HORIZON 2020

HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

Nuclear Fission and Radiation Protection 2018 (NFRP-2018-4)

Project acronym:	**SANDA**
Project full title:	**Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities**
Grant Agreement no.:	**H2020 Grant Agreement number: 847552**

Workpackages:	***WP1***
Identification N°:	***M.1.1***
Type of document:	***Milestones***
Title of milestone:	Completion of the simulation for the coupling of FALSTAFF and FIPPS at ILL
Dissemination Level:	***PU***
Reference:	
Status:	***Achieved***
Actual Delivery date:	08 October 2020
Comments:	

	Name	Partner	Date	Signature
Prepared by:	T. Materna & D. Doré	3	08-10-2020	
WP leader:	M. Kerveno	5	1-11-2020	
IP Co-ordinator:	E. González	1	1-12-2020	

SUPPLYING ACCURATE NUCLEAR DATA FOR ENERGY AND NON-ENERGY APPLICATIONS (SANDA)

WP 1 DEVELOPMENT OF NEW INNOVATIVE DETECTOR DEVICES.

MILESTONE 1.1

REPORT ON THE SIMULATION FOR THE COUPLING OF FALSTAFF AND FIPPS AT ILL

T. MATERNA AND D. DORÉ

SEPTEMBER 2020

INTRODUCTION

The main idea behind coupling one arm of the FALSTAFF fission fragment spectrometer with the gamma-ray spectrometer FIPPS installed at the research reactor of the ILL is the possibility of reaching a better sensitivity on the measurement of nuclear data related to the fission process.

In its current stage, the new gamma-ray spectrometer of the ILL, FIPPS (Fig.1), consists in a ring of eight HPGe clover detectors that can be arranged around a target placed at the end of a dedicated thermal neutron guide [Michelagnoli2017]. Studies on FIPPS concern nuclear data on neutron-rich nuclei close to the valley of stability obtained by neutron capture on stable or radioactive targets, or on fission fragments using fissile targets. In the last decade, our group at IRFU started to conduct research on the de-excitation of fission fragments via the study of their prompt gamma-rays with the spectrometer EXILL temporary installed at ILL [Materna2017, Rapala2018]. FIPPS brings new possibilities thanks to its better energy resolution and the use of active fissile targets. Active targets allow tagging on fission events and therefore rejecting the large part of the background produced by beta-decay of fission fragments [Kandzia2020]. We participated to recent long experimental campaigns on FIPPS with active targets made of ^{235}U and ^{233}U.

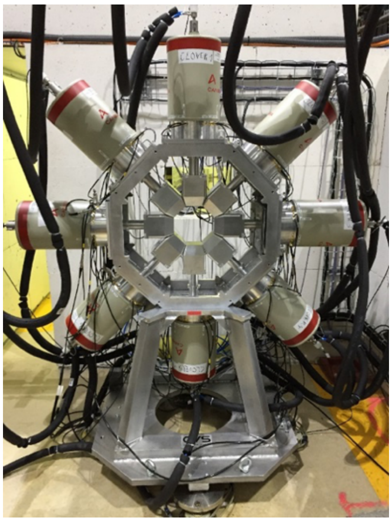
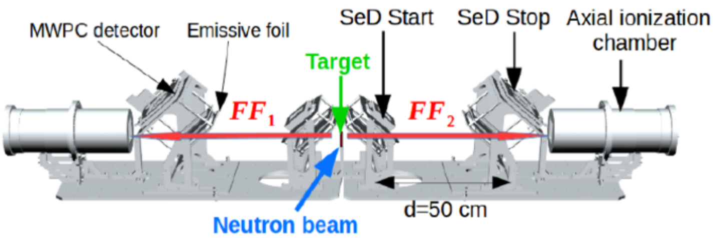


Fig. 1. FIPPS array of HPGe detectors.

The FALSTAFF project [Doré2014, Thulliez2017] aims to provide highly constraining data to improve significantly the description of the fission process. The goal is to determine the neutron multiplicity as a function of the fragment characteristics (mass and kinetic energy) in neutron-induced fission of specific actinides in the MeV range. In its final version, the FALSTAFF fission fragment spectrometer, developed at IRFU, is made of two arms that combine a time of flight device with a large ionization chamber (Fig 2a and 2b). The precise measurement of the velocity and energy of the two fission fragments emitted from a fissile target placed between the two arms will allow the determination of the fragment mass before and after neutron evaporation with a resolution (σ) of about 2%.



