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Introduction

We present in this report the achievement of the SCONE setup at the Neutron For Science (NFS) facility at GANIL. The goal is to measure (n,xn) reaction cross sections on actinides, and in the same experiment to obtain new data on fast-neutron-induced fission (prompt neutron multiplicity distributions and prompt γ-ray calorimetry). This setup has several specificities that will be developed in this document. We also present preliminary results on both type of reactions (n,xn) and neutron induced fission, from the analysis of the first test experiment performed in November 2021 on uranium 238.

SCONE Setup

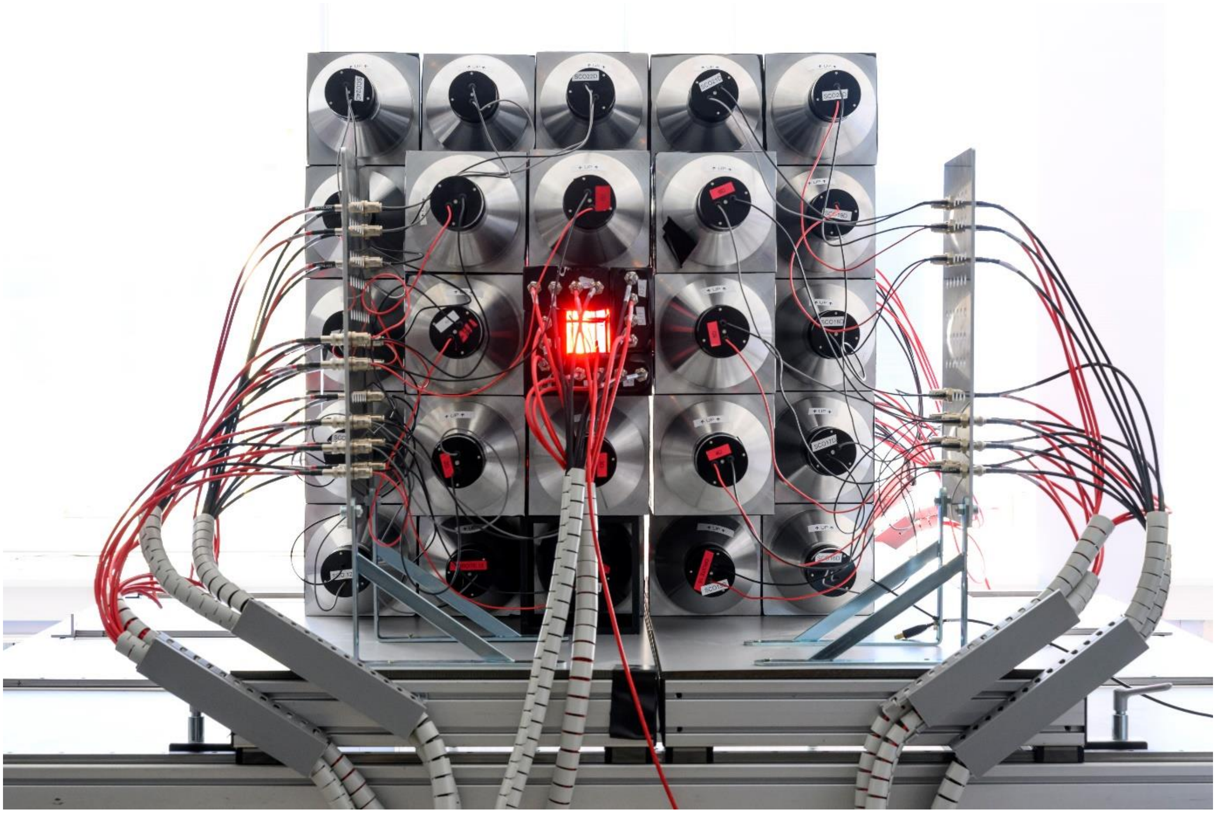

Figure 1 Picture of the SCONE detector.

