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Review

Nuclear Physics Opportunities at European Small-Scale Facilities

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Abstract: Small-scale facilities play a significant role in the landscape of nuclear physics research in Europe. They address a wide range of fundamental questions and are essential for teaching and training personnel in accelerator technology and science, providing them with diverse skill sets, complementary to large projects. The current status and perspectives of nuclear physics research at small-scale facilities in Europe will be given.

Keywords: small-scale facilities; nuclear instrumentation; detector arrays; accelerators; nuclear structure; nuclear reactions; nuclear astrophysics; accelerator-based nuclear science; education and training

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1. Introduction

In 1929, Van de Graaff developed one of the first accelerators, and the era of accelerator-based nuclear physics began. Almost one hundred years later, the pursuit continues, using complex, high-energy machines operating at large nuclear research centres like GSI/FAIR (The GSI Helmholtz Centre for Heavy Ion Research/Facility for Antiproton and Ion Research), GANIL (Grand Accélérateur National d'Ions Lourds), and others. Meanwhile, small-scale accelerator facilities still play a major role in keeping and providing knowledge in nuclear physics. Small-scale facilities in Europe encompass a large set of setups, offering the European nuclear physics community a large variety of stable beams as well as a number of radioactive beams. They provide the possibility of carrying out state-of-the-art research using different instrumentation available. They have a significant role in high-level education and training, as well as the formation of early-career-stage researchers in nuclear physics. Small-scale national facilities have an important role in providing know-how and expertise in developing novel experimental techniques and instrumentation for big-scale flagship facilities from the European Strategy Forum on Research Infrastructures (ESFRI) roadmap [1]. The Nuclear Physics European Collaboration Committee (NuPECC) has strongly recommended the continuation and expansion of training initiatives at small-scale facilities and endorsed the support of small-scale facilities' nuclear physics programs in its latest Long Range Plan (LRP) [2]. Accelerator-driven nuclear physics research at small-scale facilities has a large societal impact. Ion beam analysis (IBA) and accelerator-mass spectroscopy (AMS) techniques are reliable and cost-effective for environmental monitoring and climate change-related studies [3]. New developments in electron-beam accelerators enable their application in pollution control. Electron-beam system technologies are also widely employed in food safety [3]. The current status, available instrumentation, as well as perspectives of nuclear physics research at small-scale facilities are given. To obtain a complete overview, a few medium-scale facilities—the INFN Laboratori Nazionali del Sud, IJC Lab, and the Jyväskylä Accelerator Laboratory—are also described. The list of reviewed facilities can be found in Table 1. Although we focused on the nuclear physics research of reviewed facilities, one should stress that some reviewed facilities also perform research on atomic physics, applied physics, material science, IBA, AMS, archaeology, etc. Apart from the reviewed facilities, one should note a few notable small-scale facilities that perform research on IBA, material science, AMS, archaeology, climate research, etc. VERA (Vienna

Environmental Research Accelerator) [4] is one of the first accelerator facilities designed and dedicated to AMS all across the nuclear chart. It operates a 3 MV Pelletron tandem accelerator. The applications reach into many areas of our environment, from archaeology to climate research. The Surrey Ion Beam Centre [5] operates a 2 MV Tandetron accelerator. It allows users to perform a wide variety of research types, using ion implantation, ion irradiation, and ion beam analysis. The Dalton Cumbrian facility in Manchester, England, operates a 5 MV Tandem accelerator and a 2.5 MV Pelletron accelerator. The accelerators are used for ion irradiation damage studies, as well as for radiation chemistry studies in nuclear energy, radiobiology, space missions, and other applications. The Tandem laboratory, Uppsala University [6], provides services within ion beam analysis, ion beam modification of materials and accelerator mass spectrometry using a 5 MV Pelletron and a 350 kV high-current implanter. In addition, the Tandem laboratory, at Uppsala University, hosts MICADAS: a compact mass spectrometer specifically developed for high-accuracy C-14 dating. It is a national research infrastructure for world-leading materials analysis. The Laboratory of nuclear techniques for Environment and Cultural Heritage (LABEC) in Florence, Italy, operates a 3 MV Tandetron. As the name itself suggests, the research is mainly focused on studies of cultural heritage and environmental processes. AIFIRA (Applications Interdisciplinaires des Faisceaux d'Ions en Région Aquitaine) in Bordeaux, France, utilizes ion beams (H+, D+, and He++ with intensity up to 50 µA) produced by a 3.5 MV Singletron for the irradiation of materials and IBA. The secondary beams of mono-energetic neutrons (100 keV to 7 MeV) are also available.

Table 1. The list of European small-scale facilities reviewed in this paper. The facility, country, accelerators available, as well as the beams that can be provided, are shown.

Facility	Country	Accelerators Available	Beams
Cologne Accelerator Laboratory	Germany	10 MV FN-Tandem 6 MV Tandetron	Beams up to 120 MeV (Z up to 30) AMS *
Heavy Ion Laboratory	Poland	Isochronous heavy ion cyclotron (K_{max} = 160)	He-Xe
IJC Lab	France	15 MV Tandem (ALTO) 50 MV electron accelerator (ALTO) 4 MeV NEC pelletron accelerator (ANDROMEDE) Licorne neutron source	Proton to aggregates e^- p-Au, He, Ne, Ar, Kr, Xe n
Rudjer Bošković Institute Accelerator Facility	Croatia	6.0 MV EN Tandem 1 MV Tandetron	p to Au p to Au
Tandetron laboratory in Piešťany	Slovakia	2 MV Tandetron	p, d, α
The Oslo Cyclotron Laboratory	Norway	MC-35 Cyclotron	^{1}H (max 35 MeV), ^{2}H (max 18 MeV), ^{3}He (max 47 MeV), and ^{4}He (max 35 MeV)
S-DALINAC	Germany	Superconducting electron accelerator	e^-
The INFN Laboratori Nazionali del Sud	Italy	13 MV TANDEM—HVEC MP Superconducting Cyclotron K800	p to Au H to U, also exotic beams, see Section 2.8
The Jyväskylä Accelerator Laboratory	Finland	1.7 MV Pelletron K130 isochronous cyclotron MCC30/15	** Used mostly for material research Range of heavy and light ions up to energy of 130·Q^2/A MeV p,d
RUBION	Germany	4 MV Dynamitron Tandem 100 and 500 keV accelerators, 60 keV implanter	p to Fe ** Mainly used for material science research

Table 1. *Cont.*

Facility	Country	Accelerators Available	Beams
Frankfurt Van de Graaff accelerator	Germany	Van de Graaff	p, α, n (for n, see Section 2.11.)
IBC, HZDR	Germany	2 MV Van de Graaff 3 MV Tandetron 6 MV Tandetron 500 kV Ion Implanter 40 kV Ion Implanter	p, He p to Au p to Au ** Primarily used for solid-state physics and applications
Felsenkeller underground accelerator laboratory, HZDR	Germany	5 MV Pelletron accelerator	p, α, ^{12}C
The Atomki Accelerator Center	Hungary	MGC-20E Cyclotron 1 MV Van de Graaff 5 MV Van de Graaff 2 MV Tandetron ECR ion source 200 kV AMS	p, d, $^{3}He^{2+}$, and $^{4}He^{2+}$ p, d, He Inactive p, He, and heavier ion ** Used for atomic and plasma phys. AMS *
CANAM RI	Czech R.	2 MV Tandetron TR-24 cyclotron U-120 M cyclotron	p, He, B, C, O, S, Si, Cu, etc. p H^+, H^-, D^+, D^-, $^{3}He^{2+}$, $^{4}He^{2+}$ H^+, D^+, $^{3}He^{2+}$, $^{4}He^{2+}$, as well as generated secondary fast neutrons
		MT25 microtron 3 MV Tandetron	e^- Wide range of ions up to Au
Bronowice Cyclotron Center	Poland	Proteus C-235 cyclotron	p
CNA, Seville	Spain	18/9 MeV cyclotron 3 MV Van de Graaff Tandem 1 MV Tandetron HiSPANoS neutron source	p, d Almost all types of stable ions AMS * n
LATR, Lisbon	Portugal	2.5 MV Van de Graaff 3 MV Tandem 210 kV Ion Implanter	H, ^{3}He, ^{4}He, and heavier ions H, ^{3}He, ^{4}He, and heavier ions ** Primarily used for material research
IFIN-HH	Romania	9 MV FN Pelletron Tandem 3 MV HVEE Tandetron 1 MV HVEE Tandetron	p to Au p to Au AMS *
LUNA	Italy	400 kV HVEE electrostatic accelerator 3.5 MV Cockroft-Walton accelerator	H^+, He^+ p, α, ^{12}C
CMAM, Madrid	Spain	5 MV HVEE Pelletron Tandem	p to Au
TAL, Demokritos	Greece	5.5 MV Van de Graaff Tandem 250 keV single-stage accelerator (PAPAP) 17 MeV Scanditronix Cyclotron	n (see Section 2.22.), stable beams p, d p, d
		2.5 MV Tandetron	AMS *
MIC, JSI	Slovenia	2 MV Tandetron	H, ^{3}He, ^{4}He, and heavier ions
VERA	Austria	3 MV Pelletron	AMS *
The Surrey Ion Beam Centre	England	2 MV Tandetron	** Primarily used for IBA
The Dalton Cumbrian Facility	England	5 MV Tandem 2.5 MV Pelletron	** Primarily used for IBA, nuclear chemistry, and ion irradiation damage studies

Table 1. *Cont.*

Facility	Country	Accelerators Available	Beams
The Tandem Laboratory, Uppsala University	Sweden	5 MV Pelletron 350 kV high-current implanter	** Primarily used for IBA and AMS
CIRCE	Italy	3 MV Pelletron	H to U (up to 20 MeV)
LABEC	Italy	3 MV Tandetron	** Primarily used for cultural heritage and environmental studies
AIFIRA	France	3.5 MV Singletron	** Primarily used for irradiation of materials and IBA

* Primarily used for accelerator mass spectroscopy measurements. ** Primarily used for applied research.

2. Small-Scale Facilities

Numerous facilities listed in Table 1 and shown in Figure 1 carry out research in both fundamental and applied nuclear physics. Most of the activities in fundamental nuclear research performed at these facilities are related to nuclear structure, reactions, and nuclear astrophysics.

Figure 1. The map of European small-scale facilities reviewed in this paper (courtesy of Google Earth). The corresponding facilities are depicted with the pink placemark.

2.1. Cologne Accelerator Laboratory, Institute for Nuclear Physics (IKP), Cologne, Germany

The Cologne accelerator laboratory provides two accelerators, a 10 MV FN-Tandem and a 6 MV Tandetron accelerator [7]. The latter one serves solely for accelerator mass spectroscopy measurements (AMS), while the 10 MV FN-Tandem is used for research in nuclear structure and nuclear astrophysics. The 10 MV Tandem provides beams of light and heavy ions (Z up to 30) and energies up to 120 MeV. Typical beam currents are 10–100 nA [8]. Various experimental setups equipped with several high-purity germanium (HPGe) as well as silicon particle detectors are used to perform research on nuclear reaction rates, nuclear lifetimes, and the structure of excited states.

Nuclear astrophysics research is focused on low-energy, charged-particle-induced reactions at low energies (of astrophysical interest). The proper knowledge of cross-sections is necessary for reaction network calculations of different stellar scenarios. For γ-ray spectroscopy, the high-efficiency γ-ray spectrometer HORUS (High-efficiency Observatory for γ-Ray Unique Spectroscopy) [9] is available. HORUS comprises up to fourteen HPGe detectors. In order to actively suppress the Compton background, six of them can be equipped with active BGO (bismuth germanate) shields. The detectors are placed at five different angles with respect to the beam axis, enabling the five angular distribution measurements that are required to precisely determine the absolute cross-sections.

A detailed understanding of the nuclear physics processes is needed to properly describe different astrophysical scenarios. The γ-process [10] is assumed to be responsible for the largest contribution to the abundance of 35 neutron-deficient p nuclei. It creates a vast network of photo-disintegration reactions that include a plethora of different reactions on mainly unstable and exotic nuclei. In the absence of experimental results, theoretical cross-sections have to be considered. The cross-sections at astrophysically relevant energies, i.e., inside the Gamow window (the range of energies where nuclear reactions occur in stars) are extremely low (usually of the order of μB); therefore, the development of sensitive measurement techniques is very much needed.

Different direct methods are used to measure the radiative capture cross-sections. One of the most widely applied methods is the activation method [11]. In the activation method, unstable reaction products are first produced, and then, the radioactive decay, usually the γ-ray transitions from the daughter nucleus, is observed. The limitation of this technique is that it has to yield an unstable reaction product with a half-life that is long enough to transfer the sample to the corresponding counting setup. To overcome this limitation, two different methods are mostly applied, namely, the in-beam 4π-summing technique [12] and the in-beam high-resolution γ-ray spectroscopy technique [13]. The in-beam 4π-summing technique uses a large scintillator crystal, which covers a solid angle of almost 4π around the target position and sums the energies of all γ rays emitted in a certain time window. In the high-resolution γ-ray spectroscopy technique, the prompt γ-decays of the excited compound nucleus are observed. Absolute reaction cross-sections can be determined by measuring the angular distributions using an HPGe array (e.g., HORUS). Moreover, nuclear structure information such as spin and parity assignments can be obtained. The ^{89}Y(p,γ)^{90}Zr commissioning experiment has demonstrated the reliability of the measured cross-sections obtained using the HORUS array [14]. SONIC@HORUS is a setup for particle-γ coincidence measurements. It consists of the recently developed particle spectrometer SONIC (Silicon Identification Chamber), which can house up to 12 ΔE-E telescopes for the identification of ejectiles and measurement of their energy, and the spectrometer HORUS, which has been used to investigate the nuclear structure by measuring gamma rays from fusion–evaporation reactions as well as from capture reactions. The identification of the ejectile is necessary to select non-dominating reaction channels like light-ion scattering and specific transfer reactions. By measuring the energy of the ejectile, nuclear-level schemes can be studied in detail (the excitation energy of the nucleus can be calculated from the ejectile energy). The knowledge of the complete reaction kinematics also enables a precise and reliable determination of lifetimes using the Doppler-Shift Attenuation Method (DSAM) [15]. The DSAM method is commonly used for the measurement of sub-ps lifetimes of excited nuclear states. The excited nucleus (obtained in the nuclear reaction) moves with a certain velocity and slows down during the time interval of the order of ps. The emission of γ rays during this time interval leads to the observation of a line shape, whose characteristics are sensitive to the time evolution of the population of the level of interest, and specifically, to its lifetime.

