The PANDORA project: a setup for in-plasma β-decay studies in nuclei of astrophysical interest

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Abstract. Theoretical predictions as well as experiments performed at Storage Rings have shown that a high degree of ionization can affect the half-life of β-radionuclides. The PANDORA project aims at investigating, for the first time, beta decay rates in a plasma, simulating specific stellar-like conditions. A description of the physics motivations and the experimental setup developed to accomplish this task is given. The physics cases selected for the first experimental campaign are also presented.

1 Introduction

Beta decay rates in stars represent a fundamental ingredient in the study of heavy element production since the attempt to reproduce the elemental abundances in the Universe calls for an accurate knowledge of β-decay half-life in stellar environment and the comprehension of the possible mechanisms affecting its variation. Even though beta decay constant λ has been measured for a wide range of nuclei, a major difference exists between terrestrial and stellar conditions. In fact, stellar nucleosynthesis proceeds in a hot and dense environment which affects the degree of ionization of the atoms involved in the process and could play an important role in altering the beta decay process. Early studies of a possible effect of the environment on the nuclear β decay constant didn't show any evidence of a marked variation, indicating, in the best cases, a change smaller than 0.05% [1]. However, in 1947 two independent papers from E. Segrè [2] and R. Daudel et al. [3] suggested the possibility that beta decay rates could be affected by a change in electron density, at least for low Z nuclei. Such an effect, which could play a significant role in altering beta decay rates in stars, was observed for the first time in the electron capture process of ^{7}Be leading to ^{7}Li. A lifetime variation of 3.5% was measured [1].

An important breakthrough in the field was achieved with the advent of Storage Rings due to the possibility of preserving, for extended periods of time (up to several hours), highly ionized ions and mapping their decay. A new decay mechanism, called "bound state β-decay" in which the electron emitted in the decay process is captured in one of the inner shells of the atom was observed for the first time in highly ionized atoms [4]. In neutral atoms or ions with only a few holes in the atomic levels such decay mechanism is hindered or even blocked because the emitted electron is unable to access to a bound final state but in highly ionized ions the decay becomes possible or, somehow, energetically favored. Experimental results

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showed sizeable changes in beta decay half-life. For example, fully stripped $^{187}Re^{75+}$ ions decayed by 9 orders of magnitude faster than neutral ^{187}Re atoms, which have a half-life of 42 Gyr [5]. This phenomenon can be understood in the framework of Fermi beta decay theory which is fundamental to calculate the effect of stellar conditions on β-decay half-lives [6].

On a terrestrial level three classes of beta decays are studied, β^+, β^- and electron capture, typically from K-shell, while in stellar environment two further decay modes should be taken into account, the bound-state beta decay and the free electron capture. Besides, in star environment, due to the high temperature, atoms can be ionized and ions can be in excited states making the evaluation of the reaction Q-value more complex than the one calculated for neutral atomic species. The additional terms in the Q-value calculation needed to take into account the previously described effects can modify its sign, especially for small Q-values, making the decay process possible, differently from the one evaluated in neutral atoms. The total decay rate, in Fermi's theory, is conventionally written in terms of half-life ($t_{1/2}$) and can be evaluated from the expression for the *ft*-value of the decay given by:

$$f_L(Z',Q)t_{\frac{1}{2}} = \frac{(ln2)2\pi^3\hbar^7}{g^2 m_e^5 c^4 \left|M_{if}^L\right|^2}$$

where $f_L(Z',Q)$ is a dimensionless theoretical factor that depends on the phase space of the lepton waves, the type of transition and the type of decay, Z' is the charge of the daughter nucleus, Q is the reaction Q-value, g is the weak interaction strength, $|M_{if}^L|^2$ is the nuclear matrix element and m_e, c, h are respectively, the mass of electron, the speed of light and the Planck constant. Since *ft*-values are dependent only on the nuclear matrix element, the stronger is the coupling between the states of parent and daughter nuclei the larger is the matrix element. This implies a larger chance of a nuclear transition and consequently a smaller *ft*-value. Fixing the value of the matrix elements, the two quantities $f_L(Z',Q)$ and $t_{1/2}$ are correlated and therefore a variation in $f_L(Z',Q)$, which depends on lepton phase and Q-value, affects the $t_{1/2}$. Since plasma environment modifies the reaction Q-value due to the high degree of ionization of the atoms and to the clouds of charges, both positive and negative, which create perturbations to the atomic levels and impact level populations, the stellar and terrestrial decays can have different $f_L(Z',Q)$ and therefore different $t_{1/2}$ for a fixed type of transition. The seminal theoretical work of Takahashi and Yokoi [7] investigated the in-plasma effects due to the temperature and the electron density on beta decay rates. In particular, it was clearly shown the role played by the temperature (and electron density) in reducing the beta decay half-life, the predicted variation attaining even many orders of magnitude, depending on the physics cases investigated.