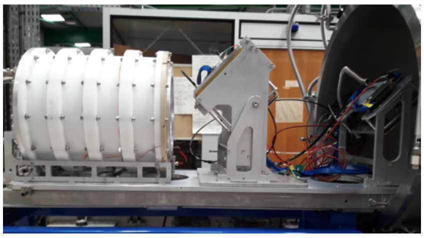


Fig. 2. (a) Sketch of Falstaff spectrometer and (b) Picture of one arm of FALSTAFF.

Our proposal is to couple one arm of the FALSTAFF spectrometer to FIPPS at ILL and to perform a long experimental campaign (a reactor cycle of 50 days) with a thin ^{235}U target (100 ug/cm^2). In this configuration, about 10^4 fissions/s would be produced in the target by a 1-cm-diameter neutron beam. For each event, one of the two fission fragments is stopped in the target or in the target backing. The other one can exit the target and eventually reach FALSTAFF to be identified in mass. Prompt gamma rays from both fragments are detected in FIPPS.

Two types of analysis are of interest. The first one consists in the precise calibration of FALSTAFF spectrometer with known (flying) fragments thanks to the identification of the stopped fragment from gamma rays belonging to its de-excitation cascade and detected in coincidence in FIPPS. The second one consists in the use of FALSTAFF for the identification of the flying fragment and in the analysis of de-excitation cascade in the stopped fragment. The use of FALSTAFF should e.g. allow more specific studies related to fragment deformations thanks to the measurement of the kinetic energy of the flying fragment.

In the current report, we will explain the simulation package that was implemented to assess the expected performances of such coupled setup and present some preliminary results.

SIMULATION SOFTWARE

Simulation of the FIPPS spectrometer

The simulation of the FIPPS spectrometer was implemented with GEANT4 and it is largely inspired from the simulation of the GRIFFIN detector [Svensson2013]. We adapted an existing GRIFFIN simulation package to match FIPPS geometry, which includes the internal structure of the clover detectors (e.g. HPGe crystal dimensions). Fig. 3 shows the simulated setup and a zoom on the internal structure of a clover. FIPPS simulated detection efficiency ranges from about 20% around 100 keV to about 4% around 1400 keV. In Fig. 4 the simulated and experimental efficiencies show a rather good agreement with a discrepancy of about 3% at high energy and about 10 % at low energy.

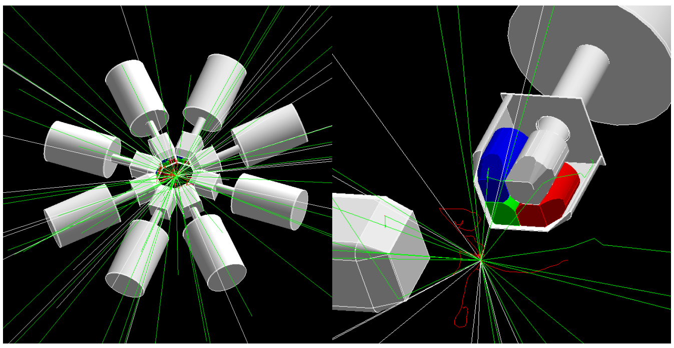


Fig. 3. Geant4 simulation geometry of FIPPS.

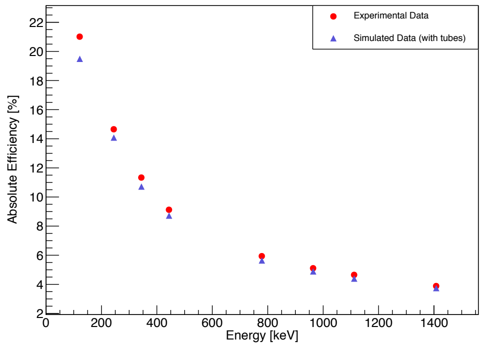


Fig. 4. FIPPS detection efficiency as a function of the gamma energy.