2.2. Heavy Ion Laboratory (HIL), Warsaw, Poland

HIL is a Polish infrastructure that hosts a K_{max} = 160 isochronous heavy ion cyclotron. The cyclotron provides beams (from He up to Xe) of energies 2–10 MeV/u and intensities up to a few hundred pnA [16]. Experiments can utilize different setups and apparatus including IGISOL ((Ion Guide Isotope Separation On-Line) [17]—a Scandinavian type on-line separator. The setups are described in the following. The Coulomb Universal Detector Array Chamber (CUDAG) [18] is a small scattering chamber. CUDAG can accommodate an array of backward hemisphere semiconductor detectors and forward hemisphere monitoring Si counters. It is mostly utilized for Coulomb excitation research and measurements of fusion barrier distributions. The former Strasbourg-based ICARE (Identificateur de Charges a Rendement Eleve) [19] is a particle spectroscopy chamber. ICARE can accommodate up to forty-eight telescopes. Charged particle detection, identification, and energy measurement are performed using them. The research performed in this setup encompasses barrier distribution measurements, reaction mechanism studies, and novel detector tests. The experimental efforts are devoted to barrier-level distribution studies and experiments using ^{10,11}B, ^{18}O, and ^{14,15}N beams on light targets such as ^{6,7}Li, ^{9}Be, ^{12,13}C. EAGLE [20] is a Central European Array for Gamma Levels Evaluation. It can host up to thirty HPGe detectors with anti-Compton shielding. EAGLE enables research on the nuclear structure through γ-spectroscopy techniques, such as γ–γ angular correlations and lifetime measurements using methods such as the Doppler Shift Attenuation Method (see Section 2.1.) and the Recoil Distance Doppler Shift technique (RDDS) [21], and complex Coulomb excitation (Coulex) experiments relevant for nuclear structure physics. The RDDS method is the standard method to measure lifetimes of excited nuclear states in the ps range. The method uses a plunger device that consists of a stretched target and stopper-foil, which are mounted parallel to each other at a variable distance. Excited states in the nucleus of interest are populated in the target foil. The nucleus then recoils with a velocity of a few percent of the speed of light in the direction of the stopper foil where it is stopped. The lifetime of a level of interest is determined by the changing intensities of fully Doppler-shifted and stopped γ-ray components. Coincidences between gamma-rays and internal conversion electrons enable the determination of transition multipolarities. The EAGLE array could be utilized in conjunction with the ULESE (University of Lodz Electron Spectrometer) [22] electron spectrometer to perform this type of measurement. High efficiency (up to 12% at 300 keV) and good energy resolution (1% at 1 MeV) characterize this electron spectrometer. Additionally, the ULESE electron spectrometer has good suppression of the emitted photons, positrons, and delta electrons. The elimination of delta electrons is crucial in electron conversion spectroscopy performed in "in-beam" measurements. The ULESE spectrometer coupled to the EAGLE array was successfully used in measurements performed at HIL. The main objective of these experiments was to study the violation of the K selection rule for electromagnetic transitions in nuclei. The absolute transition probabilities in ^{130}Ba,^{132}Ce, ^{134}Nd, and ^{184}Pt were measured [23].

Coulex is a method to investigate nuclear structure. If one properly selects the beam energy, the Coulomb interaction between the incident and target nuclei can be described by classical electrodynamics, neglecting the nuclear forces. The use of various beams and detectors, which measure at broad ranges of scattering angles, enable measurements of electromagnetic structure key parameters up to the high-spins. Static moments and transitional matrix elements are related to spectroscopic observables, such as lifetimes, gamma-ray intensities, branching, and mixing ratios. Coulomb excitation has been one of the leading experimental techniques and was established at HIL about thirty years ago. Using the CUDAC, the first successful experimental campaigns were conducted. At first, the historical array was coupled to a set of small-size gamma detectors and was later replaced with a compact scattering chamber dedicated to work with EAGLE. A new particle array—SilCA (Silicon Coulex Array) [18], based on the DSSSD detectors—is currently under development at HIL, Warsaw. One of the main topics of recent studies performed at HIL was focused on the transitional region of the nuclear chart (A~100, Z~40, 50). In the transitional region of the nuclear chart, the phenomenon of shape instabilities is relatively common and may lead to coexisting nuclear shapes. Most of the even–even nuclei in this region are also traditionally considered the best examples of vibrational nuclei. However, recent results seriously contradict this simple interpretation. Coulomb excitation studies of shape-coexisting structures in ^{96,98,100}Mo [24] showed that triaxiality plays an important role in this region. The problem of chirality in atomic nuclei with odd numbers of protons and neutrons has attracted a lot of attention in recent years. In these nuclei, the total nuclear spin is built from the valence proton and valence neutron momenta and angular momentum of the even–even core. These three vectors can be mutually perpendicular and coupled in two manners, forming left-handed and right-handed systems. Left-handed systems and right-handed systems, namely, have opposite chirality in the intrinsic frame of the nucleus. On the other hand, in the laboratory frame, chirality manifests itself as the presence of two rotational bands, nearby degenerated, with the same parities. The measurements of the lifetimes of states belonging to the chiral bands are still lacking. Lifetimes carry important information on nuclear wave functions. Significant results on chiral symmetry breaking in low-energy excitations of atomic nuclei have been obtained at HIL. The gamma-spectroscopy methods, namely, DSAM for lifetime measurements [25,26] and the time-differential perturbed angular distribution (TDPAD) to determine g-factors [27], have been employed to investigate the chiral bands. EAGLE array was employed for gamma-ray spectroscopy. The TDPAD method is based on the nuclear magnetic moment interaction with the external magnetic field. Due to that interaction, the magnetic moment of the nucleus prcesses around the field axis and causes a specific angular distribution of the emitted gamma radiation. The gamma spectrometer (i.e., EAGLE) is used to obtain a good angular sensitivity necessary for this type of measurement. The recent search for a phase transition from not-chiral to chiral structure in ^{128}Cs [28] has been performed at HIL.

One should stress that HIL is an interdisciplinary user facility. Research on solid-state physics, biology, and applications plays an important role, so a significant amount of the beam time is distributed for these purposes. Medical applications of nuclear physics are of special significance since HIL hosts radiopharmaceuticals research and production center.

2.3. IJClab (Laboratory of the Physics of the Two Infinities Irène Joliot-Curie), Orsay, France

The IJClab hosts and supports ALTO (Accélérateur et Tandem d'Orsay), a French research platform that hosts two accelerators, unique in France: a 15 MV Tandem accelerator and a 50 MV electron linear accelerator. A linear accelerator is employed for the production of radioactive beams by photofission. The platform enables research in nuclear physics, astrophysics, as well as multidisciplinary studies [29]. It also hosts the ANDROMEDE facility. ALTO provides rare energetic beams, such as ^{3}He and ^{14}C. It is a unique facility in Europe since it produces low-energy neutron-rich beams via uranium photofission. It is also unique in its capacity to provide a high-flux naturally directional neutron beam with the LICORNE neutron converter [30]. LICORNE is a high-flux directional neutron source based at the Tandem accelerator of the ALTO facility. It produces intense, kinematically focused quasi-monoenergetic beams of neutrons in the energy range of 0.5 MeV to 4 MeV. The neutron production is achieved using the capability of the ALTO Tandem accelerator to produce an intense primary beam of ^{7}Li, which results in secondary beams of kinematically focused neutrons. The neutron cone allows sensitive detectors to be placed around the sample to be irradiated; the former is particularly crucial if HPGe detectors are used since they are easily damaged by the fast neutrons. LICORNE allows for both high-flux and beam collimation.

Decay spectroscopy is performed on the Low Energy Branch using the BESTIOL or alias BEDO (Beta Decay Studies at Orsay) setup [31] on the High Energy Branch using the LICORNE neutron source and the NuBall array. BEDO is a movable-tape-based experiment setup. The tape's trajectory in BEDO is chosen to make the most of the space around the beam collection point, enabling the most effective deployment of various types of detectors. Significant experimental and theoretical interest has been shown in BEDO for nuclei at the Z = 28 shell closure and in the mass range of N = 50. The gap between the n1g$_{9/2}$ and n2d$_{5/2}$ orbitals corresponds to the N = 50 shell effects and is essential to understanding the formation of this magic closure. Also, it contributes to the understanding of the origin of the strong gaps associated with spin-orbit magic numbers throughout the whole nuclear chart, in which 3-body terms of the *N*–*N* interaction are now thought to play a key role [31]. Also, BEDO has conducted significant research on the region close to $N = 82$.

NuBall array [32] is an array that consists of the HPGe (for precise gamma-spectroscopy) and $LaBr_3$(Ce) (for fast-timing measurements) detectors that, coupled to the LICORNE directional neutron source, enable calorimetry to select reactions and study gamma energy and multipolarities of fission products. The array's key characteristic is its ability to combine the largest peak-to-total ratio for precision gamma spectroscopy with the best time resolution conceivable.

Numerous experiments are covered under the LICORNE physics program. The research focuses on nuclear reactions and the study of the prompt gamma and neutron emission in nuclear fission, as well as on the nuclear structure and the production of exotic neutron-rich nuclei. Fission is an important reaction process. It can occur either spontaneously or following a reaction or nuclear decay in the region of heavy and superheavy nuclei. Although significant research on fission has been performed for decades, fission is still rather poorly understood nowadays. One of the recent results concerns the observation of the angular momentum generation in nuclear fission [33]. The splitting of the heavy atomic nuclei is observed to produce spinning fragments. The internal generation of typically six or seven units of angular momentum in each fragment is particularly interesting for systems that start with zero (or almost zero spin). It was shown [30] that the spins of the fragment partners do not significantly correlate, which indicates the conclusion that in fission, angular momentum is created once the nucleus splits (post-scission). The comprehensive data showed that the average spin is strongly mass-dependent, varying in saw-tooth distribution. The lack of observable fragment dependency on partner mass or charge supports the spin mechanism's uncorrelated post-scission nature. The first NuBall campaign at ALTO had a diverse nuclear physics program [34], i.e., studying the superallowed beta-decay of ^{10}C to test the weak interaction and unitarity of the CKM matrix or studying the Giant-Dipole Resonance (GDR—giant resonances are collective excitations of the atomic nucleus) feeding of low-energy structures with different deformations using NuBall coupled to the PARIS array (Photon Array for Studies with Radioactive Ion and Stable beams). The second NuBall campaign at ALTO took place in 2022.

Concerning the low-energy radioactive beams, a number of complementary installations are being prepared for online commissioning. POLAREX (POLARized EXotic nuclei) is a unique facility to study nuclear magnetic properties of neutron-rich nuclei produced by the ALTO facility, with the technique of low-temperature nuclear orientation combined with the on-line implantation of a radioactive beam. It will also enable the studies of nuclear structure (γ multipolarity, nuclear magnetic moment μ, nuclear deformations) [29]. MLLTRAP is a high-precision mass measurement setup [29]. It consists of two trap electrode modules. The ions are cooled and manipulated in the first trap and then injected into the second trap, where the actual mass measurement takes place by determining the cyclotron frequency of the ions. This module will be used to measure masses of fission fragments. LINO is a collinear laser spectroscopy setup [29] that will enable studies of hyperfine structure, electromagnetic moments, and mean charge radii. Collinear laser spectroscopy is a robust experimental method that enables high-precision measurement of nuclear characteristics with atomic laser excitations. The LINO setup was successfully commissioned with the stable beams in 2019. The Split-Pole spectrometer is mainly used to study two-body reactions (transfer, elastic and inelastic scattering, charge exchange). It is a very useful tool to study key nuclear astrophysics reactions that require the use of transfer reactions or inelastic scattering reactions (angular distribution measurements and excitation energy spectrum measurement with high energy resolution) to access, with high precision, the spectroscopic information (e.g., partial widths) needed to calculate the reactions' rates. Recently, the coupling of this spectrometer to an array of DSSSD-s (Double-Sided Silicon Strip Detector) in the reaction chamber has opened up opportunities to have access to the charged-particle decay branching ratios. Examples of angular distributions and correlations include studies of the reactions: ^{70}Zn(d,^{3}He)^{69}Cu, ^{19}Fe(^{3}He,t)^{19}Ne(α)^{15}O [29]. ALTO also hosts a radiograph precision dosimetry beamline for radiobiology as well as SPACEALTO, an irradiation station for space applications.

Andromede is a 4 MeV NEC Pelletron accelerator [35] and delivers ion beams from proton to gold, the rare gases He, Ne, Ar, K, and Xe, as well as molecular beams and metal clusters. One of the experiments recently performed at Andromede is the study of ^{12}C + ^{12}C fusion cross-section using the STELLA (STELlar LAboratory) experimental station. The ^{12}C + ^{12}C fusion reaction is crucial for the understanding of the evolution of massive stars. A straightforward extrapolation down to the Gamow window and the energy range relevant to carbon burning in massive stars is difficult due to resonances in this reaction at energies near and below the Coulomb barrier. The STELLA setup has enabled the studies of the ^{12}C + ^{12}C fusion cross-section at low energies, using an advanced particle-gamma coincidence technique. The method of particle-gamma coincidence is employed for background suppression. In this project, annular silicon strip detectors customized at IPHC-CNRS, Strasbourg [36], were integrated with $LaBr_3$(Ce) detectors from the FATIMA (FAst TIMing Array) [37]. The sensitivity of the technique has effectively removed ambiguities in existing measurements made with gamma-ray or charged-particle detection alone and made it possible to obtain reliable excitation functions for the ^{12}C + ^{12}C reaction, spanning eight orders of magnitude in the cross-section [38].

