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Beta decay studies and search for octupole deformation in the $A \sim 225$ Po-Fr nuclei

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Summary. — In the landscape of nuclear shapes, dominated by reflection-symmetric forms leading to either spherical or axially deformed arrangements, the occurrence of asymmetric pear-like nuclei has long been searched for. Evidence for static octupole deformation has only been found in selective areas of the nuclear chart, in the mass regions $A \sim 222$ and $A \sim 146$, the so-called "Islands of Octupole Deformation" (IOD). This paper is focused on β decay studies in the Po-Fr nuclei in the $220 \leq A \leq 230$ island of octupole deformation exploiting the FRS+DESPEC setup at GSI in Spring 2021. The experimental setup and the analysis techniques employed to perform this study are here shown and discussed, together with preliminary results from the on-going analysis.

1. – Introduction

The HISPEC-DESPEC Collaboration aims at investigating the nuclear structure of exotic nuclei formed in high-energy projectile-fragmentation reactions. The experiment here discussed was performed as part of the Phase-0 GSI-FAIR campaign, with the aim of investigating $A \sim 225$ Po-Fr nuclei in the south-east frontier of the $A \sim 222$ IOD populating the nuclei of interest using β decay.

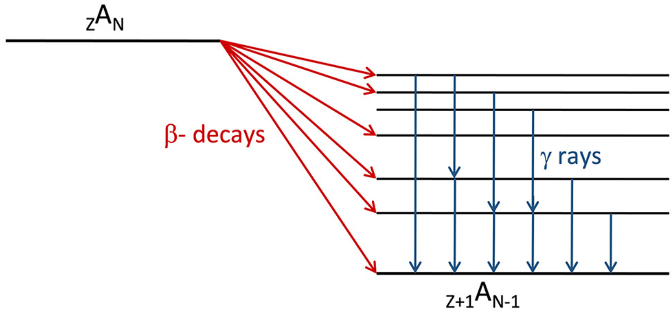

Fig. 1. – Example of a typical β-decay scheme of de-excitation.

Beta decay can serve as a tool to explore the inner structure of nuclei. The γ transitions caused by the de-excitation of the nucleus, and following the β decay, carries information on the de-excitation pattern of daughter nucleus, as shown in fig. 1. γ-γ coincidence studies allow us to to define the structure of the level scheme of the nuclei under investigation, while the relative intensities can give information on the probability of a particular level to be populated. One of the applications of β decay is the study of the decay heat of a reactor. Once the reactor is shut down, the energy released in radioactive decays provides the main source of heating. Estimation and control of the heat emitted by the decay of fission products has a key role in the safe operation of reactors. These calculations require extensive libraries of cross sections, fission yields, and decay data [1].

In our specific case, we use β decay to reach out to n-rich nuclei and extract details on the presence of permanent octupole deformation in our nuclei of interest. Octupole deformation is associated to octupole correlations, which result in a non-zero β_{30} term, resulting in reflection asymmetric shapes, also known as pear-like shapes [2]. Octupole correlations are the result of the long-range octupole-octupole interaction between nucleons occupying pairs of orbitals which differ by 3 units in both orbital- and total-angular momentum. These states approach each other at the Fermi surface when either Z or $N \sim 34$, 56, 88, 134, at values just greater than the magic numbers, where nuclei are nearly spherical [3].

These exotically deformed nuclei can be found only in selective areas of the nuclear chart, in particular in the mass region $A = 146$ (Xe-Sm region) and $A = 222$ (Rn-Th region), called Islands of Octupole Deformation (IOD). To find direct experimental evidences of these elusive shapes proves to be very challenging, and it is worth exploring several spectroscopic properties in a wide range of nuclei. The main experimental signatures are a large $B(E3)$ transition strength, an enhanced $B(E1)$ transition strength, due to the separation of the centre of charge and the centre of mass of the nucleus, and interleaving negative and positive parity states that are nearly degenerate in energy. This was confirmed by theoretical calculations performed for nuclei in the light actinide region, as shown in refs. [4, 5].

