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Lifetime measurements using a plunger device and the EUCLIDES Si array at the GALILEO γ-ray spectrometer

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ABSTRACT

The GALILEO γ-ray spectrometer, installed at the Laboratori Nazionali di Legnaro (LNL), benefits from intense stable beams provided by the Tandem-ALPI-PIAVE accelerator complex and from radioactive beams to be delivered in the near future by the SPES facility. The spectrometer is complemented with a variety of ancillary devices to allow for nuclear structure and reaction studies. The 4π Si-ball array EUCLIDES coupled to the GALILEO γ-ray spectrometer represents one of the commonly used setup for experiments aiming at spectroscopic studies. High-efficiency detection of light-charged particles in a fusion–evaporation reaction guarantees good discrimination of different reaction channels and provides essential information for the kinematic reconstruction. In this paper we discuss a configuration of the EUCLIDES array developed for the lifetime measurements of nuclear excited states populated in a fusion–evaporation reaction. In such a configuration a part of the EUCLIDES detectors is disassembled allowing for the installation of

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a plunger device in the reaction chamber. The reduced configuration of EUCLIDES provides high detection efficiency necessary for reliable light charged-particle discrimination. We report on the commissioning experiment focused on the ^{58}Ni(^{58}Ni,3p)^{113}I reaction. The lifetimes of $11/2^-$ and $15/2^-$ states were measured by applying the Recoil Distance Doppler Shift method to be equal to 206(20) ps and 7.9(12) ps correspondingly and were in good agreement with the values cited in the literature. Thus, the combination of the GALILEO and EUCLIDES arrays, and the plunger device has resulted in a powerful experimental setup to determine lifetimes of excited states in neutron-deficient nuclei in the picosecond range.

1. Introduction

In the last decades rapid developments of experimental techniques have boosted the γ-ray spectroscopy field. As a matter of fact efficient γ-ray spectrometers and a wide range of available nuclear reactions to produce exotic nuclei have pushed spectroscopy studies towards the edges of the nuclear stability. One of the most important quantities for the nuclear structure, which can be directly determined from experiments, are the lifetimes of excited states in nuclei. An excited state, once populated in a nuclear reaction, will remain excited for the mean lifetime $\tau = \hbar/\Gamma$, where Γ is the level width [1], until it decays to a state of lower energy. The probability of this decay is inversely proportional to τ and determined by the matrix element, which links the initial and final states by a transition operator. Therefore, the aim of the lifetime measurements is to obtain information on the electromagnetic matrix elements which is a crucial test for validation of various theoretical models. The developed experimental techniques cover a different range of lifetimes and can be divided into the direct and indirect methods. The direct ones, such as the recoil distance Doppler shift method (RDDS) and the Doppler shift attenuation method (DSAM), provide τ as a result of measurements. The indirect methods, such as the nuclear resonance fluorescence method and the Coulomb excitation, derive τ using measured Γ-width or from the excitation cross-sections extracted from the measured discrete γ-ray intensities. A considerable number of experiments have been performed using the γ-ray Doppler shift techniques: the lifetime of an excited state can be inferred using the measured velocity of a recoiling nucleus in the excited state and the Doppler energy shift of γ rays depopulating the level. DSAM typically yields the lifetime of a state, τ, in the range of 1 fs $\lesssim \tau \lesssim$ 1 ps, while the RDDS method yields values in the range of 1 ps $\lesssim \tau \lesssim$ 1 ns.

Excited states in neutron-deficient nuclei can be populated in fusion–evaporation reactions utilizing high-intensity stable beams. The compound nucleus typically lives long enough for all of the excitation energy to be shared equally between nucleons such that all memory of formation is lost, hence, the probability of various decay modes is independent of the formation of a compound nucleus. Due to a high excitation energy of the compound nucleus there is a large probability of decaying via particle emission, and if the daughter nucleus still has a high excitation energy this process will continue to occur in sequence. Finally, the recoil nucleus will de-excite to its ground state via γ-ray emission. However, the most exotic species may be produced at small part of the total cross-section. Therefore, γ-ray spectrometers are usually coupled to ancillary detectors and magnetic spectrometers in order to investigate weakly-populated reaction channels. The new γ-ray spectrometer GALILEO, the resident array at Legnaro National Laboratories [2], benefits from intense stable beams provided by the ALPI-PIAVE and XTU-Tandem accelerators.

