

GEANT4 simulations for γ -ray detector array design for in-plasma β -decays studies of nuclear astrophysics interest

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Abstract. The PANDORA project aims to investigate, by a new experimental approach, the β -decays lifetimes of isotopes of nuclear astrophysics interest as a function of thermodynamic conditions of a laboratory plasma able to mimic some stellar-like conditions. A γ -ray detection system was designed by GEANT4 simulations to tag the in-plasma β -decays via the γ -rays emitted from the excited states of the daughter nuclei. The feasibility of PANDORA, in terms of significance levels, was checked by a "virtual experiment run", also investigating the sensitivity for discriminating among different theoretical predictions.

1 Introduction

Laboratory plasmas can be generated by Electron-Cyclotron-Resonance (ECR) heating - through electromagnetic waves interacting with gases or vapours in presence of a magnetic field - which allows to produce highly charged ions, very relevant for studies of nuclear astrophysical interest. Theoretical predictions have in fact shown that the ionization state of nuclei can dramatically modify, even in orders of magnitudes, the lifetimes [1, 2], due to the bound state β -decay mechanism [3]. Only few experimental evidences have been collected up to now mainly using as setups storage rings [2–4]. If confirmed, these evidences are expected to have a huge impact in the study of nuclear-astrophysics processes and cosmology (BBN, s-processing, Cosmo-chronometers, Early Solar System formation) [5–9].

The PANDORA (Plasma for Astrophysics, Nuclear Decay Observation and Radiation for Archaeometry) project [10], supported by the INFN, proposes a new experimental approach to measure the variation of the half-life of β -decaying nuclei in the magnetically confined ECR plasma, correlating the decaying rate with thermodynamic plasma properties. ECR plasmas can be maintained in a dynamic-equilibrium for weeks with on-average constant local electron density n_e and temperature T_e ($n_e \sim 10^{11} - 10^{13} \text{ cm}^{-3}$, $T_e \sim 0.1 - 100 \text{ keV}$), which univocally determine the ion charge state distribution (CSD). The β -decaying isotopes can be directly fluxed inside a plasma chamber (where a buffer plasma is preliminary ECR heated) to be turned into plasma-state; while the isotopes decay, the daughter nuclei emit γ -rays of energy of hundreds of keV that can be detected with an array of γ -ray detectors. Thus, the in-plasma radioactivity can be correlated with T_e and n_e , monitored by a multi-diagnostic setup [11].

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The sketch of the system that will equip the PANDORA trap [12] is shown in Fig. 1(a), with the array of HPGe detectors [13] and several diagnostic tools surrounding the trap. Fig. 1(b) shows the whole superconducting magnetic system (red), the cryostat (blue) and the external iron yoke (grey).

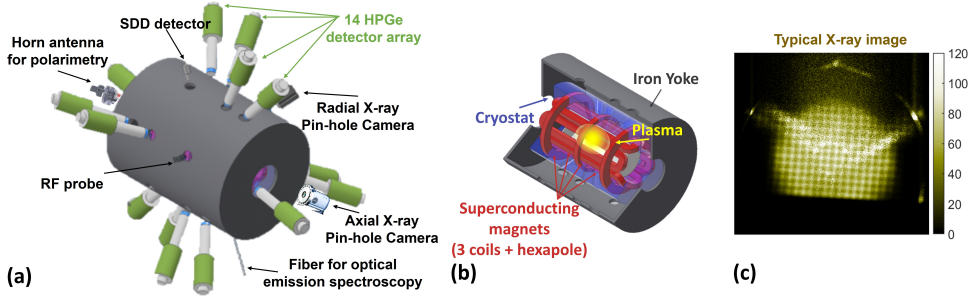


Figure 1. (a) Rendering of the PANDORA trap with the experimental setup for measuring the in-plasma activity (14 HPGe detector array) and on-line monitoring n_e and T_e (i.e., two X-ray CCD cameras, optical spectrometer, interfero-polarimetry, two-pin RF probe, SDD). (b) Sketch of the superconducting magnetic system (red), cryostat (blue) and iron yoke (grey). (c) Typical Argon energy-filtered X-ray image.

