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A novel technique for lifetime measurements in heavy neutron-rich nuclei: The reversed plunger

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Abstract. A novel technique, the so-called 'reversed plunger', was used for the first time to measure lifetimes of nuclear excited states on the order of picoseconds in heavy neutron-rich nuclei at the Legnaro National Laboratories. Preliminary spectra show that the commissioning of the technique was successfully performed employing the Advanced Gamma-Ray Tracking Array (AGATA), the magnetic spectrometer PRISMA, and the plunger device in the reversed configuration.

1 Introduction

The coupling of large acceptance magnetic spectrometers to large γ-ray arrays provides the possibility to measure lifetimes of nuclear-excited states populated via multi-nucleon transfer reactions by exploiting the 'differential plunger' technique [1, 2]. This technique is well established and has been used extensively to measure lifetimes of nuclear-excited states [3–6]. A schematic representation of this technique is shown in Fig. 1. The target and the degrader foil are placed parallel to the entrance of the magnetic spectrometer. The beam is tilted with respect to the normal of the target surface as much as the grazing angle θ_g, thus the beam-like fragments travel with a given velocity $\vec{v}_{BL1}$ perpendicularly to the degrader surface as seen in Fig. 1. The beam-like fragments (in this case the nuclei of interest) lose a part of their energy in the degrader foil and enter the magnetic spectrometer with velocity $\vec{v}_{BL2}$. If an excited state with a lifetime in the sensitive range of the technique, from a few to hundreds of picoseconds, decays by γ-ray emission in between the two foils or after the degrader, the observed energy of the γ-ray in the two cases is different, due to Doppler effect ($v_{BL1} > v_{BL2}$). Consequently, two peaks corresponding to the same γ-ray transition will appear in the measured γ-ray spectrum. Taking advantage of the kinematic reconstruction from the spectrometer and the intensities of these two peaks, measured for different distances between the target and the degrader,

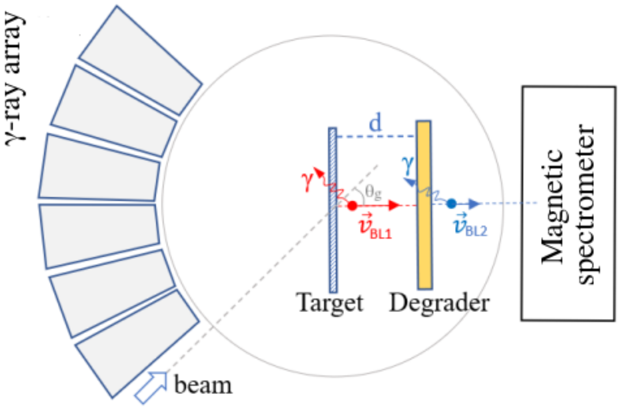

Figure 1. Schematic representation of the differential plunger configuration: γ-ray array coupled to a magnetic spectrometer (used to identify the reaction products in mass, atomic number, charge state, and velocity) and a plunger device. The velocity of the beam-like particles between the target and the degrader is $\vec{v}_{BL1}$ and after the degrader is $\vec{v}_{BL2}$. θ_g is the grazing angle.

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the lifetime of the state of interest can be obtained.

In a binary reaction, the isotope identification provided by the magnetic spectrometer can be exploited to perform spectroscopic studies not only of the isotope detected by the spectrometer, but also of the undetected partner, whose kinematics can be reconstructed based on the angle of entrance and the velocity vector of the ion measured in the spectrometer. This technique has been successfully exploited in the past and allowed the first measurements of γ rays from excited states of several nuclei, as for example: ^{196}Os and ^{200}Pt [7, 8] or even heavier elements like ^{240}U [9]. The identification of beam-like fragments allows one to reconstruct the kinematics of the target-like fragments and perform a Doppler correction on an event-by-event basis.

The differential plunger is an excellent tool to measure lifetimes of nuclear-excited states in the picosecond range. The regions of the nuclear chart that can be explored by using this technique are restricted by the identification capabilities of the magnetic spectrometer, which typically have an atomic charge resolution $\Delta Z/Z \approx 1/60$ [10]. Based on experience, for nuclei with Z>54 and relatively low energy, the identification with sufficient resolution by the spectrometer becomes difficult. As a result, performing lifetime measurements of excited states in nuclei heavier than Xe become challenging.

