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A new approach to β-decays studies impacting nuclear physics and astrophysics: the PANDORA setup

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Abstract. Theory predicts that lifetimes of β-radionuclides can change dramatically as a function of their ionization state. Experiments performed in Storage Rings on highly ionized atom have proven nuclei can change their beta decay lifetime up to several orders of magnitude. The PANDORA (Plasmas for Astrophysics, Nuclear Decay Observation and Radiation for Archaeometry) experiment is now conceived to measure, for the first time, nuclear β-decay rates using magnetized laboratory plasma that can mimic selected stellar-like conditions in terms of the temperature of the environment. The main feature of the setup which is based on a plasma trap to create and sustain the plasma, a detector array for the measurement of the gamma-rays emitted by the daughter nuclei after the decay process and the diagnostic tools developed to online monitor the plasma will be presented. A short list of the physics cases we plan to investigate together with an evaluation of their feasibility will be also discussed.

1 Introduction

Stellar nucleosynthesis in massive stars proceeds through subsequent fusion reactions until iron, where it stops because the fusion of still heavier nuclei needs energy instead of providing it. Heavier nuclei are created by the interplay between neutron captures and β-decays; these two processes represent the driving mechanism allowing to increase nuclear mass and charge up to the limits imposed by the nuclear stability [1,2], according to the so-called s-process and r-process. This interplay determines the pathways of stellar nucleosynthesis and, thus, the abundances of atomic nuclei observed in the Universe. However, a major difference exists between terrestrial and stellar conditions: stellar nucleosynthesis proceeds in a hot and dense environment that affects the degree of ionization of the atoms involved in the stellar nucleosynthesis and allows the population of atomic excited states that can induce significant effects on the nuclear beta decay constant or make the beta decay possible in nuclei stable in terrestrial conditions [3-5]. Actually, our knowledge of the effects of the external environment on the nuclear β-decay rates is rather limited. Early attempts showed variations lower than about 0.05% (see, e. g. [6]) as a function

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of pressure and temperature, whilst near the end of the ’60s a chemically induced change of about 3.5% in the half-life of ^{7}Be (see, e. g. [6]) was observed. An important breakthrough was achieved using storage rings. The so-called “bound-state β-decay” [7] was observed for the first time on many isotopes. For example, fully stripped $^{187}Re^{75+}$ ions decayed by 9 orders of magnitude faster than neutral ^{187}Re atoms that have a half-life of 42 Gyr [8]. Moreover, bare $^{163}Dy^{66+}$ nuclei, being stable as neutral atoms, become radioactive, with a half-life of 33 days, thus allowing the occurrence of a branching reaction in the s-process path [9]. In order to get a deeper knowledge of the effect of the environment on the beta decay main features and evaluate the possible implications in s-process nucleosynthesis we are developing a new experimental setup, named PANDORA [10,11]. This facility will be dedicated to the measurement of the β-decay process in stellar-like conditions where, due to the high temperature of the plasma, a charge state distribution (CSD) of the ions is established in non-local thermodynamic equilibrium (non-LTE) conditions, and its effect on the decay can be investigated as a function of the temperature. Such a measurements can be extremely relevant for those radionuclides involved in nuclear-astrophysics processes (BBN, s-process, CosmoChronometers, early solar system formation).

2 Pandora experimental setup

The PANDORA project aims to build a compact minimum-B magnetic trap (with B_{max} = 3.0 T at the injection and extraction sides) [12], where plasmas are heated by microwaves via Electron Cyclotron Resonance (ECR) mechanism at 18-21 GHz, up to densities n_e~10^{11}-10^{13} cm^{-3}, and temperatures T_e~0.1-30 keV. The predicted variation of decay rates will be measured as a function of the thermodynamic plasma properties (density and temperature), whose combination determines the CSD of the in-plasma ions. This paper will describe the overall setup including the array of 14 HPGe detectors dedicated to the measurement of the γ-rays emitted after β-decays, supported by a plasma multi-diagnostics system consisting of RF polarimeters, optical and X-ray spectroscopy, X-ray imaging and space resolved spectroscopy for the simultaneous measurement of plasma density and temperature.

