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Beta-decay studies with the Total Absorption Gamma-ray Spectroscopy technique

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The investigation of the structure of exotic nuclei is at the forefront of modern nuclear physics. β-decay spectroscopy experiments with implanted radioactive beams serve as a powerful tool for exploring such nuclei. The Total Absorption γ-ray Spectroscopy (TAGS) technique plays a crucial role as the most effective method for measuring the β-decay strength distribution free from the Pandemonium effect. This article presents two ongoing β-decay measurements using the TAGS technique. The first one is experiment IS707, recently carried out with the Lucrecia spectrometer at ISOLDE-CERN, aimed at studying nuclear shape in odd-A mercury isotopes. The second one is experiment E891_23, which will be performed in the near future at GANIL, focusing on several proton-rich nuclei in the Cr-Zn region, which are of significant interest for both nuclear structure and nuclear astrophysics. This experiment will, for the first time, utilize the new-concept hybrid spectrometer, STARS. Currently under development, STARS will offer a unique combination of the large γ efficiency characteristic of total absorption calorimeters and the superior energy resolution and timing of $LaBr_3$(Ce) crystals, enabling unprecedented studies of exotic nuclei.

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1. Introduction

The investigation of nuclei near the limits of nuclear stability, known as *exotic nuclei*, is a leading area of modern nuclear physics. These nuclei are characterized by features such as large charge asymmetry (high isospin values) and the weak binding of excess nucleons. They exhibit intriguing phenomena across the nuclear chart, including changes in level ordering as predicted by the Nuclear Shell Model (shell evolution) [1], shape coexistence and shape evolution [2, 3], nuclear *halo* or *skin* structures [4]. New types of radioactivity [5, 6] and exotic decay modes [7] are also observed as these nuclei become more and more weakly bound.

Studying these nuclei is demanding but increasingly achievable due to the development of new-generation, large international facilities capable of producing and accelerating beams of exotic nuclei (*radioactive ion beams*, or RIBs). Today, more exotic nuclei can be produced on both the proton- and neutron-rich sides of the nuclear chart. Typically, decay studies provide the first insights into exotic nuclei. While the boundaries of nuclear stability for most neutron-rich nuclei remain inaccessible, neutron-deficient nuclei can be populated even up to the proton *drip-line*, enabling the study of the decay of the last proton-bound nucleus in certain isotope chains [8].

Detailed decay spectroscopy experiments using implanted RIBs are a powerful technique for exploring exotic nuclei, offering access to rich structural information [7–12], which provides a crucial testing ground for nuclear models under extreme conditions. Furthermore, β decay gives direct access to the absolute values of the Fermi B(F) and Gamow-Teller B(GT) transition strengths, which are important observables for nuclear structure. Comparing these transitions in pairs of *mirror nuclei*, where the number of neutrons and protons are exchanged, allows for the investigation of isospin symmetry [13] and isospin mixing phenomena [7]. Another topic of interest is the accumulated Gamow-Teller (GT) strength distribution, which is sensitive to nuclear shape and can therefore shed light on the shape of the decaying nucleus [14–16]. In addition, nuclear properties such as half-lives, masses, and β-strengths are paramount for nuclear astrophysics, as many of these exotic nuclei lie on the reaction pathways involved in nucleosynthesis processes, where the chemical elements composing our Universe are produced.

High-resolution β-decay spectroscopy experiments use high-purity germanium (HPGe) detectors to measure the individual γ rays emitted after β decay. Usually, HPGe detectors have excellent energy resolution but low efficiency for detecting high-energy γ rays. This, combined with the higher fragmentation of the γ cascades de-exciting levels located at high excitation energies, makes the measurement of β feeding at high excitation energies more challenging. This effect is known as the Pandemonium systematic error [17]. The Total Absorption γ-ray Spectroscopy (TAGS) technique [18, 19] is the best method to measure the β-intensity distribution free from Pandemonium. This technique has been successfully employed in β-decay studies for many years, yielding important results relevant to nuclear structure, nuclear astrophysics, and applications in reactor and neutrino physics (see [19] for a recent review). It is worth emphasizing the complementarity of high-resolution and TAGS measurements, as the former provides valuable knowledge of low-energy levels, which is important for the proper application of the latter. Finally, the Pandemonium effect can be especially significant in exotic nuclei since higher-energy levels can be populated in β decay due to the larger Q_β value compared to more stable nuclei. Hence, TAGS measurements are crucial for studying nuclei far from stability.