Takahashi-Yokoi predictions, together with the first experimental results achieved using Storage Rings, have fundamental implications in the *s*-process nucleosynthesis based on the competition between neutron capture and beta-decay rates. This is particularly true in the so-called branching points as a variation in the decay rate directly affects the population of a specific nucleus and the subsequent reaction process. Therefore, to get a deeper knowledge of the in-plasma beta decay rates, it seems mandatory to face up a new experimental challenge, reproduce in laboratory some stellar-like conditions and measure the predicted variations in β-decay half-life.

2 The PANDORA project

In order to elucidate the possible effects connected to the dependence of the beta decay constant on the charge state distribution (CSD) of the decaying ions which is related to the thermodynamical condition of the environment, a totally new approach was conceived by the PANDORA (Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry) project [8]. It is based on the realization of an innovative plasma trap [9] to be built at the INFN - Laboratori Nazionali del Sud, and devoted to measure, for the first time, nuclear β-decay rates in a plasma emulating some stellar-like conditions in terms of CSD. Such an approach is complementary to the one adopted in Storage Ring experiments where a single charge state at a time can be investigated and has the advantage that the results can be directly compared to theoretical models once the plasma conditions (density, temperature, CSD) are measured and kept under control during the experiments.

In stars a plasma, defined as a quasi-neutral gas made of charged particles exhibiting a collective behavior, is gravitationally confined while, to run experiments in laboratory, a magnetic confinement based on Lorentz force is used. A proper shaping of the magnetic field is fundamental to achieve the plasma confinement and at the same time to limit the plasma deconfinement losses. Such an approach is typically used in ion sources where charged particles spiralyze around the field lines and can be trapped for several millisecond before being extracted and injected in the accelerators. In the PANDORA project, the plasma will be confined in the trap using a magnetic field configuration called *minimum-B* where the magnetic field strength has a minimum at the center of the trap and increases both axially and radially [9]. It will be achieved using three superconducting coils for axial confinement generating a tunable magnetic field up to 3 Tesla and a superconducting hexapole for radial confinement as shown in fig.1a. The ideal confinement also requires some stringent conditions on plasma equilibrium and stability. These aspects can be investigated looking into the equilibrium between the plasma kinetic pressure and the magnetic confining field pressure: a magnetically stable condition is reached when the plasma kinetic pressure is much smaller than the magnetic pressure.

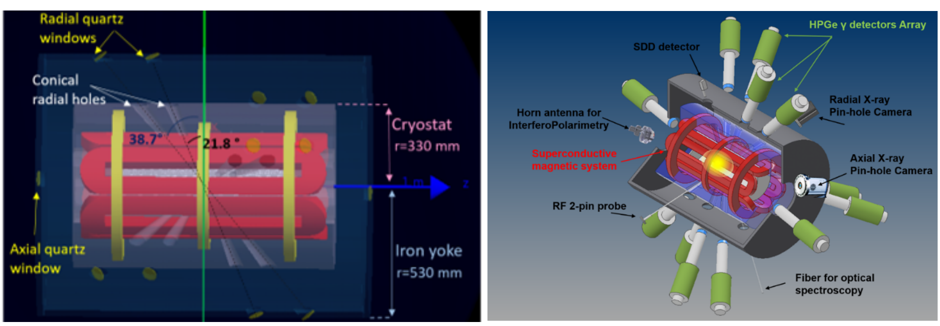

Fig.1 a) Drawing of the PANDORA magnetic system made of 3 superconducting coils (in yellow) for axial confinement and a superconducting hexapole (in red) for radial confinement. The magnetic system is contained in a single cryostat shown in light grey. An iron yoke is used to confine the magnetic field (dark blue area). Conical line of sight are created in the yoke and the cryostat to have direct access to the plasma chamber and used for HPGE detection system and diagnostics. b) Drawing of the PANDORA setup with HPGe around the trap and some diagnostic tools.