Simulation of FALSTAFF

GEANT4 is also used for the FALSTAFF setup simulations. The emissive foils of the TOFs detectors and the axial ionization chamber are implemented (Fig. 5). The geometrical efficiency is about 0.4% of 2π. For the results presented here, only one arm of FALSTAFF was simulated. Concerning the energy loss of the fragments in Mylar foils, tables with the EMZ prescription were used. The expected time, position and energy resolution are taken into account after the event tracking in the setup.

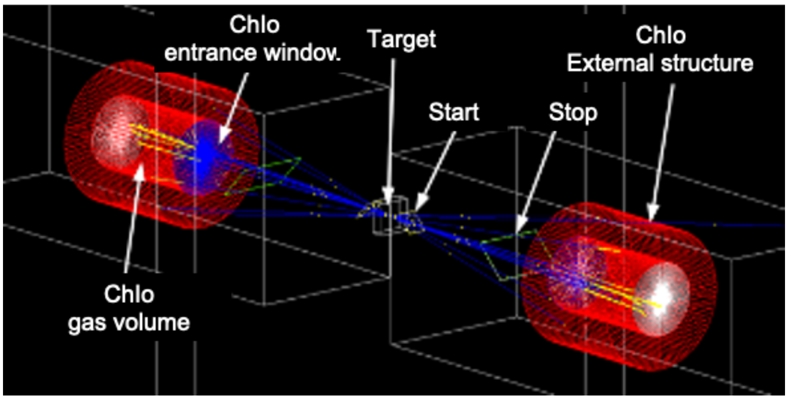


Fig. 5. Geant4 simulation geometry of two arms of FALSTAFF.

Simulation of fission events for FIPPS and FALSTAFF

The simulation of fission events and their de-excitation through the emission of neutrons and a cascade gamma-rays is performed by the Monte Carlo code FIFRELIN [Litaize2010]. It was shown that the standard version of FIFRELIN better reproduces neutron observables than gamma-ray ones [Loic2019, Rapala2018]. Despite that fact, we decided to run the standard version in order to reproduce the correct fission yields. Around 20 million fission events on the **^{235}U(n_{th},f) reaction** were generated with FIFRELIN.

Beta-decay of fission fragments, which generates delayed gamma rays, are not taken into account, neither the prompt gamma rays background produced by neutron capture on the setup material.

A 50-day experimental campaign with 10^4 fissions/s rate corresponds to more than 4×10^{10} fissions in total and such amount of fission events cannot be generated with FIFRELIN in a realistic time. On the other hand, 20×10^6 fission events correspond to 2000 sec of beam time and is too short to have a proper estimation of the results. Some biases are possible considering the geometry of the spectrometers. An important bias is that we only generate fission events with a fragment that can reach FALSTAFF. Here we limit the direction of the flying fragments to a cone of 5°, thus restricting the solid angle to about 0.38 % of π. This operation is done in a post-generation phase, where we regenerate the directions of the fragments and of all the gamma-rays provided by FIFRELIN. The initial 20×10^6 fission events cover in that a way about 146 hours of beam time. The 50-day campaign can thus be simulated by reprocessing 8 times the same FIFRELIN fission events.

Relativistic Doppler effects are implemented in the post-generation phase. It modifies the energy and direction changes of gamma-rays emitted by the flying fragments. Taking into account this effect is critical in the simulation because Doppler broadening is much larger than the energy resolution of the detectors.

Coupled Simulation of FIPPS and FALSTAFF

To speed up the design phase, we decided to couple FIPPS and FALSTAFF simulation results instead of constructing a simulation geometry with both spectrometers. Therefore, FIPPS simulations are run with, in input, a list of gamma-rays in coincidence, produced in the above-mentioned post-generation phase. FALSTAFF simulations are run with the corresponding (flying) fission fragments. The results - ROOT trees - are mixed in a post-processing phase. The scheme of the process is present in Fig. 6.

A drawback of this strategy is that we do not really follow in GEANT4 the flying fragments while they emit gamma rays. The gamma-ray emission position is calculated in the post-generation phase, from the expected position of the fragment, knowing its initial speed and direction, and from the gamma-ray emission time. The speed of fission fragments is around 1 cm/ns. Most of the prompt-gamma rays are thus emitted very close to the target, much before the fragment could reach the beam tube or FALSTAFF. This approximation is therefore acceptable in most cases, except for gamma-ray transitions from isomeric states (ns-isomers or longer) in flying fragments. In that rare cases, the calculated gamma-ray emission positions may not be valid because the fragments could have been stopped in the beam tube or in FALSTAFF at the emission time.