The SCONE setup is composed of three detectors:

1. The SCONE (Solid Counter for Neutron) detector itself
2. An active fission chamber
3. An internal BGO array

The SCONE detector is a long-counter similar to those invented for the study of neutrinos [i]. In such detectors, neutrons are detected twice: they are first detected on the nanosecond time scale, like this is the case in common neutron detector, but they are subsequently individually counted through delayed capture events in the detector itself. This second step, that happens on the tens of microseconds scale, is possible because the long-counter are large volume detectors loaded with a high neutron capture cross section isotope (most of the time this is natural Gd which has an averaged cross section of 48890 barns). The fast neutrons are thus slowed down, and then thermalized before being captured. Very high detection efficiency are obtained (about 77 %) together with very high counting efficiencies (typically 70 % for prompt fission neutrons). SCONE is composed of 928 scintillating plastic bars, which are 25x25 mm large, and with lengths ranging from 0.4 to 1 m. Figure 1 presents a picture of the SCONE detector, where its structure is seen: the scintillating bars are assembled in groups of 36 bars. Height of these assemblies compose a first ring, while other 16 assemblies forms a second outer ring. Eight small assemblies (8 bars each) are designated as central assemblies, and allows to have a beam entrance/exit in the setup.

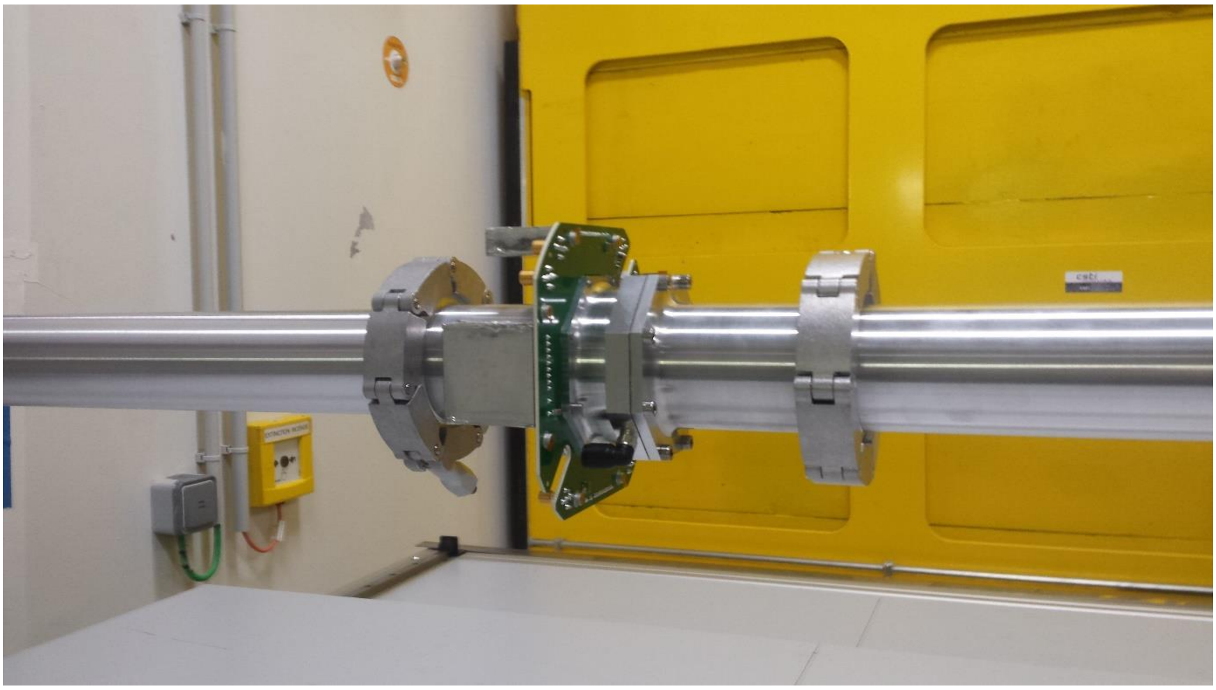

Figure 2 Fission chamber installed in November 2021 on the NFS neutron pipe.

The use of a fission chamber (see Figure 2) allows to identify fission events, and conversely the (n,xn) reaction events. We thus target measurements more precise than the unique direct existing measurement made at CEA/Bruyères le Châtel [ii]. The drawback of the use of an active fission target is the presence in the beam of parasitic reaction on structural material (detector windows, sample backings, and gas). It is thus mandatory to measure these parasitic reactions, through the use of a blank fission chamber (with no actinide). Unfortunately due to restricted allocated beam time (only 1/4th of the requested beam time), this second measurement could not be performed during our first test experiment in November 2021. We will see that we cannot extract (n,xn) reaction cross section, but at most we can study the feasibility of these measurements in this first experiment.

