence of octupole collectivity could not be confirmed due to very low statistics. In the particular case, the 2n–transfer reaction cannot be used for the population of states that could provide lifetimes and reduced matrix elements relevant to octupole degrees of freedom, despite it has been successful in other cases, such as in ^{66}Ni [12]. As barium is a difficult target to make and use in a stable beam experiment (e.g. using a plunger device to measure lifetimes), a plausible solution is to consider a radioactive beam experiment, likely in inverse kinematics. A lower lifetime limit of $\tau > 1$ ps was determined based on the limitations of DSAM, but further work is necessary to that direction.

For the case of ^{180}Hf, the analysis is ongoing and seems very promising. In the

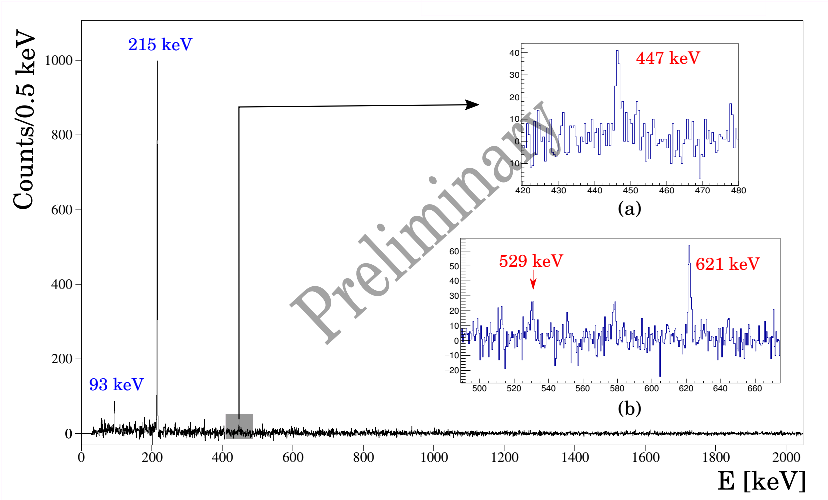

Figure 4. A spectrum produced after gating on the 1066 keV transition, $(4^-) \rightarrow 4_1^+$. In inset (a) the events coming in coincidence with the 447 keV transition depopulating the non–band 1821 keV state (3^-) in ^{180}Hf are shown. In inset (b), part of the coincidence spectrum gated on the transitions 1198 ($3_1^+ \rightarrow 2_1^+$) and 1200 keV ($2_3^+ \rightarrow g.s.$) shows the 621 and 529 keV transitions, which also depopulate the 1821 keV state. The structure and the lifetime of this state is currently unknown.

near future, the focus will be on angular correlations of states, search for short–lived states that could be measured with DSAM and the scrutiny of the nature of states that do not belong in a particular band and may provide evidence for large deformation or isomerism. The charge–pickup reaction seems to produce sufficient statistics, so as one could potentially use it in a plunger experiment for measuring lifetimes with low uncertainty, thus providing data to study the evolution of transition matrix elements and shapes in ^{180}Hf.

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