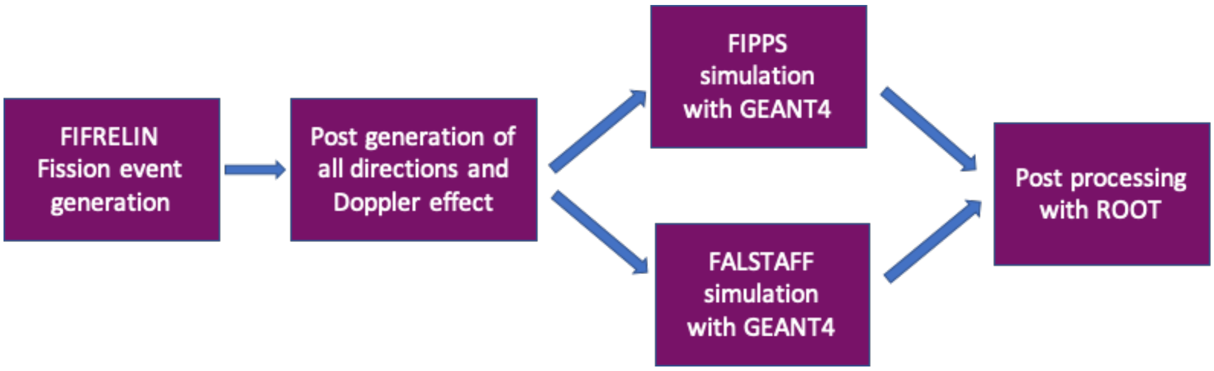


Fig. 6. Scheme of the GEANT simulations.

SIMULATION RESULTS

FIFRELIN and FIPPS results

In Fig. 7-10 some results from FIFRELIN are displayed. Fig. 7 shows the mass distribution of fission fragments after neutron evaporation. Fig. 8 shows the gamma-ray multiplicity (distribution of the number of gamma rays per fission event). Fig. 9 shows the generated fission prompt gamma-ray energy spectrum. Fig. 10 shows the observed spectrum in the clover detectors (in addback mode) according to the GEANT4 simulation of FIPPS. In that last case, the energy resolution of the HPGe detectors is taken in account in the simulation by blurring the energy of the detected gamma-ray with the expected (experimental) detector resolution at that energy. The impact of the energy resolution and of the detection efficiency is clearly visible.

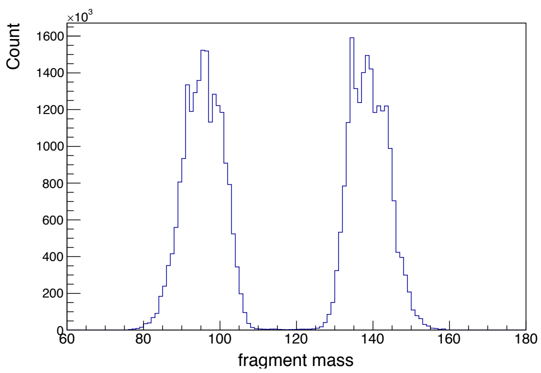


Fig. 7. Post evaporation mass.

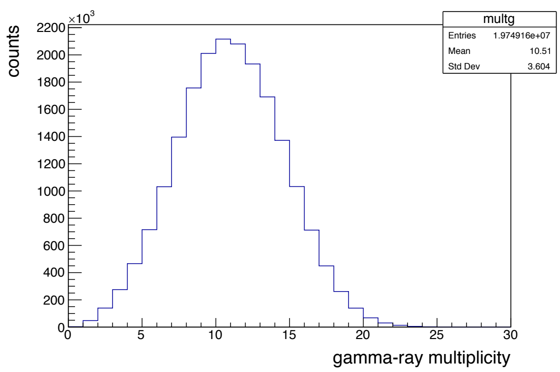


Fig. 8. Gamma-ray multiplicity.