2.1 The magnetic system

A plasma trap that uses a magnetic field for plasma confinement will be employed in PANDORA [12]. It consists of a group of 3 axial solenoids and an hexapole nested inside, coaxial with the solenoids (SEXT-IN-SOL configuration). This configuration produces a superposition of an axial magnetic field (from the axial coils) and a radial magnetic field (from the hexapole coils) called *minimum-B* in which the field grows in every direction, both axially and radially starting from the plasma chamber center. The whole superconducting magnetic system is enclosed in a single cryostat, surrounded by an iron yoke. Its warm bore allows to place a cylindrical plasma chamber with inner radius R_{CH_IN} = 140 mm and a length L = 700 mm. Due to the need to place the gamma detection array and some diagnostic tools around the trap, 16 tapered holes has been created in the cryostat, yoke and properly positioned in the interspace of the six hexapole (as shown in fig.1). Such a choice allows the detection of gamma-rays without any significant absorption effect due to the crossing of the material except the plasma chamber walls that, in correspondence to the holes, will be properly reduced in thickness. The magnetic system will be able to operate at any point inside the operative ranges shown in Table 1, while ensuring plasma stability. The plasma trap confines the plasma in a Magneto-Hydrodynamical stable mode. The plasma is heated using microwaves at 18 + 21 GHz via ECR. Three klystrons (see fig 2) will generate an RF power of up to 6.5 kW, scalable up to a value of 10 kW in full-power operations. The trap procurement started in May 2021. The tender for procurement (a special type called

"Competitive Dialogue", according to Italian regulations) is expected to end by March. 2023, then the construction will start.

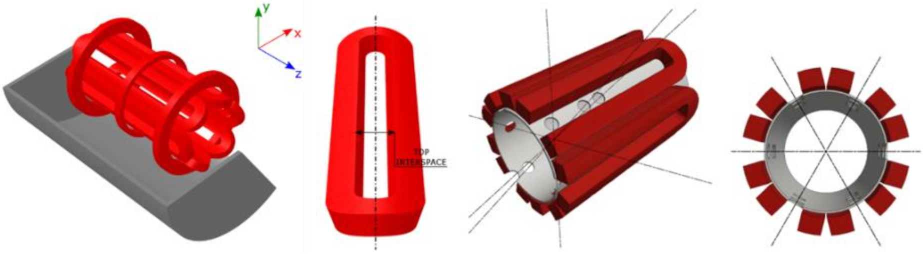

Fig. 1 – Final design of the magnetic superconducting trap (on the left), with details about the hexapole structure and the radial holes in the plasma chamber made to allow gamma-rays to be detected by the HPGe detectors surrounding the trap.

Tab. 1 – List of requirements for the superconducting magnetic trap of PANDORA.

MAGNETIC FIELD REQUIREMENTS	
B_{inj} **max @ z = - 350 mm**	3 T
B_{inj} **operative range**	1.7 T – 3 T
B_{ext} **max @ z = 350 mm**	3 T
B_{ext} **operative range**	1.7 T – 3 T
B_{min} **@ z = 0 mm**	0.4 T
B_{hex} **@** R_{CH_IN} **= 140 mm**	1.6 T
Liquid He	Free
Warm Bore radius	150.5 mm
Distance between mirrors	700 mm
Stray field	Less than 0.02 T

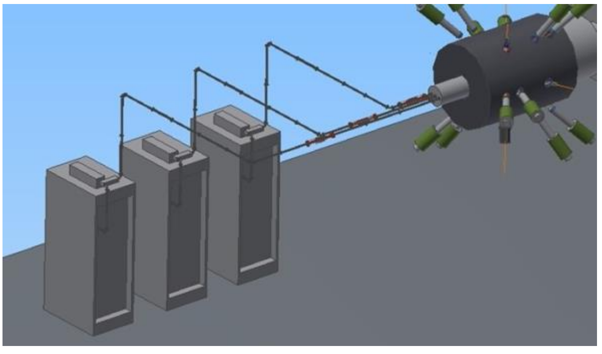

Fig. 2 – Render view of the PANDORA trap surrounded by HPGe detectors, showing the three Klystrons used to produce the high-power RF (18+21 GHz) and the corresponding microwave branching (waveguides) needed to generate the plasma via ECR.

