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The Tandem Accelerator Laboratory of NCSR "Demokritos": current status and perspectives

S. Harissopulos[1,a], **M. Andrianis**[1], **M. Axiotis**[1], **A. Lagoyannis**[1], **A. G. Karydas**[1], **Z. Kotsina**[1], **A. Laoutaris**[1,3], **G. Apostolopoulos**[2], **A. Theodorou**[2], **T. J. M. Zouros**[3], **I. Madesis**[3], **E. P. Benis**[4]

[1] TANDEM Accelerator Laboratory, Institute of Nuclear and Particle Physics, NCSR "Demokritos", 153.10 Aghia Paraskevi, Athens, Greece
[2] Institute of Nuclear and Radiological Science and Technology, Energy and Safety, NCSR "Demokritos", 153.10 Aghia Paraskevi, Athens, Greece
[3] Department of Physics, University of Crete, 700.13 Heraklion, Greece
[4] Department of Physics, University of Ioannina, 451.10 Ioannina, Greece

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Abstract The TANDEM Accelerator Laboratory of NCSR "Demokritos," Athens, Greece, is presented. A technical description of the laboratory, the installed setups together with currently implemented upgrades and associated funded projects are given. A few highlights as well as future upgrade plans and access possibilities to external users are also presented.

1 Brief history of the laboratory

It was in March 1973 when the first ion beam produced by the 5.5 MV T11/25 Van de Graaff Tandem accelerator of the, at that time, Nuclear Research Center "Demokritos" was guided to a target. Forty-eight years later the accelerator is still providing ion as well as secondary neutron beams to the local scientific community and users from abroad, to conduct scientific research in nuclear physics and apply ion beam techniques to study problems of societal impact.

The Tandem Accelerator Laboratory (TAL) is nowadays the major research facility of the Institute of Nuclear and Particle Physics (INPP) of the National Centre for Scientific Research "Demokritos" (NCSRD) and a unique research infrastructure in Greece. The T11/25 was manufactured by the High Voltage Engineering Corporation (HVEC) and was shipped from Amsterdam to "Demokritos" in 1971. Snapshots from its shipment and installation are shown in Fig. 1. It is worth noting that HVEC produced only two T11/25 Tandems, with the first one being installed and still operating at the homonymous institute INPP [1] of the Ohio University, Athens, Ohio, USA, and the second one, dubbed the Tandem hosted by "Demokritos," Athens, Greece.

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[a] e-mail: sharisop@inp.demokritos.gr (corresponding author)

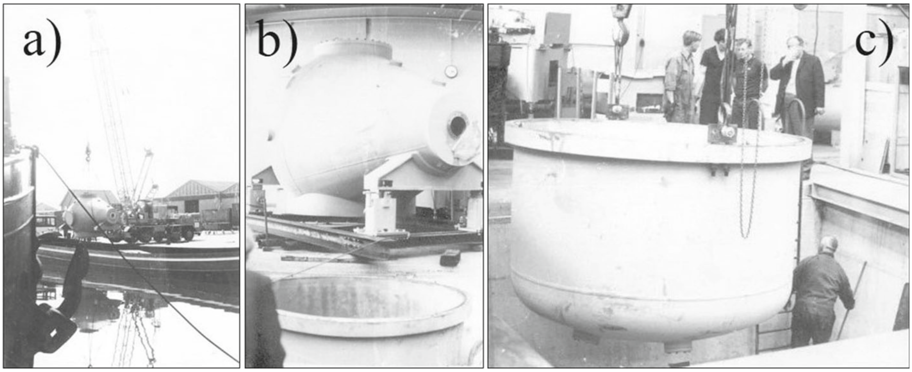

Fig. 1 Shipment and installation snapshots of the 5.5 MV T11/25 Tandem accelerator. **a** Shows its loading at the Amsterdam port. The pictures in **b**, **c** were taken during its installation. Note the ≈ 2.8 m-deep duct in the floor shown in **c** that was dug to accept the vertical end of the T-shaped accelerator tank shown in **b** and **c**

By mid-seventies, a fully equipped accelerator laboratory had been established and the accelerator was the main workhorse of the in-house nuclear physics research program, implemented by a vibrant research team. Nuclear structure was the major research topic and the relevant experiments were carried out using proton, deuteron and light-ion beams. Some typical works of that period can be found in [2–6]. In addition, experiments were performed using secondary neutron beams produced via the d+D reaction (see, e.g., in [7,8]).

The nuclear-structure research program was gradually becoming more and more difficult to realize, due to the limited terminal voltage of the accelerator that could not deliver heavy-ion beams with sufficiently high bombarding energies. Nevertheless, around the beginning of the eighties, a proposal for the upgrade of the accelerator with a post-accelerating cavity-based system was submitted to the funding authorities without, however, the hoped success. Almost immediately after losing this upgrade opportunity, the research program of nuclear physics split into two major research directions and groups. The first focused on Ion-Beam Analysis (IBA) and X-ray fluorescence spectrometry (XRF) and continued conducting experiments at the in-house Tandem. The second one carried on with nuclear-structure studies at accelerator facilities abroad within large European multi-group collaborations.

The year 1988 was determinant for the future of the in-house experimental nuclear physics program: It was the year when Themis Paradellis from the Tandem Accelerator Laboratory and Claus Rolfs from the Ruhr-Universität Bochum, Germany, jointly organized in Crete the first European Nuclear Astrophysics Conference entitled "Quests in Nuclear Astrophysics and Experimental Approaches." The success of this conference, not only gave birth to the nuclear astrophysics program of "Demokritos," but also stimulated a whole subsequent series of international conferences, the nowadays-well-established "Nuclei in the Cosmos" [9].

In the following 20 years, the laboratory faced various challenges both in terms of funding and staffing. The situation has been decisively improved in 2009, when a competitive grant of ≈1.5 M€ was awarded to the laboratory within the FP7/REGPOT program of the European Commission. The relevant project with the acronym LIBRA allowed, among others, for critical upgrades and refurbishing of the accelerator. Using LIBRA funds, the PAPAP single-stage 250-keV proton–deuteron accelerator [10] was transferred from CSNSM, Orsay, France, to "Demokritos," where it is now installed. LIBRA ran until the end of 2012.

In 2014, a proposal entitled Cluster of Accelerator Laboratories for Ion Beam Research and Applications, in short CALIBRA, aiming, among others, at the complete refurbishing of the

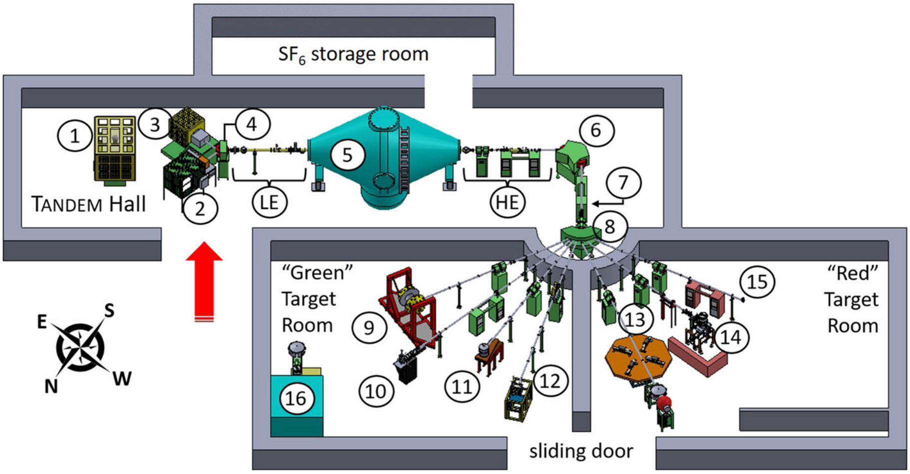

Fig. 2 Schematic layout of the Tandem hall and the two target rooms, marked as "Green" and "Red," of the laboratory. The former is 35 m long and 9 m wide, whereas each target room is 17.5 m long and 17 m wide. The height of all areas is 6.8 m. The main accelerator components and setups are labeled with numbers in circles and are described in Table 1

