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Study of intruder states in ^{83}Se via lifetime measurements

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Summary. — The ^{83}Se nucleus is at the mid of the proton fp-shell and thus it is a good candidate for studying the properties of particle-hole intruder states lowered in energy by large quadrupole correlations. Lifetime measurement of the low-lying intruder states will provide information on their wave function and will allow one to estimate the degree of $N = 50$ core breaking in the ground state of Se isotopes. The lifetime of the 540-keV $1/2^+$ state of ^{83}Se was measured using the Recoil Distance Doppler-Shift method. A beam of ^{82}Se, with intensity 0.02 pnA, accelerated at 270 MeV by the ALPI-TANDEM accelerator at LNL-INFN, was sent into a deuterated polyethylene (C_2D_4) target which was evaporated on a 6 mg/cm^2 thick gold layer. The GALILEO γ-array was coupled to the SPIDER silicon-array, providing the needed channel selectivity through coincidence measurements between γ rays and protons from the (d,p) reaction.

1. – Introduction

Shape coexistence is an ubiquitous feature in the nuclear structure that has been studied both theoretically and experimentally. This phenomenon is manifested in the nuclear landscape because of the interplay between two opposing tendencies: the stabilizing effect of closed shells which causes the nucleus to retain a spherical shape and the residual quadrupole interaction between protons and neutrons which drives the nucleus into deformed configurations at low excitation energies [1]. Intruder states, which appear as multiparticle-multihole excitations across a closed shell gap, become lower in energy especially for nuclei with a nearly closed proton or neutron shell, and with the partner nucleon having a near mid-shell nucleon number. In regions of the nuclear chart where the shell gap is reduced, these deformed configurations may even become the ground state, giving rise to the so-called "island of inversion" [2].

Around the $N = 50$ shell gap, intruder states with spins $1/2^+$ and $5/2^+$, originating from the $s_{1/2}$ and $d_{5/2}$ orbitals were first observed in ^{83}Se [3, 4] and, later on, in the other $N = 49$ isotones ^{87}Kr, ^{81}Ge and ^{79}Zn. In ^{83}Se, these intruder states reach energies of around 500 keV, the lowest among the other $N = 49$ isotones. The ^{83}Se nucleus is at the mid of the proton fp-shell and it should have the maximum of quadrupole correlations which makes it a good candidate to understand the collectivity of the particle-hole intruder states in this region [5]. Indeed, large-scale shell-model calculations predict a quenching of the energy of the intruder states in ^{83}Se, at variance with the experimental data [6]. Lifetime measurements of the intruder states of ^{83}Se would give an indication about their wave function and would allow estimating the degree of the $N = 50$ core breaking in the ground state of Se isotopes. Moreover, such measurements could shed light on the behavior of the $N = 50$ shell gap towards ^{78}Ni, a double-magic nucleus in which intruder configurations competing in energy with the spherical ones have also been found [7].

2. – Experimental method and setup

Low-lying excited states in ^{83}Se were populated using a (d,p) reaction. A beam of ^{82}Se with intensity of 0.02 pnA and energy of 270 MeV, accelerated by the ALPI-TANDEM accelerator complex at Laboratori Nazionali di Legnaro - INFN, impinged on a deuterated-polyethylene (C_2D_4) target which was evaporated on a 6 mg/cm^2 gold backing (to allow the stretching of the target). For the detection of the emitted γ rays, the GALILEO γ-ray detector array [8] in the phase II configuration was used. GALILEO consists of 50 HPGe crystals, 20 single Compton suppressed GASP detectors, and 10 triple clusters with anti-Compton shields, positioned in rings covering different angles as represented in the schematic view in fig. 1.

To reach the desired channel selectivity, the GALILEO γ-ray detector array was coupled to SPIDER [9]. SPIDER is a striped silicon detector designed to work as an ancillary device coupled with γ-ray detector arrays and it is used for detecting charged particles. In our experiment, this detector was used for the proton tagging of the (d,p) transfer reaction. SPIDER was placed inside the vacuum chamber, as shown in fig. 1, covering backward angles, from 130 to 165 degrees, with respect to the beam direction.

To measure the lifetime of the 540-keV $1/2^+$ state, the Recoil Distance Doppler-Shift method (RDDS) [10] was employed. It is a Doppler-based technique for measuring lifetimes in the range of picoseconds to nanoseconds. This technique requires a plunger device [11] to be used. The plunger consists of two parallel foils: the target where the reaction takes place, and the "stopper", a thick foil of a high Z material that is used to stop the reaction products. The deuterated target and the gold stopper, with thickness 30 mg/cm^2, were mounted on the plunger device and in-beam measurements were performed in 5 days for several distances between them, ranging from tenths of micrometers to a few millimeters. Additional 5 days of beam time were dedicated to measure lifetimes of other intruder-band states, like the 1100-keV $3/2^+$ and the 1472-keV $3/2^+$