The total amount of decays can be determined according to the following formula:

$$N(t_{meas}) = \lambda n_i V_p t_{meas} \quad (1)$$

where λ is the decay constant, n_i is the isotope ion density, V_p is the plasma volume and t_{meas} is the overall measurement time over which the γ -rays produced by the excited states of the decays products are counted by the detector array. Due to dynamical equilibrium, the number of measured decays scales linearly with t_{meas} . Equation 1 implies that the in-plasma ion density and volume must be known all along the measurement to deconvolve λ . The plasma volume can be diagnosed with high spatial resolution ($\sim 400 \mu m$) by means of the soft X-ray imaging through the pin-hole CCD camera technique [14]. This system allows spectrally-resolved imaging [15]. A typical X-ray image, energy-filtered selecting the fluorescence K_α Argon lines, is shown in Fig. 1(c). The plasma radius thus can be estimated from imaging, with an uncertainty of 5%. A model to link the experimental information to local plasma parameters (n_e , n_i , T_e) is under development [16]. In PANDORA, two CCD pin-hole cameras will be used simultaneously (along the axial and radial lines) to estimate the plasma volume and thermodynamic conditions in each voxel.

2 GEANT4 simulations for the PANDORA detector array design

In order to design the PANDORA γ -ray detector array, GEANT4 [17] simulations were carried out (geant4-10-06-patch-02 version and reference physics list QBBC). The system, as designed in [12], consists of a stainless steel chamber (external radius of 15 cm, length of 70 cm and thickness of 1 cm) surrounded by a magnetic system made of three NbTi superconducting coils and a NbTi hexapole. The cryostat was simulated as an Al cylindrical structure and an external ARMCO iron yoke was implemented. Twelve azimuthal conical holes (lower diameter of 4 cm) were performed along the conductor hexapole interspaces both in the cryostat and in the plasma chamber. The goal is to use the hollowed cryostat as multi-collimator

to suppress the photon flux coming from the walls and not directly from the plasma core, improving the signal-to-background ratio. At the end of each collimator a quartz window of thickness of 0.3 cm was placed. An array of 14 γ -ray HPGe detectors [18] (2 axially and 12 radially placed) has been placed collinearly at each collimator.

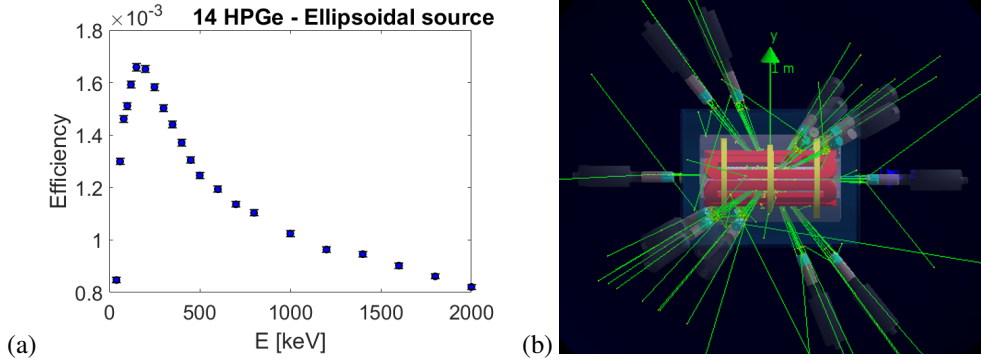


Figure 2. (a) Efficiency vs. γ -ray energy for the HPGe array. (b) Ray-tracing simulations for γ -rays.

Simulations were performed considering an isotropic ellipsoidal source placed around the center of the plasma chamber, having semi-axes lengths of 79 mm, 79 mm and 56 mm, respectively for the x, y and z axis (corresponding to the plasma volume and shape provided by the magnetic field profiles in the PANDORA plasma trap). The γ -ray energy range explored extends from 40 keV to 2 MeV. The trend of the array efficiency as a function of the incident γ -ray energy is shown in Fig. 2(a) assuming 14 HPGe detectors. An example of ray-tracing simulations for γ -rays in the 100 keV – 1 MeV range and trajectories of the γ -rays impinging in the detectors is sketched in Fig. 2(b). For the evaluation of the background spectrum due to plasma self-emission, a density of $n=10^{13}\text{cm}^{-3}$ and a volume of 1500 cm^3 were considered. It was evaluated starting from measurements on existing traps and rescaling them to higher densities and volumes according to an emissivity model [19]. Starting from this spectrum it has been possible, once the total efficiency vs. γ -ray energy was determined by GEANT4 simulation, to evaluate the background-rate that would be measured by the PANDORA setup. Such a rate was compared to the rate of the γ -rays emitted from the daughter nuclei after the β -decay and detected in the array in order to determine the measurement time needed to reach a 3σ significance (see section 3.1).