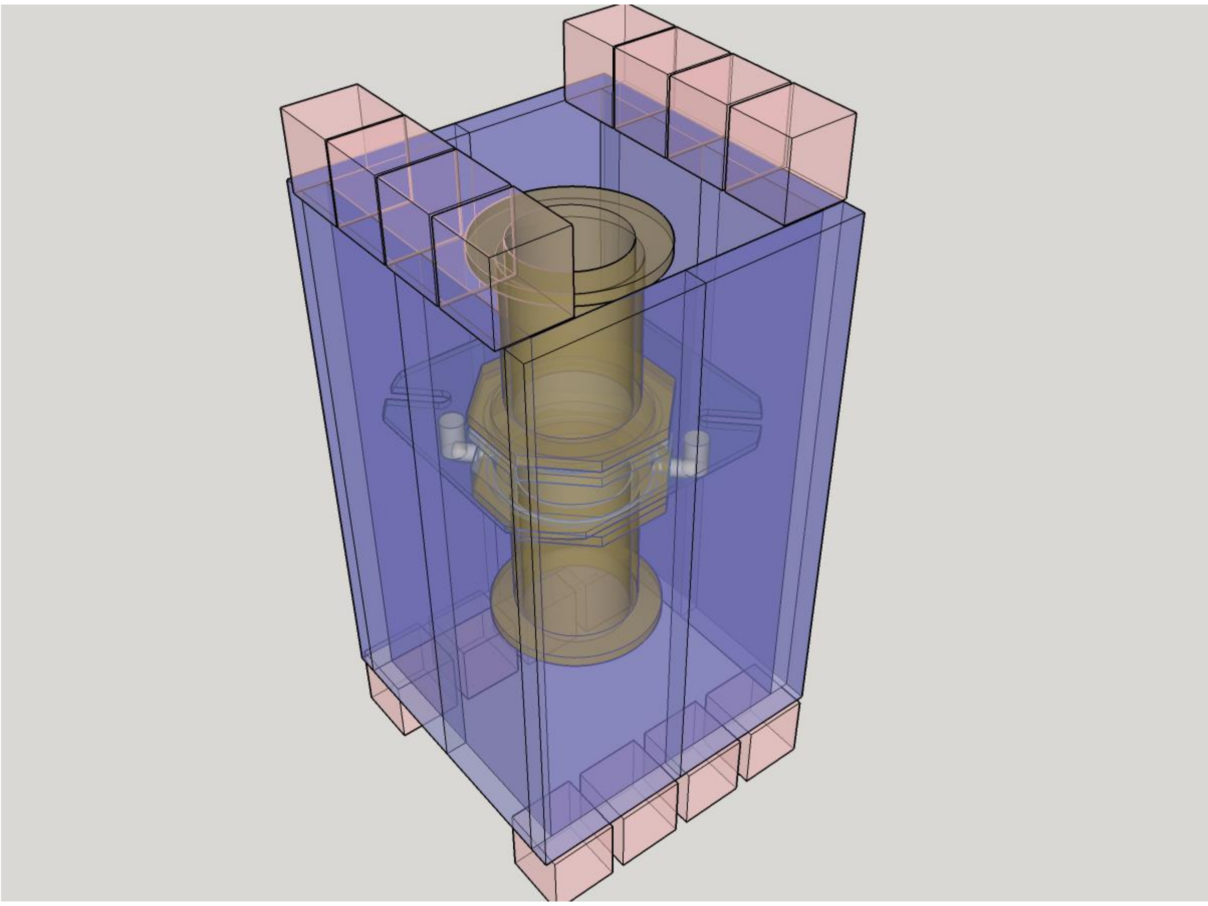

Figure 3 Three-dimensional drawing of the internal BGO array. In blue: 8 BGO crystals. In pink: 16 compact photomultipliers (2/crystal). In brown: the fission chamber.

The BGO array is presented on Figure 3. It is composed of 8 crystals, 250 mm long, 10 mm thick. Four of them are 62.5 mm and four are 72.5 mm wide. This detector has been added to the setup in order to lower the γ-ray detection threshold. Indeed, a low energy threshold is needed in order to trigger on (n,xn) reaction events when the incoming neutron energy is just above the reaction threshold.

Preliminary results on the uranium 238

The SCONE detectors is able to count the neutrons, but it has also a very high detection efficiency for both neutrons and γ-rays. Due to its large volume (about 700 kg of scintillating plastic) it can be used to perform γ-ray calorimetry measurement in fission reactions.