2.2 The detectors array

The gamma-ray detectors array of PANDORA [13,14] (see figure 3) plays a fundamental role in the project. It will be used to measure the in-plasma decay rate of selected radionuclides, β emitters, through the detection of the *γ*-rays emitted by the daughter nuclei populated in the β decay process. The presence of the coils and the hexapole poses important limitations on the number of detectors that can be placed around the trap without being shielded by the magnetic system. Therefore, the design of the *γ* array represents a compromise between the best detection efficiency achievable and the mechanical constraints imposed by the feasibility of creating many apertures in the cryostat and the yoke without altering the magnetic field shape. The results of the design study suggest that the best configuration for the *γ* array is made of 14 large volume HPGe detectors, twelve placed radially in correspondence to dedicated apertures, created between the warm bore radius and the external iron yoke through the cryostat and the inner cold mass, and two axially, as illustrated in figure 3. They will "look" into the plasma through aluminum windows made in the walls of the plasma chamber. The whole array has a photopeak efficiency which reaches its maximum value of 1.8×10^{-3} around 200 keV and then progressively decreases down to 8×10^{-4} in the range 1400-2000 keV, where it is rather constant. Such a value is sufficient, due to the high number of decaying ions present in the plasmoid, to measure the predicted variations in the decay rates of the first physics cases selected in PANDORA such as ^{176}Lu, ^{134}Cs, ^{94}Nb. In these cases preliminary simulations indicate that a 3-sigma confidence level is achievable in few months (Lu), days or weeks (Cs and Nb), depending on the activity of the specific nuclide under investigation. For the initial experimental campaign, it will be possible to use 16 HPGe detectors of the GALILEO experiment [15] thanks to a collaboration agreement between PANDORA and GAMMA collaborations signed in Oct. 2021. The gamma detection array will work under harsh conditions due to the self-emitted background produced by electron Bremsstrahlung which will lead to a counting rate of about 50 kHz background in each detector. For this reason, dedicated pre-amplifiers, developed at the LNL, showing a limited worsening in detector energy resolution at high rates will be used [14].

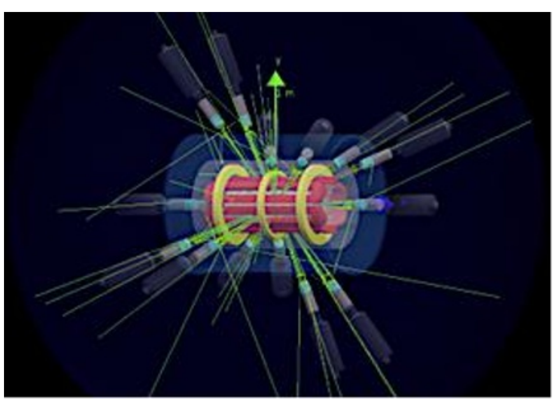

Fig. 3 – Render view of the experimental setup showing the magnetic trap, the HPGe detectors and the GEANT4 ray tracing simulations of the γ-rays.

However, detector performances can deteriorate with time especially considering the harsh conditions to which they will be exposed. Therefore, it was decided to build, at the LNS, a dedicated detector laboratory to cope with these needs with the support of the GAMMA collaboration and the LNL DetLab in order to be able to repair, test and run ordinary maintenance procedures on the HPGE detectors.