Tandem Accelerator Laboratory, was submitted to the General Secretariat for Research and Technology (GSRT), the Greek research funding agency, within its call for the establishment of the National Roadmap of Research Infrastructures (RIs). CALIBRA was evaluated by an international expert committee and scored excellent. As a result, the proposed CALIBRA RI was included in the National Roadmap in December 2014. However, due to the financial crisis engulfing Greece in the meantime, and revisions in the funding strategy adopted by the new leadership of the GSRT, who were appointed by the new government elected in the beginning of 2015, the CALIBRA proposal had to be re-written. It was re-submitted in October 2016 so as to comply with the national smart specialization strategic priorities (RIS3). It was subsequently re-evaluated and passed successfully all funding criteria. The formal ministerial notice was received 1 year later and, in November 2017, the project's kick-off meeting took place. CALIBRA is now running with a budget of $\approx$ 3.5 M€.

2 Layout, instrumentation and experimental setups of the laboratory

The TAL is hosted by a two-story building having a total surface of ≈ 5520 m^2. The building was built so as to cover all radio-protection rules and shielding against ionizing radiation and especially the production of secondary neutron beams. The accelerator is at the ground floor and is confined by borated concrete walls with up to 1.2 m thickness. TAL's total surface is ≈ 1900 m^2 from which ≈ 900 m^2 are covered by the Tandem accelerator hall and the two "target" rooms ("Green" and "Red"), where the experimental setups are installed. The remaining area is covered by a machine workshop, a target preparation room, an XRF laboratory, the accelerator's control room, working spaces and offices.

The layout of the main accelerator components and beamlines, labeled with circled numbers, is shown in Fig. 2. The low-energy and high-energy beamlines of the Tandem accelerator are marked with "LE" and "HE," respectively. Their lengths are 4.31 and 5.57 m, respectively. The 250-keV single-stage PAPAP accelerator [10] is labeled with the number

Table 1 Tandem accelerator components and beamlines (see also Fig. 2)

Circled number	Description	Installed setup/Comments
1	Electronics Faraday Cage	Hosts nine power supplies (PS); Four PS for the Duoplasmatron ion source (Filament, ARC, Magnet coil, Einzel lens), three PS for the Sputter source (Ionizer, Cathode, CS reservoir controller) and two PS shared by ion sources (Extraction, Preacceleration)
2	Duoplasmatron ion source	Peabody Scientific PSX-100 model; Off-axis; equipped with extraction electrode and electrostatic Einzel lens; Production of H^- and D^- beams with currents up to $\approx$ 30μA; Water cooled; Operated with a $BaCO_3$-coated mesh Pt filament
3	Sputter ion source	Kingston Scientific 200 model; Production of ion species from lithium up to copper with currents in the μA range
4	30° inflector magnet	Ports at 0°, ± 30°; Radius = 18.5 in; Max. current=150 A; Water cooled Mass-Energy-Product (MEP) = 24 @30°
5	Tank hosting the Generator (terminal)	Tank length/height = 6.65/5.04 m; Length of low-energy/high-energy tubes = 2.65/2.65 m Van de Graaff Length of vertical column = 2.45 m; Belt total length/width = 5.42/0.52 m Filled with SF_6 insulating and arc suppressing gas; Equipped with carbon-foil stripper and a nitrogen-gas-filled stripper; Upcharge by a metal mesh screen connected to a 30 kV power supply at the bottom of the belt
6	90° Analyzing Magnet	HVEC Mod. 90–40; MEP = 140; Radius = 40 in; Max. current = 300 A; Water cooled
7	Poststripper	Distance from Analyzing magnet = 3.05 m; see in [11] for details
8	Switching magnet	Ports at 0°, +15°, −25°, +32.5°, ±45°, ±60°; MEP = 140 @45°; Radius = 48 in @45°; Max. current = 300 A; Water cooled; Distance from Analyzing magnet = 5.37 m
9	60° beamline (R60)	GASPAR BGO array: Calorimeter and γ-multiplicity filter for nuclear reaction studies
10	45° beamline (R45)	Microprobe: Non-destructive elemental analysis at the μm scale of solid sample surfaces
11	32.5° beamline (R32.5)	Chamber for Rutherford Backscattering (RBS) and Channeling; PIXE/PIGE chamber
12	15° beamline (R15)	NEOPTOLEMOS Calorimeter [12], for nuclear astrophysics studies and depth profiling
13	25° beamline (L25)	Universal scattering chamber for Nuclear Reaction Analysis (NRA) & ion irradiation (see in [12,13] for details); Array of up to five hyper-pure Ge detectors (HPGe) on a turntable for γ spectroscopy and PIGE analyses
14	45° beamline (L45)	Zero-degree Auger Projectile Spectrometer (ZAPS) for ion–atom collision studies [11]
15	60° beamline (L60)	Multi-purpose beamline for material irradiations or neutron production with D-filled gas cell (d+D reaction)
16	PAPAP accelerator	See in [10] for details

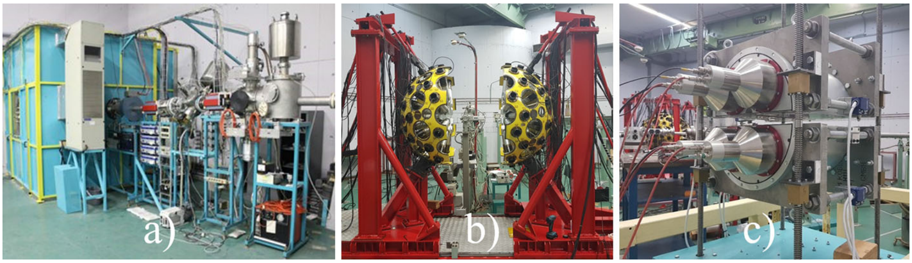

Fig. 3 **a** The *Petit Accelerateur pour l'Astro-physique* (PAPAP) [10], now installed at the Tandem Accelerator Laboratory of NCSR "Demokritos." **b**, **c** Depict, respectively, the GASPAR BGO Ball installed at the R60 beamline and the NeoPtolemos calorimeter mounted at the R15 beamline (see also in Fig. 2)

16. The different accelerator components and beamlines are summarized in Table 1. As a multi-user multi-disciplinary facility, the setups installed at the TAL are diverse, serving different research interests and application techniques. The currently available experimental instruments are presented below.

The PAPAP accelerator: As already mentioned in Sect. 1, the laboratory hosts the 250-keV single-stage accelerator PAPAP [10] that was initially built and installed at CSNSM, Orsay, France, with the purpose of investigating the ^{7}Be$(p,\gamma)^8$B reaction related to the solar neutrino problem (see, e.g., in [14]). PAPAP's construction was partially funded also by the INPP of NCSR "Demokritos." As a result, when the aforementioned research program was terminated, PAPAP was donated to the INPP, where it is now installed (see Fig. 3).