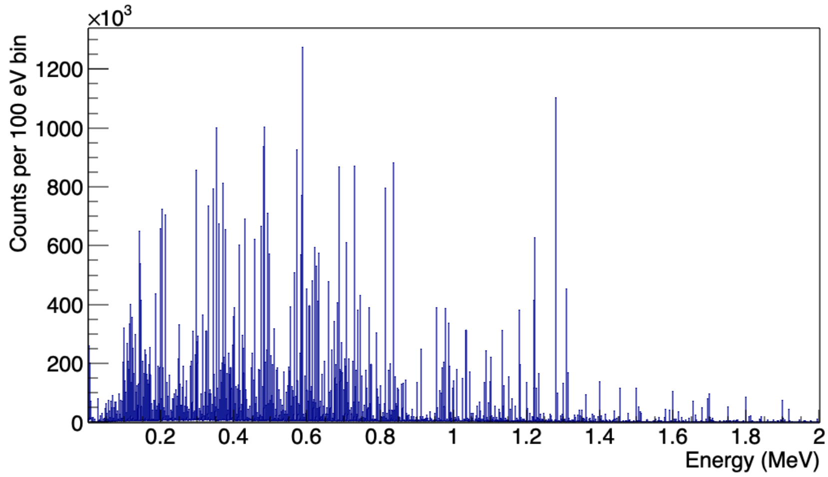


Fig. 9. Generated gamma-ray spectrum according to FIFRELIN.

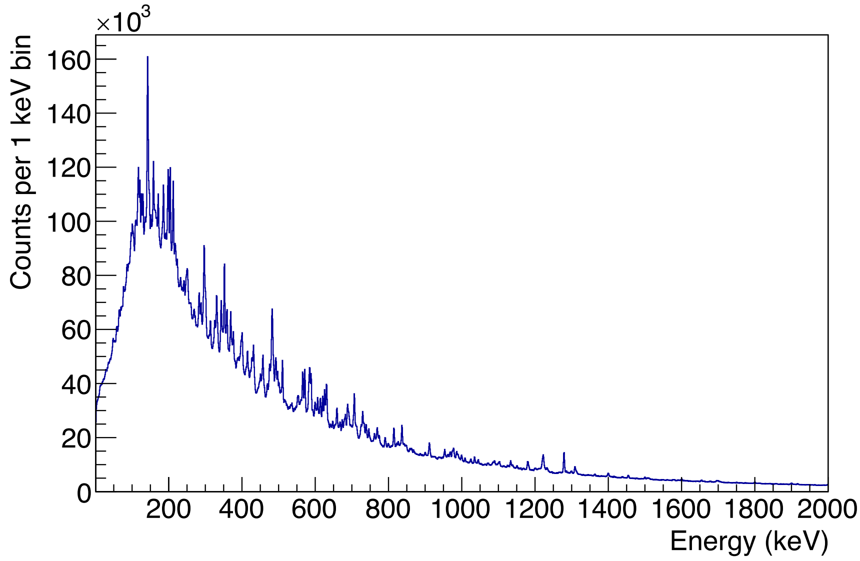


Fig. 10. Observed gamma-ray spectrum in the clover detectors according to the simulation of FIPPS.

FALSTAFF calibration

We evaluated the possibility of calibrating FALSTAFF at ILL with FIPPS using the gamma-ray transition at 204.2-keV from the isomeric state in ^{98}Y (see Fig. 11). ^{98}Y is well populated in the thermal fission of ^{235}U. Its fission yield is about 2.5%. The decay of the 35.8-ns isomeric state can be easily isolated from the prompt gamma-rays by choosing a delayed coincidence time window of (5-100) μs after the fission timestamp. A major advantage is that according to FIFRELIN there is no other light fragments emitting a prompt gamma ray in the region around 204 keV within this time window. Still according to Fifrelin, the associated (post neutron-evaporation) heavy fragments are the isotopes of Iodin displayed on Fig. 12.