2.4. Rudjer Bošković Institute Accelerator Facility, Zagreb, Croatia

The Rudjer Bošković Institute (RBI) Accelerator Facility hosts two accelerators: a 6.0 MV Tandem Van de Graaff accelerator and a 1.0 MeV Tandetron accelerator that provide a wide range of ions, from H and He to heavy ions [39]. One of the beamlines is dedicated to nuclear studies. The research is based on a large silicon detector array. The current experimental setup consists of up to four silicon detector telescopes, assembled from thin single-sided (ΔE) SSD and thick double-sided (E) DSSSD detectors. Research topics are concentrated on the molecular and cluster structure of neutron-rich isotopes of Be, B, and V and on performing measurements of the three-body quasi-free reactions based on the Trojan Horse Method (THM) to accurately investigate nuclear astrophysics reactions [40]. The THM is an indirect method, unaffected by Coulomb suppression or the electron screening effect. It is used for calculating the bare nucleus astrophysical S-factor for charged particle reactions at astrophysically relevant energies. This is obtained by measuring a suitable three-body process' quasi-free cross-section. The suitable Trojan Horse (TH) nuclei must be chosen for the method's successful use; these nuclei should have a prominent cluster structure to transfer (such as nucleons, deuterons, or α particles). A crucial technique for examining the behavior of nuclear forces in few-body interacting systems is the study of cluster formations in neutron-rich nuclei. Concerning the cluster and the molecular structure in the neutron-rich isotopes of the Be, B, and V measurement of the $^{7}Li + ^{7}Li \rightarrow \alpha + \alpha + ^{6}He$ reaction provided the first strong indication for the molecular $\alpha + 2n + \alpha$ structure in ^{10}Be [41]. The measurement of the $^{9}Be + ^{4}He$ resonant scattering confirmed strong $^{9}Be + ^{4}He$ clustering in the ^{13}C nucleus [42].

The RBI Accelerator facility also performs fundamental and interdisciplinary studies related to the analysis and modification of materials with ion beams. Research related to analysis techniques relevant to biomedicine, environment, as well as to studies of cultural heritage objects is also performed.

2.5. Tandetron Laboratory in Piešt'any, Institute of Physics, Slovak Academy of Sciences

The Tandetron laboratory in Piešt'any hosts a 2 MV Tandetron accelerator [43]. It is able to deliver proton and deuteron beams up to 4 MeV energy with an intensity of up to 25 µA and α beams up to an energy of 6 MeV with an intensity of up to 3 µA. Four coaxial HPGe detectors and three $LaBr_3$(Ce) detectors for charged particles are available for use. Measurements of the angular distribution can be made with great accuracy using a precise goniometer for gamma-ray detector mounting, allowing for the determination of M1/E2 mixing ratios for $\Delta J = 1$ transitions, which are currently poorly characterized. A gas target has been constructed for the production of quasi-monoenergetic fast neutrons through the (d,D) reaction. It is intended to conduct systematic studies of the lifetimes of excited states in stable isotopes utilizing inelastic neutron scattering and gamma-ray detection [43].

2.6. The Oslo Cyclotron Laboratory (OCL), University of Oslo, Norway

Research at the OCL is concentrated on spectroscopy experiments for nuclear structure and nuclear astrophysics. The laboratory hosts the K = 35 cyclotron [44]. The cyclotron accelerates $^{1}H^{+}$ in the energy range of 8 MeV to 35 Me, $^{2}H^{+}$ in the energy range of 4 MeV to 18 MeV, $^{3}He^{2+}$ in the energy range of 6 MeV to 47 MeV, and $^{4}He^{2+}$ in the energy range of 8 MeV to 35 MeV.

The tools and techniques for research of the statistical properties of highly excited nuclei in the quasi-continuum region have been developed over the years in the OCL group. The Oslo Scintillator Array (OSCAR) [45] consists of 30 large-volume $LaBr_3$(Ce) detectors. It measures high-energy γ rays with excellent timing, high efficiency, and good energy resolution. Most nuclear physics experiments need the detection of high-energy γ rays in coincidence with the scattered charged particles. The silicon ring (SiRi) detector array is used to detect light-ion ejectiles from transfer reactions [46]. In SiRi, 64 ΔE-E silicon telescopes are placed in eight trapezoidal pads in a lamp-shade geometry. For the investigation of statistical decays that require a high particle-γ coincidence rate, the OSCAR-SiRi is used. A Nuclear Instrument for Fission Fragments (NIFF) [47] can be installed within the target chamber to study actinides. NIFF consists of four individual parallel-plate avalanche counters (PPAC). Nuclear levels become increasingly close in energy as excitation energy increases, making discrete spectroscopy challenging or sometimes even impossible. In this statistical region, average properties like the nuclear level density (NLD) and γ-ray strength function (γSF) replace the well-defined states and the decay rate between them. The Oslo method [48] allows for simultaneous determination of the functional form of the NLD density (ρ) and γSF function (f). This method is based on a factorization of the decay probability. Thermodynamic properties in the microcanonical ensemble were obtained for $^{237,238,239}U$ [49] using the Oslo method. The level density curves are exponentially increasing, suggesting a linear entropy as a function of excitation energy. The almost linear entropy means that the NLD follows a close-to-constant temperature model characteristic with a critical temperature of T_c~0.4 MeV. This indicates that heating the nuclear system results in the breaking of Cooper pairs rather than an increase in temperature (phenomenological analogy to the melting ice). The study of the γSF in the quasi-continuum has been quite successful. One of the most unexpected findings was that the γSF starts to increase for decreasing gamma energies below a few MeV for many light nuclei. The scissor resonance embedded in the quasi-continuum has been systematically studied. One has to note that with a large number of data obtained for a wide range of nuclei, OCL is a major contribution to the IAEA (International Atomic Energy Agency) reference database for photon strength function [50].

According to their substantially different time scales, slow (s) and rapid (r) neutron-capture processes [51] have each produced half of the heavy-element isotopes observed in the solar system, while the proton-capture/photodisintegration (p) process is in charge of roughly 35 nuclides that are not produced by the s- and r-processes. In addition to the aforementioned nucleosynthesis processes, an intermediate (i) neutron-capture process [52] might be important in certain stellar environments. In order to understand the heavy-element nucleosynthesis and elemental abundances, large nuclear reaction networks are applied. These networks need as an input various creation and destruction probabilities. Since both i and r processes involve very neutron-rich nuclei, there is still a lot of missing experimental information on these rates. Although the s-process mostly follows the valley of stability, there are still missing data for s-process branchings (radiative neutron-capture rates). Charged-particle reactions such as (p,γ) and (α,γ) for the p-process reaction network are very difficult to measure directly for sub-Coulomb energies. One relies on theoretical estimates when there are not any experimental data available. The estimates can diverge by orders of magnitude. One method of establishing experimental constraints on the astrophysical rates is to measure the NLD and γSF of the residual nucleus in the radiative capture process, either (n,γ) for the s, i, and r-process or (p,γ) and (α,γ) for the p-process. Using these experimental NLDs and γSFs as the inputs to nuclear reaction rates significantly improved the prediction of the radiative capture rates, which could then be obtained.

Hoyle predicted (in 1954) a resonant state in ^{12}C [53] and explained the production of carbon through the triple α-process. An excited 0^+ state at the predicted excitation energy of 7.65 MeV, named the Hoyle state, was discovered soon afterwards and studied thoroughly since. The experiment at OCL used inelastic proton scattering on ^{12}C to populate the Hoyle state [54]. The measured value is about 34% higher than the currently adopted value, and if experimentally confirmed, will impact models of stellar evolution and nucleosynthesis. To confirm the discrepancy, new experiments with OSCAR are currently being performed.

The OCL also performs studies in nuclear chemistry. In addition, isotopes are produced for nuclear medicine.

2.7. The Superconducting Darmstadt Linear Electron Accelerator (S-DALINAC), Institut für Kernphysik, (IKP), Darmsatdt, Germany

The IKP of the Technische Universität Darmstadt hosts a superconducting electron accelerator, the S-DALINAC. The astrophysics research at IKP [55] focuses on electron scattering studies of the form factor and the monopole transition matrix element of the Hoyle state, the near-threshold transition in ^{9}Be, as well as the extraction of level densities and gamma strength functions. The most notable nuclear structure studies include [55] giant quadrupole resonance, the scissors mode (the scissors mode in nuclei refers to a pictorial image of deformed proton and neutron distributions oscillating against one another) in deformed nuclei, and the competitive double gamma ($\gamma\gamma/\gamma$) decay.

S-DALINAC was initially constructed as a twice-recirculating accelerator with a maximum energy of 130 MeV in a continuous wave operation. In 2016, it was converted into a three-recirculating accelerator [55]. The beam is either produced in a thermionic gun or in the S-DALINAC Polarized Injector (SPIN). Following both sources, the beam is firstly prepared for acceleration and then guided through the superconducting injector accelerator, which is able to accelerate the beam up to 10 MeV with beam currents up to 60 µA. The injector beam can be used for the research of nuclear resonance fluorescence (NRF) or it can be deflected into the main accelerator for further acceleration and recirculation. Recirculating the beam up to three times leads to a final energy of up to 130 MeV with a beam current of up to 20 µA. Electron beams from the S-DALINAC are delivered to four major experimental setups. The Darmstadt High-Intensity Photon Setup, (DHIPS) [56], is a low-energy high-flux bremsstrahlung setup located after the linac injector. The experimental hall accommodates two magnetic spectrometers. A highly energy-resolving spectrometer (LINTOTT) [55] is used for elastic electron scattering experiments, while Quadrupole CLAMshell (Q-CLAM) is used for inelastic electron scattering experiments. Q-CLAM has a large solid angle coverage and a quadrupole-dipole magnet arrangement. The facility also hosts a high-energy photon tagger NEPTUN. NEPTUN is being upgraded to considerably larger momentum acceptance. By utilizing photo-fission, photo-activation, or photon-scattering reactions, the DHIPS bremsstrahlung beams are mostly employed for nuclear structure studies. Photo-scattering reactions are frequently used in NRF experiments, where the resonantly scattered γ rays are detected with large-volume HPGe detectors. This method is highly selective on nuclear low-spin excitation because of the low momentum transfer induced by the photons. Experiments performed at DHIPS have significantly contributed to the studies of the fine structure of the pygmy dipole resonance in stable nuclei, studies of electromagnetic (EM) transitions between the scissors mode and intrinsic nuclear vibration, and their relation to the modelling of the $0\upsilon\beta\beta$ decay reactions. LINTOTT is used for the studies of spectrometry of electron-scattering reactions with low momentum transfer and high energy. It has been applied in various research studies of stable key nuclei from the deuteron, light, and medium-heavy nuclei up to ^{208}Pb (see, for example, [57–59]). For the highest energy resolution, LINTOTT can be operated in a dispersion-matching mode. Four ninety-six-fold segmented silicon strip detectors and a Cherenkov counter for background suppression compose the focal plane detectors. The Q-CLAM spectrometer consists of a quadrupole magnet with a large horizontal aperture and a dipole magnet with inclined pole shoes. This allows for large solid angles essential for coincidence measurements of the type (e,e′x) where x = γ,n,p. (see, for example, Ref. [60]). To estimate the momentum and angle of the scattered electron in the resulting complex ion optics, it is necessary to track the electron trajectory in the spectrometer. The trajectory is reconstructed using a stack of multiwire drift chambers, which provide the respective position and the angle. A large Cherenkov counter is used to suppress the background. Measurements can be performed over a large angular range (25–255°) and in a special chicane arrangement at 180° [57]. The latter allows for especially sensitive studies of nuclear magnetic excitation since the longitudinal electric nuclear excitation modes are kinematically suppressed at the backward angles by several orders of magnitude. For coincident γ-ray detection, the GALATEA (GAmma LAnthanum bromide Top Efficiency Array) array can be placed around the target chamber. The GALATEA consists of seventeen medium-size $LaBr_3$(Ce) detectors and was employed in the observation of the competitive double-gamma decay [61]. The double-gamma ($\gamma\gamma$) decay of an excited quantum system is a fundamental second-order process of quantum electrodynamics (QED). The double-gamma decay can be distinguished from the well-known single-gamma (γ) decay by the simultaneous emission of two gamma quanta, each having a continuous energy spectrum. The S-DALINAC's electron beam can be utilized to create a beam of energy-tagged bremsstrahlung photons by means of the NEPTUN setup [55]. The NEPTUN tagger setup is suitable for high-resolution studies of astrophysically relevant cross-sections. Reaction-tagged photons can be utilized to more accurately estimate the photodissociation cross-section energy dependence, particularly in the astrophysically significant region just above the threshold for (γ,n) reactions. Additionally, NEPTUN is employed for the extraction of the dipole polarizability, as well as the observation of the complete dipole strength from well below the threshold to well above the giant resonance peak.