Therefore, we have developed a new technique which overcomes such limitation and allows measurements for nuclei with Z>54: the reversed plunger configuration. In the standard configuration of the differential plunger, the target is followed by the degrader while in the reversed configuration, the degrader faces the beam. The target and the degrader, placed parallel to each other, are tilted in such a way that the target-like fragments (the heavy nuclei of interest) travel from the target toward the degrader. A schematic representation of the geometrical arrangement of the setup is shown in Fig. 2. In this configuration of the plunger, the beam passes through the degrader, loses some of its energy, and interacts with the target in which the multi-nucleon transfer reaction occurs. The reaction may also occur from the interaction of the beam with the degrader, but by choosing them with slightly different masses, the respective grazing angle will differ, preventing the products from the reaction of the beam with the degrader from entering the spectrometer. After the reaction in the target, the beam-like fragments, with a sufficiently light mass and atomic number, enter the magnetic spectrometer. In contrast, the heavy target-like fragments travel from the target to the degrader, which is thick enough to stop them completely. Therefore, one ends in a situation similar to that of the differential plunger configuration introduced previously, where the nuclei of interest travel between the two foils with a given velocity. The deexcitation of the nucleus of interest in flight or at rest will give rise to the shifted and the unshifted γ-ray peak in the measured γ-ray spectra. The intensity of the two can be used to determine the lifetime of the state of interest.

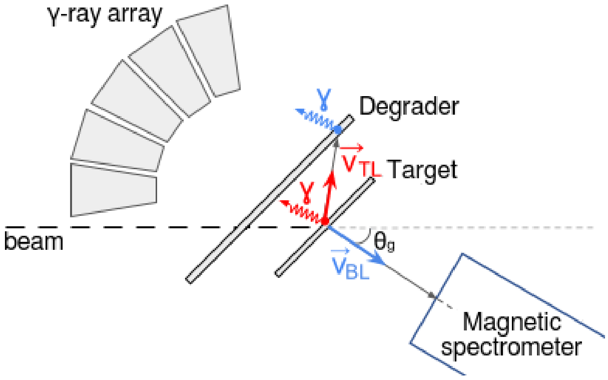

Figure 2. Schematic representation of the reversed plunger configuration: γ-ray array + magnetic spectrometer + plunger in the reversed configuration. The beam passes through the degrader foil and interacts with the target. Beam-like fragments enter the spectrometer, while target-like fragments (heavy neutron-rich nuclei of interest) travel towards the degrader foil. The deexcitation of target-like fragments may take place in flight with velocity v_{TL} (velocity in between the degrader and target) or at rest after being stopped in the degrader foil. Due to the Doppler effect a stopped and a shifted component should be observed in the γ-ray spectrum.

2 Experimental considerations

For the proposed technique it is crucial to account for the kinematics of the beam-like and target-like particles, in order to define appropriately the geometry of the experimental setup. The yields and the kinematics of the particles are calculated using the GRAZING code [11]. Calculations for the one-proton transfer reaction ^{93}Nb(^{34}S, ^{35}Cl)^{92}Zr were performed and are shown in Fig. 3. The beam energy is set at 150 MeV, around 30% above the Coulomb barrier. As seen in the left panel of Fig. 3, the differential cross-section for the beam-like particles, ^{35}Cl, is peaked at 44°, while target-like particles are scattered at 62° with respect to the beam direction. The plot on the right shows the total kinetic energy of the beam-like and target-like particles. Beam-like particles have an energy of around 3 MeV/u, enough to allow their identification with sufficient resolution in atomic number, while target-like particles travel from the target to the degrader with $\beta = 3\%$.

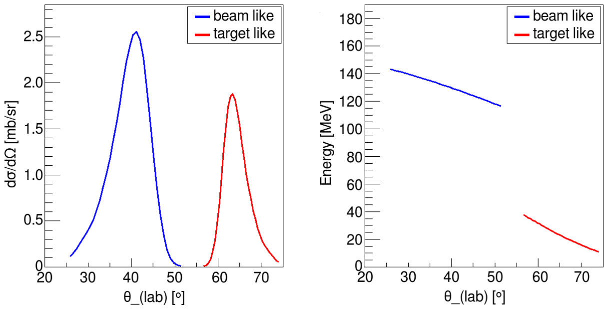

Figure 3. *Left:* The angular distribution of the differential cross-section for beam-like and target-like particles. *Right:* The total kinetic energy of beam-like and target-like particles.