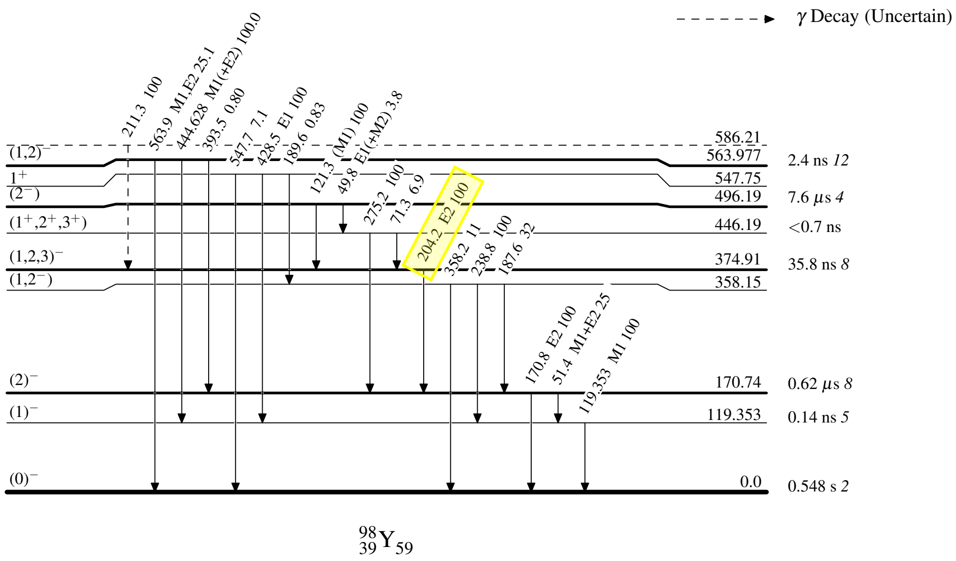


Fig. 11. Partial level scheme of ^{98}Y.

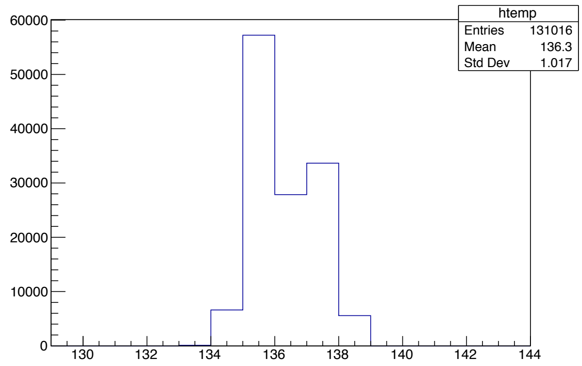


Fig. 12. Heavy fragments associated with the same selection cut (emission of a gamma-ray within (201-207) keV by the light fragment in the delayed time window (5-100) µs.

This case was analyzed with the simulations of FIPPS and FALSTAFF. The spectrum of gamma rays detected in delayed coincidence in FIPPS detectors is shown in Fig. 13. The gamma-ray transition at 204.2 keV is strong but the background below the peak brings some parasitic light fragments in the selection (see Fig. 14).

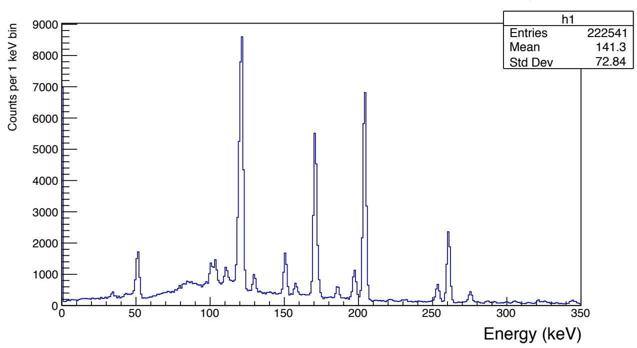


Fig. 13. Energy spectrum observed in the clover detectors of FIPPS when a delayed coincidence is applied with a time window of (5-100) µs.

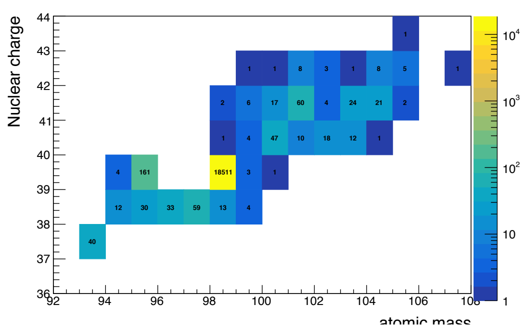


Fig. 14. Light fragments associated which a gamma-ray **detected** in FIPPS within the energy range (201-207) keV and within the delayed window (5-100) µs.