2.3 The plasma diagnostics

The main aim of the PANDORA project is to map the evolution of β decay nuclear lifetime as a function of plasma density and temperature. Therefore, an online monitoring on the plasma parameters during the measurement is fundamental to correlate the variation of the decay lifetime to plasma properties. A simultaneous measurement of density and temperature resolved in space and time is thus needed to reconstruct the spatial structure of the plasma and its temporal behavior, in stable and turbulent regimes. ECRIS plasmas are in non-LTE conditions, with three different electron populations: hot, at kT~100 keV or more; warm from kT~100 eV up to tens of keV; cold, at kT~1 eV ÷ 100 eV. Only the warm component of the electron energy distribution function has the right energy to ionize the atoms up to high charge states, since the cold electrons have insufficient energy to remove electrons from the inner shells of atoms (although they are highly involved in the confinement dynamics) and in the hot electron domain the ionization cross section is inversely proportional to the electron energy. A complete characterization of ECR plasmas, which can emit radiation in a broad range of frequencies, requires a multi-diagnostic setup [16] able to measure the density and temperature of the different components. PANDORA diagnostics will consist of:

- A Silicon Drift Detector (SDD) for plasma density and temperature measurements in the warm electron domain [17];
- Two X-rays pin-hole cameras for 2D space resolved spectroscopy [18,19];
- A High-purity Germanium detector for hard X-rays time resolved spectroscopy;
- A spectrometer for the plasma-emitted visible light characterization (resolution of R=13900, Δλ= 0.035nm at λ=486 nm);
- A microwave Polarimeter for line integrated total density measurement [20];
- RF probes and fast scopes for time-resolved measurements and monitoring of plasma instabilities (via a 80 Gs/s-20 GHz bandwidth oscilloscope) [21];
- RF probes connected to a Spectrum Analyzer (SA) for plasma radio-emission in GHz ranges [22].

Some other tools are under development to improve the performances of the setup. In particular, the collaboration is working on the implementation of the Microwave Imaging Profilometry (MIP), to achieve an online measurement of local values of the electron density that can be synergic with the microwave polarimeter already described [23], as well as on the Incoherent Thomson Scattering (ITS) [24], which is an alternative technique for investigating the absolute plasma density, the electron energy distribution functions, and even the electron global drift velocity.

2.4 Injection of radioisotopes in the plasma

The short list of physics cases for PANDORA phase 1 is made of three solid elements. In order to inject them inside the ECR plasma it is necessary to produce a neutral vapor first, or an "ejection" of neutral particles towards the plasma chamber. Two techniques are planned to be used: the resistive oven (for the ^{176}Lu and ^{134}Cs) and the sputtering (for ^{94}Nb). In the first case, the efficiency is estimated to be larger than 30% and ion density is expected to amount to 1-10% of the plasma buffer's. In the second case (sputtering), the efficiency drops to 10% or lower, with a relative concentration around 1%. As it concerns the case of ^{134}Cs lifetime investigation, a dedicated protocol is planned. Such an isotope is commercially available in liquid solutions of HCl: Cesium dissociates after the drying of the compound, at T<500 °C, making it available for ionization by plasma electrons. The results of these feasibility tests are fundamental to plan the next experiments campaign focused on the evaporation of isotopes like ^{176}Lu and ^{133}Cs.

3 Physics cases: perspectives

Tens of physics cases of potential interest for astrophysics have been identified, with a shortlist of priorities which includes ^{94}Nb ($t_{1/2}$ ~ 2 x10^4 y), ^{134}Cs ($t_{1/2}$ ~ 2 y) [25], ^{176}Lu ($t_{1/2}$ ~ 3.8 x 10^{10}). Theoretical calculations in fact suggest that an important variation in β-decay lifetime is expected for all these isotopes, as a function of plasma temperature, which could have important implications in s-process nucleosynthesis branchings. For example, the half-life dependence on plasma temperature is reported in fig. 4 for ^{176}Lu.