The present paper reports on the first lifetime measurements via the RDDS method using γ-γ spectra recorded by GALILEO in coincidence with light charged particles detected by the EUCLIDES Si-array. The details of the experimental setup are covered in Section 2, the analysis procedure and the results are discussed in Section 3.

2. GALILEO γ-ray spectrometer

The GALILEO γ-ray spectrometer in Phase I [2] consists of 25 Compton-suppressed High Purity Germanium (HPGe) tapered detectors, originating from the GASP array [3], grouped into 4 rings. Three backward rings at angles of $\Theta_0 = 152°$, $\Theta_1 = 129°$ and $\Theta_2 = 119°$ support 5 detectors each, while the fourth ring at angle of $\Theta_3 = 90°$ comprises 10 detectors. The detectors of ring 3 can be relocated to the rings at Θ_4=61° and Θ_5=51° to maximize the efficiency for the lifetime measurements using Doppler shift method [4]. The angles Θ_{0-5} are given with respect to the beam axis. The measured absolute efficiency is $\sim$ 2.3% and the average resolution (Full Width at Half Maximum, FWHM) is around 2.5 keV for 1.3 MeV energy γ-rays, with the Peak to Total ratio $\sim$ 55%. GALILEO can be run in a stand-alone mode or coupled to ancillary devices. During the first experimental campaigns it was used together with ancillary detectors such as the light-charged-particle detector array EUCLIDES [5]; pixel-type silicon detector TRACE [6,7]; the heavy ion detector for Coulomb excitation measurements SPIDER [8]; the plunger device [9] and the NEUTRON WALL [10,11]. To increase the γ-ray efficiency for high-energy transitions a LaBr$_3$ array [12,13] can be used additionally to HPGe detectors. The GALILEO data acquisition system [14] is fully digital and it is synchronized by a distributed clock using Global Trigger System (GTS). Details on the digital data acquisition and electronic channels available for ancillary detectors can be found in Ref. [5]. The light charged-particle identification of EUCLIDES relies on the ΔE-E method. The energy loss in the thin ΔE detector is related to the total energy loss in the thick E detector by the Bethe–Bloch equation [15]. Almost 4π coverage of the solid angle and high granularity of EUCLIDES ensure its high particle detection efficiency and the possibility to reduce the Doppler broadening of peaks in the recorded γ-ray spectra by an event-by-event kinematic reconstruction of the trajectory of the recoiling nucleus [5]. In the plunger configuration, presented in Figs. 1 and 2, EUCLIDES consists of 5 segmented ΔE-E telescopes placed at the most forward angles (at $\sim$ 30°) and 10 single-plate telescopes in the second forward ring (at $\sim$ 60°), which are arranged in a self-supported semi-sphere covering about 30% of the solid angle. The rest of the telescopes are removed allowing the installation of the support for the plunger device. The ΔE-E detectors are secured in the printed circuit board (PCB) which can be itself anchored to the holding structure in the GALILEO reaction chamber. Inside the chamber, see Fig. 2.A, the plunger is supported by the structure which is itself fixed directly to the output port of the beam line.

The 1 mm thick active Ta-collimator of ⌀ 5 mm is installed at the centre of the beam line output port for the purpose of beam tuning. To reassure that none of the elastically scattered particles could enter the Si telescopes two absorbers are needed. The first one is a 50 mm-length and 14 μm-thick Al tube inserted from the exit port of EUCLIDES parallel to the beam direction. The tube is isolated from one end to touch the stopper support, see Figs. 1 and 2B. The second absorber is a disc of ⌀ 21 cm, with a central hole (to insert the tube-absorber) of ⌀ 3.2 cm, made of 42 μm-thick Al, isolated using 7 μm Upilex-75S foil from the ΔE-E telescopes. The disc absorber shields completely all the EUCLIDES detectors as is shown in Fig. 2C. Thus, the channel selection capability of EUCLIDES can be exploited also in RDDS experiments.