2.8. The INFN Laboratori Nazionali del Sud, (LNS), Italy

LNS hosts two particle accelerators: a Superconducting Cyclotron (SC) with a bending limit of K_b = 800 and focusing limit of K_f = 200 [62,63] and a 13 MV HVEC MP TANDEM accelerator. The 13 MV TANDEM provides ion beams from proton to gold with a maximum energy of 25 MeV/u for masses around 200 and 90 MeV/u for fully stripped light ions, such as carbon. SC is a cyclical compact three-sector accelerator capable of accelerating ion beams from protons to uranium at energies up to 80 MeV/A. It is also possible to produce the radioactive ion beams by applying in-flight fragmentation. The FRIBS@LNS (In Fight Radioactive Ion Beams at LNS) facility produces RIBS (Radioactive Ion Beams) at intermediate energies (20–50 MeV/u). Exotic beams from ^{6}He to ^{68}Ni have been provided over the past few years using the fragmentation of various stable beams accelerated by the SC on a Be target. A high granularity charged-particle multi-detector called CHIMERA (Charged Heavy Ion Mass and Energy Resolving Array) surrounds the target in roughly 95% of the solid angle. It comprises 1192 telescopes (300 µm thick Si as a ΔE detector and a 3–12 cm thick CsI(Tl) crystal as a residual energy (E) detector). The implemented pulse height analysis technique allows particle identification and energy measurement in a wide dynamical range including Tandem energies. Chirone is an experiment that uses the high granularity of the CHIMERA [64] detector array as well as the correlator FARCOS (Femtoscope ARray for COrrelation and Spectroscopy) [65] for reaction and spectroscopic studies in identifying the mass and charge of reaction products in order to study the effects of isospin on the reaction mechanism and the density dependence of the symmetry term of the nuclear matter equation of state (EOS). FARCOS is a modular array of telescopes arranged in a single cluster, each one consisting of three detection stages. Measurements of the angular distributions of neutron transfer reactions were obtained with the kinematical coincidence method. A study of cluster structure and levels of ^{10}Be [66] was also performed. In the presence of additional neutrons, clustering effects could take on significantly different features from the self-conjugated nuclei's α-clustering. These neutrons can take the role of covalent particles acting as a glue between the α cluster centers and leading to the so-called nuclear molecules. The study of the cluster structure in exotic nuclei and the "pygmy resonance" manifestations of a particular collective nuclear motion carried out using the exotic beams produced by FRIBS have been performed. The isoscalar excitation of the Pygmy Dipole resonance in ^{68}Ni was investigated for the first time [67] (the term "Pygmy Dipole Resonance" (PDR) has been commonly used for the E1 strength around and below the neutron-separation energy, Sn). One of the PDR's main characteristics is the behavior of isoscalar and isovector transition densities, which have the same order of magnitude at the surface. The PDR population consequently employs both isoscalar and isovector probes.

Tandem and low energy Cyclotron experiments are the primary aim of MAGNEX [68] experiments. MAGNEX is a high-resolution magnetic spectrometer with a large solid angle and momentum acceptance based on the reconstruction of the ion trajectory. It consists of a vertically focusing quadrupole magnet, a bending dipole, and a number of surface coils for quadrupole and sextupole corrections. In the focal plane, a detector consisting of a gas ΔE stage, and the wall of silicon strips as the residual energy detectors (E)€ are positioned. Some methods for populating light neutron-rich nuclei are one and multi-neutron transfer or charge exchange reactions. Due to the spectrometer's high performance, their excitation spectrum can be determined in detail. Since the beginning of the Tandem operation, the focus of research has been the study of reaction mechanisms typical of low-energy processes, such as fission, transfer, and complete and incomplete fusion. The study of cluster and molecular configuration at high spin states has also been performed.

The nuclear astrophysics program has a primary emphasis on the application of THM [40] to the processes relevant to the understanding of stellar evolution and the element nucleosynthesis. The THM can provide an indirect measurement of the astrophysical factors, which, in direct experiments, can be inferred only by extrapolation (see Section 2.4). The method can be applied to resonant and non-resonant charged particle reactions, as well as to neutron-induced reactions. Both stable and radioactive beams can be used. The method has been developed at LNS, and some of the experiments at the local INFN-LNS infrastructure will be described (many that are not stated here are performed worldwide). The ^{9}Be(p,α)^{6}Li reaction is important for the understanding of light element abundances (lithium, beryllium, and boron). The measurement of the ^{9}Be(p,α)^{6}Li S(E) factor by properly selecting the Quasi-Free (QF) contribution of the three-body reaction ^{2}H(^{9}Be,α^{6}Li)n has been performed [69,70]. Deuterons were used as "TH nuclei" because of the obvious p-n structure and their relative motion mainly occurring in the s-wave. The astrophysical S(E)-factor was extracted and compared to direct data. No information about the electron screening effect could be extracted due to the poor resolution of the indirect data. The ^{10}B(p,α_0)^{7}Be reaction has been measured for the first time at the Gamow peak [71] by means of the THM applied to the ^{2}H(^{10}B,α ^{7}Be)n QF reaction. The study of the ^{10}B(p,α)^{7}Be reaction is of importance in nuclear astrophysics because of the challenging measurements of the corresponding S(E)-factor at low energies (Gamow window) and the astrophysical importance of the production/destroying processes of the unstable ^{7}Be isotope [72]. The absolute value of the astrophysical S(E)-factor has been deduced, providing, for the first time, the measurements at the corresponding Gamow peak. Since the THM S(E) factor does not suffer from electron screening effects, it has been used to evaluate the electron screening potential value needed for the description of the low-energy direct data. This was the first independent measurement of the electron screening potential, U_e, for the ^{10}B(p,α_0)^{7}Be. The ^{11}B(p,α_0)^{8}Be reaction was studied from 1 MeV down to astrophysical energies by applying THM to the ^{2}H(^{11}B,α_0)^{8}Be three-body reaction [73]. The ^{27}Al(p,α)^{24}Mg reaction rate was measured by means of the THM applied to the ^{2}H(^{27}Al,α^{24}Mg)n three-body reaction [74]. The high-accuracy measurement of the strength of the 84.3 keV resonance was obtained. The stricter constraints on the upper limits of the 71.5 keV, 193.5 keV, and 214.7 keV resonances lead to a reduction of a factor of approximately three in the reaction rate at temperatures where the MgAl cycle is especially important. Due to its high yield from 150 keV down to zero energy, the neutron capture reaction $^{10}B(n,\alpha)^{7}Li$ is becoming more and more significant for applied nuclear physics. The $^{10}B(n,\alpha)^{7}Li$ reaction has been investigated [75] via the Trojan Horse Method (through $^{2}H(^{10}B,\alpha^{7}Li)H$ reaction) from 0 to 1 MeV. The α_0 and α_1 channels, corresponding to ^{7}Li in its ground state (g.s.) and first excited level, respectively, have been analyzed, and cross-sections have been measured for the two reaction channels. Understanding the fluorine abundance in the outer layers of asymptotic giant branch stars depends significantly on the $^{19}F(p,\alpha)^{16}O$ reaction (AGB stars are stars that are brighter than the Sun but have lower surface temperatures). Recently, direct measurements of the $^{19}F(p,\alpha_0)^{16}O$ reaction [76] at center-of-mass energies from 0.4 MeV to 0.9 MeV were performed. The LHASA (Large High-resolution Array of Silicon for Astrophysics) detector array has been used. It consists of six 300 μm thick YY1 silicon strip detectors [77] mounted in a lamp-shade configuration. The emerging α particles can be detected by LHASA over a wide angular range (from 10° to 32°).

The current upgrade project of the SC is opening new perspectives and possibilities. The upgrade will enable further investigation of isospin physics in the range of Fermi energies by means of reactions with high isospin asymmetric projectiles. Additionally, astrophysically relevant reactions utilizing low-energy degraded beams will be performed. A new fragment separator called FRAISE (Fragment In-flight Separator) [78] is also being built in order to fully benefit from the intensity upgrade.

LNS also performs applied research, such as accelerator physics and plasma physics. Accelerator-based research in medicine, biology, and cultural heritage, as well as irradiation of components for the aerospace industry is also performed.

2.9. The Jyväskylä Accelerator Laboratory, University of Jyväskylä, Finland

The Jyväskylä Accelerator Laboratory (JYFL, short for Jyväskylän Yliopiston Fysiikan Laitos) hosts three large-scale accelerators: the 1.7 MV Pelletron, the MCC30/15 cyclotron, and the K130 cyclotron. The K130 isochronous cyclotron, which serves as the laboratory's workhorse, can produce a very wide range of heavy and light-ion beams up to an energy of $130 \cdot Q^2/A$ MeV for use in research and applications. The MCC30/15 compact cyclotron can produce protons in the energy range between 18 and 30 MeV and deuterons in the energy range between 9 and 15 MeV, while the Pelletron is a 1.7 MV Tandem accelerator mostly used for accelerator-based material research. One of the core components of the nuclear physics research infrastructure is the IGISOL (Ion Guide Isotope Separation On-Line) mass separator [79]. Access to intense beams of protons and deuterons from a new MCC30/15 cyclotron, as well as the possibility to deliver heavy-ion beams from the K = 130 MeV cyclotron, offers extensive opportunities for nuclear physics research. The IGISOL method is a sub-ms approach for creating low-energy radioactive ion beams. It was developed in Jyväskylä in the early 1980s. Since the IGISOL method is chemically insensitive, radioactive beams of any element can be produced, including refractory elements, which are often challenging to manufacture at ISOL (Isotope Separation On-Line) facilities. A wide variety of low-energy (30 keV) radioactive and stable ion beams are produced by IGISOL for research on atomic nuclei and their properties. Two recoil separators are also located in the JYFL and are mostly utilized for the research of nuclei generated in fusion–evaporation reactions. While MARA (Mass Analyzing Recoil Apparatus) [80] is a vacuum-mode recoil-mass spectrometer better adapted to the study of nuclei with masses below 150, RITU (Recoil Ion Transport Unit) [81] is a gas-filled recoil separator ideal for the research of heavy and superheavy nuclei. RITU was initially constructed to explore the decay properties of heavy nuclei.

An integral component of IGISOL is the JYFLTRAP, a cylindrical double Penning trap [79], which is used for high-precision atomic mass measurements and beam purification. Around 400 atomic masses, including around 50 isomeric states, have been measured using the JYFLTRAP [82]. JYFLTRAP has also been used as a high-resolution mass separator for decay spectroscopy experiments as well as an ion counter for fission yield studies. Recent mass measurements with JYFLTRAP include the measurements of nuclei in the vicinity of ^{78}Ni. The evolution of the Z = 28 and N = 50 shell closures and the magicity of ^{78}Ni can be probed via mass measurements. In addition, the masses of neutron-rich nuclei close to N = 50, i.e., the strength of the N = 50 shell closure, are relevant to understanding in detail the core collapse phase of supernovae, where electron captures on nuclei play a key role [83]. Several neutron-rich Ni, Cu, and Zn isotopes were measured at JYFL [84]. Nuclei that are in the vicinity of the doubly magic ^{132}Sn (Z = 50, N = 82) are important both for nuclear structure and astrophysical studies (r-process). Mass measurements in this region provide information on the evolution of the Z = 50 and N = 82 shell closures, one- and two-neutron separation energies, and pairing effects in the region. Recent studies have also shown that the masses of the nuclei close to ^{132}Sn have the highest impact on the calculated r-process abundances for different astrophysical scenarios [85]. Neutron-rich silver isotopes $^{113-124}$Ag were investigated at JYFLTRAP. The mass measurements of silver isotopes at JYFLTRAP have been performed with the PI-ICR (Phase-Imaging Ion-Cyclotron-Resonance) technique [86]. The technique is based on projecting the ion motion in the Penning trap on a position-sensitive multichannel-plate ion detector. Concerning neutron-rich rare-earth isotopes, fourteen isotopes have been measured for the first time. These include the first measurements of ^{158}Nd, ^{160,161}Pm, ^{162,163}Sm, ^{164,165}Eu, $^{164-167}$Gd, and ^{165,167,168}Tb [87,88]. The rare-earth masses are important for understanding the formation of the rare-earth abundance peak at A = 165 in the r-process. It has been proposed as forming via fission cycling [89] or during the freezeout when matter is decaying toward stability. Heavier neutron-deficient nuclei close to the N = Z line have been recently studied using an upgraded version of the heavy-ion ion guide, HIGISOL, at IGISOL [90]. The first online experiment with the upgraded system employed 222 MeV ^{36}Ar^{8+} ions impinging into a Ni target [91]. At IGISOL, charged particle-induced fission has been used since the 1980s to create nuclei rich in neutrons for spectroscopy. The method is appropriate for fission product yield distribution measurements, enabling studies of the fission process itself, since the ions that are obtained from the ion guide are primary fission products, and ions of any element may be extracted in tens of ms. In addition, using JYFLTRAP to identify the fission products based on their mass improves the fission yield measurements even more. A newly constructed neutron converter can be used to study neutron-induced fission in addition to charged particle-induced fission. ^{88}Tcm and ^{89}Ru masses were measured for the first time, and the precisions of ^{82}Zr, ^{84}Nb, and ^{88}Tc were improved significantly. JYFLTRAP has also been facilitated to determine independent fission ion yields [92]. Neutron-rich isotopes at IGISOL are typically produced by proton-induced fission on a ^{nat}U or ^{232}Th target. If the isomeric excitation energy is high enough, even independent isomeric yield ratios can be obtained from these studies. The results for isomeric yield ratios for ^{81}Ge, ^{96,97}Y, ^{128,130}Sn, and ^{129}Sb in proton-induced fission on ^{nat}U and ^{232}Th at 25 MeV were reported in Ref. [93].