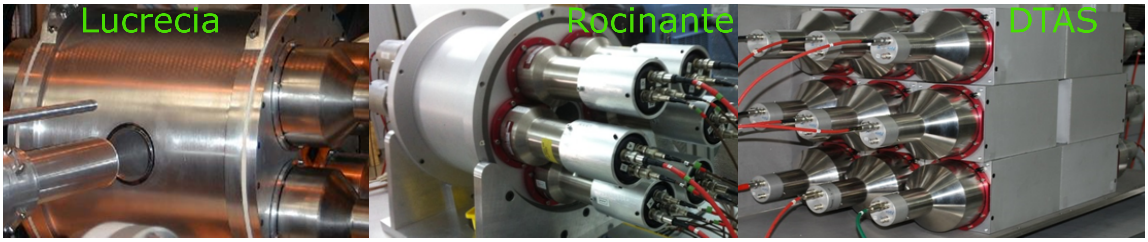

Figure 1: TAS spectrometers developed at IFIC-Valencia, from the left: Lucrecia, Rocinante and DTAS.

2. The Total Absorption Gamma-ray Spectroscopy technique

The TAGS technique [18, 19] is based on detecting the full energy of the γ cascades following β decay in large calorimeters, known as Total Absorption Spectrometers (TAS), which are characterized by high γ efficiency. An iterative algorithm [20] is then used to obtain the β-intensity distribution, $I_\beta(E)$, by deconvoluting the measured TAS total energy spectrum with the TAS spectrometer's response to the decay, according to the following equation [18]:

$$D_i = \sum_j R_{ij} I_\beta(E_j) \,, \tag{1}$$

where D_i is the data measured in the TAS spectrum in channel i, and R_{ij} is the TAS response matrix, representing the probability that feeding at energy E_j produces a count in channel i. The response, determined by Monte Carlo simulations benchmarked against calibrations, depends on knowledge of the branching ratios of the energy levels in the daughter nucleus. TAGS analyses developed by the IFIC-Valencia group use results from high-resolution measurements for the low-lying levels and the nuclear statistical model for the unknown high-lying states [21]. Decay contamination in the spectra is either measured separately or simulated based on available decay information. Segmented TAS also have the advantage of providing module-multiplicity gated spectra, allowing for the extraction of information on the γ-cascade multiplicity.

The TAGS technique, which provides the β-intensity free from the Pandemonium effect, enables us to determine the β-strength distribution as a function of the excitation energy in the daughter nucleus. This is a fundamental quantity for comparison with theoretical microscopic models [16, 19, 22], allowing for a highly sensitive test of these models and improving our understanding of residual interactions between nucleons. In fact, precisely determining the β-strength imposes constraints on the theoretical models, offering complementary insights to integrated observables such as half-lives, total proton (neutron) emission probabilities, and masses — all of which are essential components in the calculations of rapid proton (neutron) capture process nucleosynthesis.

Fig.1 shows, in chronological order, the TAS spectrometers that have been developed at IFIC-Valencia and are currently available for these studies. The first one on the left in the figure, Lucrecia, is permanently installed at ISOLDE-CERN (Switzerland), where it has been widely and successfully used over the last 20 years [16, 23]. It is a large NaI(Tl) scintillator crystal of cylindrical shape (ϕ=h=38 cm) used with a tape station where the beam is implanted. Rocinante, shown in the center of Fig.1, is made of 12 BaF_2 crystals. It was the first segmented TAS [24] and has been used in several experiments at IGISOL-JYFL (Finland). The most recent one is the DESPEC TAS spectrometer (DTAS) [25], on the right in Fig. 1. It is a compact array of 18 large, movable NaI(Tl) crystals, first successfully used at IGISOL with a tape station for beam implantation [22, 26], and more recently at both RIKEN (Japan) [27] and GSI (Germany) [28], combined with AIDA, a high-pixel-density double-sided silicon strip detector (DSSSD) array.

Currently, under the framework of the $(NA)^2$STARS project [29], we are developing a next-generation hybrid TAS spectrometer, named STARS, which will be used for a wide range of topics in nuclear structure and astrophysics (see Section 3.2).

3. Beta-decay measurements with the TAGS technique

In the following, I will present two β-decay measurements using the TAGS technique, each aimed at a different goal and currently underway.

3.1 Nuclear shape in odd-A mercury isotopes at ISOLDE-CERN

A measurement of the GT strength distribution in the daughter nucleus is a useful probe for investigating the shape of the progenitor state. This is because the GT strength distribution reflects the overlap between the wave functions of the initial and final nuclear states involved in the β-decay transition. Thus, the GT strength is sensitive to the nuclear shape of the β-decaying parent state [14, 15]. Under favorable conditions, theoretical calculations of the GT strength assuming different deformations (oblate or prolate) reveal distinct patterns based on the shape of the parent nucleus [15]. Comparing these calculations to the experimental GT strength distribution, measured free from the Pandemonium effect using the TAGS technique, enables deducing the shape of the parent state [16]. This approach has been successfully applied in numerous experimental studies with Lucrecia at ISOLDE (see [16, 19, 23] and references therein). Typically, calculations assume the same shape for both parent and daughter nuclei. Recently, an improved analysis method has been developed [30] to handle more complex scenarios in which parent and daughter nuclei may exhibit different degrees of oblate-prolate mixing.