Designed to comply with the geometrical restrictions imposed by the EUCLIDES array, the dedicated plunger device holds two stretched

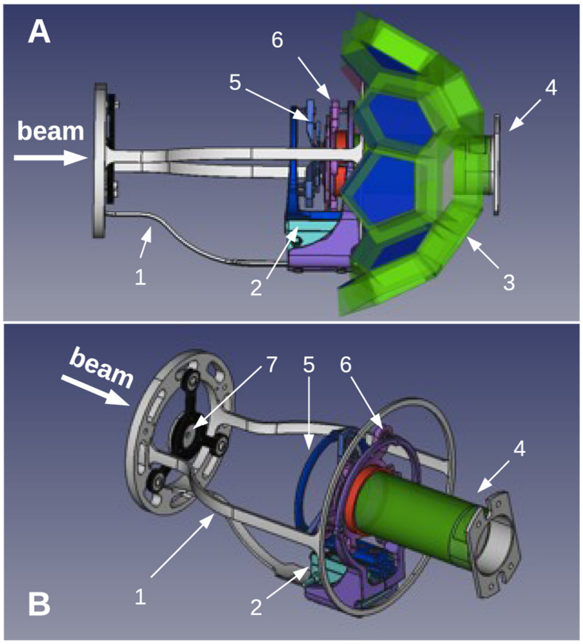

Fig. 1. CAD drawing of the 15 ΔE-E telescopes arranged around the plunger device and its support. By numbers are denoted: *1* — mechanical support for the plunger; *2* — plunger motor; *3* — ΔE-E telescopes; *4* — tube absorber; *5* — target support; *6* — stopper support; *7* — beam collimator.

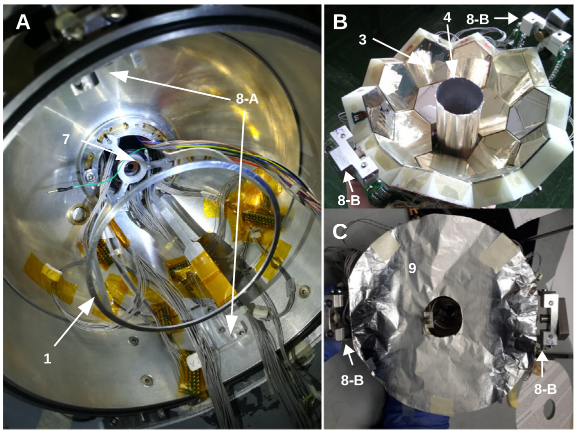

Fig. 2. (A) Internal view of the reaction chamber: labels *1, 3, 4* and *7* as in Fig. 1. *8 - A* — ancoring structure for the EUCLIDES PCB; (B) photo of 15 ΔE-E telescopes arranged in the self-supported structure secured in PCB *8 - B*; (C) the same as (B) but shielded with the disc absorber *9*.

foils installed at the centre of the GALILEO reaction chamber on the beam axis. Details on the designs and commissioning of the plunger device are fully reported in Ref. [9].

3. Experiment

The structure of nuclei far from the line of β stability has been the key subject for both experimental and theoretical investigations. One of the exciting regions for the lifetime measurements is the neighbourhood of ^{100}Sn. Indeed, the Sn isotopes from ^{100}Sn to ^{132}Sn, considering up to 32 valence neutrons, represent a unique testing ground for different many-particle shell models. However, the direct study of the properties of neutron-deficient Sn-isotopes is challenging due to the presence of low-lying isomeric states [16]. Therefore, one of the means to infer properties of semi-magic Sn isotopes is the systematic investigation of nuclear structure in the neighbourhood of ^{100}Sn. Having three valence protons and ten valence neutrons above the doubly magic closed shell, ^{113}I is a good system to study the interplay between collective and single particle nuclear models. The level scheme of ^{113}I has been well established up to high spin states, see Ref. [17] and references therein. In the low energy part the scheme reveals the positive and negative sequences of states. Collective prolate (quadrupole) deformation developed in the yrast bands gradually approaches the single particle oblate configuration towards high spin states [18,19]. The lifetimes of low-lying states are well established in both the negative and positive parity yrast states providing thus a robust reference point for validation of our setup.