The RITU and the MARA separators with ancillary detector arrays at their target area and the focal plane spectrometers are state-of-the-art systems in the world for in-beam spectroscopic studies of proton-rich and super-heavy nuclei. JUROGAM3 [94] is an array of Compton-suppressed HPGe detectors that has been constructed for use at the target position of the RITU or MARA recoil separators. The detectors have been provided by the GAMMAPOOL collaboration [95]. Several ancillary devices can be used in combination with JUROGAM3. The JYTube (Jyväskylä-York Tube) charged-particle veto detector [96] surrounding the target brings additional sensitivity to probe neutron-evaporation channels, while the SAGE (Silicon and GErmanium) spectrometer [97] is used for simultaneous in-beam studies of internal conversion electrons and gamma rays. The JYTube comprises 96 independent plastic scintillator detectors. Each detector consists of an Eljen plastic scintillator coupled to a prism-shaped perspex guide and joined to a square SiPM. SAGE was designed to investigate physics cases when the quantity of information available through independent study of either internal conversion or γ-ray emission is limited due to their high competition. It combines the JUROGAM germanium detector array with a highly segmented silicon detector and an electron transport system. Lifetimes of states de-exciting via γ-ray emission can be measured using a plunger device, such as DPUNS (a Differential-Plunger For Lifetime Measurements Of Tagged Exotic/Unbound Nuclear States) [98]. The GREAT spectrometer [99] is used to measure the decay properties of reaction products transported to the focal plane of a recoil separator. GREAT consists of a system of silicon, germanium, and gas detectors optimized for detecting the arrival of the reaction products and correlating with any following radioactive decay. MARA enables the separation of reaction products from the primary beam in symmetric and inverse kinematics fusion–evaporation reactions. It is an excellent tool for decay spectroscopy of very proton-rich nuclei. Nuclei ranging from ^{45}Cr to ^{170}Hg have been successfully studied, including the discovery of five new isotopes [100,101]. Some of the most recent results involving MARA and JUROGAM3 are about probing triaxiality beyond the proton drip line and spectroscopy of ^{147}Tm. The experimental data were obtained in a recoil-decay tagging experiment using the MARA separator coupled with the JUROGAM3 array [102]. In recoil-decay tagging experiments, the prompt γ radiation (or conversion electron emission) at the target is tagged with its isotopic character by measuring the radioactive decay properties of the nucleus at the focal plane of a recoil separator. The α decay of a new isotope ^{190}At has been studied via the ^{109}Ag(^{84}Sr, 3n)^{190}At fusion–evaporation reaction by employing a gas-filled recoil separator RITU and GREAT Spectrometer. An α-particle energy of 7750(20) keV and a half-life of $1.0^{+1.4}_{-0.4}$ ms were measured [103]. The measured decay properties agree with an unhindered α decay. The study of the α-decay fine structure and the associated $E\alpha$-$E\gamma$ correlations in the decays of ^{171,172}Os and ^{171,172,174}Ir was performed [104]. The nuclei of interest were produced in ^{92}Mo(^{83}Kr,xpyn) fusion–evaporation reactions. The fusion products were selected using the gas-filled ion separator RITU, and their decays were characterized using the GREAT spectrometer. Prompt γ-ray transitions were detected and correlated with the decays using the JUROGAM II germanium detector array surrounding the target position. The 13 new α-decay energy lines have been resolved, and three new γ-ray transitions have been observed following the new decay branches to ^{168}Re and ^{167}W. It was found that the nucleus ^{171}Os is one of few nuclei observed to exhibit three different decay modes from the same excited stat. A recoil-beta-tagging experiment has been performed to study the excited T = 0 and T = 1 states in the odd–odd N = Z nucleus ^{94}Ag, populated via the ^{40}Ca(^{58}Ni,1p3n)^{94}Ag reaction. The experiment was performed using the MARA recoil separator and JUROGAM3 array. Through correlating fast, high-energy beta decays at the MARA focal plane with prompt γ-rays emitted at the reaction target, several transitions between excited states in ^{94}Ag have been identified. Nine prompt (including two tentative) γ-ray transitions have been observed that are associated with a short-lived β-decaying A = 94 nucleus, produced via the 1p3n charged-particle evaporation channel, and whose half-life is consistent with the currently accepted value for the ^{94}Ag ground-state β-decay. A new proton-emitting isotope ^{149}Lu has been identified using the fusion–evaporation reaction ^{96}Ru(^{58}Ni,p4n)^{149}Lu and the MARA separator [105]. The measured decay Q value of 1920(20) keV has been the highest measured for a ground-state proton decay. It has led to the shortest directly measured half-life of 450^{+170}_{-100} ns for a ground-state proton emitter. Low-lying states in the odd-Z isotopes ^{221}Ac and ^{225}Pa have been studied using α-particle and $\alpha\gamma$ -coincidence spectroscopy in the ^{225}Pa $\rightarrow$ ^{221}Ac $\rightarrow$ ^{217}Fr decay chain [106]. The target was located at the center of the SAGE spectrometer. SAGE was used to detect prompt γ-rays and internal-conversion electrons. Downstream of the target, recoiling evaporation residues were separated from fission fragments and unreacted beam ions using the RITU separator and were transported to its focal plane. The reaction products were then implanted into one of two double-sided silicon strip detectors. Advanced detectors, like DTAS (Decay Total Absorption γ-ray Spectrometer) of HISPEC/DESPEC (HISPEC (HIgh-resolution in-flight SPECtroscopy)/DESPEC (DEcay SPECtroscopy)) at GSI/FAIR, have also been used in decay spectroscopy experiments at

IGISOL. The β decays of more than twenty fission fragments were measured in the first experiments with radioactive-ion beams employing the DTAS [107].

JYFL also hosts the RADiation Effects Facility (RADEF). RADEF is specialized in the study of radiation effects in electronics and related materials. RADEF has been one of the three official test sites of ESA since 2005.

2.10. Dynamitron-Tandem Laboratory, RUBION (Ruhr-Universität Bochum Ionenstrahlen), Ruhr-Universität Bochum, Germany

RUBION [108] is a central unit for Ion Beams and Radioisotopes of the Ruhr-University, Bochum, Germany. It hosts a 4 MV Dynamitron Tandem accelerator providing a wide spectrum of ions, typically from protons up to iron with energies from 100 keV up to several MeV. A 100 keV accelerator, 500 keV accelerator, and 60 keV implanter are also available. In addition to a large volume NaI detector covering a solid angle of 98% for photons emitted at its center, RUBION is equipped with high-efficiency HPGe detectors. These detectors are suitable for studying capture reactions at energies relevant to Nuclear Astrophysics. Especially in the cases where low cross-sections are involved, a 4π detector (such as the one included in RUBION) allows the total cross-section of a reaction to be determined in comparatively short time periods. One of the fields of the study at RUBION [108] is (α,γ) reactions that are relevant to the p-process, in particular, ^{102}Pd(α,γ)^{106}Cd and ^{73}Ge(α,γ)^{77}Se. The goal of this research is to provide experimental data in unexplored energy regions and at beam energies where the available experimental data are insufficient to firmly constrain the theoretical model calculations. In recent studies, the ^{63}Cu(α,γ)^{67}Ga reaction cross-section [109] was measured in the energy range between 5 and 9 MeV, relevant to p-process nucleosynthesis. The experiment was performed at a 4 MV Tandem accelerator by applying the 4π γ-summing method, using an aforementioned NaI(Tl) detector. One should note that RUBION performs extensive research on material science.

2.11. Frankfurt Van de Graaff Accelerator, University of Frankfurt, Germany

The Frankfurt Van de Graaff accelerator can provide proton or alpha beams up to an intensity of 10 µA. The terminal voltage is in the range of 1 to 2.5 MeV [110]. Neutron production via the ^{7}Li(p,n) reaction is also possible. The neutrons with energies of astrophysical interest (1 keV–1 MeV) are produced via bombarding thin, metallic lithium layers with protons with energies up to 2.5 MeV and intensity up to 20 µA. A suite of ^{3}He and Li-glass neutron detectors are also available. These detectors can be used to study an astrophysically important neutron production reaction like ^{13}C(α,n). Activation experiments can be analyzed with a head-to-head setup of two Broad-Energy-Germanium-Detectors (BEGe Detectors). In the future, an RFQ-IH-based high-current accelerator will be used to produce a very intense neutron beam [111]. The energy of the primary proton beam will be adjustable between 1.8 MeV and 2.2 MeV. In addition, proton-induced experiments are planned, where different samples will be directly irradiated with the high-intensity proton beam.

2.12. Ion Beam Center (IBC), Helmholtz Zentrum Dresden Rossendorf (HZDR), Germany

IBC hosts three ion accelerators that accelerate ions in the energy range between 0.2 MeV and 60 MeV (depending on a charge state) [112]. The 2 MV Van-de-Graaff accelerator accelerates hydrogen and helium ion beams with energies between around 600 keV (for protons) and 1.7 MeV. The 3 MV Tandetron is a tandem-type accelerator that operates ions in the energy range of 0.6–50 MeV. The 6 MV Tandetron is also a tandem-type accelerator that operates ions in the energy range of 0.2–8 MeV. Ion beams of almost all stable elements with masses between 1 and 197 can be provided at the tandem machines, except Ne, Ar, Kr, and Xe. Ion beams of d, Be, certain rare earth metals, and all radioactive elements are not provided at IBC. In addition, IBC hosts 40 kV and 500 kV ion implanters. Precise values for certain resonance strengths could be used as normalization points [113] in nuclear reaction experiments. This is especially important for astrophysically significant nuclei, for which precise cross-section values are often required to constrain astrophysical scenarios. Mirror nuclei like ^{40}Ca are thought to be a part of the α-rich freezeout process that produces the supernova nuclide ^{44}Ti [114]. The experiment has been performed at the HZDR 3 MV Tandetron accelerator in which the strength of the E_p = 1842 keV resonance in the ^{40}Ca(p,γ)^{41}Sc reaction has been remeasured [115]. The measured resonance strength, $\omega\gamma$ = (0.192 $\pm$ 0.017) eV, was found to be higher than the value obtained in the previous studies [116,117]. In addition, the ratio of strengths of the latter resonance and the 4.5 MeV resonance triplet in the ^{40}Ca(α,γ)^{44}Ti reaction has been determined to be 0.0229 $\pm$ 0.0018. The measured value may be used as a normalization point in future precision experiments on ^{40}Ca targets.

A powerful technique for determining the concentration and profile of hydrogen in thin layers of material is nuclear resonance reaction analysis (NRRA). Usually, this technique requires the use of a standard of well-known composition. The work performed at the 3 MV Tandetron dealt with standard-less hydrogen depth profiling. This approach required precise nuclear data, e.g., on the widely used ^{1}H(^{15}N,α)^{12}C reaction, which has a resonance [118] at the incident beam energy of 6.4 MeV. The strongly anisotropic angular distribution of the emitted γ rays from this resonance has been remeasured, resolving a previous discrepancy. It was also shown that for samples with high hydrogen content, the textbook approach of determining the hydrogen content by scaling with the yield on a standard of known composition [119,120] may lead to deviations if the stopping power contribution of the hydrogen atoms is neglected.

The ^{14}N(p,γ)^{15}O reaction is the slowest reaction of the carbon–nitrogen cycle of hydrogen burning, and therefore, it determines its rate [121]. The precise knowledge of its rate is necessary to correctly model hydrogen burning in asymptotic giant branch (AGB) stars. Also, it is a necessary ingredient for a possible solution to the solar abundance problem by using the solar ^{13}N and ^{15}O neutrino fluxes as probes of the carbon and nitrogen abundances in the solar core. The study reported precise S factor data at twelve energies between 0.357 and 1.292 MeV for the capture to the 6.79 MeV excited state in ^{15}O (the strongest transition), and at ten energies between 0.479 and 1.202 MeV for the capture to the ground state in ^{15}O (second strongest transition) [122].

2.13. Felsenkeller Underground Accelerator Laboratory, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany

The Felsenkeller underground accelerator laboratory in Dresden, Germany, is a shallow underground laboratory as opposed to the deep underground laboratories (such as LUNA) [123]. It is located under 45 m of hornblende mazonite rock overburden (140 m.w.e.). With the exception of muons, this depth is sufficient to entirely shield all cosmic ray radiation's components. In the case of Felsenkeller, the key finding was that at γ-ray energies of 5–8 MeV, the background rate in detectors at the shallow underground location with active detector shielding is only 2–3 times worse than at the deep underground laboratory [124]. That background is low enough for a shallow underground accelerator, which can be a complementary facility to deep underground ones. The Felsenkeller underground accelerator laboratory hosts a 5 MV Pelletron accelerator. Typical ion beam currents up to 30 μA are reached for helium and carbon ions, and similar performance is expected for proton and other beams. The Felsenkeller underground laboratory's scientific agenda comprises the investigation of several important astrophysical processes, including ^{3}He(α,γ)^{7}Be and ^{12}C(α,γ)^{16}O [125]. A number of HPGe detectors surrounded by active veto detectors will be used to fully utilize the background reduction capabilities of the shallow underground laboratory.

2.14. The Atomki Accelerator Center

The Atomki Accelerator Center [126] hosts a K = 20 cyclotron, two Van de Graaff accelerators with a maximum terminal voltage of 1 MV and 5 MV, respectively, and a 2 MV Tandetron accelerator installed in 2015. ATOMKI operates also an ECR ion source (for atomic and plasma physics research and applications) and a 200 kV AMS accelerator for radiocarbon dating. The MGC-20E Cyclotron is a compact isochronous cyclotron capable of accelerating the four lightest ions (p, d, $^{3}He^{2+}$, and $^{4}He^{2+}$). At the beginning of 2020, the decision was made to stop the 5 MV Van de Graaff accelerator. The Tandetron and the cyclotron have been widely used for astrophysical research.