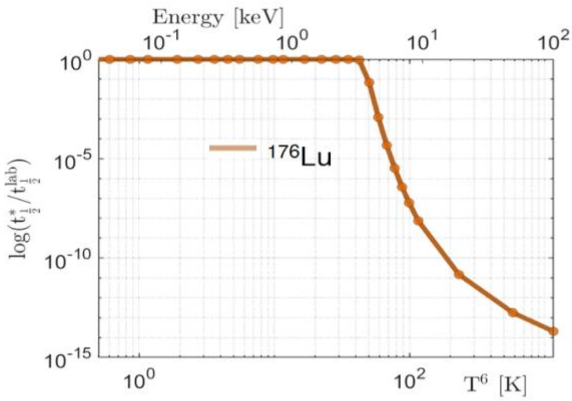

Fig. 4 – Theoretical prediction of stellar half-life to terrestrial half-life ratio for ^{176}Lu nucleus as a function of plasma temperature expressed in T^6 [10^6 K] (Energy [keV]). Calculations were performed at plasma densities of 10^{12} cm^{-3}.

^{176}Lu nucleus, whose role as a cosmo-thermometer or a cosmo-chronometer is not fully defined yet, plays a major role in s process nucleosynthesys as it determines the abundance of ^{176}Hf, an s-only nucleus. The ^{176}Lu/^{176}Hf ratio is largely affected by the branch at ^{176}Lu, which is strongly sensitive to the temperature during the thermal pulses. Therefore the measurement of the dependence of the beta half-life dependence on the temperature might shed light on this issue. The decay rate of ^{134}Cs influences the abundances of two s-only isotopes ^{134}Ba and ^{136}Ba that are not well reproduced by the present-day nucleosynthesis models, the uncertainty affecting the ^{134}Ba/^{136}Ba ratio being mainly associated to the β-decay rate of ^{134}Cs. The ^{94}Nb nucleus provides the main production channel for ^{94}Mo in conditions typical of the s process.
Simulations were performed on all physics cases foreseen, considering the expected lifetime variation and, therefore, the effective activity in the plasma, assuming a plasma volume of 1500 cm^3 with a realistic concentration of the radioactive isotope to be studied. Taking into account the HPGe array detection efficiency, to reach a 3-sigma confidence level the experimental run should last from about one day up to about three months depending on the physics case investigated and the lifetime variation observed [13]. Numerical simulations [26, 27] are now ongoing to estimate the expected density and temperature distribution in PANDORA, and then to perform a kind of "virtual experiment" addressing and supporting the data taking that will start at the end of 2024.

The possibility to investigate of β decay rates in stellar-like conditions is expected to show a strong dependence on the temperature T, while a very weak dependence on plasma density [5] is foreseen. At a given T, not only the CSD, but also a complex configuration of atomic/electronic excited states in the various ions is achieved in plasma. Hence, ECR plasmas that are in non-LTE conditions give the unique opportunity to investigate the actual effect of electron temperature on the decay rate. An equivalent CSD can be then extrapolated to LTE scenarios applying to many astrophysical plasmas allowing for a direct comparison with stellar model predictions. This new approach has, therefore, all the potential to provide a more complex but more coherent and "realistic" picture of the decay, closer to astrophysical contexts than any result obtained from storage rings experiments.
Within PANDORA we also intend to provide, in the forthcoming years, critical new nuclear and atomic physics inputs from experiments and advanced theoretical models, in particular, the in-plasma atomic physics knowledge on the opacity of several metallic r-process elements. These data will allow us to extend our understanding of the microphysics of kilonovae (KN). Preliminary work has been already carried out in the framework of the PANDORA collaboration to support first-of-its-kind experimental measurements of plasma opacity with in-laboratory plasmas resembling these KN-stage conditions. In this view, the results of recently performed experiments at the INFN-LNS to reproduce stable early-stage ejecta thermodynamical conditions of under-dense and low-temperature plasmas are reported in [28]. These are the grounds to tackle the astrophysical problem in laboratory plasmas with an interdisciplinary approach.

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