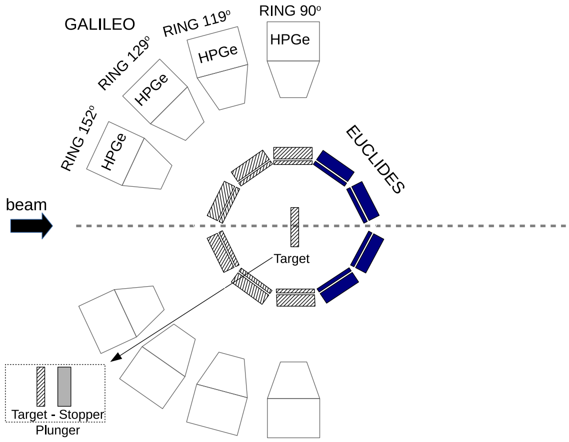

Fig. 3. Schematical view of the GALILEO γ-ray array coupled to EUCLIDES. The target and the stopper are installed at the centre of the reaction chamber. The hatched part of EUCLIDES is dismounted to allow plunger installation. See text for more details.

Fusion–evaporation reactions is a powerful method which provides access to the neutron-deficient region above the semi-magic Sn isotopes. In the commissioning experiment lifetimes of low-lying states in the neutron deficient ^{113}I, produced via the ^{58}Ni(^{58}Ni,3p) reaction, were measured using the coincidence RDDS method [20]. A 2 pnA beam of ^{58}Ni, delivered by XTU-Tandem, impinged into a 1 mg/cm^2 self-supporting ^{58}Ni target followed by a 15 mg/cm^2 Au-stopper foil. The beam energy was fixed to 250 MeV. Emitted γ-rays were detected by the GALILEO γ-ray spectrometer and evaporated light-charged particles — by the EUCLIDES Si-detector array in the reduced configuration coupled to the plunger device. The overall schematical view of the setup is demonstrated in Fig. 3. The absolute particle detection efficiency, as discussed in Ref. [5], is experiment dependent. Further to the angular coverage two other parameters mainly affecting the efficiency of particle detection are the kinematics of the reaction and the thickness of the tube absorber. In a plunger experiment the additional efficiency loss is due to presence of the stopper foil. Thus, in the reported hereby symmetric reaction the resultant efficiency for protons and α-particles was $\epsilon_p \sim$ 25% and $\epsilon_\alpha \sim$ 17% respectively. The efficiencies were measured using a standard multiplicity method described in Ref. [21].

Data were collected for 9 target-to-stopper distances between 112 μm and 2000 μm in the sensitive region to determine lifetimes of the 11/2$^-$ and 15/2$^-$ states in ^{113}I at 1018 keV and 1548 keV excitation energy respectively. Only the events with the γ-multiplicity 2 were recorded. The off-line analysis was performed using two methods. For *Method I* the data were pre-sorted into a E_γ-E_γ matrix without any particle condition. The lifetime of the 15/2$^-$ state in the negative-parity yrast band was determined with the RDDS method using $\gamma - \gamma$ coincidence analysis. To ensure that any contributions from side-feeding to the state of interest were negligible the intensities of the shifted (A$_s$) and unshifted (A$_u$) components of the γ-ray transition depopulating the state at 531 keV (transition *A*) were measured in the spectrum which was obtained by gating on the shifted component of the transition at