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To validate the feasibility of the technique detailed Monte Carlo simulations have been performed with the Geant4 toolkit [12] and the AGATA simulation package [13]. The AGATA simulation package based on C++ classes of Geant4 contains important implementations that can be used for performing lifetime measurements with the Doppler-shift based techniques, as for example:

- the reaction mechanism in the target,
- interaction of the reaction products with other materials placed after the target: like a stopper foil or degrader
- reaction kinematics
- de-excitation of excited nuclei following complex decay patterns of γ-ray cascades, branching ratios and lifetimes of the nuclear-excited states.

Simulations were performed for a target-degrader distance of 200 μm. The lifetime of the 4^+ state of ^{92}Zr is known from a Coulomb excitation experiment [14] ($t_{1/2}$=102(5) ps). The nucleus of interest was populated using the aforementioned reaction. A partial level scheme of ^{92}Zr is shown on the left panel of Fig. 4 and the known half-lives of the energy levels are indicated. The results of the simulations are shown on the right panel of Fig. 4. The γ-ray energy is plotted with respect to the angle between the direction of the γ-ray photon and the direction of the ^{92}Zr ion. Since the angular coverage of the solid angle from the γ-ray array is continuous and the angles between the direction of the emitting particle and the direction of the γ-ray photon varies from 20° to 120°, to distinguish between the shifted and the unshifted γ-ray component, it is convenient to represent the data in the form shown on the right panel of Fig. 4. Gamma rays emitted at rest will appear as straight lines in the matrix since the measured energy does not depend on the angle, while the γ-rays emitted in flight will appear as curved lines due to the Doppler effect. One can see in the figure two different components, the shifted and the stopped component corresponding to the $4^+ \rightarrow 2^+$ transition of ^{92}Zr, emerging due to the lifetime of the nuclear-excited state.

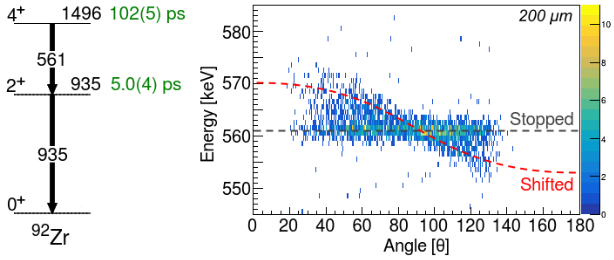

Figure 4. *Left:* Partial level scheme of ^{92}Zr. Half-lifes of nuclear excited states are indicated in green [14]. *Right:* Simulated gamma-ray energy (non-Doppler corrected) versus the angle between the direction of the γ-ray photon and the direction of the ^{92}Zr ion. The stopped and the shifted components are indicated in the figure with the black and red colors, respectively.

3 Commissioning experiment and results

An experiment was performed at the Laboratori Nazionali di Legnaro (LNL) to test the validity of the proposed technique. The aim of the experiment was to remeasure the lifetime of the 4_1^+ state of ^{92}Zr which can be used as a benchmark for the proposed technique. Excited states of ^{92}Zr were populated via the transfer reaction ^{93}Nb (^{34}S, ^{35}Cl) ^{92}Zr. A beam of ^{34}S with an energy of 180 MeV, provided by the TANDEM-XTU accelerator [15], passed through a Ta degrader, 3 mg/cm^2 thick, losing a part of its energy, approximately 30 MeV. After that, the beam impinged on a self-supporting target of ^{93}Nb, 1 mg/cm^2 thick. The target and the degrader were mounted in the plunger device [16], which was placed at the geometrical center of the reaction chamber and titled at an angle of 50° with respect to the beam direction in order for target-like fragments to travel towards the degrader foil. Beam-like reaction products entered the PRISMA spectrometer placed at the grazing angle of 44° with respect to the beam direction.