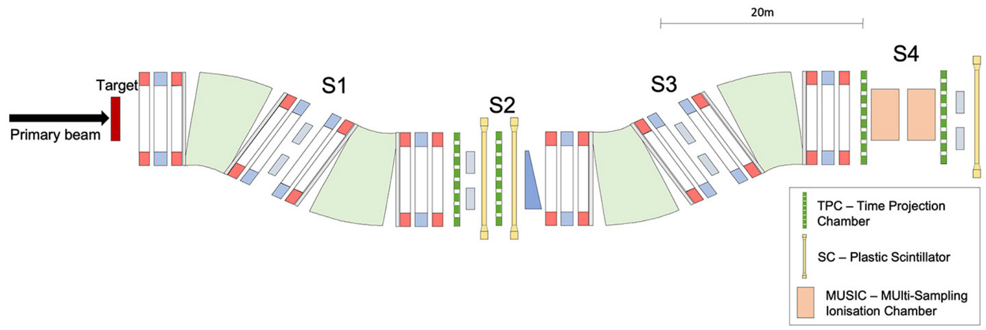

Fig. 2. – Schematic of the FRS magnetic spectrometer: the main detectors for ion identification are labeled in the box on the bottom-right.

Very few direct measurements of octupole correlations were performed in recent years, and $E3$ transitions were measured directly in selected cases, in particular in ^{220}Rn, ^{224}Ra [6] and ^{228}Th [7], highlighting a typical de-excitation pattern.

The experiment here described was performed at GSI Darmstadt, Germany in April 2021 with the following main aims: finding evidence of octupole deformation in the nuclei of interest, provide new β-decay data to test models for r-process, to measure super-deformed bands in $^{220-222}$Po. We plan to measure directly octupole correlations by using β decay and fast timing to locate 1^- and 3^- states and their correspondent transition strength, and compare them with predicted values [4]. In order to study shape isomers in $^{220-222}$Po, we plan to use delayed isomer spectroscopy to locate the super-deformed 2^+ states at low energies [8].

2. – Experiment

The experiment was performed at the GSI-FAIR laboratories within the DESPEC Phase-0 campaign. The ions of interest were formed in a fragmentation reaction of a ^{238}U beam impinging on a ^{9}Be target. The primary beam was accelerated using the UNIversal Linear ACcelerator (UNILAC) and the SIS-18 synchrotron, producing a beam with $\sim 10^9$ pps intensity and spill length on 4 s. The fragments' secondary beam here produced forms a so-called cocktail beam composed of many nuclear species. Therefore, there is a need to select and identify each different ion species in order to perform focused studies on their properties and decays. In order to do this, the fragments are selected with the $B\rho$-ΔE-$B\rho$ method using magnetic elements and energy loss in materials. The ions can also be identified with the TOF-$B\rho$-ΔE method [9] in the FRS FRagment Separator where several detectors collect information on the ions' time of flight, position in the focal planes, and atomic number Z (see fig. 2). This powerful magnetic spectrometer allowed us to produce and transport ions in the Po-Fr region with mass $A \sim 225$ towards our DESPEC setup.

The DEcay SPECtroscopy station [10] was commissioned in 2019 and used in the following campaigns. It comprises several detector systems used for decay experiments.

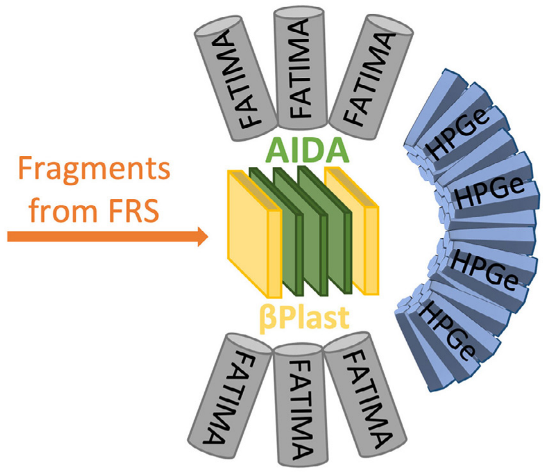

Fig. 3. – Schematic of the DESPEC decay station.