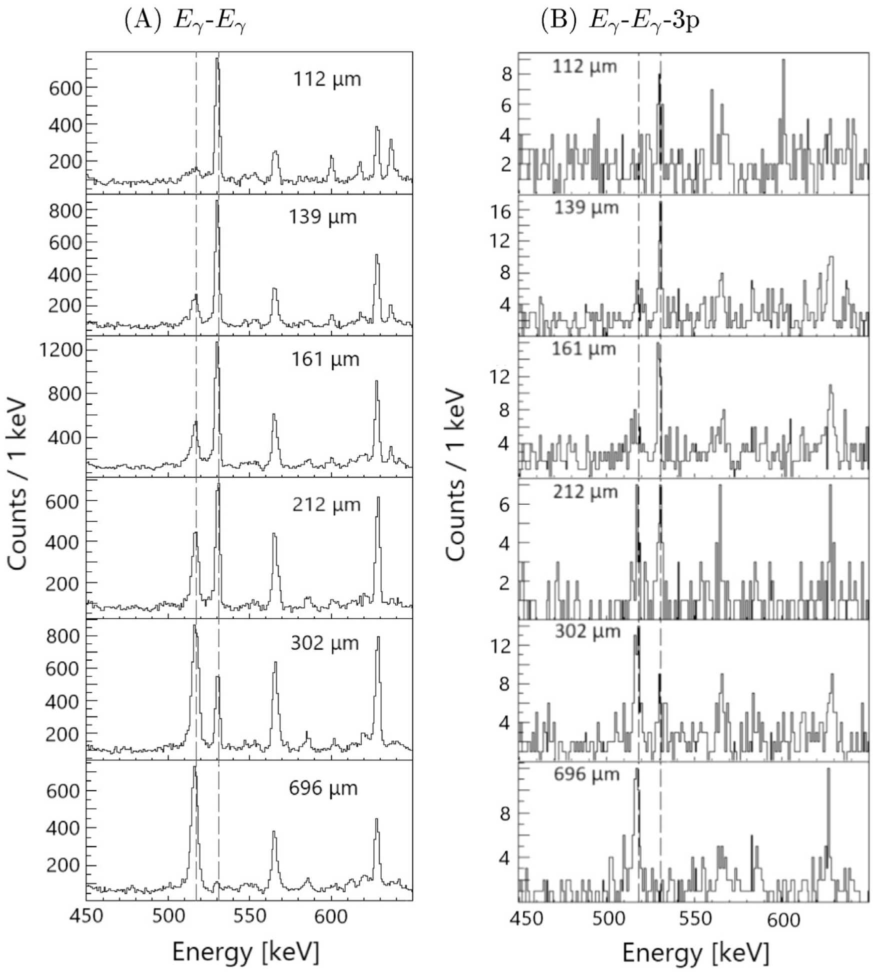

Fig. 4. Coincidence E_γ-E_γ (left) and E_γ-E_γ conditioned by 3 protons (right) spectra obtained by gating on the shifted component of the $19/2^- \to 15/2^-$ transition in ^{113}I at 626 keV (ring 2). The shifted (at 517 keV) and stopped (at 531 keV) components of the depopulating transition recorded by the ring 1 of GALILEO are indicated.

638 keV populating the state (transition *B*). A spectrum to illustrate the quality of the data is shown in Fig. 4A.

The lifetimes were determined via the well-established Differential Decay Curve Method (DDCM) [20]:

$$\tau = \frac{\{B_s, A_u\}}{\frac{d}{dx}\{B_s, A_s\}}\frac{1}{v} \tag{1}$$

where the figure brackets denote time coincidence between transitions B and A, s (u) stands for the shifted (unshifted) components, respectively, and v is the recoil velocity. The mean value of v = 3.8(2)% of the speed of light was determined for the recoil of interest by the Doppler-shift in energy of the various observed transitions belonging to ^{113}I in each detector ring at angles greater than $\Theta_3 = 90°$.

The lifetime analysis was carried out using the *napatau* software [22]. The resulted τ-curve of the $15/2^-$ state at 1548 keV excitation energy, using events in the detector ring Θ_1 coincident to the $19/2^- \to 15/2^-$ populating transition detected in ring Θ_2, is plotted in Fig. 5A (top). Additionally, the intensities of the shifted and unshifted components are plotted as a function of the target-to-stopper distance *d*. The distances in which the slope of the fitted curve was well defined were selected for the lifetime determination and were ranged from 112 µm to 696 µm. The lifetime of the $15/2^-$ state measured using *Method I* resulted in 11.0 (14) ps value, which was the weighted average from independently extracted lifetimes for each ring to ring combination using the E_γ-E_γ matrices recorded for every distance. Thus, the present value overestimates by ∼ 50% the literature one. A longer lifetime is often a sign of either unobserved feeding or contaminant transitions in other nuclei populated in the reaction.

One of the way to reduce contaminant γ-ray transitions is to request an additional condition on evaporated particles. Thus, for *Method II* in the off-line analysis for every distance the 3 proton (3p) evaporation channel leading to ^{113}I was fully selected by requiring a condition that only events in coincidence with 3 protons, detected in ΔE-E Si telescopes of EUCLIDES, were incremented into E_γ-E_γ-3p matricies.