Plasma heating is achieved through the interaction of the plasma electrons and electromagnetic waves in the range of few GigaHertz and few kW of power injected in the plasma. The optimum condition for the energy transfer is achieved in the so-called electron-cyclotron resonance region for electromagnetic frequencies equal to the cyclotron frequency given by the relation $\omega_e = eB/m$ where e is the particle charge, B is the magnetic field and m is the particle mass. Ions with high charge states are primarily produced by sequential ionization. In PANDORA they will remain cold, the average temperature (expressed in terms of kT) being of the order of 1 eV while electrons will reach up to about 100 keV.

This hot environment, characterized by an electron density of 10^{12}-10^{14} cm^{-3} and a radioactive ion density of about 10^{11} cm^{-3} will be used to investigate the predicted evolution of the β decay rate as a function of the plasma parameters. To reach this task the plasma will be maintained in a dynamic equilibrium by equalizing input fluxes to the losses from the magnetic confinement. When the plasma operates in magneto-hydrodynamic equilibrium, the dynamical equilibrium can be reached under proper tuning conditions of the magnetic field profile, background pressure, and radiofrequency (RF) power. The β decay events will be tagged detecting the γ-rays emitted by the daughter nuclei, still confined in the plasma, using an array of high efficiency High Purity Germanium (HPGe) detectors [10]. The in-plasma measured radioactivity will be directly correlated to the plasma thermodynamical properties (density and temperature) which will be monitored on-line using a multi-diagnostics setup.

The detection of gamma-rays emitted in the decay process of the daughter nuclei (populated after the beta decay) is a rather complex issue to achieve when a plasma trap is used. In fact, the trap poses many mechanical constraints related to the presence of the magnetic system and the cryostat which affect the positioning of the detectors. Detectors have to be placed in regions free of coils to be able to detect the gamma-rays without any shielding effect due to the presence of materials and, at the same time in regions of low magnetic field to avoid charge collection effect which could limit their performances.

The HPGe detectors will work in rather harsh conditions due to the X-rays' and γ-rays' background of about 50 kHz (in each detector) produced inside the plasma trap due to the electron bremsstrahlung. Dedicated electronics able to run at such a high rate without any significant worsening in energy resolution and efficiency have been already developed by the GAMMA collaboration, which will lend 16 HPGe detectors of the GALILEO Array [11] for the first experimental run of PANDORA.

Simulations focused on optimizing the detection efficiency led to the design of an array made of 14 HPGe detectors be placed around the trap, 12 radially and 2 axially (see fig 1b) [12]. Detectors will measure the γ-rays emitted the plasma through conical lines of sight made in the cryostat and the external yoke (see fig.1a) which pass through the center of the magnetic system. The total photopeak detection efficiency of the array reaches a maximum value of 0.17% at about 200 keV and then smoothly decrease down to 0.09% at about 1.5 MeV keeping the same value up to 2 MeV. Although the array efficiency seems to be rather low, such a value is compensated by the large number of decaying ions in the trap which allows to detect the expected variation of the radionuclide half-lives as shown by the GEANT4 simulations in a time ranging from a couple of weeks for the simplest cases to about 3 months for the longer-living isotopes, as a function of the ionization degree.

A crucial role in the project is played by the plasma multi-diagnostics which will work synergically with the HPGe detector array to on-line monitor main plasma parameters. The ionization states and the charge distributions are, in fact, determined by the plasma temperature, once fixed the density and the confinement time, and therefore their knowledge is fundamental to relate the plasma thermodynamical properties to the measured half-lives.

To deduce plasma properties one can exploit the radiation emitted by the plasma in a broad range of frequencies from radio to γ-rays. Its full characterization calls for the development of different tools to investigate all energetic domains and various analysis methods [13,14]. One important role is played by the shape of the electron energy spectrum which is characterized by the presence of three main components, a cold (E_e < 1 keV), a warm (1 keV < E_e < 30 keV) and a hot one (E_e > 30 keV). The warm one is playing a major role in the ionization process and can be monitored using a silicon drift detector allowing for volumetric soft X-ray spectroscopy which gives access to electron temperature and density. Similar information can be extracted for the hot and cold components using an HPGe detector and an optical spectrometer, respectively [15]. The multi-diagnostic system includes also an interfero-polarimeter [16] to measure the line-integrated total density and a RF probe coupled to a spectrum analyzer or a scope for time resolved spectroscopy [16] and for monitoring and mastering the plasma stability. A pin-hole camera will be used for high resolution spatially-resolved soft X-ray spectroscopy to investigate the plasma structure and the confinement dynamics in the range 2 – 20 keV [17].

