

FIPPS (Fission Product Prompt γ -ray Spectrometer) and its first experimental campaign

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Abstract. FIPPS is the new nuclear physics instrument of ILL for the spectroscopy of nuclei produced in neutron-induced reactions. The performance of the first implementation of the setup will be shown, together with an overview of the first experimental campaign (December 2016-March 2017). Future perspectives and physics opportunities will then be discussed.

1 Introduction

Thermal neutron capture γ -ray spectroscopy and prompt γ -ray spectroscopy of fission fragments are powerful tools to obtain detailed nuclear structure information for nuclides close to stability and medium mass neutron-rich isotopes. The extracted nuclear structure information can be used to test nuclear models, as well as for the extraction of quantities important for nuclear applications. The power of coupling a high-efficiency Ge-detector array with an intense pencil-like neutron beam provided by the ILL reactor, has been recently demonstrated by the success of the EXILL (EXogam at ILL) campaign [1–4]. This success led to the installation of a permanent setup at ILL, the new instrument FIPPS (Fission Product Prompt γ -ray Spectrometer). In its first phase, it consists of an halo-free pencil neutron beam incident on a target surrounded by an array of 8 Ge. This setup has been recently commissioned and it is presently being exploited for a variety of (n,γ) experiments.

In Sect. 2 the layout of the instrument will be presented with its different components, while in Sect. 3 the performance of the instrument, from a preliminary data analysis of first experiments, will be outlined. An overview of the first experimental campaign and the future perspectives will be given in Sect. 4 and Sect. 5 respectively.

2 Instrument layout

FIPPS consists in its first phase (operational since Dec. 2016) of an intense pencil-like thermal neutron beam and an array of HPGe clover detectors mounted symmetrically around the target position, as shown in Fig. 2. The instrument is located at the thermal neutron guide H22 in the neutron guide hall ILL7 and its layout is represented schematically in Fig. 1a. Slow-neutron-induced reactions on stable or radioactive, in particular actinide, targets are possible as well as the use of ancillary detectors.

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2.1 The neutron beam

The thermal neutron beam from the H22 guide ($7 \times 10^8 \text{ n cm}^{-2} \text{ s}^{-1}$, $d = 2 \text{ cm}$) is collimated to target position, as represented schematically in Fig. 1a. The collimation consists of a sequence of apertures made of natural boron carbide. At the exit of the apertures, 5 cm thick lead absorbers are placed in order to reduce the beam-related γ -ray background. Enriched ^6LiF is used on the aperture located closer to the detection system. The sequence of apertures is installed in a round vacuum tube, coated with 1 cm-thick borated plastics that are useful to absorb the scattered neutrons. The beam spot at the target position, as detected via a CCD camera viewing a ^6LiF coated ZnS screen, is shown in Fig. 1b. The thermal neutron flux is $1 \times 10^8 \text{ n cm}^{-2} \text{ s}^{-1}$ (measured via activation of a gold foil) with $\approx 1 \text{ cm}$ diameter.

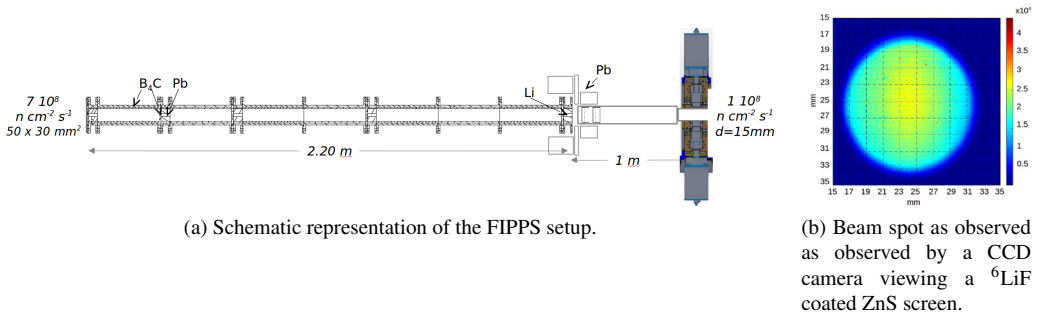


Figure 1: FIPPS setup and collimated neutron beam

2.2 The γ -ray detectors

The γ -ray detection system consists of HPGe clovers mounted symmetrically, at 90 degrees with respect to the beam direction, around target position (see Fig. 2). It consists of 8 HPGe clover detectors with crystal dimensions of 50mm diameter and 80 mm length before tapering, arranged in a compact configuration at 9 cm from the target position. The energy resolution of the array at 1.3 MeV (^{60}Co , 300 Hz count rate per crystal) is about 2 keV. The signals are processed with digital electronics (CAEN V1724 cards) with a sampling frequency of 100 MHz (10 ns time-stamping). The events are built (in a variable time window, typically 200 ns wide) from the data recorded in list-mode.