The coincidence spectra were obtained by gating on the shifted component of the $19/2^- \to 15/2^-$ populating transition in ^{113}I at 638 keV. A spectrum to illustrate the quality of the data is shown in Fig. 4B. The resulted τ-curve of the $15/2^-$ state, using events in the detector ring Θ_1 coincident to the $19/2^- \to 15/2^-$ populating transition detected in ring Θ_2, is plotted in Fig. 5B (top). Additionally, the intensities of the shifted and unshifted components are plotted as a function of the target-to-stopper distance *d*. The same normalization and recoil velocity as in *Method I* were considered. The adopted value $\tau_{15/2-}$ = 7.9(12) ps, was the weighted average from independently extracted lifetimes for each ring to ring combination. It agrees within the error bar with the known value cited in the literature, see Table 1. The larger error bars in this case are due to the limited statistics, see Fig. 4, as a result of additional particle gate applied to enhance the resolving power of the GALILEO γ-ray array. Thus, the reliable measurement of the $\tau_{15/2-}$ lifetime was only possible due to the additional gate on the detected charged particles applied to the recorded γ-ray spectra to reduce contribution from contaminant transitions. The resulted spectra were also gated on γ-ray multiplicity and the shifted energy of the populating transition. The discussed procedure allowed to suppress contribution from strongly populated α channels, such as 1α2p (^{110}Te) leaking in 2p particle gate.

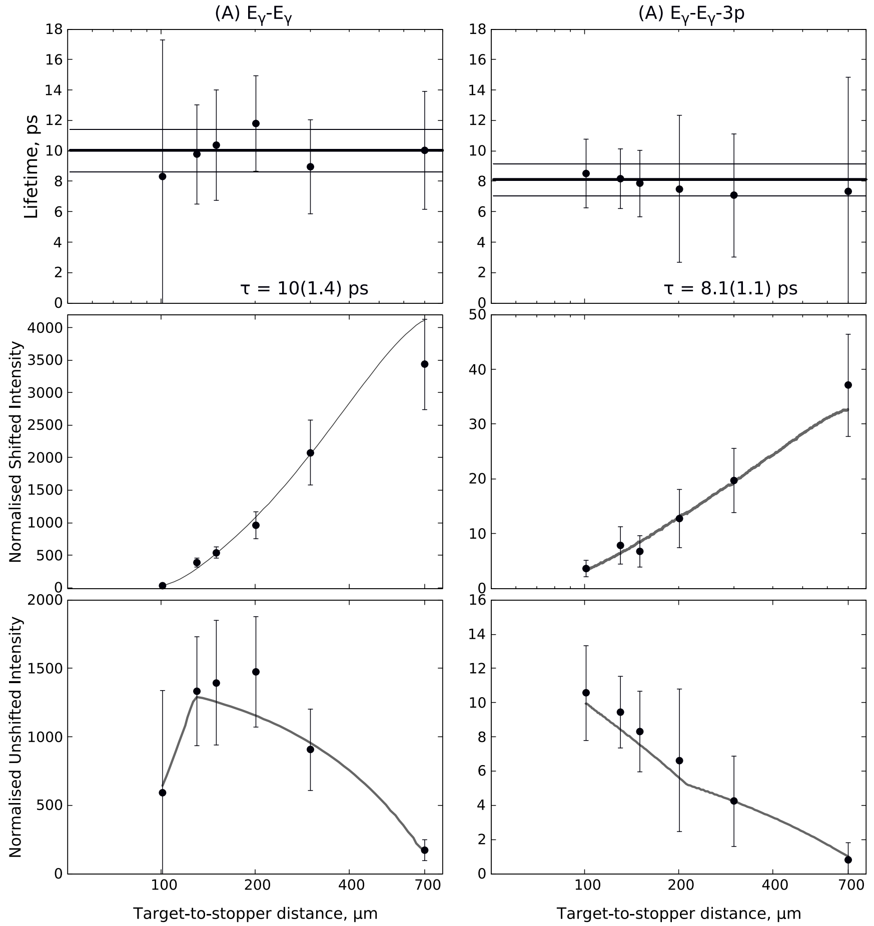

Fig. 5. τ-curves of $15/2^-$ state (upper panels) using Θ_1 ring with a gate on the feeding $19/2^- \rightarrow 15/2^-$ transition in Θ_2 ring; additionally, the intensities of the shifted (middle panels) and stopped (bottom panels) components of the depopulating $15/2^- \rightarrow 11/2^-$ γ-ray transition, using E_γ-E_γ (left) and E_γ-E_γ-3p (right) matrices, as a function of the target-to-stopper distance are shown. The lifetime values obtained using the indicated ring combination for the sensitive region are shown in the top panels.