The shape-transitional region around mass $A = 186$ is considered a benchmark for studies on shape transitions and shape effects ([30] and references therein). An almost unique feature emerges in the nuclear chart within exotic mercury nuclei: a staggered change in mean-square charge radii, which indicates an interplay of single-particle and collective degrees of freedom and is generally associated with oblate/prolate shape changes [31]. In particular, charge radii measurements suggest that different nuclear shapes are expected for the ground and isomeric states of odd-A mercury isotopes. These nuclides are of significant interest for studying shape coexistence effects, as they represent the first case in the entire nuclear chart where two different shapes are expected to coexist within the same nucleus.

Very recently, we have performed an experiment at ISOLDE-CERN using the Lucrecia TAS to measure the β decay of the odd-A mercury isotopes (experiment IS707 [32]). It is worth emphasizing that this is the first TAGS study of isomers with different deformations coexisting in the same nucleus. This experiment was made possible by a clever combination of ancillary detectors with Lucrecia, along with the high selectivity of the ISOLDE ion source, which enabled the separation of different isomers. The ultimate goal of the experiment is to extract the decay strength distributions and compare them to recent theoretical calculations [3], thereby providing conclusive insights into the shapes of both ground and isomeric states in these nuclei.

3.2 Beta-decay of proton-rich nuclei at GANIL with STARS

The new experiment E891_23 [33], recently approved to be performed at GANIL, will be the first study of proton-rich exotic nuclei using the TAGS technique in combination with charge-exchange (CE) reactions. We plan to measure the β decay of a variety of proton-rich nuclei in the Cr-Zn region using the TAGS technique, with expected outcomes in nuclear structure and nuclear astrophysics, as well as advancements on the TAGS technique itself.

Over the last decade, we have extensively investigated the β decay of proton-rich nuclei by high-resolution experiments, employing HPGe detectors and DSSSD arrays at both the GANIL (France) and RIKEN fragmentation facilities [7–12], complemented by (^{3}He,t) CE reactions on the mirror nuclei, conducted at RCNP (Japan) [13]. From a nuclear physics perspective, pairs of mirror nuclei are expected to be identical. In reality, their properties — such as the structure of levels, quantum numbers, half-lives, β-decay strengths, etc. — are very similar but not identical. Small differences can break the ideal isospin symmetry, allowing us to investigate fundamental questions related to the role of isospin in atomic nuclei. This is what we can learn by comparing Fermi and GT transitions in pairs of mirror nuclei, through a combined study of the β decay of a given nucleus and the CE experiment carried out using its (stable) mirror nucleus as the target.

The comparison between β-decay and CE results offers valuable insights into the potential occurrence of the Pandemonium effect in the aforementioned high-resolution measurements, underscoring the necessity of performing new measurements with the TAGS technique for specific nuclear cases. The new experiment E891_23 will make possible the determination of the GT strength free from Pandemonium in these nuclei, with important implications for both nuclear structure models and nucleosynthesis simulations. Some of these decays are relevant for the ^{44}Ti nucleosynthesis. Additionally, the availability of CE data will allow us to compare the accumulated GT strength in mirror nuclei, enabling the investigation of isospin symmetry without Pandemonium. Furthermore, this unprecedented comparison between TAGS and CE results will provide an additional validation of the TAGS technique in the high-energy region, where the analysis methods developed by the IFIC-Valencia group rely on the nuclear statistical model (see Section 2).

Experiment E891_23 will be the first to be performed using the new hybrid TAS spectrometer, STARS, currently under development within the framework of the (NA)^{2}STARS project [29]. This innovative spectrometer will benefit from the excellent energy resolution and timing of LaBr$_3$(Ce) crystals, while maintaining the large efficiency for γ detection typical of TAS spectrometers. It will be the first device in the world to achieve such a unique combination. This, along with the device's increased segmentation, will enable detailed decay measurements of exotic nuclei, aiming at a broad study of nuclear structure and astrophysics across the nuclear landscape.