Due to its multi-cusp source, PAPAP can provide proton and deuteron beams with currents of hundreds of μA. In addition, it is equipped with an advanced scattering chamber for material analysis, with the possibility to cool samples down to liquid nitrogen temperatures.

Although PAPAP's energies and equipment are appropriate for material surface analyses, there are plans for using it as a source for neutrons via the ^{3}H(^{2}H,n) reaction. At the energy range covered by PAPAP, the cross section of this reaction varies between 2 and 5 b, with the latter value being measured at a deuteron energy of 100 keV, where the produced neutrons have an energy of $\approx$ 14.2 MeV. Assuming the maximum ^{2}H-beam current of 0.5 mA, for which PAPAP is capable of producing, and the use of a Ti(T$_2$) target with an activity of 92.5 GBq (2 Ci), that contains $\approx 3\times10^{19}$ atoms, a neutron flux of 1×10^{11} neutrons per second can be achieved allowing for a wide spectrum of research, with emphasis on the study of materials relevant to fusion technology, as well as industrial applications.

The major challenges in using PAPAP as a neutron source, which are currently under investigation, arise from radiation-safety considerations. The major issue hereby is the Tritium targetry, which requires an appropriate target design allowing for minimizing contamination. Safeguards and the necessary licensing for safe operation are also of paramount importance. Finally, the heavy shielding required to operate PAPAP under the aforementioned conditions makes its transport to a new location, properly prepared to fulfill all safety requirements, mandatory.

The NeoPtolemos **summing spectrometer:** Capture reactions play a prominent role in nuclear astrophysics studies. Often, the associated cross sections of interest are very small making the use of highly efficient hyper-pure Germanium detectors (HPGe), even equipped with Anti-Compton shields, impractical in in-beam cross section measurements. This is usually the case in γ cascades when a very large number of γ-ray spectra have to be measured to obtain, also numerous, γ-angular distributions. As a result, the data analysis itself is a very time-demanding task.

Motivated by solving these problems, the TAL group developed a technique, coined 4π γ-summing, that enables measurement of angle-integrated γ spectra instead of numerous γ-angular distributions. This technique is based on the use of a large-volume NaI(Tl) crystal detector with the highest possible absolute γ-ray detection efficiency. Such a device sums, ideally, all γ-rays, which de-excite the entry state of a compound nucleus and form γ cascades. This practically allows to analyze only one single peak, coined "sum peak" instead of numerous γ transitions. Details on the working principle of such a 4π γ-summing spectrometer, the new technique itself and a few examples of its application can be found in [12,15–19].

The NeoPtolemos γ-summing spectrometer, shown in Fig. 3, was purchased with LIBRA funds for the needs of the TAL's nuclear astrophysics research program. It is a cylindrically shaped (14 inch $\times$ 14 inch) NaI(Tl) detector with a borehole of 32 mm diameter along its axis. Its absolute efficiency for a twofold γ cascade is better than 50%.

The GASPAR BGO Ball: The acronym GASPAR stands for "GASP for Astrophysics Research," with "GASP" referring to the GAmma SPectrometer [20] previously operating at the Laboratori Nazionali di Legnaro (LNL), Padova, Italy. GASP consisted of 40 Compton suppressed hyper-pure high-efficiency n-type germanium detectors (HPGe), and a 4π calorimeter composed of 80 Bismuth Germanate Oxide (BGO) crystals covering 80% of the solid angle.

During GASP's utilization at LNL, its BGO ball was used as a multiplicity filter, in order to provide the total energy and multiplicity of γ cascades. Each BGO crystal has a thickness of 65 mm that is sufficient to absorb 95% of 1 MeV γ-rays. In this case, the resulting total efficiency was 70% . When high multiplicity events are detected, the total BGO ball efficiency is very close to 100%. With the replacement of GASP with the new GALILEO array [21] at LNL, the BGO ball became available for other research topics and was loaned by LNL to TAL to be used for the study of nuclear reactions relevant to nuclear astrophysics.

The major advantage of the GASPAR BGO Ball, over the NeoPtolemos calorimeter, is its ability, not only to sum γ transitions forming a γ cascade, but also to provide the multiplicity of the γ-cascade, which determines the detector's summing efficiency. This way, Monte Carlo efficiency simulations could be by-passed, a task that in the case of NeoPtolemos is unavoidable. GASPAR is now installed at "Demokritos" (see Fig. 3) and was recently equipped with new digital electronics for signal processing using funds from the CALIBRA project.

The RBS/Channeling setup: Well-established Ion Beam Analysis (IBA) techniques are extensively used at the TAL for material characterization, surface analysis and environmental monitoring. Rutherford Backscattering Spectrometry (RBS), Channeling, Nuclear Reaction Analysis (NRA) and Particle-Induced X-ray Emission (PIXE) are the main applied techniques for which dedicated experimental setups are installed.

The RBS/Channeling measurements are performed with the chamber shown in panel a) of Fig. 4 that was manufactured by Charles Evans and Associates (model RBS-50). The chamber is made of stainless steel and is cylindrically shaped with a 20-inch diameter. It contains a sample positioning manipulator, which is illustrated in panel b). A horizontal cross section of the chamber is shown in panel c). In addition to the flanges shown in this panel, there are four more flanges available at the bottom of the chamber (three CF40; 2.5 inch and one CF100; 4 inch). One of them is electrically isolated from the chamber through a ceramic break.

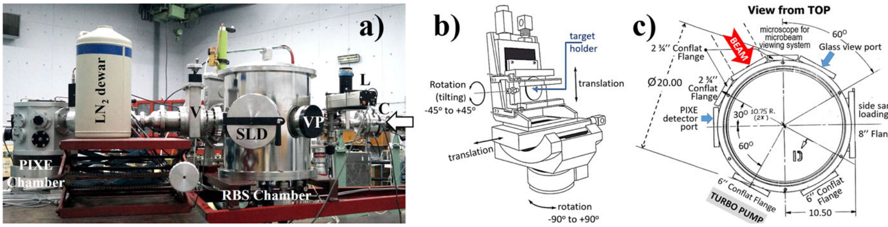

Fig. 4 **a** The RBS/Channeling and PIXE chambers installed at the R32.5 beamline. The ion beam is coming from the right as indicated by the white arrow. The sample manipulator and its possible translations and rotations are illustrated in **b**. A horizontal cross section of the RBS chamber is sketched in **c**. For details see text

The samples are mounted on a cylindrical holder made of stainless steel or aluminum, which has a diameter of 5 cm and a thickness of 1.5 cm. The sample manipulator is capable of positioning the samples with an accuracy of 1 µm for the translations and 0.01° for rotations that are indicated in panel b). The range of angles covered is from -45° to +45° for rotations around the horizontal axis (tilting) and from -90° to +90° for rotations around the vertical axis. The four different motions are provided by four stepper motors controlled either from the front panel of a motor driver (KLinGER) or from a computer that is connected to the motor driver through an ISA (Industry Standard Architecture) card. In the latter case, the software package HYPRA v3.0 is used.

The incoming particle beam is collimated by means of one adjustable tantalum collimator and one double collimator that are mounted at 35 and 60 cm, respectively, from the entrance of the chamber. The former is marked with the letter C in panel a) of Fig. 4. The latter one consists of one 2-mm and one 3-mm circular Tantalum collimators, that can be manually selected. A laser (L) mounted outside the RBS chamber is used for the placement of the detectors at the desired scattering angles and for beam alignment. Samples are loaded through a sample loading door (SLD). A glass view port (VP) allows for visual monitoring of the chamber's interior, the sample's translations and rotations and the beam spot's location and shape. The target holder is being monitored by a CCD camera placed inside the vacuum chamber. Between the RBS and the PIXE chamber that follows downstream, an isolation valve (V) is mounted.