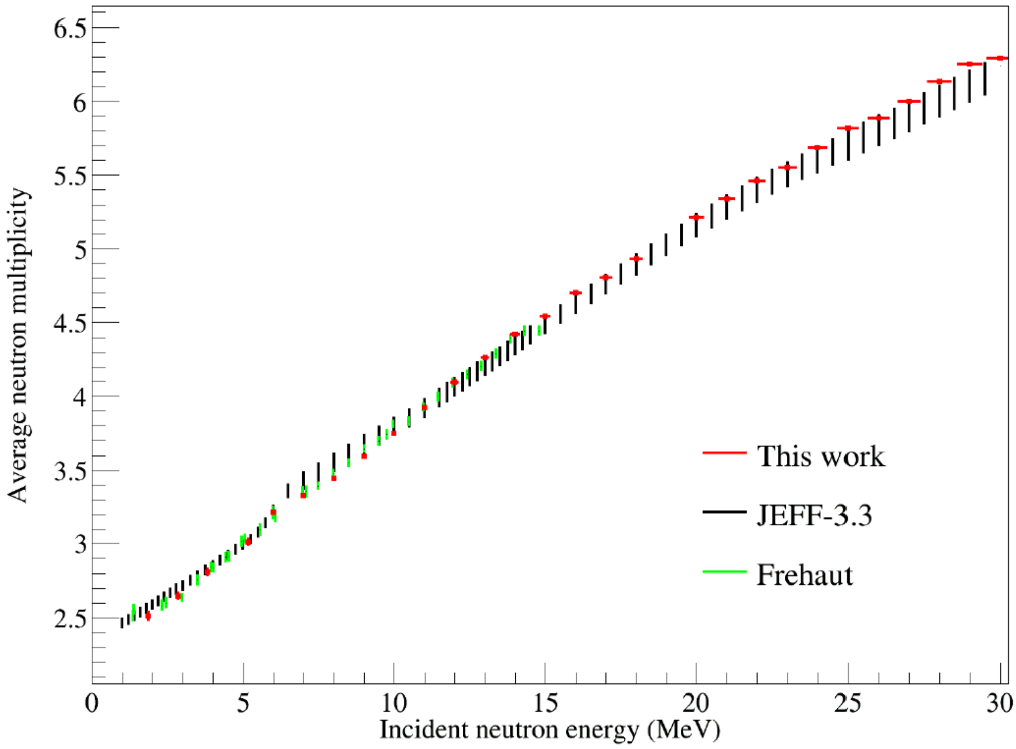

Figure 4 Averaged prompt fission neutron multiplicity in neutron induced fission of 238U against incident neutron energy. Red dots: our preliminary results. Black bars : JEFF-3.3 evaluation. Green points : measurements performed by J. Fréhaut.

Concerning the fission neutron multiplicities, a Tikhonov inspired regularization method has been implemented [iii]. This method allowed us to extract complete neutron multiplicity distributions. This is the first determination of these distributions for fast-neutron-induced-fission. Despite existing measurements, this could not be performed before because this is an ill-conditioned inverse problem. While the average neutron multiplicity is easy to extract without a complete inversion (see our result on Figure 4), this is not the case for the complete distribution. Figure 5 presents the complete prompt fission neutron multiplicity distributions obtained after the deconvolution of the SCONE detector response through the Tikhonov regularization. From these distributions, we extracted the standard deviation shown on Figure 6. This moment presents systematics dips at each fission chance opening. We have shown [iii] that this observable can be used in order to extract partial fission probabilities.