The STARS spectrometer will be developed by upgrading our existing TAS spectrometers, Rocinante and DTAS, with the addition of up to 16 LaBr$_3$(Ce) modules arranged in a star configuration between the TAS instrument. This upgrade will also allow for the placement of the DSSSD in the middle of the spectrometer. In particular, DTAS was designed for use at fragmentation facilities and has already been coupled with a DSSSD detector in recent experiments [27, 28]. The STARS geometry is currently under study through ongoing GEANT4 simulations [34]. Figs.2 and

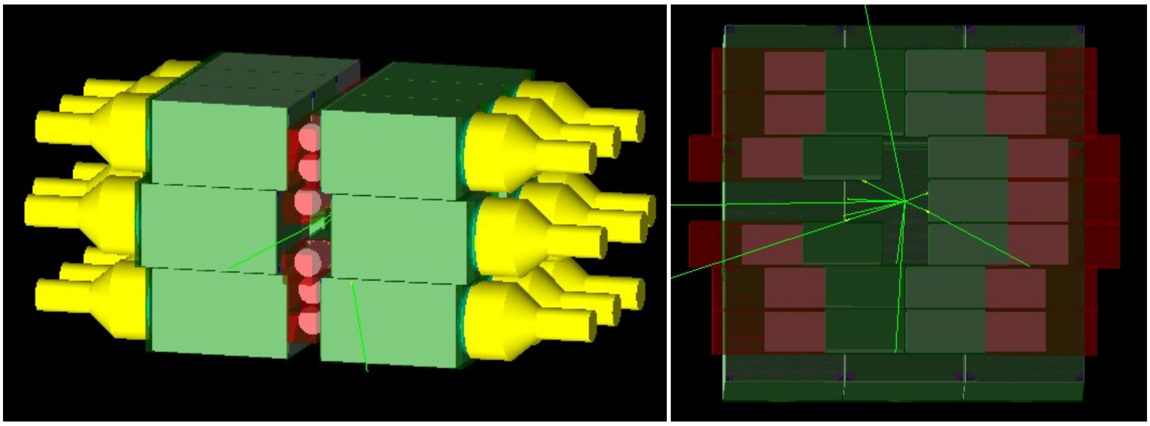

Figure 2: GEANT4 simulations of possible geometries for STARS [34]. The left figure shows the coupling of DTAS and LaBr$_3$(Ce) crystals, arranged according to configuration 1, which is displayed on the right, with the beam entering from the left.

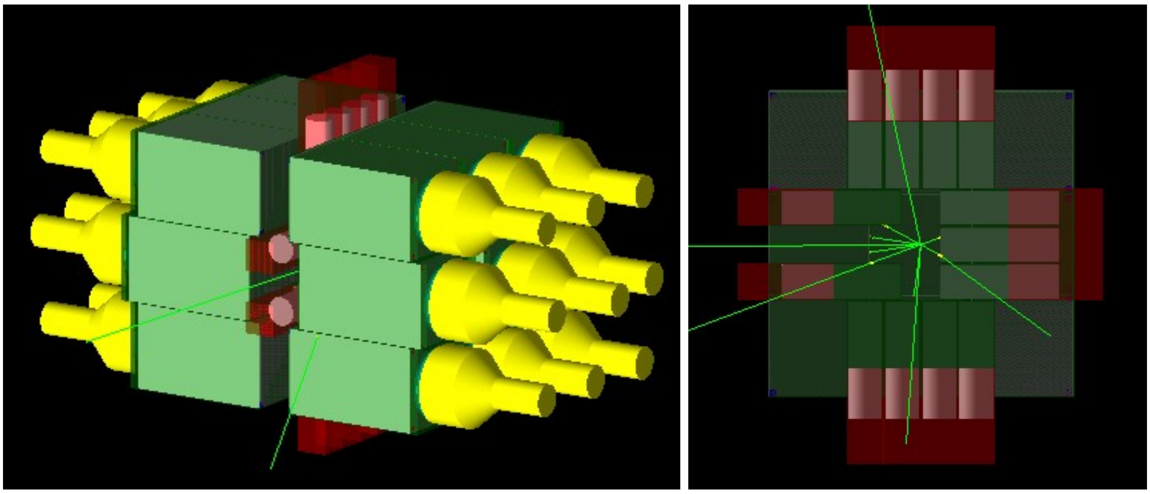

Figure 3: GEANT4 simulations of possible geometries for STARS [34]. The left figure shows the coupling of DTAS and LaBr$_3$(Ce) crystals, arranged according to configuration 2, which is displayed on the right, with the beam entering from the left.

3 show two potential configurations of the LaBr$_3$(Ce) detectors and their coupling with DTAS. It is significant to stress that both Rocinante and DTAS will be upgraded, expanding the potential for use at various international facilities.

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