The Nuclear Microprobe: For the determination of the elemental composition of surfaces of solid materials a microbeam system was purchased from Oxford Microbeams Ltd. with LIBRA funds. The arrangement of the different beam defining and focusing elements as installed at the R45 beamline is shown in Figs. 5 and 6. The object slits, i.e., a set of high-precision micrometer tantalum collimators, are installed at a distance of 6.55 m from the switching magnet. The quadrupole triplet is mounted on an artificial granite plinth to eliminate vibrations that could affect the spatial resolution of the system.

The beamline is pumped down by means of two turbo-molecular pumps, each one equipped with a vibration damper and an oil-free fore-pump. The first pumping station is located almost at the middle of the distance between object and image slits, as shown in Fig. 5. The second one is mounted at the bottom of the vacuum chamber, which has a spherical shape and a diameter of 25 cm (see inset in panel a) of Fig. 6).

The chamber has 22 ports at several angles, where detectors and auxiliary equipment can be attached. It is furthermore equipped with a load lock chamber, which permits the change of samples without the need to vent the whole vacuum chamber, and a microscope just above

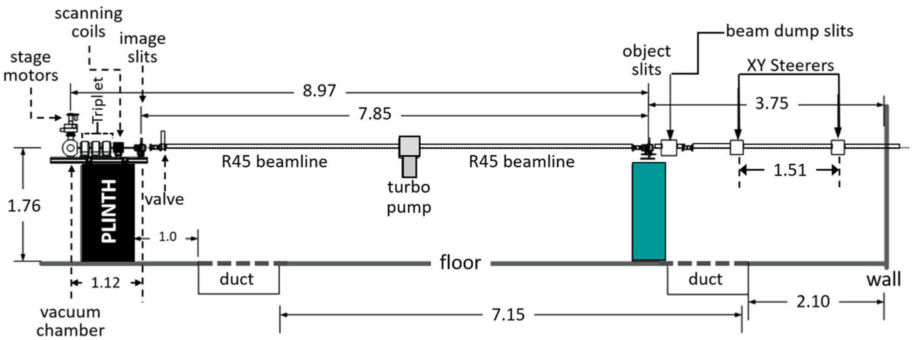

Fig. 5 Sketch of the R45 beamline hosting the nuclear microprobe. The distances shown are in meters

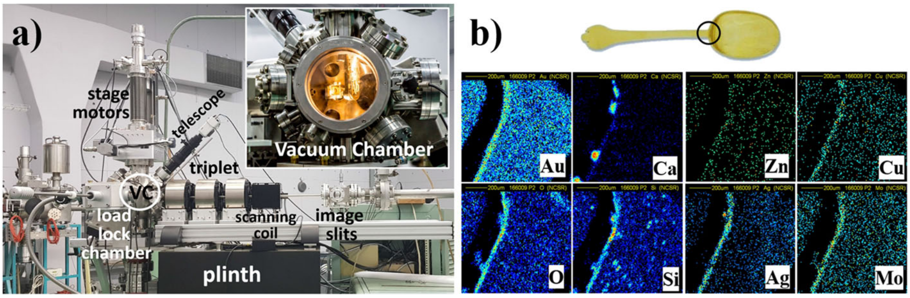

Fig. 6 **a** Picture of the microbeam setup and its vacuum chamber. **b** Depicts elemental mappings obtained for a spoon found during the excavation of ancient Mycenae, an archaeological site on north-eastern Peloponnese, Greece. The scanning region on the spoon's surface is marked with a black circle

the chamber entrance with a large focal length. A CCD camera is installed at its eyepiece in order to remotely monitor the exact spot of the beam on the sample.

The target holder is mounted on a high-precision multistage that can rotate by 360° around the vertical axis and be translated across all three dimensions. All sample movements, apart from rotation, are motorized and computer controlled. The holder offers also the possibility of heating or freezing the sample. The microbeam system shown in panel a) of Fig. 6 can focus the beam down to a $\approx$ 2–3 μm size. Typical elemental mappings measured with this system are shown in panel b).

The ZAPS Spectrometer: A few years ago, the group of Prof. Theo Zouros from the University of Crete, launched a research project entitled "Atomic Physics with Accelerators: Projectile Electron Spectroscopy" (APAPES) that was funded by the GSRT and was hosted by the TAL. For the needs of APAPES, a new experimental setup was installed at the L45 beamline, which is now a unique experimental device for atomic physics research with ion beams in Greece. This setup comprises a complete Zero-degree Auger Projectile Spectroscopy (ZAPS) apparatus to perform high-resolution studies of Auger electrons emitted from projectile ions excited in ion–atom collisions.

The main components of the APAPES L45 beamline are shown in panel a) of Fig. 7. The workhorse of the ZAPS setup is the single-stage hemispherical deflector analyzer (HDA) combined with a two-dimensional position-sensitive detector (PSD) and a four element injection

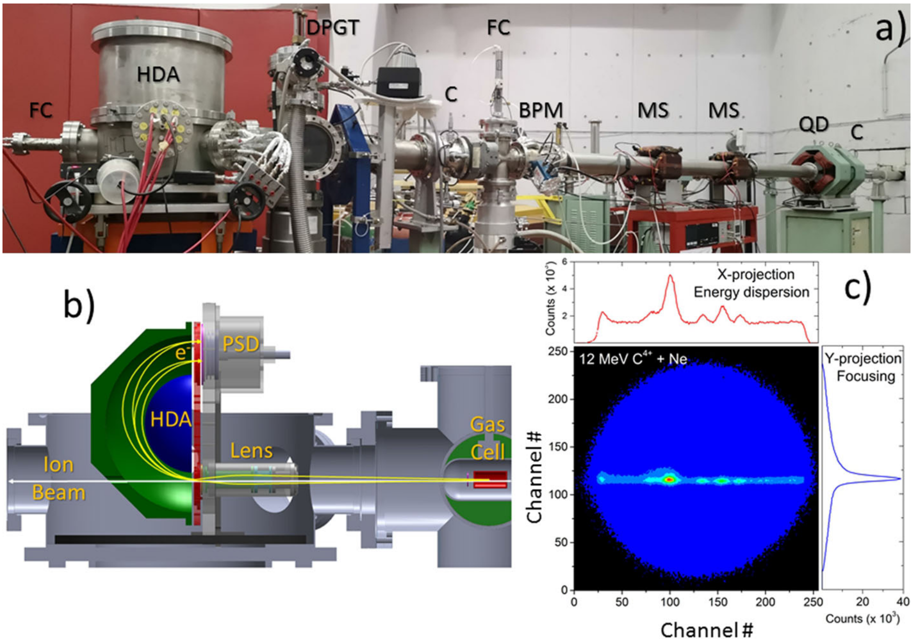

Fig. 7 **a** The APAPES L45 beamline and the ZAPS apparatus: QD, Quadrupole Doublet; MS, Magnetic Steerer; BPM, Beam Profile Monitor; FC, Faraday Cup; C, Collimators; DPGT, Differentially Pumped Gas Target. ZAPS is housed in the last chamber at the end of the beamline. **b** Details of the ZAPS apparatus: The projectile ion beam traverses the gas cell and the entry stage of the spectrograph exiting into a Faraday cup at the end of the beamline. The length of the gas cell (in red) is 50 mm and its distance (center) to the lens entry is 286 mm (from [11]). The Auger electrons (yellow trajectories) exit the gas cell (where the ions are excited to auto-ionizing states by the collision in the gas target) along the ion direction (0°), enter the lens and are dispersed by the HDA (mean radius of 101.6 mm). They are focused onto the PSD where their positions are recorded leading to a typical 2-D image shown on the right. **c** Two-dimensional image provided by position-sensitive detector (256 × 256 channels here). The x-axis is the energy-dispersion axis. The y-axis shows the quality of the focusing

lens. In addition, a doubly differentially pumped gas target is utilized to allow for a vacuum of $\approx 10^{-7}$ Torr, even when the gas cell is loaded.