Elements heavier than iron are mostly produced via neutron-capture (s- or r-process) reactions. However, the "p nuclei" on the proton-rich side of the valley of stability cannot be created by these processes. The γ-process (see Section 2.1. for more details about the γ-process) is mainly responsible for the production of these isotopes. The synthesis of heavy, proton-rich isotopes in the γ-process proceeds through photodisintegration reactions. The (γ,α) and (α,γ) reaction cross-section calculations are highly sensitive to the selection of the α-nucleus potential, which comprises a Coulomb and a nuclear part (the latter one consists of a real and an imaginary part). The knowledge of α-nucleus model potential (OMP) is very important in the studies of nuclear structure, reactions, and nuclear astrophysics. Moreover, in several astrophysical applications, such as modeling the nucleosynthesis in explosive scenarios like the γ process, the reaction rates are taken from the Hauser–Feshbach (H–F) statistical model (see Sections 2.1 and 2.6) using global OMPs. In recent years, significant efforts have been devoted to improving the α-nucleus optical potential parameterizations for astrophysical applications. The predicted cross-sections using different global α-nucleus optical potential parametrizations can vary by an order of magnitude. The parameters of the global α-nucleus optical potentials are usually obtained from the analysis of the angular distributions of elastically scattered α particles (and are adjusted to α-induced cross-sections if experimental data exist). The elastic scattering cross-sections for the reactions ^{110,116}Cd(α,α)^{110,116}Cd at energies above and below the Coulomb barrier were measured and provided a sensitive test for the α-nucleus optical potential parameter sets [127]. The rates of the reaction network have to be known for a proper understanding of the γ-process. It was found, in previous rate variation studies, that the reaction ^{128}Ba(γ,α)^{124}Xe influences the abundance of the p nucleus ^{124}Xe [128]. Since the stellar rate for this reaction cannot be determined by direct measurement, the cross-section of the inverse ^{124}Xe(α,γ)^{128}Ba reaction [128] was measured. Simultaneous studies of the ^{124}Xe(α,n)^{127}Ba reaction channel at a higher energy have allowed for the further identification of the source of a discrepancy between data and prediction. The α-beam for the irradiations was provided by the MGC-20 cyclotron of ATOMKI. An upper limit for the ^{128}Ba(γ,α)^{124}Xe stellar rate was inferred from the measurements. For the first time, measurements of the elastic scattering cross-sections of the ^{113}In(α,α)^{113}In [129] reaction have been performed at energies close to the astrophysically significant energy region. The high-precision experimental data were used to evaluate the predictions of the recent global and regional α+nucleus optical potentials. Parameters for the local α-nucleus optical potential were derived from the measured angular distributions. In addition, α-induced reaction cross-section measurements on gold were measured (^{197}Au(α,n)^{200}Tl and ^{197}Au(α,γ)^{201}Tl [130]), which could be performed almost at the astrophysically relevant energy region. The new experimental data were then facilitated to test statistical model predictions and to constrain the α-nucleus optical model potential. Recent nucleosynthesis studies have demonstrated that (α, xn) reactions play a particularly significant role in the production of light ($30 \leq Z \leq 45$) neutron-rich isotopes. The cross-section of the ^{100}Mo(α, n)^{103}Ru [131] was measured by means of the activation method (see Section 2.1 for the details of the method). Measurements of cross-sections have been performed at a number of energies below the Coulomb barrier. Large discrepancies between the experimental values and statistical model prediction employing α-OMP were found. However, the discrepancies could be excellently described by the Atomki-v2 potential. The ^{144}Sm(α,n)^{147}Gd reaction was studied [132]. α-beams were provided by the cyclotron accelerator of Atomki. The cross-section was determined using the activation method. The γ rays produced in the decay of the ^{147}Gd were measured with an HPGe. The cross-section was measured from close to above the (α, n) threshold. The comparison of measurements with statistical model calculations using various approaches and parametrizations for the α-nucleus optical potential were made and excellent agreement was obtained for two recent potentials. Nuclear reactions of astrophysical relevance are studied using the activation method. The $^{3}He(\alpha,\gamma)^{7}Be$ reaction plays a crucial role in solar hydrogen burning. Its reaction cross-section has been measured [133], which contributed to a better understanding of the investigated stellar processes. The α-beam was provided by the MGC-20 cyclotron of ATOMKI. The p-process is one of the least-known processes of nucleosynthesis; the model calculations are not able to well-reproduce the abundances of p-isotopes observed in nature. ^{92}Nb is one of the isotopes present in the early Solar System, which may be used to test the models since among the suggested sites is a thermonuclear supernova explosion. The cross-section of the $^{91}Zr(p,\gamma)^{92m}Nb$ has been measured using the activation method (only the partial cross-section leading to the isomeric state of ^{92}Nb could be measured, as the ground state has a half-life of $3.47{\cdot}10^{7}$ years) [134]. The theoretical cross-sections employed in previous astrophysical models and the $^{91}Zr(p,\gamma)^{92m}Nb$ measurements showed good agreement. One of the fundamental mechanisms for hydrogen burning in stars is the CNO (Carbon–Nitrogen–Oxygen) cycle. The cycle is a sequence of reactions converting H into He on preexisting CNO nuclides, and it represents the main hydrogen burning mode in stars with $M \geq 1.3\ M_o$. The first reaction of the cycle is the radiative proton capture on ^{12}C, and the rate of this $^{12}C(p,\gamma)\ ^{13}N$ reaction is related to the $^{12}C/^{13}C$ ratio observed, e.g., in the Solar System. The low-energy part of the cross-section was already measured a few times; however, the experimental data are scarce in a wide energy range, especially around the resonance energy (1.7 MeV). Therefore, the $^{12}C(p,\gamma)^{13}N$ cross-section was measured in the energy range between 300 keV and 1900 keV using the activation method [135].

One of the most significant nuclear astrophysics reactions,$^{14}N(p,\gamma)^{15}O$, affects the generation of energy in stars, stellar evolution, and nucleosynthesis. Consequently, the low-energy part of the cross-section must be accurately known in order to calculate reaction rates reliably. The cross-section was measured in the center-of-mass (cms) range between 550 keV and 1400 keV with the means of the activation method [136]. The annihilation radiation (e^-e^+) following the β^+ decay of the ^{15}O was detected. This approach, which directly yields the astrophysically important total cross-section, was never used before for the cross-section measurement in the investigated energy range.

Recently, several experimental anomalies were raised as possible indicators for a new light particle. According to some predictions, the experimental findings could be explained by light neutral bosons, with masses between 10 MeV and 10 GeV as dark matter anomalies that couple to electrons and positrons (see Ref. [137] and references therein). The possible anomalies were studied in the $^{7}Li(p,\gamma)^{8}Be$ reaction. The reaction was used to populate 17.6 and 18.5 MeV 1^+ states in ^{8}Be using the incident proton beams from the Atomki 5 MV Van de Graaff accelerator [137]. The e^+e^- pairs were detected by five plastic ΔE–E detector telescopes. The positions of the hits were determined by multiwire proportional counters (MWPC) placed in front of ΔE and E detectors. Electron-positron angular correlations were measured for the isovector magnetic dipole transition from the 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state to the ground state ($J^\pi = 0^+$, $T = 0$), and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 1$) state to the ground state transition in ^{8}Be. A significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of 2.5 σ. The observation could be either due to a nuclear reaction interference effect or might indicate that as an intermediate step, a neutral isoscalar particle, hypothetical X17 boson, with a mass of $16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV/c^2 and $J^\pi = 1^+$ was created. The experiment has been repeated at the ATOMKI 2 MV Tandetron accelerator using the thinner carbon backing, an increased number of telescopes (six instead of five), and DSSSDs instead of MWPCs. The anomalous angular correlation was reproduced using the new independent setup [138]. Further pieces of evidence for the X17 particle have been found in the following ATOMKI group experiments, studying two additional reactions. The angular correlation spectra of e^+e^- pairs produced in the $^{3}H(p,e^+e^-)^{4}He$ nuclear reaction have been studied at the proton energies of 510, 610, and 900 keV, respectively [139]. It is possible to comprehend the key characteristics of the spectra by considering the internal and external pair creations that followed the direct proton capture by ^{3}H. The observed peak in the angular correlation spectra at about 115° cannot be explained by these processes. This anomalous excess of e^+e^- pairs can be described by the creation and subsequent decay of a light particle during the direct capture process. The derived mass of particle is $m_X c^2$ = 16.94 ± 0.12(stat) ± 0.21(syst) MeV. According to this mass, this is likely the same X17 particle. Moreover, the new anomaly observed in ^{12}C [140] supported the existence and the vector character of the hypothetical X17 boson. The angular correlation of e^+e^- pairs was investigated in the ^{11}B(p,γ)^{12}C reaction and angular range of $40° \leq \theta \leq 175°$ for five different proton energies in the energy range of 1.50 MeV and 2.5 MeV. The measurements were performed at the 2 MV Tandetron accelerator of ATOMKI. The Ex = 17.23 MeV, $J^\pi = 1^-$ state in ^{12}C was populated by the ^{11}B(p,γ) ^{12}C nuclear reaction [140]. At small angles ($\theta \leq 120°$), the results can be well-interpreted by the internal pair creation process of electromagnetic radiations with E1 and M1 multipolarities and by the external pair creation in the target backing. At angles greater than 120°, additional count excesses and anomalies were observed, which could be explained for by the existence of the hypothetical X17 particle. The results imply that the X17 particle was generated mainly in E1 radiation. The derived mass of the particle is $m_x c^2$ = 17.03 ± 0.11(stat) ± 0.20(syst) MeV. The mass and derived branching ratio ($Bx = 3.6(3) \times 10^{-6}$) indicate that this is most probably the same X17 particle that was previously proposed to explain the anomaly seen in the decay of ^{8}Be. Many experiments in the coming years are going to investigate the possibility of a new gauge boson. This will probably and finally determine the existence of such a particle and constrain its properties. One of the European experiments that aims to provide a quick and reliable test of the existence of a light dark boson that couples the standard model to the dark sector is the New Judicious experiment for Dark Sector Investigations (New Jedi) project [141]. Some of the JEDI project measurements were performed at the ANDROMEDE, IJC lab.

2.15. Centre of Accelerators and Nuclear Analytical Methods Research Infrastructure (CANAM RI), Czech Republic

CANAM RI is a Czech infrastructure for the investigation of tasks in a variety of scientific disciplines using beams of accelerated ions and neutrons. It hosts a 4130 MC Tandetron as well as TR-24, and U-120M cyclotrons [142]. In addition, the new generation multi-isotope low-energy accelerator (MILEA) system is available. The inbuilt accelerator of MILEA operates at low terminal voltages of up to 300 kV and is used for AMS studies. The medium-current (MC) version of the 3 MV Tandetron can accelerate ion beams in the energy range between 600 keV and 30 MeV. TR-24 cyclotron accelerates beams with energy ranging from 18 MeV to 24 MeV. Ion beams (p, H^-, D^+, D^-, $^3He^{2+}$, $^4He^{2+}$) are accelerated by the isochronous cyclotron U-120M. The TR-24 and U-120M cyclotrons provide the primary beams of accelerated ions as well as the generated secondary fast neutrons. Microtron MT25 is a cyclic electron accelerator. The unique ^{3}He beams and deuteron beams of the U-120M cyclotron allow for research of astrophysically relevant nuclear reactions. Since it is very difficult and sometimes even not possible to measure cross-sections directly at very low energies, indirect approaches offer an independent means of obtaining the relevant information at these (astrophysically significant) energies. Two indirect methods, namely, THM (see Sections 2.4 and 2.8 for more details) and ANC (the asymptotic normalization coefficients) are used. ^{2}H(d,d) and ^{2}H(d,t) reactions were studied at U-120M cyclotron by means of the THM method [143]. Data unaffected by the electron screening were obtained in the energy region from thermal energies to energies relevant to BBN. The ANC technique uses the direct transfer reactions' peripheral nature to deduce the direct component of radiative capture at zero energy. Depletion of ^{18}O by (p,γ) capture from the CNO cycle in AGB stars was studied [144]. The results allowed for the decision between two previous contradicting findings. The ^{26}Si(p,γ) capture was studied using a ^{26}Mg(d,p) reaction. Measurements were performed at the U-120M cyclotron [145]. The obtained data enabled the reaction rate to be updated, leading to new findings regarding the production of ^{26}Al in the galaxy. Precise angular distribution measurements and high-quality beams of ^{3}He and deuterium combined with a careful analysis are the foundations of the successful application of these methods.

CANAM-RI also performs research on IBA, dosimetry, and cultural heritage.

2.16. Bronowice Cyclotron Center (CCB) of the Institute of Nuclear Physics PAN, Krakow, Poland

The Bronowice Cyclotron center hosts a cyclotron Proteus C-235 [87]. Proteus C-235 is an isochronous cyclotron with a proton energy selector. It is able to deliver proton beams with energies between 70 MeV and 230 MeV and beam intensities ranging between 0.1 and 600 nA [146]. The available instrumentation includes the Big Instrument for Nuclear Reaction (BINA) [147], the High Energy Gamma Ray Detector (HECTOR) [148], and the Krakow Triple Telescope Array (KRATTA) [149]. The goal of the BINA detection system is to examine breakup and elastic reactions at intermediate energies. It makes it possible to record coincidences between two charged particles over roughly a 4π solid angle, allowing for the investigation of practically the whole phase space of elastic and breakup reactions. The detector is composed of two main parts, the forward Wall and the backward Ball. The backward scintillator Ball is utilized to register particles scattered at higher polar angles, and the front scintillator Ball is used to precisely reconstruct charged particle momenta. Two scintillator hodoscopes for measuring energy and energy loss are present in the forward part, along with a MWPC for reconstructing particle paths. The backward part is composed of phoswich scintillator components that serve as both the detector, and at the same time, form the vacuum chamber for a cryogenic deuterium target. The high-efficiency array, HECTOR, measures high-energy gamma rays with energies between 2 MeV and 40 MeV. The array consists of eight large-volume BaF_2 scintillators (145 mm diameter and 175 mm length). The energy resolution is ~12% for low energy (^{60}Co) and ~10% for high energy (15 MeV) gamma rays. Excellent time resolution (<1 ns) makes it possible to distinguish between gamma rays and neutron-induced events using the time-of-flight method. The HECTOR array can operate in coincidence with the KRATTA system to detect scattered protons. KRATTA measures the emission angle, energy, and isotopic composition of light-charged reaction products. It comprises thirty-eight individual modules that can be put together in any configuration. A single module consists of three identical, 500 μm thick, large area photodiodes, used also for direct detection, and of two CsI crystals. All signals are digitally processed. The middle photodiode's complex signals can be decomposed into their ionization and scintillation components via pulse shape analysis. This enables a single readout channel to obtain a satisfactory isotopic resolution. The upper energy limit for protons is about 260 MeV.

Nuclear structure studies at the Bronowice Center will encompass studies of the dynamics of few-nucleon systems and the physics of nuclear clusters in order to obtain insight into the nucleon–nucleon interaction, measurements of collective, high-energy excitations in nuclei (e.g., giant nuclear resonances) in the yet unexplored regions of excitation energy and spin, and high-resolution gamma-ray spectroscopy of nuclei produced in the process of proton-induced fission and spallation [150]. The facility will also be used to test various components of the cutting-edge detection systems being built for European ESFRI nuclear physics facilities (e.g., SPIRAL2, GSI/FAIR). One should stress that CCB performs extensive research on dosimetry, microdosimetry, radiobiology, and materials engineering. It also produces radionuclides for research purposes and develops clinical and scientific infrastructure intended for non-invasive tumor treatment.