Table 1
Adopted values for lifetimes of $15/2^-$ and $11/2^-$ states in ^{113}I in comparison with the values cited in the literature.

	$\tau_{11/2^-}$ ps	$\tau_{15/2^-}$ ps
Present	206(20)	7.9(1.2)
Petkov et al. [18]	229(52)	7.22(43)
Taylor et al. [19]	216(7)	7.2(4)

The lifetime of the $11/2^-$ state at 1018 keV excitation energy was measured via *Method II* using E_γ-E_γ-3p matrices. The distances in which the slope of the fitted curve was well defined were selected for the lifetime determination and were ranged from 302 μm to 2000 μm. All detectors in the back hemisphere were used in the analysis. The adopted value, $\tau_{11/2-} = 206(20)$ ps, presented in Table 1, is the weighted average from independently extracted lifetimes for each ring to ring combination and is consistent within the error bars with results of previous experiments.

4. Conclusions

GALILEO γ-ray spectrometer coupled to EUCLIDES Si array and the plunger device was used for the first time to measure the lifetimes in a neutron deficient nucleus populated via fusion–evaporation reaction. Due to strong population of side channels the gates on γ-ray multiplicity and on shifted energies of populating transitions were applied for reliable measurements of the lifetimes of $11/2^-$ and $15/2^-$ excited states in ^{113}I. But only the additional requirement on multiplicity of detected charged particles allowed to obtain values consistent with those cited in the literature. Therefore, EUCLIDES Si-ball installed in the reduced configuration in the GALILEO reaction chamber provides selectivity of reaction channels needed for correct measurements using a plunger device. The adopted method will be extensively applied to measure unknown lifetimes in neutron-deficient nuclei produced via fusion–evaporation reactions induced by the stable beams delivered by the Tandem-ALPI-PIAVE accelerator complex and by the radioactive beams, which will be provided in the near future by the SPES ISOL type facility at LNL Legnaro [23].

CRediT authorship contribution statement

J. Bradbury: Formal analysis, Writing - original draft. **D. Testov:** Investigation, Supervision, Formal analysis, Visualization, Writing - original draft. **S. Bakes:** Formal analysis. **A. Goasduff:** Writing - review & editing, Data curation, Software, Investigation, Formal analysis. **D. Mengoni:** Writing - review & editing, Investigation, Formal analysis. **J.J. Valiente-Dobón:** Funding acquisition, Project administration, Investigation. **G. de Angelis:** Investigation. **D. Bazzacco:** Software. **C. Boiano:** Investigation. **A. Boso:** Investigation. **B. Cederwall:** Investigation. **M. Cicerchia:** Investigation. **G. Colucci:** Investigation. **P. Čolović:** Investigation. **F. Didierjean:** Investigation. **M. Doncel:** Investigation. **J.A. Dueñas:** Writing - review & editing, Investigation. **F. Galtarossa:** Investigation. **A. Gozzelino:** Investigation. **K. Hadyńska-Klęk:** Writing - review & editing, Investigation. **G. Jaworski:** Investigation. **P.R. John:** Investigation. **H. Liu:** Investigation. **S. Lenzi:** Investigation. **S. Lunardi:** Investigation. **R. Menegazzo:** Investigation.

A. Mentana: Investigation. **C. Müller-Gatermann:** Investigation, Writing - review & editing, Formal analysis. **D.R. Napoli:** Investigation. **G. Pasqualato:** Investigation. **F. Recchia:** Investigation. **M. Rocchini:** Investigation. **S. Riccetto:** Investigation. **B. Saygi:** Investigation, Formal analysis. **M. Siciliano:** Writing - review & editing, Investigation. **Yu. Sobolev:** Investigation. **S. Szilner:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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