The ZAPS apparatus is illustrated in panel b) of Fig. 7. The projectile ion beam from the accelerator goes through the target gas cell (where the collision takes place) and continues through the lens and on via the HDA. It exits from a hole in the back, where it is collected in a Faraday cup (FC), where its charge is integrated for absolute normalization. Auger electrons emitted from auto-ionizing projectile ion states excited in the collision, also exit along zero-degrees with respect to the ion beam. They enter the spectrograph, are focused and decelerated by the lens to further improve energy resolution. Subsequently, they enter the HDA where they are energy dispersed and recorded at the exit of the HDA along the PSD. A typical 2-D image is shown in panel c) of Fig. 7.

The technique of zero-degree Auger projectile electron spectroscopy (ZAPS) has been highly successful toward an improved understanding of ion–atom collision mechanisms at the state-selective level and provides stringent testing of theory. The atomic structure and collision dynamics of multiple excited atomic states using high-resolution Auger electron spectroscopy has attracted a lot of scientific interest over the last decades. This interest results from the need to understand the collisional properties of highly stripped ions in various research domains, such as radiotherapy with light ions (hadron therapy), plasma physics

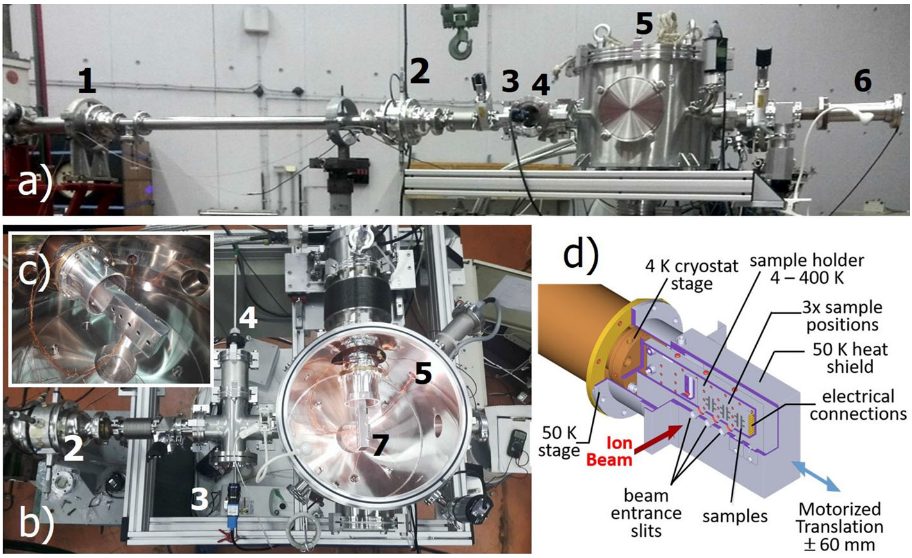

Fig. 8 **a** The L60 beamline with the IR^2 irradiation station. The different components, labeled with numbers, are explained in the text. **b** Depicts a view from the top of the vacuum irradiation chamber. The target holder is shown in the inset **c**. The different parts of the target holder are sketched in **d**

and thermonuclear fusion research. For the improved overall understanding of the relevant processes, it is necessary to determine highly accurate excitation energies, transition rates and lifetimes, as well as information on production cross section as a function of the collision energy.

The ZAPS installed at the TAL is presently the only such projectile Auger electron spectrograph worldwide, enjoying a high energy resolution ($\Delta E_e/E_e \approx 0.15\%$—capable of resolving most KLL spectra) together with the high efficiency afforded by the PSD, thus opening the field of study of ion–atom collision processes in Greece. The ZAPS setup and the associated research program are described in detail in [11].

ZAPS is the main tool for the implementation of a very successful atomic physics research program. Typical recent works from this program are given in [22–24]. It is worth noting that the success of this program depends strongly on the availability of intense, few-electron or even bare, ion beams. To fulfil this condition, the APAPES group has installed three new ion strippers at the Tandem accelerator. The first one, a nitrogen-gas stripper, was installed at the terminal inside the accelerator tank. In addition, a post stripper system consisting of a carbon-foil stripper, as well as a gas stripper was mounted between the analyzing and the switching magnet (see Fig. 2). All three stripping systems are described in detail in [11].

The IR^2 Materials Irradiation Setup: For the study of radiation damage phenomena in fusion materials, a state-of-the art irradiation facility, denoted by IR^2, was installed by members of the Fusion Technology Group of the Institute of Nuclear and Radiological Science and Technology, Energy and Safety of NCSR "Demokritos" at the TANDEM laboratory. IR^2, shown in Fig. 8, stands for "**I**on i**R**radiation with **I**n situ electrical **R**esistivity measurements."

IR^2 is an irradiation facility dedicated to radiation damage studies of metallic materials. It allows for irradiation of samples at well controlled flux and temperature, from the cryogenic range ($\leq$ 10 K) up to 700 K, by means of a dedicated cryo-cooler. Cryogenic temperatures are vital for studying the extremely mobile lattice defects generated by the irradiation, which would recombine immediately at room temperature and above making their observation extremely difficult. In IR^2, the evolution of radiation defects during cryogenic irradiation and subsequent post-irradiation annealing is monitored in real-time by means of *in situ* electrical resistivity measurements. IR^2 has been successfully used to study radiation damage and recovery in Fe–Cr-based ferritic alloys and other fusion-relevant materials [25].

The numbers displayed in Fig. 8 indicate the various components of the IR^2 facility across the L60 beamline. Hence, as shown in panel a), the incoming beam passes first through a standard Ta collimator with a 3 mm diameter circular opening, which is labeled with the number 1. At $\approx$ 1.5 m after the first collimator, the beam is re-collimated again by a set of four independent Ta slits marked with “2.” Their positions are adjustable by micrometer screws. The current of the beam can be measured on each slit.

Before impinging on the target, the incoming beam is additionally monitored: For this purpose, a CCD camera is used for viewing the beam spot on a quartz plate and a “front” Faraday cup is installed for beam-current monitoring. In panel a) of Fig. 8, they are marked by the numbers “3” and “4,” respectively. The irradiation chamber, depicted with “5,” is located at a distance of $\approx$ 2.32 m from the first Ta collimator. The last piece of the beamline is electrically isolated forming a $\approx$ 30 cm long Faraday cup, marked with “6,” for reliable beam-current measurements.

The labeling with numbers used for the various components of IR^2 applies also to panel b) of Fig. 8. In addition, the position of the target holder is indicated here with “7.” The holder itself is shown in panel c). Its components are presented in detail in panel d). Note that a “beam diffuser,” not shown in Fig. 8, is recently installed at $\approx$ 19 cm after the first Ta collimator, with the purpose of making the beam homogeneous at the target position. This is a 2μm-thin aluminum foil inducing angular spread of the beam.