3 FIPPS performance

The FIPPS phase-I compact configuration was chosen in order to maximize the solid angle coverage and efficiency for multiple γ -ray coincidences after (n,γ) reactions. The symmetry around the target position is ideal for angular correlation and lifetime measurements using coincident γ -rays. The use of digital electronics allows high count rates on the HPGe crystals ($>10 \text{ kHz}$ per channel) while preserving good spectroscopic performance. Typical energy spectra (after applying add-back for the individual crystals inside a clover) are shown in Fig. 3, for ^{49}Ti and ^{210}Bi populated following (n,γ) reactions. A FWHM of 2.6 keV is obtained for the 1.38 MeV γ -ray produced in the $^{48}\text{Ti}(n,\gamma)^{49}\text{Ti}$ reaction ($\approx 7 \text{ kHz}$ count rate per crystal). The main source of background is the 478-keV γ ray that comes from $^{10}\text{B}(n,\gamma)$ reactions on the collimation system and its Compton background, that do not significantly influence the coincidence spectra. The γ -ray background shielding will be further improved for the next campaign.

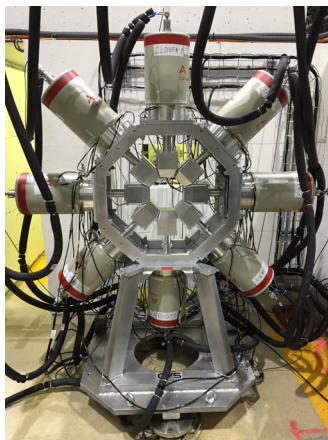


Figure 2: Arrangement of the 8 HPGe clovers of FIPPS phase 1 around the target position as used for the first FIPPS campaign. The different detectors are connected to the LN2 automatic filling system.

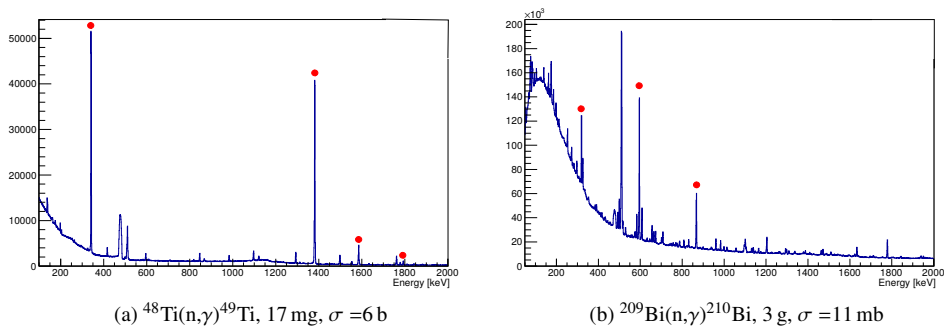


Figure 3: Examples of FIPPS spectra. Some of the main γ -ray lines belonging to the produced isotopes are labeled with red dots.

3.1 Efficiency

The absolute γ -ray efficiency of FIPPS phase I (from a preliminary data analysis) is 4% at 1.4 MeV. The efficiency curves obtained with a ^{152}Eu source (≈ 5 kHz per crystal) and from in-beam data (≈ 7 kHz per crystal) are reported in Fig. 4. The values extracted from the singles analysis are rescaled using the ones obtained from the γ - γ analysis of the ^{152}Eu source data (dead-time of about 10%) treating the data from the individual crystals, rather than in add-back mode. The add-back factors for the clovers found from a preliminary analysis are the following: 1.11 (2) @ 340 keV, 1.27 (3) @ 1.4 MeV and 1.55 (6) @ 6.8 MeV.