Gamma rays were measured with the Advanced GAmma-ray Tracking Array (AGATA) [17, 18]. Beam-like particles were identified in mass, atomic number, and velocity by the PRISMA spectrometer [19]. Measurements were performed for three different distances between the plunger and the degrader foil: 100 μm, 200 μm, and 700 μm, and the γ-ray spectrum measured with AGATA is shown for each case in Fig. 5. As one can see from the figure, at 100 μm distance, γ rays are emitted at rest. When increasing the distance, the shifted component appears in the spectrum, as expected. The stopped component at 561 keV is marked with a dashed line in the spectrum.

The analysis to extract the lifetime of the 4^+ state and compare it with the literature value is ongoing. The experiment successfully confirmed the power of the suggested technique for measuring lifetimes of neutron-rich nuclei which could not be measured with the existing techniques.

4 Summary and future perspective

The reversed plunger configuration was tested for the first time in the Laboratori Nazionali di Legnaro. The experiment aimed at remeasuring the lifetime of the 4^+ state in ^{92}Zr using the proposed technique. The AGATA array was coupled to the PRISMA magnetic spectrometer and the plunger device in the reversed configuration. The preliminary γ-ray spectra shows that the proposed technique is able to separate the two γ-ray components, shifted and stopped. The analysis employing the standard techniques, the Differential Curve Method and the Differential Decay Curve Method [1], is still on going and will demonstrate if the reversed plunger reduces the uncertainty of the measured lifetime compared to the result from the literature. A new technique to analyze the data taken with the reversed plunger, which employs Geant4 simulations, is being developed. This analysis technique will also consider the energy spread of the beam due to the loss in the degrader, which might affect the resolution of the lifetime measurement.

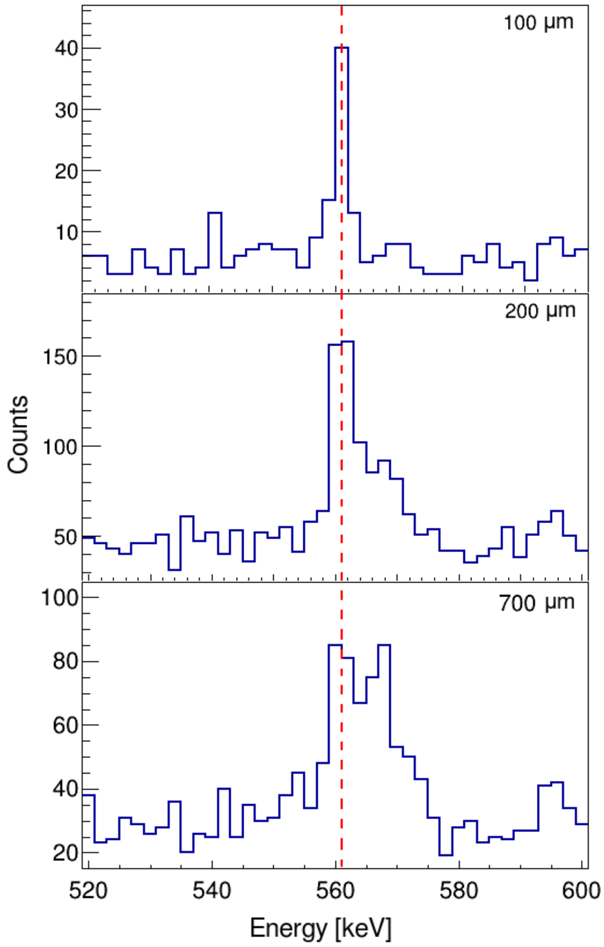

Figure 5. Gamma-ray spectrum for different distances between the target and the degrader (measured with the condition that the angle between γ-ray photons and direction of ^{92}Zr ions is smaller than 60°). The stopped component at 561 keV is marked with the dashed line.

This technique opens new possibilities for performing lifetime measurements of nuclear-excited states in heavy ions produced via multi-nucleon transfer reactions that due to their high atomic number and mass could not be identified in the magnetic spectrometer, allowing one to reach nuclei in regions of the nuclear chart yet to be explored. The shortest lifetime that one can measure with this technique depends on the kinematics of the reaction. In heavy systems,with mass around 190, lifetimes down to a few picoseconds can be measured.

An experiment using the reversed plunger was performed after the commissioning of the technique aiming to study nuclei in the vicinity of N=126 where shape transitions from prolate to oblate are expected to appear [20].

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