3 Virtual experimental run for the physics case of the ^{134}Cs isotope

A subset of physical cases were chosen to start the study. The selection was based on the scientific relevance, on the expected effects on the lifetime due to CSD and on the maximum ionization state that can be reached by the trap design. Moreover, being the identification of the decay products based on the γ -ray detection, isotopes whose daughter nuclei emit γ -rays were chosen. The selection procedure has given as output three isotopes: the ^{176}Lu (which might play a crucial role as cosmo-clock), the ^{134}Cs (involved in s-processes and relevant for the production of the s-only isotopes ^{134}Ba and ^{136}Ba) and the ^{94}Nb (relevant for the abundance of ^{94}Mo in single or binary systems of stars). In this work we only focus on the ^{134}Cs case.

A scheme of the reaction branching at ^{134}Cs in s-process [5, 7] is shown in Fig.3. The s-process contribution to the Ba starts from neutron captures on the stable isotope ^{133}Cs and

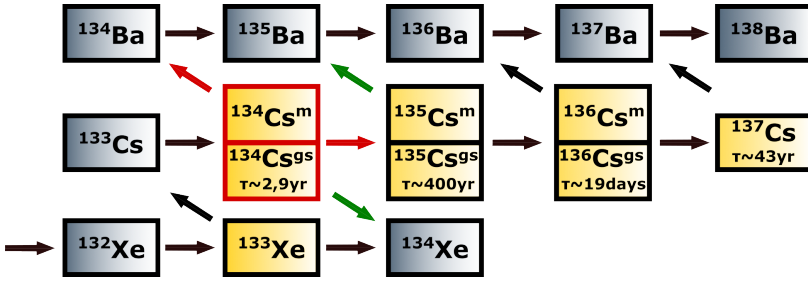


Figure 3. The s-process path through Cs and Ba isotopes. The stable isotopes are shown in grey boxes, the unstable ones in yellow boxes. The ^{134}Cs and ^{135}Cs branching points are highlighted by red arrows.

proceeds through a branching point (red squared) at the radioactive ^{134}Cs , where n-captures compete with β -decay (laboratory $\tau \sim 2.9$ yr) to excited states of ^{134}Ba and, much less effectively, with electron captures to ^{134}Xe . From ^{134}Cs , neutron captures feed the longer-lived ^{135}Cs and then ^{136}Cs and ^{137}Cs , which are sites of branching points for the s-process path.

According to theoretical predictions [1] the ^{134}Cs lifetime is reduced to 48 days at $T=3 \cdot 10^8 \text{ K}$, whilst the ^{137}Cs decay rates remain unchanged for varying temperatures. However the rate of ^{134}Cs decay estimated from [1] seems currently unsatisfactory [20], as it inhibits the proper reproduction of the two s-only isotopes ^{134}Ba , ^{136}Ba in suitable proportions. In particular, in [5] one needs to assume that the temperature dependence of the decay rate is less steep by around a factor of 8 (as modelled in [21]) to level the production of ^{134}Ba and ^{136}Ba .

Hence, in-plasma measurements could shed light on the role played by the ionization state affecting the β -decay and a simulated virtual experiment was carried out to assess the feasibility and sensitivity of the PANDORA setup and experimental approach to be adopted.

3.1 Results of a virtual experimental run for the ^{134}Cs physical case

In order to estimate the measurement time needed to reach 3σ significance taking into account different lifetimes, i.e. different rates in the detector array, a dedicated plot showing the total counts and the expected significance in function of the measurement time was made.