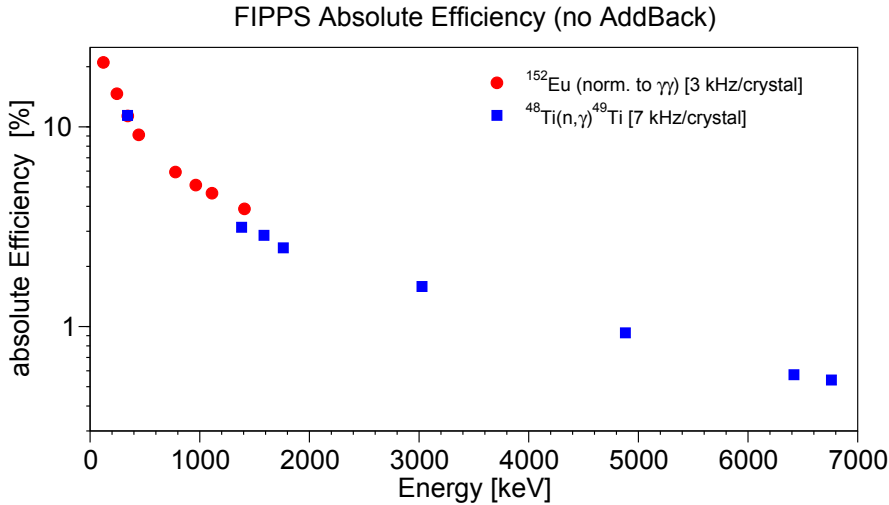


Figure 4: Efficiency curve obtained using a ^{152}Eu calibration source and from in-beam data from the $^{48}\text{Ti}(n,\gamma)^{49}\text{Ti}$ reaction, normalized to the efficiency extracted from $\gamma - \gamma$ coincidences in ^{152}Eu . Spectra obtained without using add-back treatment of the data have been used for this analysis. The discrepancy observed at ≈ 1.4 MeV between the two data sets is due to summing effects in the Ti data, not corrected in this analysis.

3.2 Angular correlation capabilities

The symmetry around the target position is ideal for the measurement of angular correlations of coincident γ -ray transitions. When using the single Ge crystals independently, those can be evaluated over 23 different angles, from 19 to 180 degrees. The angular correlation plot obtained for the $0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ (1293 keV, 463 keV) cascade in ^{116}Sn populated after (n,γ) reactions on ^{115}Sn is reported in Fig. 5 together with the result of the fit used for the extraction of the q-values. For this example $q_2 = 0.90(3)$ and $q_4 = 0.825(12)$ from a preliminary analysis.

4 The first experimental campaign at ILL

After the commissioning of the setup in December 2016, six different experiments were performed during the first experimental campaign (Dec. 2016, Jan-March 2017) by over 30 users from 11 universities and laboratories. The scientific aims were achieved by γ -ray spectroscopy studies after (n,γ) reactions on stable isotopes. 15 targets were used, in order to investigate nuclear phenomena such two hole excitations around the doubly magic ^{208}Pb (N. Cieplicka et al.), isovector quadrupole excitations in ^{146}Nd (T. Kröll et al.) and intruder 0^+ states in ^{124}Te (P. Garrett et al.). The first γ -ray coincidence spectrum obtained after about 40 min of neutron beam on a ^{205}Tl target is reported in Fig. 6. New spectroscopic information about the ^{206}Tl nucleus will be derived and compared with large-scale shell model calculations [5]. The possibility to analyze multiple γ -ray coincidences after (n,γ) reactions allows for complementary spectroscopic studies with respect to the ones already feasible at ILL with the GAMS spectrometer [6, 7]. In particular, the directional analysis of γ -ray cascades detected with

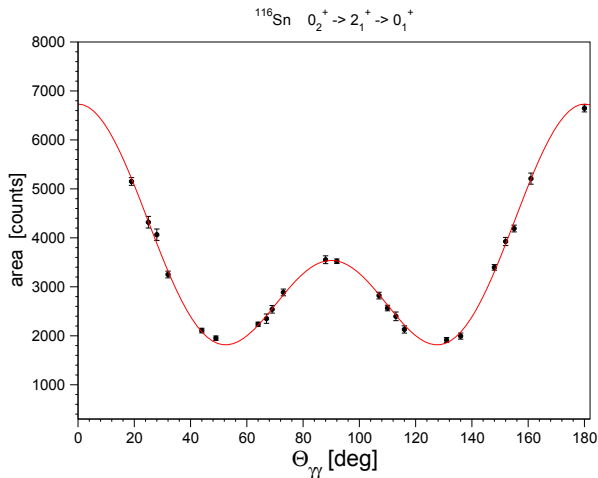


Figure 5: Angular correlation plot obtained for the $0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ (1293 keV, 463 keV) cascade in ^{116}Sn . The calculated a values are used to fit the q values (see text).

the good energy resolution of the FIPPS detectors gives access to the measurement of sub-picosecond lifetimes by means of the γ -ray induced Doppler Shift attenuation method, an extension of the GRID method used at GAMS (F. Crespi, M. Jentschel et al.) to a larger variety of targets.