The IR^2 facility of the “Demokritos” Tandem accelerator offers unique capabilities for the study of fundamental radiation damage processes in materials, which are of particular importance for the validation of new multiscale theoretical models and tools that are being developed with the aim of understanding and predicting the behavior of materials under fusion irradiation conditions. With its real-time characterization potential by means of the in situ electrical resistivity measurement option, IR^2 can provide valuable information for a number of highly important radiation effects in fusion materials as: the structure of primary damage, the kinetics and interactions of radiation defects and, finally, phase stability and precipitation under irradiation.

The external ion-beam setup: Driven by the needs for the analysis of objects relevant to the country’s rich cultural heritage, the external ion-beam setup shown in Fig. 9 has been

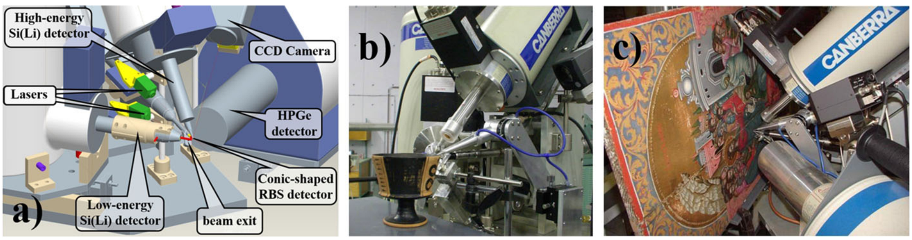

Fig. 9 **a** Sketch of the external ion-beam setup. **b** Picture of the setup as was previously installed, without the hyper-pure Ge (HPGe) detector during the analysis of an authentic ceramic vase (Thetis Authentics LtD). **c** Pigment analysis of an eighteenth-century painting from the Benaki Museum (Valladoros collection)

developed and installed at the Tandem laboratory [26]. The setup allows for a complete elemental and near-surface structural characterization of samples in an almost non-destructive way and without any limitation concerning their size or conductive state. This is achieved by utilizing simultaneously five detectors, i.e., two Si(Li) detectors for the implementation of Particle-Induced X-ray Emission (PIXE) analysis, one for Rutherford Backscattering Spectrometry (RBS), one hyper-pure Ge (HPGe) detector for Particle-Induced Gamma-ray Emission (PIGE), and one X-ray detector for the dose monitoring.

The setup has a compact geometry. Its ion-beam exit nozzle is covered by a 100-nm-thin Si_3N_4 foil. This applies also for the case of the small vacuum chamber hosting the RBS detector. It allows for the detection of X-rays with energies down to 1 keV. It is also equipped with a CCD camera, for visual inspection of the sample point under analysis, and lasers for the necessary alignment. Data are collected by means of a digital acquisition system. For the digital pulse processing of the X-ray, γ-ray and charged-particle detector signals, novel hardware and software tools were developed based on a custom field-programmable gate array (FPGA) configuration. The setup was properly developed so as to offer also the possibility to be used with ion beams heavier than protons.

Up to date, the setup was used in analytical diagnostic studies of a few representative paintings of contemporary Greek painters in order to identify and document pigments, materials and techniques and prevent trade of fakes. In addition, ancient glass beads were also examined with respect to their Na concentration and their in-depth homogeneity. The setup is currently under refurbishing funded by the CALIBRA project. The relevant upgrades include:

- Replacement of the previous old-generation X-ray detectors by three state-of-the art Silicon Drift detectors (SDDs). The data-acquisition system will include dedicated digital signal processor units which will optimize the performance of the SDDs in terms of energy resolution, stability, accurate and effective dead-time and pile-up corrections. Hereby, the replacement of the current 30 mm^2 Si(Li) detector by a novel 150 mm^2 SDD in the so-called high-energy PIXE channel is critical for trace-element analysis, as it is expected to increase its throughput by more than an order of magnitude considering that Si(Li) detectors are restricted to operate with relatively low input count rates. Furthermore, the substitution of the small-area (few mm^2) monitoring Si-PIN detector by a 30 mm^2 SDD will allow for precise recording of the incident proton dose even for short measuring times and low beam currents.
- The installation of a fast XYZ motorized stage (75 cm $\times$ 75 cm $\times$ 25 cm) would allow the positioning of large objects in front of the external proton beam and the possibility to perform scanning measurements over extended areas (several tens of cm^2), thus generating PIXE-induced elemental distribution maps.

Other setups and scientific instruments: Among the experimental devices used the most are the multi-purpose large-volume scattering chamber and the deuterium-filled gas cell for the production of quasi-monochromatic neutrons. They are described in detail in, e.g., [12,13] and [7,27,28], respectively, and will therefore not be presented here. In addition to these instruments, an array of 16 ^{3}He-gas-filled neutron counters is available for the study of neutron-emitting reactions. This array is presented in detail in [29]. All three experimental devices are shown in Fig. 10.

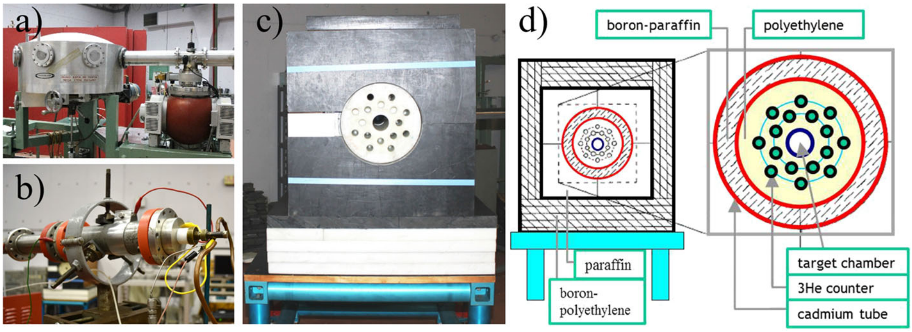

Fig. 10 **a** The TECNOLICS multi-purpose scattering chamber installed at the L25 beamline. It is extensively used for Nuclear Reaction Analysis (NRA) of materials or for charged-particle irradiations and for particle-spectroscopy, in general (see, e.g., in [30–32]). **b** Depicts the gas cell used for the production of neutrons via the d+D reaction. It is installed at the L60 beamline and is the main tool for the study of neutron-induced reactions, primarily $(n, 2n)$. **c** Shows the array of 16 ^{3}He-gas-filled neutron counters, whereas **d** displays the different components of the array. The array can be mounted per demand at the L60 beamline

3 Current upgrades and the CALIBRA project

A number of upgrades of the laboratory's infrastructure are currently implemented with funds of the CALIBRA project. The concept of CALIBRA is to establish, operate and exploit a Cluster of Accelerator Laboratories for Ion-Beam Research and Applications at "Demokritos." The cluster will be based on the operation of four accelerators. These machines will be grouped into three strongly interacting laboratories, i.e., the Tandem, the Cyclotron and the AMS Labs, equipped with state-of-the art setups and scientific instruments that will integrate a number of common auxiliary facilities and supporting workshops.

The core idea behind CALIBRA is to take advantage of a wide variety of ion species delivered from the accelerators, partly with very high intensity, as well as of secondary neutron beams in order to produce new scientific knowledge in fundamental science (nuclear astrophysics, nuclear reaction studies and atomic physics with accelerators), develop novel analytical techniques and provide highly specialized services and products related to human health, cultural heritage, nanotechnology, environmental monitoring, and the development and testing of materials and detectors.

