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Recent developments of the FALSTAFF experimental setup

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Abstract. The study of nuclear fission is encountering renewed interest with the development of GEN-IV reactor concepts, mostly working in the neutron fast energy domain. To support the fast reactor technologies, new high quality nuclear data are needed. New facilities are being constructed to produce high intensity neutron beams from hundreds of keV to few tens of MeV (Licorne, NFS, nELBE, ...). They will open new opportunities to provide nuclear data. In this framework the development of an experimental setup called FALSTAFF for a characterisation of actinide fission fragments has been undertaken. Fission fragment yields and associated neutron multiplicities will be measured as a function of the neutron energy. Based on time-of-flight and residual energy technique, the setup will allow the simultaneous measurement of the complementary fragment velocity and energy. The FALSTAFF setup and the upgrade of the first arm prototype with the new ionisation chamber CALIBER will be presented. The performances of the experimental apparatus is discussed.

1 Introduction

Fission is a highly complex process and despite the remarkable achievements realised, after more than 70 years from the fission discovery, many questions remain still opened. In fact to this day there are no models that can reliably predict the properties of fragments for various compound systems and excitation energies. The systematic study in the actinide region of the fission fragment kinetic energy, mass and charge for neutron-induced fission over a wide incident neutron energy range can drive the theoretical modelling and provide data for model validation.
A new instrument called FALSTAFF is under development with the purpose to study neutron-induced fission at different excitation energy in order to provide high precision measurements of the fission fragment properties. These measurements are necessary not only for the development of models used in the evaluation of nuclear data, but also for the important implications in the fundamental understanding of the fission process. In fact this device will give access to the simultaneous measurement of pre and post neutron fragment properties, allowing the study of the shared excitation energy between the two fragments. In particular, the evolution of fission properties and neutron

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multiplicity may be studied as a function of the available excitation energy.

2 FALSTAFF experimental apparatus

The FALSTAFF [1, 2] instrument consists of two detector arms each containing two timing detectors with a position sensitive readout and an energy detector. Fig. 1 shows the schematic representation of the two-arms FALSTAFF spectrometer. As presented in the figure the source or target material is placed between the 2 arms. During the measurement operation the arms are kept under vacuum at a pressure of 10^{-5} mbar.

The mass before neutron evaporation A^* is determined via the 2V method [3]. Experimentally the

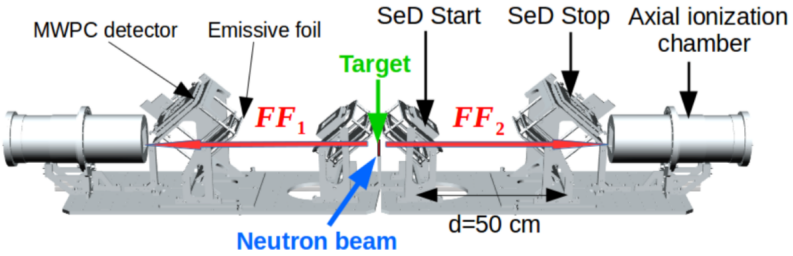

Figure 1. Schematic representation of the two-arms FALSTAFF spectrometer. Each arm is made of two TOF Secondary Electron Detectors (SeD), as two timing position sensitive detectors, and one axial ionisation chamber as the residual fission fragment energy detector.

direct measurement of the time-of-flight (TOF) is performed to obtain the fission fragment velocities. In reality the velocities of the primary fragments, v^*, cannot be measured. However, if one assumes the momentum conservation principle, the mean of the fragment velocity distribution is not affected by the evaporation process [4, 5], thus $v*=\langle v\rangle$. It is then possible to directly apply momentum conservation to calculate the pre-neutron mass $A^*_{1,2}$ of both fragments:

$$A^*_1 = \frac{v_2 A_{CN}}{(v_1 + v_2)} \tag{1}$$

$$A^*_2 = A_{CN} - A_1 \tag{2}$$

where A_{CN} is the mass of the fissioning system.

This approximation is valid as long as the neutron emission is backward/forward symmetric, this means that no scission neutrons are emitted, and the excitation energy of the fissioning system remains below the neutron-emission threshold.