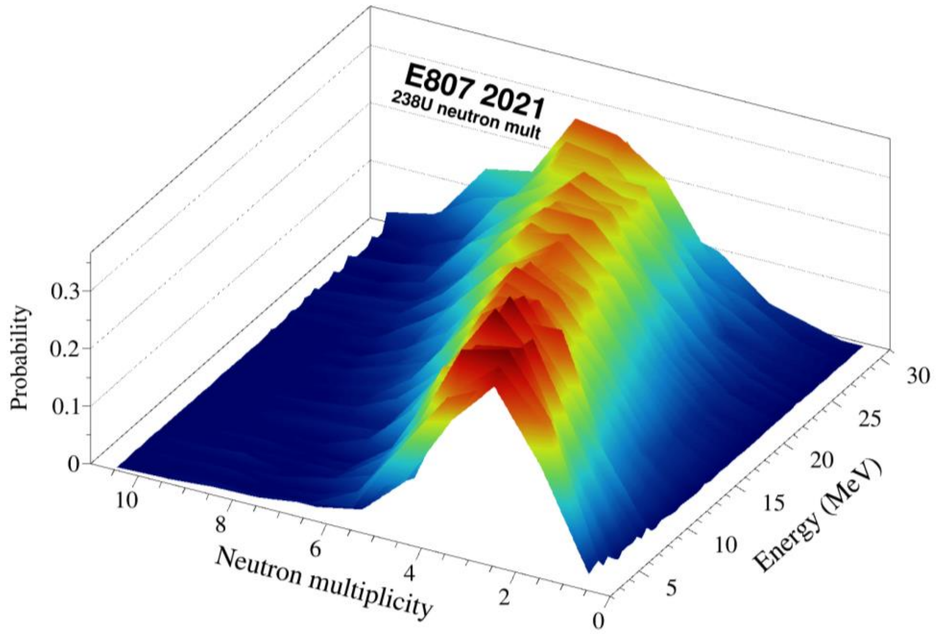

Figure 5 Complete prompt fission neutron multiplicity distributions against incident neutron energy.

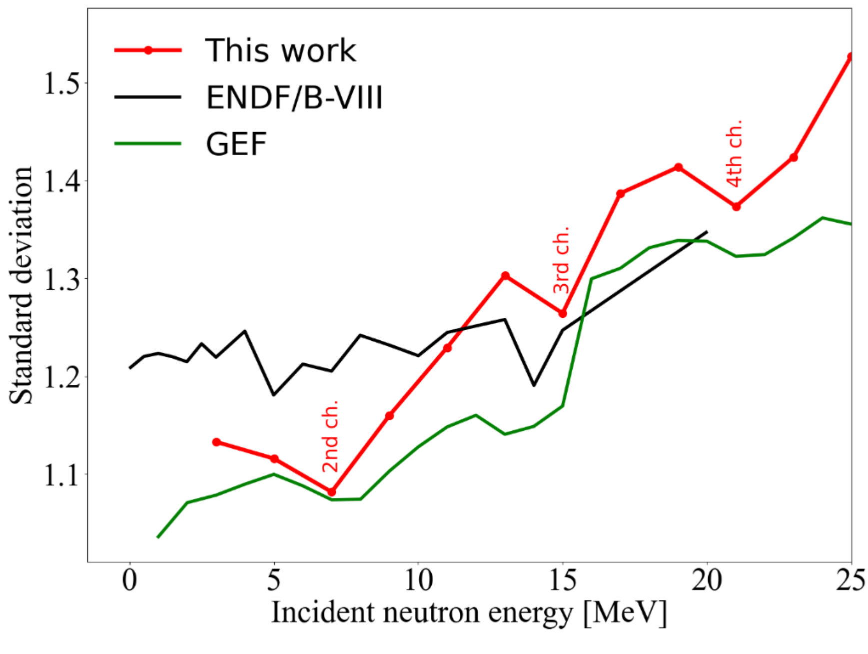

Figure 6 Standard deviation of the prompt fission neutron multiplicity distribution against the incident incident neutron energy. In red: our results. In black : ENDF/B-VIII [] data evaluation. In green : calculation performed with the GEF code[].

The capability of the SCONE detector to perform calorimetric measurements on γ-rays was used to determine the total γ-ray energy in the ^{238}U neutron induced fission. Figure 7 shows this observable. Once again we see structures, which are closely connected to the multi-chance feature of fission (energy staggering at the 2nd and 3rd chance fission openings).