5 Future perspectives

The next experimental campaign will be devoted to spectroscopy and fast-timing lifetime measurements after (n,γ) reactions on stable (rare) targets. A casemate serving for dynamic confinement of the atmosphere in the experimental zone as been installed for the use of radioactive and fissile targets. In 2018 also experiments employing the neutron-induced fission of $^{233,235}\text{U}$ targets are foreseen, including the use and the test of fission event tags (as active targets or diamond detectors sandwiched around the fission target). Using this fission tag information in anticoincidence enables clean (n,γ) spectroscopy of fissile actinides by removing the background of fission γ rays. Also other fissile targets, e.g. $^{239,241}\text{Pu}$, can be used. Moreover, the studies of (n,γ) reactions on gaseous and (long-lived) radioactive targets are possible. The progressive installation of additional Ge detectors (up to 16 clovers), anti-Compton shields and ancillary methods (LaBr₃:Ce detectors, magnetic fields for magnetic moment measurements, X-ray detectors...) is also foreseen.

5.1 FIPPS phase-II

In a second phase (foreseen to be operational in 4 years) the HPGe detection setup of the phase I will be complemented with a recoil spectrometer based on a gas-filled magnet (GFM, [8]). This will increase the sensitivity and selectivity for nuclear spectroscopy of fission products and enable fission studies of the correlation between kinetic energy, excitation energy and angular momentum. The possibility to perform γ -ray spectroscopy studies of mass-separated fission fragments will allow for complementary studies of the fission mechanism and structure of neutron-rich nuclei with respect

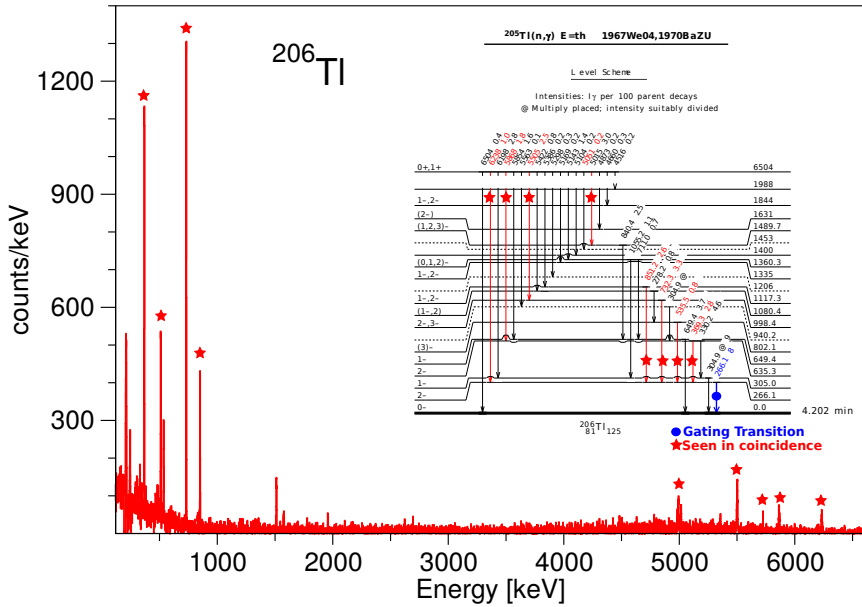


Figure 6: $^{205}\text{Tl}(n,\gamma)^{206}\text{Tl}$: the very first γ -ray coincidence spectrum gated on the 266 keV $2_1^- \rightarrow 0_1^-$ transition (≈ 40 min statistics, the identified transitions are marked with red star symbols, a detailed analysis is ongoing).

to the ones performed at the ILL instrument Lohengrin [9, 10] as already demonstrated during the EXILL campaign [11]. A mass resolution around 2% is expected with an acceptance of about 3% after tracking of the ions in the GFM. The proof of principle of the method has been given during a test measurement at Lohengrin [12] and the magnet is designed by LPSC Grenoble [13] to provide a magnetic field of ≈ 2 T with 1% precision.

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