The mass identification after neutron evaporation $A_{1,2}$ is obtained, via the 2EV [3] method, by measuring the fission fragment energies $E_{1,2}$, and velocities $v_{1,2}$. With this method the mass is calculated as

$$A_{1,2} = \frac{2E_{1,2}}{v^2_{1,2}} \tag{3}$$

Moreover from the pre-neutron and post-neutron mass, it is possible to calculate the average number of neutrons emitted by each fragment by computing event by event the difference between the pre-neutron and post-neutron mass. The prompt neutron multiplicity can then be investigated as a function of fragment mass and kinetic energy, which is related to the excitation energy sharing between the fission fragments. The velocity determination and the kinetic energy measurement from the Eqs. 1 and 3 are the crucial points in this development and therefore great care has to be devoted to the measurement of these quantities. In fact these observables are degraded by the passage of fragments in the various materials as the target thickness, the target support, the TOF detectors and finally the ionisation chamber entrance window. Thus it is important to correct the energy of the fragments of their losses to retrace their initial energy. This feature makes the FALSTAFF goal very challenging to reach. For this reason the technological aim is to reduce the thickness of material layers as much as possible and to measure the ion positions at a millimeter level accuracy on the different layers in order to calculate the crossed thickness and then to apply reliable energy loss corrections. FALSTAFF has to ensure also a time resolution of about one hundred ps and an energy resolution of 1%. These specificities allow an average post-neutron mass yield resolution ∼1.7 amu for the light fission fragment.

The following sections describe each detector and their performances in detail.

3 SeD detectors

The TOF detectors consist in two Secondary Electron Detectors (SeD) [6, 7] separated by 50 cm. These detectors are specially conceived to reduce the interaction between the fragments and the detector material as much as possible and, at the same time, to be able to track the trajectory of the incoming particle. This purpose is achieved by assembling an emissive foil and a multi-wire proportional counter (MWPCs). The emissive foil consisted of a 0.5 μm thick, aluminised Mylar foil polarised to -10 kV. When a fragment crosses the Mylar foil, the interaction leads to the emission of electrons that are accelerated by the electric field up to the MWPC detector. The electron cloud arrives with a mean energy of about 10 keV and ionises the gas inside. The detector is filled with pure isobutane at a pressure of about 5 torr. The isobutane was chosen for its low ionisation energy and high quenching power at low pressures [7]. The ionisation electrons are then multiplied by the avalanche process in the gas and gathered on the anode.
These detectors allow to cover a large area without degrading the time and spatial resolution, which have been measured to be $\sigma_t \sim 120$ ps and $\sigma_X \sim 1$ mm, respectively[7].

3.1 Emissive foil thickness measurement

To correctly identify the fission fragments, a complete knowledge of the material thickness is needed. To reduce the thickness uncertainty given by the manufacturer, a device to measure the mylar foil effective thickness has been developed. These measurements are based on the α-transmission technique that consists in the measurement of the α energy loss through the foil. The measured energy loss is then converted in the foil thickness with the help of the energy loss/thickness table obtained from the SRIM software [8]. To realise these measurements our device has two moving arms to ensure the relative translation on the Y-axis of an ^{241}Am source fixed on one of them with respect to a PIPS Silicon detector mounted on the other arm. Between the source and the Silicon detector a mylar foil is arranged on a moving board that ensure the scan on the foil on the X-axis. The scan of a 14x22 cm^2

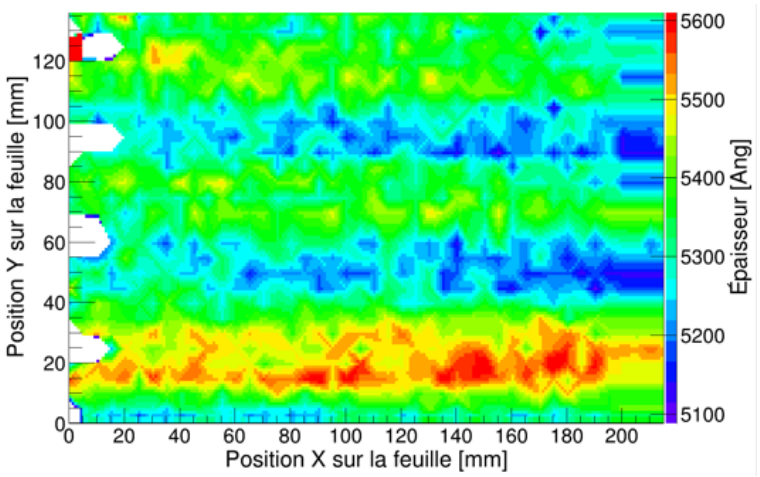

Figure 2. The thickness profile of a mylar emissive foil obtained with the α-transmission technique. The colour differences depend on the way in which the mylar foil is stretched on the frame.

mylar foil of Fig. 2 allows to infer the true average thickness of 0.53 μm [2] that differs from the one (0.50 μm), indicated by the manufacturer. Nevertheless this apparently small difference in the foil thickness has a strong effect on the average neutron multiplicity shown in Fig. 3. As expected the influence of a wrong thickness on the neutron multiplicity is huge (of about 1 neutron) for the heavy fragment.
In this study it was also pointed out that thickness inhomogeneities have no significant impact on the average neutron multiplicity, and then only the average thickness is needed.