The ions are implanted in a stack of 3 Double-Sided Silicon-strip Detectors (DSSD) segmented in 128×128 strips (16384 pixels) with 0.6 mm strip pitch, the AIDA (Advanced Implantation Detector Array) [11]. This active stopper is also used to detect α and β particles emitted by the ion after its decay. The three silicon detectors are sandwitched between two plastic scintillators, the bPlast detector, which are made of tiles of BC-400 scintillator material, readout by a series of SiPM glued to each side, used for timing measurements of the β particle emitted in the decay. The γ rays emitted in the de-excitation of the daughter nuclei are detected using a hybrid array for γ-ray detection. The FATIMA (FAst TIMing Array), comprising 36 $LaBr_3$(Ce) detectors, arranged in three concentric rings [12], is used for timing measurements. Each detector is composed of a crystal with a diameter size of $1.5\times2\,\mathrm{inch}^2$ length coupled to Hamamatsu R9779 photo-multiplier tubes. The detectors are equipped with a lead shield of 4 mm thickness around the crystal to minimise scattering among neighbouring detectors [13]. The FATIMA detector system has a full-energy peak efficiency of 2.9% at ~ 1 MeV. Precision γ energy measurements are performed with four 7-fold HPGe clusters, in forward position as depicted in fig. 3. This germanium array has an efficiency of 2% at ~ 1 MeV. All the subsystems involved have independent data acquisition systems that are synchronised using a time sorter. Time stamping correlations are established between the systems using a distributed clock: the so-called White Rabbit, and a 2 Hz pulser.

This setup allows to perform β-decay measurements by correlating the implanted ion and the β particle in the silicon detectors, using position and timing conditions. The γ rays detected in the FATIMA and HPGe detectors can then be correlated to the ion and β to probe the inner structure of the daughter nuclei, establishing β-γ-γ correlations. Alpha decay studies can be performed in a similar fashion by correlating the implanted ion with an alpha detected in the silicon detectors.

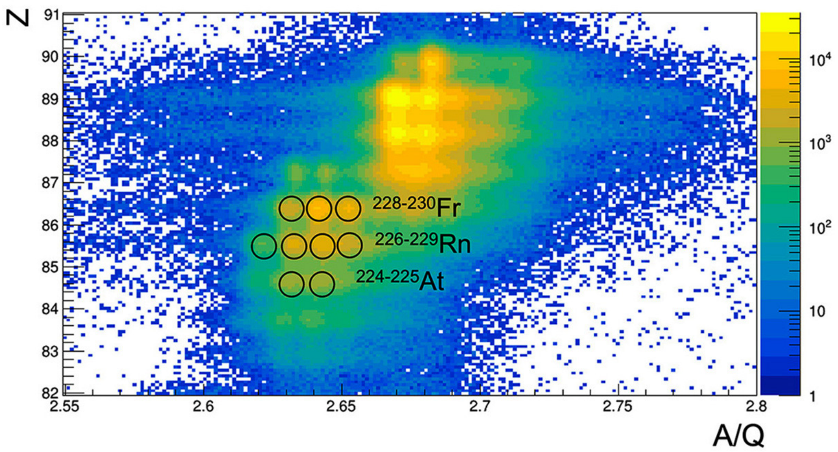

Fig. 4. – Particle identification plot obtained for our experimental run.

3. – Initial stages of analysis

The ions of interest were measured in the FRagment Separator as explained in sect. **2**. The identification was performed after accurate calibrations and corrections of all the detectors used. We therefore obtain an identification plot (also called ID plot) in which the atomic number Z of each ion produced is plotted against the mass over ionic charge ratio (A/Q). As shown in fig. 4, we were able to produce all the ions of interest: $^{228-230}$Fr, $^{226-229}$Rn, $^{224-225}$At, together with several other ion species that can therefore be investigated with this measurement. Some of the ions were produced in a different charge state, and form a structure on the right-hand side of fig. 4. The ions are well separated, and with software conditions it will be possible to focus on each single species to perform β decay and γ spectroscopy.

The data-processing is on-going and will be now focused on the ion-β coincidence reconstruction developing *ad hoc* codes for ion-β and β-γ-γ correlations. This analysis will be exploited to study of the inner structure of the daughter nuclei to identify new decay transitions and evaluate the presence of octupole deformation. In parallel, α decay analysis is being performed in Rn isotopes in order to confirm the ion-decay correlations and to enrich the knowledge on the α-decay mode of these nuclei.

4. – Conclusions

This paper reports an experimental study on octupole deformation exploiting beta decay in the Po-Fr region with mass $220 \leq A \leq 230$. The experiment was performed at GSI-FAIR in April 2021 within the DESPEC phase-0 campaign using the FRS-DESPEC setup to select and identify the ions of interest produced in fragmentation reactions of a ^{238}U beam. Preliminary results from the on-going analysis were presented in this work.

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