The associated composition of the flying fragment beam is displayed on Fig. 15. The beam is mainly composed of Iodin isotopes. The simulation of FALSTAFF response is displayed on Fig. 16. The distribution is Gaussian with sigma = 2.08, which is rather close to the expected FALSTAFF resolution for a pure beam of ^{136}I (sigma = 1.8). The displayed statistic is for about 6 days of beam time. Additional studies would be needed to estimate whether gamma-ray background (e.g. from beta-decay) may be a problem.

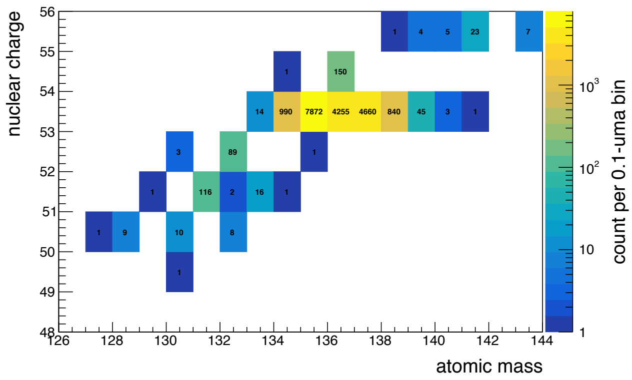


Fig. 15. Associated heavy fragment with the same selection condition as explained in Fig 14.

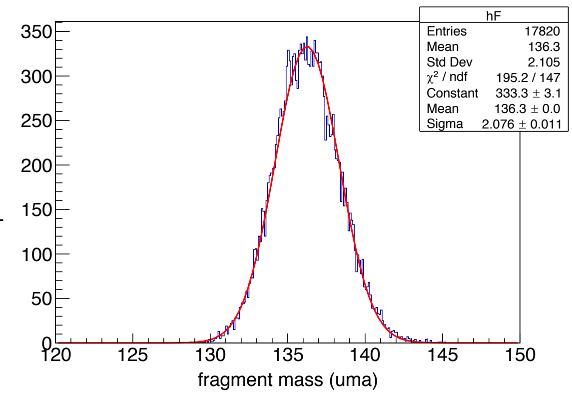


Fig. 16. Mass distribution detected in FALSTAFF (heavy fragment part) when the selection is done as explained in Fig 14.

Spectrometric results with FALSTAFF and FIPPS

The use of FALSTAFF as a selection filter for spectroscopic studies has been tested on the ^{142}Ba - ^{92}Kr fission fragment couple, which is well produced in the thermal fission of ^{235}U. A selection centered on mass 92 for the fragment detected in FALSTAFF was applied. The gamma-ray spectrum detected in FIPPS is displayed on the top part of Fig17. In addition, a second selection was applied on coincident events that contain a gamma-ray with an energy close to the $2^+ \rightarrow 0^+$ transition in ^{142}Ba (at 359.6 keV). The result is plotted on the bottom part of Fig. 17. The other main transitions in ^{142}Ba ($4^+ \rightarrow 2^+$ at 475.2 keV, $6^+ \rightarrow 4^+$ at 631.2 keV and $8^+ \rightarrow 6^+$ at 693.4 keV) are clearly visible. Although encouraging, this result shows that this configuration does not perform very well, statistically speaking, compared to FIPPS alone. The displayed statistic on Fig. 17 is for about 50-days of beam time.

Fig. 18 shows a similar analysis but on the simulation of FIPPS alone with an active target. The analysis consists in the selection of events in coincidence with the main transition to the ground state in ^{92}Kr (gamma-ray at 769 keV). The result is plotted on the upper part of Fig. 18. A second selection is then done on the transition at 359.6 keV in ^{142}Ba. The result is shown on the bottom part of Fig. 18. The displayed statistic is for about 5.5 hours of beam time. The same main three peaks of ^{142}Ba are visible on the last spectrum. Their intensity is roughly 10 times lower but with a 200 shorter beam time. This relative factor of about 20 between the two configurations can be explained from the lower efficiency of FALSTAFF (about 0.3%) compared to FIPPS (about 6% at 800 keV). Similar results are obtained for other couples of even-A even-Z nuclei, which possess a rather simple level scheme and for which de-excitation populates the ground state band mainly. In that cases, the configuration with FALSTAFF does not seem to improve the performance of FIPPS. Additional studies should be performed to evaluate such configurations for even-odd and odd-odd nuclei.