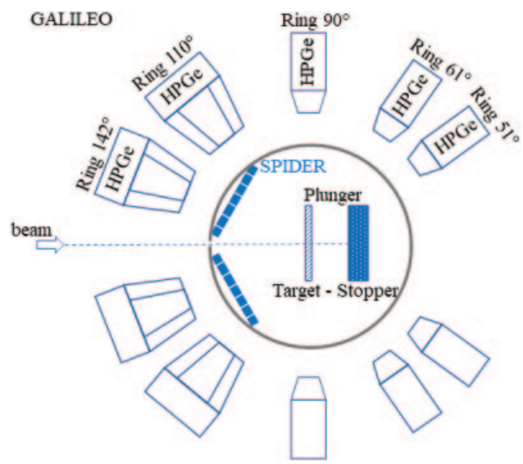

Fig. 1. – Schematic representation of the experimental setup. The GALILEO γ-ray detector array coupled to SPIDER (charged particle detector array) and the plunger device for lifetime measurements.

state, employing the Doppler Shift Attenuation Method [10]. This technique is similar to the RDDS but is suitable for measuring shorter lifetimes, ranging from femtoseconds to picoseconds.

3. – Data analysis and results

Since several channels are open in the reaction, *i.e.*, fusion-evaporation on ^{12}C or Coulex from the interaction of the beam with the gold backing of the target, a selection of the γ rays coming from the decay of the nucleus of interest is necessary. The detection of protons from the (d,p) reaction helps to clean up the spectrum from the background. Moreover, the measured proton energy allows gating on the reaction Q-value which helps to deal with one of the major problems when it comes to lifetime measurements: feeding of the state of interest from long-living levels. Thanks to our setup (GALILEO+SPIDER) γ rays of ^{83}Se depopulating the states of interest could be measured. This selection is provided by reconstructing the kinematic lines. The kinematic line of the 540-keV state, which decays by emitting a 311-keV γ ray, is shown in fig. 2(a). The energy of protons, measured in coincidence with γ rays ranging in energy from 300 to 320 keV, is plotted as a function of the detection angle. From the figure, it can be seen that the protons with energy in the range from 1.5 to 3 MeV emerge from reaction events that directly populate the state of interest. The experimental data and the predicted kinematic line from "NPTool" [12] are in very good agreement with each other.

Gamma-ray spectra at 4 mm distance between target and stopper measured on the 61, 90, and 142 degrees ring of GALILEO in coincidence with protons in the energy range from 1.5 to 3 MeV are shown in fig. 2(b). As it can be seen in the figure, close to the 311 keV peak (a peak coming from the decay of the nucleus at rest), another peak emerges in the spectra from the decay of the nucleus in flight. Due to the Doppler effect, this peak appears shifted at higher energies at forward angles and lower in energy at backward angles. The ratio of the intensity of the shifted and the unshifted component for every distance allows one to construct a decay curve and information on the lifetime of the state, from where this transition depopulates, can be extracted.

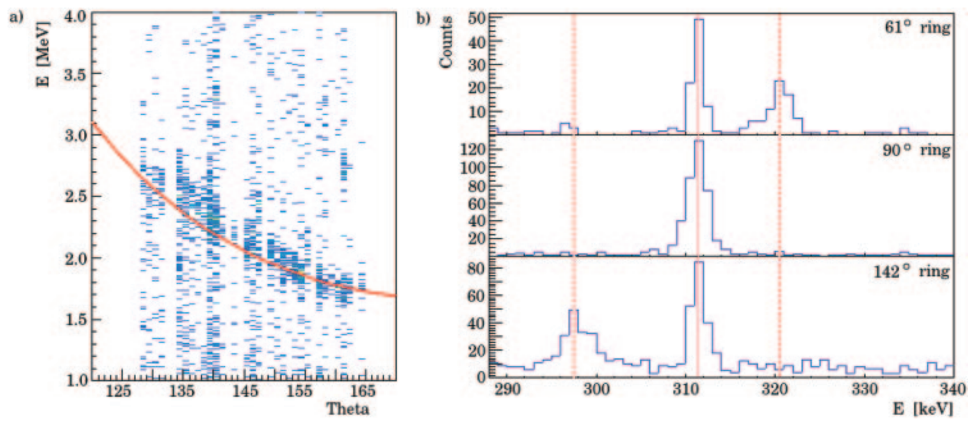

Fig. 2. – (a) The kinematic line for the $1/2^+$ intruder-state at 540 keV in ^{83}Se: proton energy plotted as a function of the detection angle with respect to the beam direction, obtained by gating in the γ energy from 300 to 320 keV. The line represents the fit from NPTool [12]. (b) Gamma-ray spectra at 4 mm distance between target and stopper measured on the 61, 90, and 142 degrees ring of GALILEO. The line at the 311-keV peak marks the unshifted component, while the dashed line indicates the shifted component due to the in-flight emission of the 311-keV γ ray.

4. – Conclusions and future perspective

Low-lying excited states of ^{83}Se were populated using a (d,p) reaction and lifetime measurements of intruder-band states were performed using a plunger device coupled to GALILEO γ-ray detector array and SPIDER silicon-detector. This measurement aims at investigating the degree of $N = 50$ core breaking in ^{83}Se. The results of this experiment presented in this paper are still preliminary and a more detailed data analysis is still ongoing. Experimentally measured lifetimes of the intruder-band states will provide information on their transition probabilities and the comparison with theoretical calculations will give an insight into the nuclear structure of ^{83}Se.

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