2.17. The Centro Nacional de Aceleradores (CNA), University of Seville, Spain

CNA hosts three particle accelerators, namely, a 3 MV van de Graaff Tandem accelerator, a 18/9 MeV cyclotron, and a 1 MV Tandetron that serves as a mass spectrometer [151]. CNA is an official collaborating center of IAEA in AMS applications in marine studies. Cyclotron is able to provide 18 MeV protons and 9 MeV deuterons. Seven of the cyclotron's eight targets are used to create positron emitters, while an external beamline has been put in the eighth port to conduct nuclear physics research. The nuclear physics beamline at the 3 MV Tandem hosts a high-volume vacuum chamber, where nuclear instrumentation (detectors, electronics, DAQ), that will be used in international Nuclear Physics facilities, can be developed and tested. One of the detectors is a mini SeD: a gas ionization multiwire chamber that operates at low pressure and has proven to be very suitable for the detection of low-energy ion beams with large angular and energy straggling, thus enabling precise reconstruction of the TOF and position of beam particles at high production rates [152]. A 3 MV tandem also hosts external, microbeam, multipurpose, channeling, ion luminescence beamlines, among others. The first accelerator-based neutron source in Spain is called the HiSPANoS, short for Hispalis Neutron Source. [153]. The reactions p(^{7}Li, n), d(^{7}Li, n), d(D, n), and p(^{9}Be, n) at HiSPANoS create neutrons in a broad-energy range, from thermal to fast neutrons with energies up to 9 MeV.

2.18. The Laboratory of Accelerators and Radiation Technologies (LATR) of Instituto Superior Técnico (IST), Portugal

LATR is a Portuguese infrastructure that hosts three accelerators, namely, a 2.5 MV Van de Graaff accelerator, a 3 MV Tandem [154], as well as a 210 kV ion implanter.

Elastic scattering reactions ^{12}C + ^{16}O and ^{16}O + ^{16}O were measured at the nuclear physics beamline of the 3MV Tandem [154]. The AMS line of the Tandem was facilitated to measure the cross-section of the reaction ^{35}Cl(n,γ)^{36}Cl. ^{36}Cl has a half-life of 3.01×10^5 years. That implies that the amount of ^{36}Cl existing in the earth's soil may only be explained by either continuous production in the sun, wind, or bombardment of the earth's surface by cosmic neutrons. The targets were obtained by the bombardment of ^{35}Cl by thermal neutrons. The content of ^{36}Cl was measured by AMS, leading to a cross-section value that, within the uncertainties, is in agreement with the average of previously published results [154]. The measurement of the elastic scattering of protons, namely, the reactions ^{6}Li(p,p′)^{6}Li, ^{7}Li(p,p′)^{7}Li, ^{12}C(p,p′)^{12}C, ^{19}F(p,p′)^{19}F, ^{31}P(p,p′)^{31}P at both forward and backward angles were performed at the LATR facility and gave reliable information both for the purpose of acquiring precise optical model parameters and for the purpose of characterizing the excited states of nuclei. Apart from nuclear physics research, LATR performs a wide scope of activities in materials characterization and modification, nanotechnology, health, biomedicine, environmental sciences, and cultural heritage.

2.19. The Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) Tandem Accelerator Complex, Romania

The IFIN-HH tandem accelerator complex in Romania consists of a 9 MV FN Pelletron Tandem, 3 MV HVEE Tandetron accelerator, and 1 MV HVEE Tandetron accelerator dedicated to AMS experiments [155,156].

The 9 MV FN Pelletron Tandem can provide beams from hydrogen to gold and can deliver currents up to µA. The 9 MV Tandem hosts different setups.

The ROmanian array for SPectroscopy in HEavy ion Reactions (ROSPHERE) [98] is a multi-detection array. The "mixed" configuration, which combines fast $LaBr_3$(Ce) scintillators and large-volume HPGe detectors that have been Compton-suppressed, is the most common one used in the ROSPHERE array, which can hold up to 25 detectors. For cases requiring a high-resolution and high-efficiency detection system, ROSPHERE can alternatively be used as a full HPGe array. A variety of subjects have been addressed in the physics cases, including the role of the negative-parity neutron intruder orbitals in the structure of low-spin states configurations for nuclei near the "island of inversion" [157,158], the study of the nuclear structure near shell and/or subshell closures (see, for example, [159–161]), the study of neutron-rich nuclei using low energy transfer/incomplete fusion reactions induced by ^{7}Li beams ([162,163]), as well as the interplay between collective and single-particle degrees of freedom (see Refs. [159–163]). The main tool to investigate collective phenomena is that of lifetime measurements. Lifetime measurement observables are closely related to the determination of the reduced matrix elements of nuclear transitions. These quantities are, in turn, very sensitive to details of the nuclear, structure and their knowledge is necessary for the testing of different theoretical models. A broad range of experimental techniques to cover the relevant interval for lifetimes of excited states in nuclear systems was employed: the fast-timing technique, the RDDS method, and the DSAM method (see Refs. [157–163] and references therein). Far from the valley of stability, deviations are observed from the conventional single-particle shell structure. Neutron-rich nuclei with $Z{\sim}10$ and $N{\sim}20$ have unexpectedly high binding energies due to the onset of deformation [164]. The deformation occurs from the filling of the $f_{7/2}$ intruder orbital. In stable nuclei, the $f_{7/2}$ intruder orbital lies above the N = 20 shell closure [165,166]. The size of the N = 20 shell gap is reduced for neutron-rich $Z{\sim}10$ nuclei, allowing excitations from the $d_{3/2}$ to the $f_{7/2}$ orbital to become favored, leading to the region of the anomalous shell structure known as the "island of inversion". The island of inversion is known to extend from neutron numbers N = 20–22 for the Ne, Na, and Mg isotopes (Z = 10–12) [167]. The half-life of the $I^{\pi} = 4^{-}$, E = 2305 keV intruder state in ^{34}P has been measured as $t_{1/2}$ = 2.0 (1) ns. The result was obtained using γ-ray coincidence and fast-timing techniques with the mixed $LaBr_3$-HPGe ROSPHERE detector array. The ^{18}O(^{18}O,pn)^{34}P fusion–evaporation reaction at a beam energy of 36 MeV [157] was used to populate states in ^{34}P. For small values of the mixing ratio, the B(M2) value was found to be consistent with similar transitions associated with the occupation of neutron $f_{7/2}$ configurations in this mass region. In the medium-mass region of nuclei approaching the N = 40 subshell closure with $Z{\sim}28$, it is assumed from empirical observations and theoretical calculations that states with different structures such as single-particle, intruder, and collective states coexist at low- and medium-excitation energies [168,169]. The half-lives of the $9/2^{+}$, $13/2^{+}$, and $15/2^{+}$ yrast states in the neutron-rich ^{67}Cu nucleus were determined by using the in-beam fast-timing technique [101]. The ^{67}Cu nuclei were produced in an α-induced reaction on a ^{64}Ni target at an incident energy of 18 MeV. The 9 MV tandem accelerator produced α-beams. Gamma rays were detected using a setup that consisted of five HPGe detectors, four planar HPGe detectors, and eight $LaBr_3$(Ce) scintillation detectors. The experimentally obtained E3 transition strength for the decay of the $9/2^{+}$ level to the $3/2^{-}$ ground state suggests that the wave function of this level might contain a collective component arising from the coupling of the odd proton $p_{3/2}$ with the 3^{-} state in ^{66}Ni. The measurement of electromagnetic transition rates in nuclei in transitional regions between shell closures and permanently axially deformed nuclei can shed light on the validity of corresponding models of nuclear structure. Excited states in ^{136}Ce were populated via the ^{124}Sn(^{16}O,4n) fusion–evaporation reaction. The gamma rays were detected using the mixed configuration of the ROSPHERE array, which consisted of fourteen HPGe detectors and eleven $LaBr_3$(Ce) scintillator detectors. Each of the HPGe detectors was surrounded by active Compton suppression shields. The half-lives of the I^{π} = 5^{-} and $I^{\pi} = 7^{-}$ yrast states with E_x = 1978 keV and E_x = 2307 keV in the N= 78 isotone ^{136}Ce have been measured to be 496(23) ps and 270(24) ps, respectively, using the coincident fast-timing spectroscopy technique [161]. The fusion–evaporation reaction ^{124}Sn(^{7}Li,2n) was used to populate excited states in ^{129}I [162]. The array of eight HPGe detectors and five $LaBr_3$(Ce) scintillation detectors were used to measure in-beam γ-ray coincidences. A positive parity band structure built on the $7/2^{+}$ ground state was established, and the $\pi g_{7/2}$ configuration at oblate deformation was assigned to it based on the $\gamma\gamma$ coincidence data. The ground state collectivity of a nucleus can be accurately determined by measuring the reduced transition probability $B\left(E_2; 2_1^+ \to 0_1^+\right)$, and half-life measurements are anticipated to shed light on the structure of nuclei in this transitional region. The ROSPHERE array has also been used to measure the half-life of the yrast $I^{\pi} = 2^{+}$ state in the neutron-rich nucleus ^{188}W. The fast-timing technique has been used. The resulting value of $t_{1/2}$ = 0.87(12) ns is equivalent to a reduced transition probability of $B\left(E_2; 2_1^+ \to 0_1^+ = 85(12) W.u.\right)$ for this transition. Even with a rather significant uncertainty, it seems to indicate a more abrupt decrease in collectivity compared to the trend of lighter tungsten isotopes. According to the estimates for this mass region, this predicted a possibly higher softness for ^{188}W compared to stable tungsten isotopes.

One of the most important findings in the study of nuclear structure at IFIN-HH was the discovery of a shape isomer in ^{66}Ni utilizing gamma spectroscopy and heavy-ion transfer reactions at energies below the Coulomb barrier [170]. It was the discovery of the lightest-ever atomic nucleus that exhibits a photon decay, hindered solely by a nuclear shape change. It is an extremely rare process involving a transition between totally distinct microscopic configurations, coexisting at similar excitation energy. This result was obtained from lifetime measurements of the first three excited 0^+ states pointing to the oblate, spherical, and prolate nature of excitations.

The tape station for beta-decay experiments is also available at IFIN-HH, using three clover detectors with 120% relative efficiency and anti-Compton shields, as well as fast $LaBr_3$(Ce). The setup consists of multi-strip silicon detectors for particle detection that may move radially and longitudinally around the target. The setup is used for nuclear reaction and astrophysics studies.

Nuclear astrophysics research takes advantage of ion beams from a 3 MV Tandetron accelerator as well as of the ultra-low background laboratory in a salt mine at Slanic-Prahova [171]. The ultra-low background radiation laboratory was built and became operational in 2006 in the former Unirea (Slanic-Prahova) salt mine at 208 m below the surface (estimated to a 560 m water equivalent (m.w.e)). In comparison to the identical spectrum recorded at the surface, in the open field, it was discovered that the overall gamma background spectrum between 40 keV and 3 MeV was 100 times smaller at the laboratory level. Given that proton and alpha-capture reactions serve as an important proxy in nucleosynthesis, two of the reactions that were studied at IFIN-HH are α + ^{64}Zn and α + ^{58}Ni [172,173]. Both reactions are important for explosive nucleosynthesis, and in both cases, the measurements conducted at the IFIN-HH were able to investigate the Gamow window. However, up to now, the most significant result was that obtained for the ^{12}C + ^{12}C fusion reaction [174,175]. The ^{12}C + ^{12}C fusion reaction is a cornerstone case in nuclear astrophysics. There are few experimental data at energies below the Coulomb barrier, and theoretical model predictions on the fusion mechanisms often significantly disagree with the experimental results (see the references in Ref. [172]). The adjacent reaction ^{13}C + ^{12}C was studied to obtain information on the fusion interaction at such low energies. The extra neutron in ^{13}C allowed for the production of the unstable ^{24}Na ($T_{1/2}$ = 15.0 h) and the use of the activation method (see Section 2.1). The proton evaporation channel leads to an activity with a half-life of 15 h, suitable for the samples' transfer to the salt mine. The study was able to measure the cross-section of the proton evaporation channel down to E_{cm} = 2.3 MeV.

2.20. Laboratory for Underground Nuclear Astrophysics (LUNA), Gran Sasso National Laboratories (GSNL), Italy

Due to the suppression of the natural background, studying nuclear reactions that emit gamma rays is especially advantageous underground. At γ-ray energy exceeding 3 MeV, the 1.4 km of rock above the LUNA facility suppresses the cosmic-induced background by a factor of six. The γ rays emitted in the radioactive decay of naturally occurring isotopes dominate the γ-ray background at lower energies. Typically, this background component is reduced by surrounding the detector with high-purity, high-Z passive shielding. The interaction of cosmic rays with such shielding is constrained by the fact that the interaction of the cosmic rays with the shielding itself produces radioactive isotopes and secondary radiation. Additionally, this issue is mitigated underground, where there is considerably thicker shielding. The LUNA 400 kV accelerator provides 1 mA H^+ beams and 500 µA He+ beams. It has two beamlines, one of which houses a solid target station and the other of which houses a windowless gas target system [125].

LUNA has hosted various detector setups (see Ref. [125] and references therein). Large-volume HPGe detectors are used for high-resolution spectroscopy at LUNA. To maintain the benefits of being underground, all LUNA HPGe detectors are constructed from materials with a low inherent background. Thick passive shielding constructed of lead and copper is used to suppress the environmental background caused by naturally occurring radioactive isotopes in cases where γ rays with energy lower than 3 MeV need to be detected. A large-volume BGO detector covering nearly the entire solid angle surrounding the target is employed when extremely weak cross-sections are measured and the sensitivity is crucial. The BGO detector has also been successfully used to determine γ-ray branching ratios exploiting $\gamma\gamma$ coincidences in segment pairs. Additionally, the LUNA setup offers a set of ^{3}He counters for neutron detection as well as an array of large-area silicon detectors for charged particle detection. The ^{2}H(p,γ)^{3}He reaction (Q = 5.5 MeV), which contributes to the deuterium destruction during BBN (Big Bang Nucleosynthesis), is one of the reactions that was essential in the very beginning of the existence of the universe. The windowless gas target system and an HPGe detector installed in close geometry were used at LUNA to study the reaction ^{2}H(p,γ)^{3}He at the center-of-mass energies between 30 keV and 263 keV. The reaction cross-section was measured with a systematic error of less than 3% [176]. Due to its high sensitivity to the baryon density, or alternatively, the baryon-to-photon ratio of the early Universe, deuterium abundance is utilized in BBN research as an indicator of cosmological parameters. The aforementioned findings enabled a substantially reduced uncertainty of BBN predictions of the baryon density and the effective number of neutrino families.