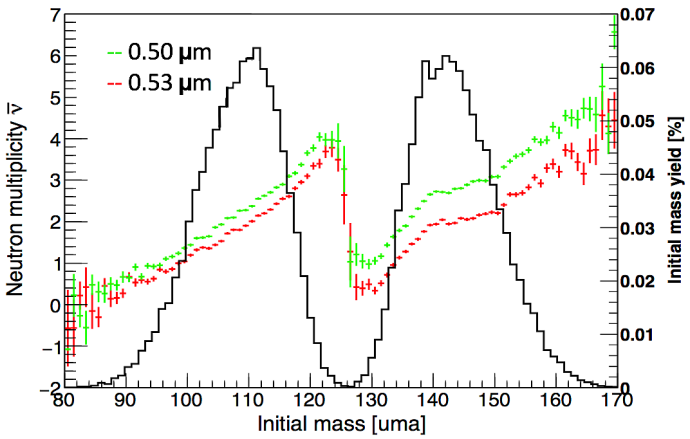

Figure 3. The neutron multiplicity as a function of the initial fission fragment mass obtained in case of an average thickness of 0.53 μm (red dots). In green the curve obtained with a thickness of 0.50 μm [2]. In black the fission fragments mass distribution is shown.

4 Ionisation Chamber

CALIBER, shown in Fig. 4, is a cylindrical axial ionisation chamber with an effective diameter of 440 mm and a length of 400 mm. The cathode represents the detector entrance window separated to

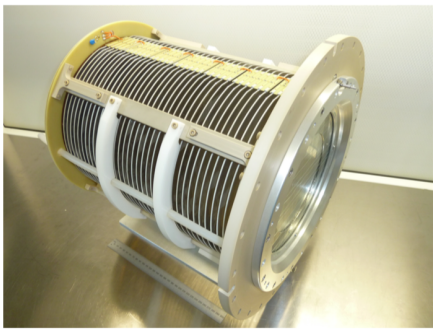

Figure 4. CALIBER the axial ionisation chamber: the 38 aluminum rings interconnected by 10 MΩ resistance that ensure the uniformity of the electric field are sketched.

the anode by a distance of 395 mm. A negative potential of ~8kV is applied to the cathode while the readout electrode is the grounded anode. The entrance window is a Mylar foil 0.9 μm thick with a diameter of 232 mm. To polarise the Mylar foil and to ensure a good conductivity, 50 nm of aluminum are deposited on each side.
In order to avoid strong mechanical tension, the entrance window is maintained by a grid of 12 nylon wires, 6 vertical and 6 horizontal. These wires have a diameter of 350 μm.
The electric field uniformity is assured by 38 aluminum rings, 270 mm in diameter, spaced out by 10 mm and interconnected by a 10 MΩ resistance allowing to maintain an uniform field along the chamber.
A Frisch grid is installed in front of the anode to ensure the shielding of the anode from the influence of the moving charges in the ionisation region. An electronic signal is induced to the anode only once the electrons have crossed the grid. The Frisch grid is made up of 68 brass wires, 170 μm in diameter and spaced out by 4 mm. Also in this case the ionising gas is the isobutane at a pressure between 20 and 30 Torr with a flow of 1.5 L/h.

4.1 CALIBER performances

The detector performances were tested with a 5 mm collimated ^{241}Am α-source mounted few centimeters far from the chamber entrance window. The collimator and the thickness of the window foil play an important role for the resolution of the detector. The detector was filled with 40 mbar of isobutane gas in order to stop the α in the chamber volume. The output of the detector was fed to a charge sensitive preamplifier (Amptek A 250) and to a spectroscopy amplifier (ORTEC 672) and finally to a ADC V785N card. A gaussian shaping for optimum signal-to-noise ratio was used and the optimum amplifier shaping time was found to be 6 μs. Fig. 5 shows the acquired energy spectrum of 5.48 MeV α particle from a collimated ^{241}Am α-source of 23100 Bq activity. The centroid of the data was obtained by fitting the acquired spectrum and the width of the α-peak are used to determine the resolution. The estimated resolution is about 1.8% FWHM. The degradation of energy due to the