For the establishment of the Cyclotron and the AMS Labs, a 17 MeV Scanditronix Cyclotron and a 2.5 MV Tandetron AMS accelerator, both fully operational machines, have been donated to the TAL by the University Medical Center Groningen (UMCG), The Netherlands, and the Institute of Archaeology of the University of Oxford, UK, respectively. The transport and installation costs of these accelerators are partly covered by the CALIBRA project.

The donated cyclotron produces and accelerates protons (p) and deuterons (d) of energy 17 and 8.5 MeV, respectively. With these projectiles, the positron-emitting radioisotopes ^{18}F, ^{11}C, ^{15}O and ^{13}N are produced and are subsequently used in the manufacture of widely used radiopharmaceuticals, such as ^{18}F-FDG, ^{18}F-FLT, ^{18}F-Dopa, and ^{11}C-Methionine. On the other hand, the Tandetron accelerator is used for ^{14}C-dating of archaeological materials, cultural-heritage objects and in some cases for environmental monitoring. These donations have a high impact in CALIBRA's sustainability: they not only allow for the creation of the cluster of accelerators as described above but also for providing unique scientific tools to the local scientific community that never had access to such facilities. It is worth noting that, in spite of Greece's very rich cultural heritage, no AMS facility has been available to date.

The planned CALIBRA Research Infrastructure, as such, will operate as an open-access Research Infrastructure for national and European research groups, providing annually more than 3000 hours of beam time and a wide spectrum of state-of-the art facilities for R&D and innovative applications, education and training for students. The CALIBRA project was practically launched in 2018. Up to date, many upgrades have been completed or are progressing according to schedule. The major upgrades are the following:

Refurbishing of the Tandem accelerator components which include:

- Replacement of the existing belt at the tank's terminal with a triple Pelletron™ chain
- Installation of a new Terminal Potential Stabilization system (TPS) at the high-voltage terminal
- Installation of a new stripping system to replace the existing old one
- Installation of a TORVIS™ ion source injector system for H^- and He^- ions
- Installation of a SNICS II™ sputter ion source injector system for negative ions
- Replacement of old diffusion pumps, aged turbo-molecular or ion pumps and their controllers with new oil-free backing pumps and turbo-molecular ones
- Installation of a computer control system to control remotely the operation of the accelerator and its components at all beamlines. This will allow also for the accelerator's operation by post-graduate students
- Installation of new beam profilers (BPM) to monitor the beam across the different beamlines.

Acquisition and installation of a TOF-ERDA spectrometer: In order to strengthen further the laboratory's Ion Beam Analysis program and in reply to increasing demands of external users, a state-of-the art Time-of-Flight Elastic Recoil Detection Analysis (ToF-ERDA) spectrometer is about to be acquired and installed at the R32.5 beamline.

Acquisition of n-type HPGe Detectors with BGO Anti-Compton shields: Aiming at the completion of a basic array of HPGe detectors, three n-type highly efficient HPGe detectors have been purchased together with the properly fitting Bismuth Germanate Oxide (BGO) Anti-Compton (AC) shields. These will be integrated with other, already available or shared HPGe detectors and AC shields to form HELGA that stands for HELlenic Gamma Array and comprises six detector units.

Acquisition of new state-of-the-art power supplies and digital electronics: These units will allow for powering up to 24 scintillator detectors (BGO or NaI crystals) or solid-state HPGe detectors whereas the latter ones will serve for signal digitization, processing and acquisition of data from both type of detectors and will be able to support at least 80 detectors. Digitizers will have a resolution of better than 12-bit and will be accompanied by the appropriate software for processing and generating spectra directly from scintillator detectors (at least 80 channels) or directly from the semiconductor detector preamplifier (at least 12 channels).

4 Some highlights from the research implemented at the Tandem Accelerator Laboratory

4.1 Nuclear astrophysics

Using the Tandem accelerator of "Demokritos" as the main experimental tool, a research program related to stellar nucleosynthesis was launched in the early nineties and a vibrant nuclear astrophysics group has gradually been formed. Since then, the group has carried out numerous measurements at the in-house Tandem, as well as abroad, in collaboration with various well-established nuclear astrophysics groups.

The current Nuclear Astrophysics program is described in detail in the recent review paper [12]. In brief, it focuses on the study of nuclear capture reactions relevant to the understanding of a nucleosynthetic mechanism occurring in certain explosive stellar environments, such as supernovae. This mechanism, termed *p*-process, is responsible for the synthesis of certain 35 neutron-deficient nuclei heavier than iron that lie "north-west" of the stability valley, between ^{74}Se and ^{196}Hg. These nuclides, known as the *p*-nuclei have, so far, been observed only in the solar system.

To date, the solar system *p*-nuclei abundances are still a challenge for all *p*-process nucleosynthesis models, which fail to reproduce them, especially in the case of the light *p*-nuclei. The observed discrepancies could be the result of uncertainties in the purely astrophysics modeling. However, on top of any astrophysical model improvements, it is imperative that the nuclear physics uncertainties entering the astrophysical calculations are reduced or set under control at least.

Given this challenge, the main goal of the Nuclear Astrophysics program is to shed light on nuclear physics aspects of the p-process puzzle. Understanding of the aforementioned discrepancies, it will enable not only to explain the isotopic composition of the solar system, but also to elucidate further our fundamental picture of its creation that still remains diffuse. For the goals of this research program, systematic cross section measurements of proton and α-particle capture reactions are performed at the in-house Tandem, as well as abroad. Up to date, more than 20 capture reactions have been investigated. Typical works from these activities are published in [13,15–19,33–35].

The already available experimental setups NeoPtolemos, GASPAR and the array of the 16 ^{3}He counters together with the about to be completed HELGA HPGe detector system will be the major devices for the continuation of the Nuclear Astrophysics research program. The refurbishing of the Tandem accelerator that would lead to a stable operation in combination with the expected higher beam currents will strengthen decisively the program. This will apply also to all programs described below.

4.2 Studies of neutron-induced reactions

Neutron-induced reactions have raised a lot of attention in the past. Nowadays, their study attracts a lot of scientific interest because of their importance to fundamental research in Nuclear Physics, as well as to a wide spectrum of applications in technological- and industrial-related fields including medicine.

Among the most important technological applications is also the design of innovative Accelerator-Driven Systems (ADS) for the future production of clean and safe nuclear energy, as well as for the transmutation of nuclear waste. The key physical quantity required by these applications is, again, the cross section of (n, xn), (n, γ) and (n, f) reactions. Due to several, often striking, discrepancies between compiled cross section data of existing databases there is a need for new reliable measurements. In addition, $(n, 2n)$, (n, p) and (n, α) reactions, have been successfully used to measure isomeric to ground-state cross section ratios. Such measurements are of paramount importance in nuclear-structure studies as they can provide the spin distribution of the level density, which is a key parameter in calculations of nuclear reaction models.

In view of these problems, a successful research program aiming at cross section measurements of $(n, 2n)$, (n, p), (n, α) and (n, f) reactions has been established some years ago driven primarily by external users from different Greek universities and collaborators abroad. A good part of these activities is related to the research program of CERN's n_TOF collaboration. The main tool in the implementation of this program is the neutron facility of TAL that can provide monoenergetic neutron beams with fluxes of $\approx 10^5$–10^6 n cm^{-2} s^{-1} in the energy ranges from thermal to 450 keV, 4–11.5 MeV and 16–20.5 MeV by using the ^{7}Li(p, n), ^{2}H(d, n) and ^{3}H(d, n) reactions. For the latter two cases, the gas-cell presented in Sect. 2 is extensively used. Cross sections are hereby determined by means of the activation technique. Typical recent works from this research program are presented in [27,28,36,37].