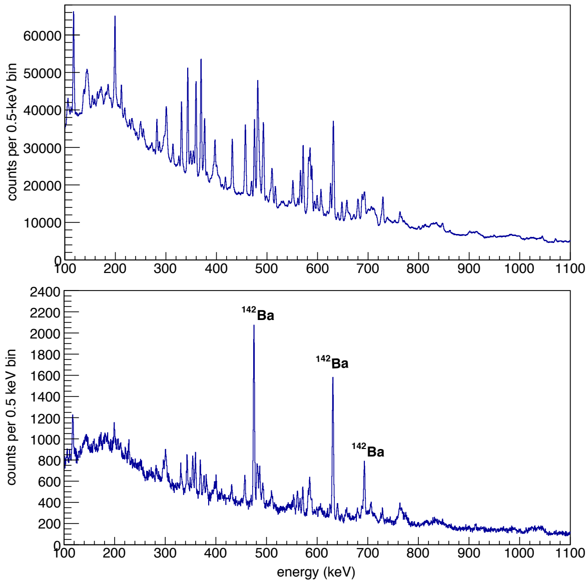


Fig. 17. (Up) Spectrum of gamma rays in coincidence with flying fragments detected in FALSTAFF with atomic mass in [90,94]. Displayed statistics corresponds to about 50 days of beam time. (Bottom) Spectrum of gamma rays in coincidence with flying fragments detected in FALSTAFF with atomic mass in [90,94] and with the transition at 359.5 keV in ^{142}Ba.

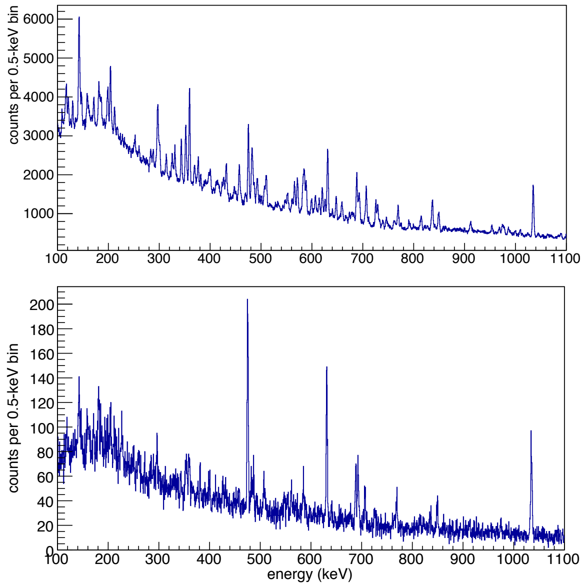


Fig. 18. (Up) Spectrum of gamma rays in coincidence with the transition at 769 keV in ^{92}Kr. (Bottom) Spectrum of gamma rays in coincidence with the transition at 769 keV in ^{92}Kr and with the transition at 359.5 keV in ^{142}Ba.

CONCLUSION

The results presented here are encouraging. The combined simulation of FALSTAFF and FIPPS allowed us to prove the feasibility of calibrating FALSTAFF with the detection of delayed gamma rays in FIPPS. The same method could be applied with a ^{252}Cf source. Then it is foreseen to install a HPGe detector close to the ^{252}Cf source on the FALSTAFF setup at Saclay.

On the other hand, coupling FIPPS with FALSTAFF was found to be less efficient than FIPPS alone (with an active target) for a systematic study of the de-excitation of fission fragments, at least for even A-even Z nuclei. To go further one could look in details the cases of even-odd and odd-odd. It could also be interesting to use the fragment kinetic energy information in the study of de-excitation of fission fragments.

A long shutdown (~1 year) at ILL has been foreseen for some years. This shutdown has been postponed many times and now the slot for the experiment will be in coincidence with other experiments with FALSTAFF. In addition, the limited free space in the FIPPS casemate makes difficult the installation of FALSTAFF. The move of FIPPS in another casemate is foreseen but the planning is not known. For all these reasons we prefer to put this experiment on hold. We will replace our contribution to SANDA by another one, closely related. It has to be defined soon with the workpackage leaders.

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