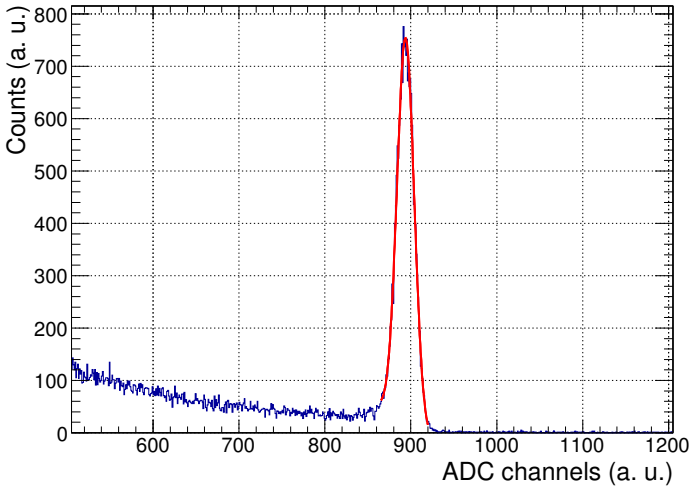

Figure 5. The energy-loss spectrum of ^{241}Am α-particle. The detector energy resolution is 1.8% FWHM taking into account the straggling due to the 0.9 μm mylar entrance window.

straggling of the 9 μm mylar foil is taken into account.

The performances of the detector for heavy ions were studied by recording the energy-loss spectrum of the spontaneous fission fragments from a collimated ^{252}Cf source. The acquired spectrum is displayed in Fig. 6.

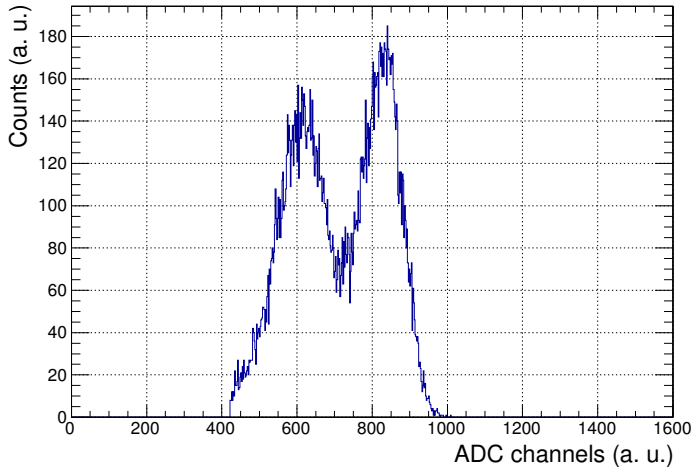

Figure 6. The energy spectrum of spontaneous fission fragments from ^{252}Cf source measured with CALIBER axial ionisation chamber.

The light (on the right) and heavy fragments (on the left) are observed to be reasonably separated. The optimum configuration is at a gas pressure of 28 mbar. The ^{252}Cf source is mounted on a 6 mm collimator to reduce the edge effects. The ^{252}Cf fission spectrum parameters, as NL, NH and NV that are respectively the numbers of counts per channel at the peaks of the light and the heavy-fragment groups and at the minimum in the valley, are described for a semiconductor detector in [10]. The spectrum parameters considered to be indicative of detector performance are the peak to valley ratio for light and heavy fragments quoted greater than 2.80 and of about 2.2 respectively. These parameters are evaluated for the present detector and depicted in Table 1. In the present case they are thus within reasonable limit.

Parameter	ref [9]	ref [10]	This work
NL/NV	2.74	2.90	2.82
NH/NV	2.10	2.20	2.14
NL/NH	1.31	1.30	1.32

Table 1. Parameters of the ^{252}Cf fission fragment spectrum. The definition of the different parameters are the same as in ref [10]

5 Conclusion

To study neutron-induced fission for fissile isotopes in the fast neutron energy range, the FALSTAFF spectrometer is under development at CEA-Saclay. The challenge of the FALSTAFF development is to take into account correctly the fission fragment energy losses in the detector materials for the correct mass and charge identification. The present study shows the non-negligeable impact of the thickness uncertainty given by the manufacturer on the neutron multiplicity. In this work we have also performed a preliminary characterisation of the CALIBER axial ionisation chamber. The results show that the detector performance is in agreement with prediction. The next step is to calibrate the ionisation chamber and explore the possibility to obtain the nuclear charge Z from the energy loss profile with monoenergetic beams of ^{79}Br, ^{81}Br and ^{127}I.
To optimise the performances of the chamber a new μMesh Frisch grid was developed and other tests have been undertaken to study the Frish grid transparency to the electron cloud. To improve the chamber resolution, we are also studying the effect of the electric field ratio between the drift and the induction region.
Finally an experiment for the characterisation of the first FALSTAFF arm is planned at the end of the 2017 with a ^{235}U target and a thermal neutron beam.

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