In the first experimental campaign we will focus on the study of ^{176}Lu, ^{134}Cs and ^{94}Nb which have been selected among more than one hundred isotopes of potential interest for nuclear astrophysics. Theoretical predictions based on a model developed in [7] suggest that at the expected PANDORA electron temperatures (kT ~ 10 keV) their lifetimes may collapse by several orders of magnitudes. In particular, in the case of ^{94}Nb nucleus which provides the main production channel for ^{94}Mo through *s*-process, the predicted reduction at the PANDORA working condition is about 5 orders of magnitude. Simulation results of a real

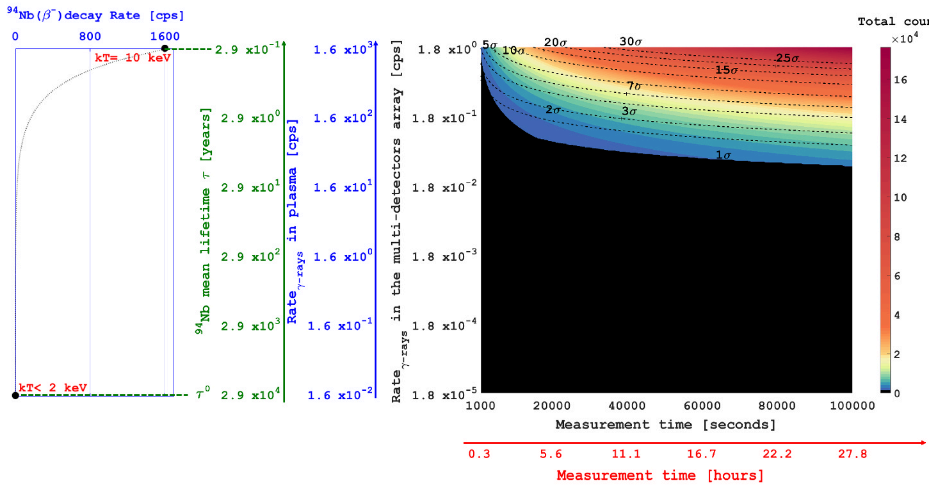

Fig.2. Measurability plot for ^{94}Nb isotope. Y-axis reports the expected variation of the lifetime (green axis); the corresponding expected rate in cps, considering the amount of isotope in the PANDORA plasma volume (blue axis); the corresponding rate of detected gammas in the multi-detectors array (black axis). The X-axis reports the measurement time, while the colors are the total counts with corresponding sigma-levels shown as dotted lines. The left part of the figure shows the decay rate in cps vs temperature.

experimental run assuming a concentration of 0.0001% of ^{94}Nb in a plasma volume of 1500 cm^3, including the efficiency of the HPGe detector array are shown in fig.2 [12]. The first (from the left) green vertical axis shows the range of lifetimes, expressed in years, that can be explored in the experiment, according to theory, starting from the lifetime of the neutral isotope. The predicted decay rate in the plasma is shown in the second, blue vertical axis. Finally, including the efficiency of the HPGe detector array the estimated counting rate of the detector array is shown in the third, black vertical axis. The x-axis shows the measurement time. Pseudo-colors show the total number of counts in the gamma peak (E_γ = 703 keV). To achieve a 3σ confidence level a run duration ranging from few hours to about one day, depending on the observed lifetime reduction, can be foreseen.

3 Conclusions

The PANDORA project is focused on the development of a new experimental setup to investigate the variation of the β-decay half-life of radioisotopes of astrophysical interest in a magnetized plasma. The setup, expected to come into operation in 2024, is based on three pillars, namely the compact plasma trap, the gamma detection array and the multi-diagnostic system which were described together with the first physics cases, ^{176}Lu, ^{134}Cs and ^{94}Nb. An important breakthrough in stellar evolution and nucleosynthesis models is foreseen if the predicted lifetime variations will be observed.

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