4.3 Ion-beam applications

Since its establishment, the Tandem Accelerator Laboratory runs a very successful research program comprising activities in basic and applied research focused mainly on the measurement of differential cross sections of reactions induced by protons and deuterons on light elements at low bombarding energies. Aiming at enhancing the reliability of the results obtained by the RBS and NRA techniques, differential cross sections at backward angles for a large number of light elements have been studied [30,38–40]. Moreover, the accuracy of these cross sections has been cross-checked by conducting benchmarking experiments [41,42].

The laboratory has also participated in a Coordinated Research Program, funded by International Atomic Energy Agency (IAEA), on improving the PIGE technique, evaluating existing PIGE data and measuring new ones [43,44]. For this purpose, a large number of differential cross sections have been measured in a wide range of energies and angles [45,46]. In addition, a new computer code for the analysis of PIGE bulk samples was developed [47].

The laboratory has also a long tradition in interdisciplinary research by applying IBA techniques for quantitative analysis and depth profiling of elements in various matrices, like in materials of technological interest ("clever" glasses for use in biomedicine, hydrogen sensors for industrial use) or in samples related to environmental monitoring (Pb patination exposed to the atmosphere) [48–50].

Of special interest is the use of ion-beam applications for the determination of fuel retention (deuterium, tritium) in the structural elements of future fusion reactors. In this context, the Tandem laboratory performs measurements focusing on the quantification of ^{12}C, ^{9}Be and ^{2}H at JET's Wall Tiles [51,52]. These activities are carried out within the WP-JET2 work package of the EuroFusion program in which the Tandem laboratory actively participates (Fig. 11).

5 Summary and outlook

The TANDEM Accelerator Laboratory of NCSR "Demokritos" is a unique research infrastructure in Greece and one of the few of its kind in Europe. It is equipped with a large variety of scientific instruments allowing for different experiments of large scientific impact and hosts a

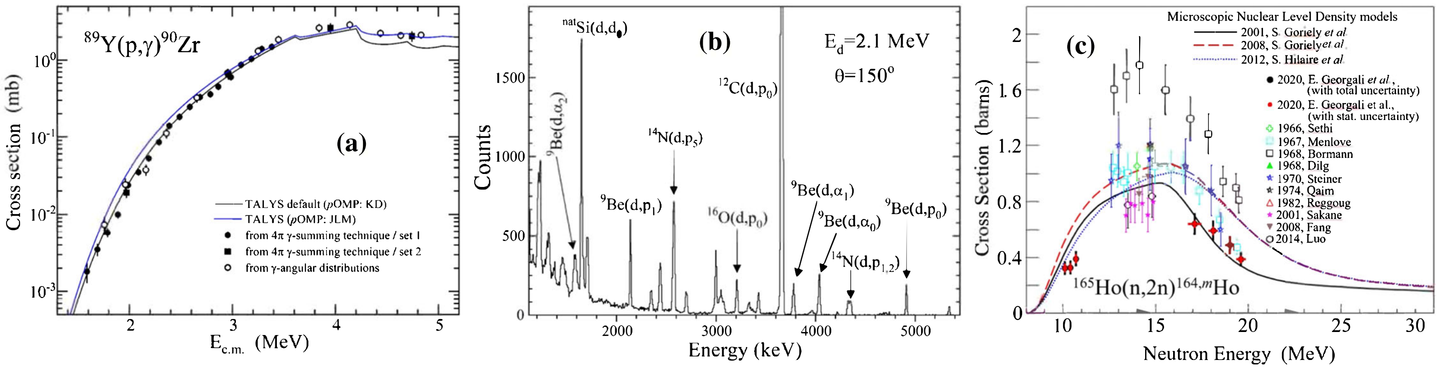

Fig. 11 Typical works obtained for each one of the highlights presented in Sect. 4. **a** Total cross section measured for the $^{89}Y(p,\gamma)^{90}Zr$ reaction by the nuclear astrophysics group with the aim the test proton Optical Model Potentials (pOMP) at energies relevant to p-process nucleosynthesis. The experimental data are from [18]. They were determined with two different methods, i.e., with the 4π γ-summing technique and from γ-angular distribution measurements. The curves indicate statistical model calculations performed with the latest version (1.95) of the TALYS code [53]. The TALYS default black curve was obtained using the phenomenological pOMP of Koning and Delaroche [54], whereas the blue one with the semi-microscopic one of Bauge, Delaroche and Girod [55,56]. **b** Typical NRA spectrum measured at 150° with a deuteron beam impinging on sample containing Be (see also in [40]). The aim of this work was to determine differential cross sections of (d,p) and (d,α) reactions on Be, which is used in various industrial components such as aircraft brake parts, audio components, X-ray windows, spacecraft structures and many other. **c** Cross sections of the $^{165}Ho(n,2n)^{164,m}Ho$ reaction. The data published by Georgali et al. [37] were measured at "Demokritos." Reprinted figure with permission from [37]. Copyright 2020 by the American Physical Society

diverse scientific program comprising basic research and interdisciplinary applications using low-energy ion-beams. Many of these experiments are performed by many external users from almost all Greek universities with nuclear physics groups.

Apart from the highlighted research topics in Sec. 4, i.e., Nuclear Astrophysics, studies of neutron-induced reactions and ion-beam applications, the laboratory hosts very vibrant research programs on Cultural Heritage, Radiation Damage Studies of Fusion Materials, and Atomic Physics with accelerated ions (Projectile Electron Spectroscopy). With the commissioning of the upgraded external ion beam, it is expected that a powerful analytical tool will become available not only for Cultural Heritage studies, but also for environmental applications and especially for the elemental analysis of atmospheric aerosol samples in support of even time-resolved source apportionment studies.

TAL is an open-access facility. Research proposals can be submitted by external users at any time and beamtime is granted after evaluation by a Program Advisory Committee (PAC) that meets twice a year. The PAC members are knowledgeable scientists from abroad. Until the recent pandemic outbreak, the laboratory was offering more than 1000 hours of beamtime to external users. In the near future, this number is expected to double, also because of the state-of-the-art facilities that the CALIBRA project will make available. The almost complete refurbishing of the Tandem accelerator will contribute decisively to the laboratory's sustainability as it will facilitate, among others, the provision of specialized services also to the private sector.

During the last decade the laboratory was able to attract funds exceeding 6 M€, with a significant part of this funding being directed to refurbishing and upgrades of its scientific infrastructure. On top of that, the various in-kind donations received in the same period were of almost equal value. Under these conditions, it is fair to say that the accumulated investment over the laboratory's life, exceeds now the amount of 25 million Euros, when taking into account also its building infrastructure.

To date, the Tandem Accelerator Laboratory of "Demokritos" is recognized by the international scientific community as a laboratory of international stature with numerous collaborations all over Europe. This status has also been documented in the reports of the international external evaluation committees who evaluated the laboratory during the last decade. The status of excellence of TAL has been achieved through important contributions at the international level, in the fields of fundamental nuclear physics research and applications.

Looking forward, the Tandem Accelerator Laboratory of "Demokritos" will continue operating as a pivotal channel transporting knowledge and technical expertise to society by providing training to young scientists and promoting unique applications of nuclear science for a better life.

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