The cosmic muon energy spectrum in a silicon semiconductor detector shows an energy maximum near zero and decreases exponentially with energy [177]. One can anticipate better signal-to-background ratios in deep-underground studies aiming to detect charged particles with Si detectors since cosmic muons are greatly suppressed underground. The ^{17,18}O(p,α)^{14,15}N reactions, which are crucial for the nucleosynthesis of key isotopes and are used to constrain stellar models of novae, AGB, and post-AGB stars, were studied in detail [178,179]. It was shown that enhanced background suppression was achieved. The combined effects of the background suppression underground and the generally improved experimental conditions (see ref. [180]) have resulted in the most accurate value to date for the E_p = 70 keV resonance strength $\omega\gamma$ in ^{17}O(p,α)^{14}N, namely, $\omega\gamma$ = (10.0 $\pm$ 1.4stat $\pm$ 0.7syst) neV. As a result, there has been a factor of two increase in the ^{17}O(p,α) ^{14}N reaction rate and a reduced ^{17}O/^{16}O ratio, with important consequences for the origin of some oxygen-rich group II presolar grain. The improved results on the ^{18}O(p,α)^{15}N cross-sections and resonance strengths, with tighter constraints on oxygen isotopic ratios, have been also obtained [179]. The sensitivity of a detector setup to the neutron background flux is closely related to the detection technique. Detectors based on neutron capture reactions (e.g., ^{3}He counters) are primarily sensitive to thermalized neutrons, while organic scintillators based on elastic neutron scattering on hydrogen are only sensitive and selective to neutrons above a threshold energy. In order to modify the neutron energy spectrum (i.e., thermalize the neutrons) or decrease the neutron flux through neutron capture reactions, materials (mainly hydrogen-rich) may be used as neutron shielding around the detection setup. The ^{13}C(α,n)^{16}O reaction is a main source of neutrons for the s-process. The reaction cross-section was measured at LUNA [181,182] using an array of eighteen stainless steel ^{3}He counters to detect the produced neutrons. The counters were positioned in two concentric rings around the target chamber and embedded in a high-density polyethene moderator to thermalize the neutrons. The combination of these techniques has allowed for the measurement of ^{13}C(α,n)^{16}O down to the astrophysically significant energies, i.e., the Gamow window. Activation measurements (see Section 2.1 for more details about the activation measurements) have been also performed at LUNA; some of the reactions measured include: ^{3}He(α,γ)^{7}Be, ^{17}O(p,γ)^{18}F, ^{12}C(p,γ)^{13}N [182–184]. The LUNA collaboration has been studying low-energy nuclear reactions relevant to astrophysics for three decades. The work has led to unprecedented precision in the measurement of key reaction cross-sections and to major breakthroughs in our understanding of the inner workings of stars. A vast number of measurements relevant to BBN, p-p Chain, CNO cycle, NeNa and MgAl Cycles, and s-process nucleosynthesis have been performed (see Ref. [125] and references therein).

Cross-section measurements spanning over as wide an energy range as possible are required in situations when the Gamow window cannot be reached in order to facilitate theoretical extrapolation. Since the reactions of more complex burning processes, such as the burning of helium and carbon, occur at higher temperatures, the laboratory studies of them require higher beam energies. The installation of the new LUNA MV machine took place in 2021. The LUNA MV accelerator is a single-ended inline Cockroft-Walton accelerator with a max 3.5 MV terminal voltage. The accelerator is able to accelerate the proton, α, and ^{12}C beams in the energy range between 300 keV and 3.5 MeV.

2.21. Centre of Micro-Analysis of Materials (CMAM) at the Autonomous University of Madrid, Spain

CMAM is a Spanish Infrastructure that hosts an HVEE (High Voltage Engineering) 5 MV tandem linear accelerator [185]. The 5 MV Tandem provides MeV ion beams of any stable element. The main nuclear physics research area is the study of relevant nuclear reactions for astrophysics, typically those with excited states of certain nuclei near the particle threshold. The nuclei and the states of interest are populated in low energy reactions and studied by particle and gamma detection. The end of the beamline is equipped with a big versatile reaction chamber. All setups share a design that can prevent the very strong signal from Rutherford scattering that would mask the reaction channel of interest. Additionally, the detector setups are easily interchangeable. A setup of fourteen Si detectors, each divided into four subdetectors, is available for charged particle detection at forward angles [186]. At backward angles, a setup of three DSSSD detectors is positioned, covering an angle from 85° to 170°. By using flanges in various directions, several gamma-detecting system types can be incorporated. As an example of the studies of astrophysical relevance carried out in this beamline, one can stress the measurement of the cross-section of the ^{3}He(^{4}He,γ)^{7}Be in the energy range 1–3 MeV [187]. Also, the excited states in ^{12}C were explored using the ^{10}B(^{3}He,p3α) reaction in order to obtain additional information of the triple-alpha process as well as to study α clustering in light nuclei. The current research focuses on the study of the ^{19}F(p,$\alpha\gamma$)^{16}O reaction [188]. This reaction helps to understand the radiative capture of α on ^{12}C, which is crucial for nuclear astrophysics since it has a major role in determining the C to O ratio during the burning of stars. CMAM also performs research on materials science, nanotechnology, environmental science, biology, archaeology, and cultural heritage.

2.22. The Tandem Accelerator Laboratory (TAL), Institute of Nuclear and Particle Physics (INPP) of the National Centre for Scientific Research "Demokritos" (NCSRD), Greece

TAL is currently the primary research facility of the NCSRD's Institute of Nuclear and Particle Physics (INPP). It hosts the 5.5 MV T11/25 Van de Graaff Tandem accelerator. Quasi-monoenergetic neutron beams can be produced. TAL also hosts the 250 keV single-stage accelerator PAPAP [189]. PAPAP can accelerate proton and deuteron beams with currents of hundreds of µA. CALIBRA's goal is to create, operate, and exploit a cluster of accelerator laboratories for ion beam research and applications at "Demokritos". The CALIBRA project's funding is being used to carry out a number of infrastructural improvements at the facility. A 17 MeV Scanditronix Cyclotron and a 2.5 MV Tandetron AMS accelerator, both fully functional 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, for the establishment of the Cyclotron and the AMS Labs. The donated cyclotron produces and accelerates protons (p) and deuterons (d) of energies of 17 and 8.5 MeV, respectively. The NeoPtolemos γ-summing spectrometer is a cylindrically shaped (14 "×14") NaI(Tl) detector with a borehole of 32 mm diameter along its axis. Its absolute efficiency for a two-fold γ cascade is higher than 50%. The TAL group created a method called "4π-summing". The method makes it possible to measure angle-integrated spectra rather than many angular distributions (see, for example, Refs. [190,191]). This method relies on the use of a large-volume NaI(Tl) crystal detector with the highest possible absolute γ -ray detection efficiency. As the name"4π-summing" suggests, all γ rays that de-excite the entry state of a compound nucleus and form γ cascades are summed. This practically allows for the analysis of only one single peak—"sum peak"—instead of multiple γ transitions. GASPAR is an acronym for "GASP for Astrophysics Research", where "GASP" stands for the GAmma SPectrometer [192] that used to be located at the INFN Laboratori Nazionali di Legnaro (INFN-LNL). GASP comprises 40 Compton-suppressed HPGe and an 80-crystal BGO calorimeter that covers 80% of the solid angle. Compared to the NeoPtolemos calorimeter, the GASPAR BGO Ball has certain advantages like 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. For the study of neutron-emitting processes, an array of sixteen ^{3}He-gas-filled neutron counters is also provided [193]. The multipurpose large-volume scattering chamber and the deuterium-filled gas cell for the generation of quasi-monochromatic neutrons are among the experimental tools that are most frequently used [189]. The primary objective of the Nuclear Astrophysics program at TAL is to further clarify nuclear physics aspects of the p-process [189]. The solar system p-nuclei abundances still pose a challenge for all p-process nucleosynthesis models, which fail to reproduce them, especially in the case of the light p-nuclei. The reduction of nuclear physics uncertainties entering astrophysical calculations are strongly needed. 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). More than twenty capture reactions have been investigated at NCSR Demokritos so far (see [189] and references therein, also refs. [191,194]). The measurements of the (n,2n), (n,p), (n,α), and (n,f) cross-sections have been the focus of the successful research program. The neutron facility of TAL, which can produce monoenergetic neutron beams with fluxes of $\approx 10^{5}$–10^{6} ncm^{-2} s^{-1} in the energy ranges of thermal to 450 keV, 4 MeV to 11.5 MeV, and 16 MeV to 20.5 MeV by using the ^{7}Li(p,n), ^{2}H(d,n), and ^{3}H(d,n) reactions [195,196], is a key tool in the implementation of this program. The laboratory has also taken part in a coordinated research program on a proton-induced gamma-ray emission (PIGE) technique improvement, evaluating existing PIGE data, and measuring new ones, funded by the IAEA. Numerous differential cross-sections have been measured in a variety of energies and angles for this purpose. [197,198].

IBA techniques are extensively used at the TAL for material characterization, surface analysis, and environmental monitoring. TAL hosts a state-of-the-art irradiation facility for the study of radiation damage phenomena in fusion materials as well as the external beamline for culture heritage studies.

2.23. Microanalytical Centre, Jožef Stefan Institute (MIC, JSI), Slovenia

The 2 MV Tandetron is the only research accelerator in Slovenia [199]. Compared to similar installations in Europe, the Ljubljana 2 MV Tandetron is particularly powerful, as in addition to two standard ion sources (sputter and duoplasmatron), it also uses an extremely bright multicusp source of negative hydrogen ions. The nuclear physics research at 2 MV Tandetron focuses on reactions between light nuclei, in particular, on the electron screening effect. The cross-sections for reactions involving positively charged nuclei are higher in the presence of atomic electrons than they are in the absence of electrons. Unfortunately, the effect is not understood well enough to predict its role in stellar plasma, but it was noticed that the presence of electrons in the solid state may enhance reaction rates by several orders of magnitude [200]. The effect is particularly large when various hydrogen isotopes are implanted into a metallic lattice. Recently, it was discovered that electrons were emitted instead of γ-rays in the nuclear reaction ^{2}H(p,γ)^{3}He at a significantly higher rate than would be expected from the internal conversion process [201]. This demonstrated that electrons actively participate in the reaction and do not just simply lower the Coulomb barrier. Since the nuclear physics group is also very active in detector development, a testing station for tests of detectors for GSI/FAIR is being currently commissioned. MIC also performs nuclear fusion research, as well as a broad spectrum of nuclear applications including biology, medicine, and archaeometry.

2.24. The Center for Isotopic Research on Cultural and Environmental Heritage (CIRCE), Italy

The CIRCE facility in Caserta, Italy, hosts a 3 MV Tandem Pelletron accelerator [202]. The measurements of radiative capture reactions can be performed in inverse kinematics. The recoils produced in the nuclear reactions are detected using a recoil mass separator (RMS). The advantage of RMS is the possibility of overcoming both the problems of unfavorable signal-to-background ratio in astrophysical measurements as well as the possible problems with the purity and production of the target. The European Recoil Separator for Nuclear Astrophysics (ERNA) is an RMS designed with the main goal of determining the $^{12}C(\alpha,\gamma)^{16}O$ reaction [203]. Since 2009, ERNA has been hosted by CIRCE laboratory. The ERNA separator proved to be a valuable tool in the measurement of the total cross-section of radiative capture reactions of astrophysical interest. The first results were from the measurement of the total cross-section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction [204]. This measurement significantly extended the energy range of the measurements available at that time, with a considerable improvement in the overall precision. The use of ERNA RMS for the measurement of the $^{3}He(\alpha,\gamma)$ ^{7}Be reaction cross-section has indicated that at energies above 1 MeV (in the c.m.s system), the energy dependence of the cross-section was significantly different from the one foreseen by the most adopted models [205]. The ERNA RMS was also used to measure the reaction yield of the $^{15}N(\alpha,\gamma)^{19}F$ resonances at Ec.m.s. = 1323 and 1487 keV. The yield of the two resonances was observed as a function of the energy; the resonance widths could be extracted for both energies [206]. Most recently, the total cross-section of $^{7}Be(p,\gamma)^{8}B$ was measured in the energy range of 367 keV to 812 keV using a radioactive ^{7}Be beam and ERNA RMS [207]. For the first time, this approach provided results with adequate precision to determine the cross-section of $^{7}Be(p,\gamma)^{8}B$ at an astrophysical energy. ERNA collaboration is also involved in the study of nuclear reactions in direct kinematics, which does not involve the RMS system (carbon burning, for example). GASTLY (GAs-Silicon Two-Layer sYstem) has been designed to detect and identify low-energy light particles emitted in nuclear reactions of astrophysical interest [208]. The GASTLY array consists of a two-stage detection system based on ionization chambers and large-area silicon strip detectors and has large solid angle coverage, as well as high angular- and energy resolution. CIRCE laboratory also performs extensive research on cultural heritage and the study of environmental processes.

3. Conclusions

The nuclear physics field focuses its top research at large-scale facilities, which encompass highly competitive research proposals as well as complex detector arrays and acquisition systems. On the other hand, small-scale facilities play an important role in the landscape of nuclear physics research in Europe. The current status, available instrumentation, as well as perspectives of nuclear physics research at nineteen European small-scale facilities are given. The small-scale facilities contribute to our understanding of nuclear physics through research in nuclear structure, reactions, and nuclear astrophysics. They perform a diverse research program in nuclear physics and applications and are specifically endorsed by the NuPECC LRP. In addition, small-scale facilities develop novel technologies and methodologies. They address a wide range of fundamental questions and are essential for teaching and training personnel in accelerator technology and science, providing them with diverse skill sets. Nuclear physics research at small-scale facilities has certainly thrived in the last decade. The current upgrades and new facilities such as, e.g., the new fragment separator FRAISE at LNS Catania, LUNA MV, and the Felsenkeller underground accelerator laboratory are paving the road to exciting new discoveries. Nuclear physics is an international venture, and we hope that this review paper will be useful for researchers working at small-scale facilities to understand the position of their facility in the European accelerator-based nuclear physics landscape and find possible synergies.

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