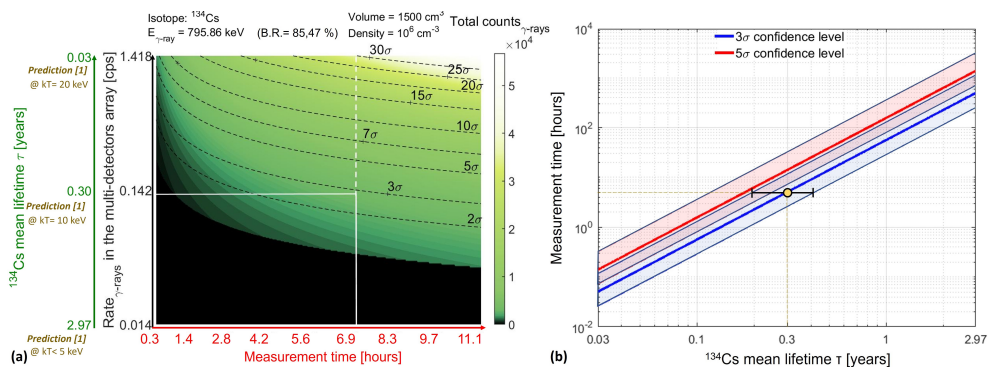


Figure 4. (a) Confidence levels that it is possible to obtain after a given t_{meas} , reported on the x axis, vs the decay-rate (or the lifetime) of ^{134}Cs . (b) - Iso-significance level at 3σ and 5σ reached after a given measurement time, reported on the y axis, versus the decay-rate (or the lifetime) of the ^{134}Cs isotope.

The results for the ^{134}Cs case are shown in Fig. 4(a). The green vertical axis reports on the lifetime expressed in years, starting from the mean lifetime of the neutral isotope (2.97 years) to the values of lifetimes predicted by the theory; the expected collapse of the lifetime [1] is about 2 orders of magnitude at electron plasma temperatures around 20 keV, about 1 order of magnitude at around 10 keV while no variations are expected for values lower than 5 keV. Considering the in-plasma activity (assuming an ellipsoidal plasma of 1500 cm^3 in volume with a relative concentration of $10^{-5}\%$ of ^{134}Cs with respect to the buffer gas plasma density) and taking into account the efficiency estimated by GEANT4 simulation, the counting rate expected in the γ detector array was obtained (black vertical axis). The x-axis indicates the measurement time. Pseudo-colors give the total number of counts at the γ peak of interest (at $E_\gamma=795.86\text{ keV}$). The error on the background was estimated as the square-root of counts in the same energy window, whilst the counts due to the real decays occurring in the plasma grow up linearly with time (see equation 1). The condition that the signal overcomes in 3σ the background level defines the measurement time needed to have a 3σ significance. Black dashed lines shown in the plot in Fig.4(a) represent iso-significance contours at each given combination of expected activity and t_{meas} . The black region is such that the significance is worse than 1σ . These simulations results indicate that a measurement of several hours is needed. The possibility to discriminate among different models will depend on the uncertainties in the measured λ values. The plot in Fig. 4(b) shows the iso-significance curves at 3σ (blue) and 5σ (red) in log-log scale with the corresponding uncertainties intervals. The in-plasma λ can be in fact estimated by equation 1 with an uncertainty of around 28% (considering errors propagation). The relative uncertainties for the parameters that will be measured are: $dN/N\sim 0.3\%$ (3σ significance measurement), $dV/V\sim 15\%$ (the error in estimating the radius is around 5% [15]) and $dn_i/n_i\sim 25\%$ (can be measured by the interfero-polarimetric tool [22] or by optical [23] and X-ray spectroscopy). New techniques of analysis are being developed to further reduce the afore mentioned uncertainties, improving the performances of the measurement.

4 Conclusion

PANDORA represents a promising experimental setup to verify the theoretical predictions on the dependence of β -decay lifetimes on plasma temperature. To evaluate the feasibility of the measurements, the run duration to get statistically meaningful results in terms of significance was estimated through GEANT4 simulations for the physical case of ^{134}Cs . It was demonstrated that PANDORA will have the adequate sensitivity to discriminate between different sets of theoretical predictions of the expected variation of the mean lifetime and to eventually better fit the data of nucleosynthesis which disagrees with the current decay rate predictions.

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