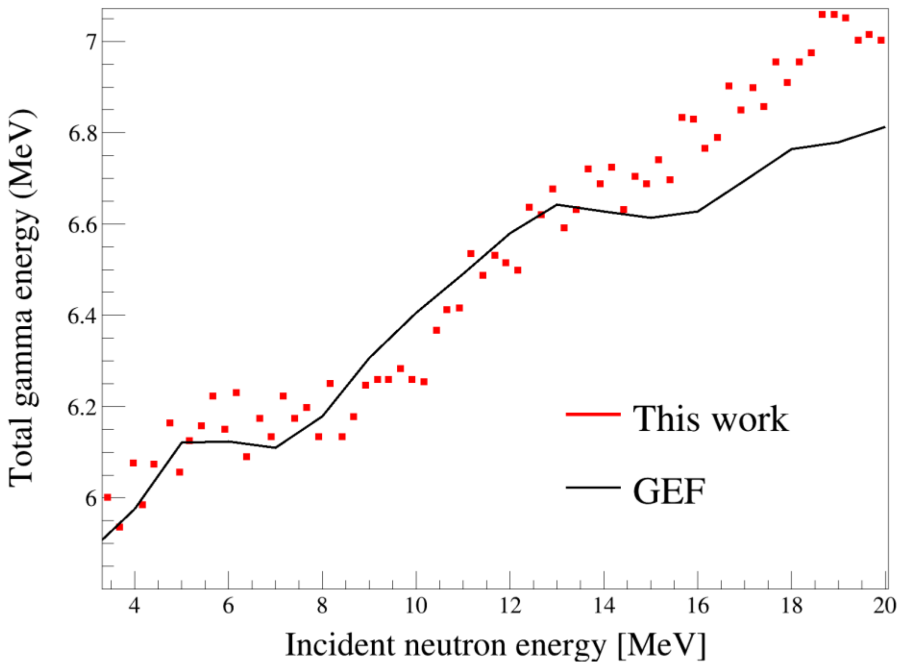

Figure 7 Total γ-ray energy in ^{238}U neutron-induced fission against incoming energy. In red SCONE datas, and in black calculation performed with GEF.

Feasibility of (n,xn) reaction cross section measurement

The (n,xn) reactions cross-sections are much more difficult to measure, since there is no specific trigger associated to (n,xn) events. Thus the only way to clearly identify those events is the neutron multiplicity. The use of an active fission target allows to identify fission events but due to inefficiency of this detector some events remains. Elastic and inelastic reactions can also mimic (n,xn) events by event pile-up effect. Hence the neutron flux in a beam burst hast to be limited in order to make this effect negligible. The electronic of the setup SCONE has been modified in order to optimize the beam conditions. Since the charge in a burst is limited, and since we want a high average beam current, the beam period has been set at a lowest value (5.6 μs) compared to the time needed by the SCONE detector to count the neutron (about 50 μs). The modification of our data acquisition modules allows to get trigger signals from the setup. These signals are then used to stop the beam for 50 μs every time an event is detected.

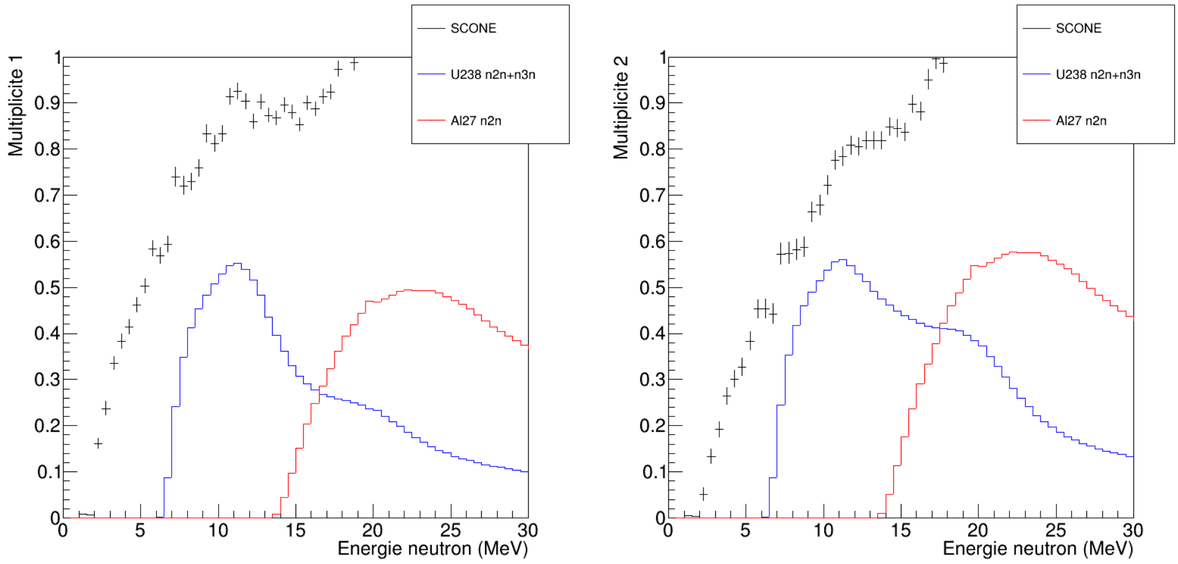

Figure 8 Spectra for multiplicity 1 (left) or 2 (right). Black: SCONE data. Blue : expected spectra from the (n,2n) and (n,3n) reactions on ^{238}U contributions. Red : same for the (n,2n) reaction on Al. Beam current 120 nA.

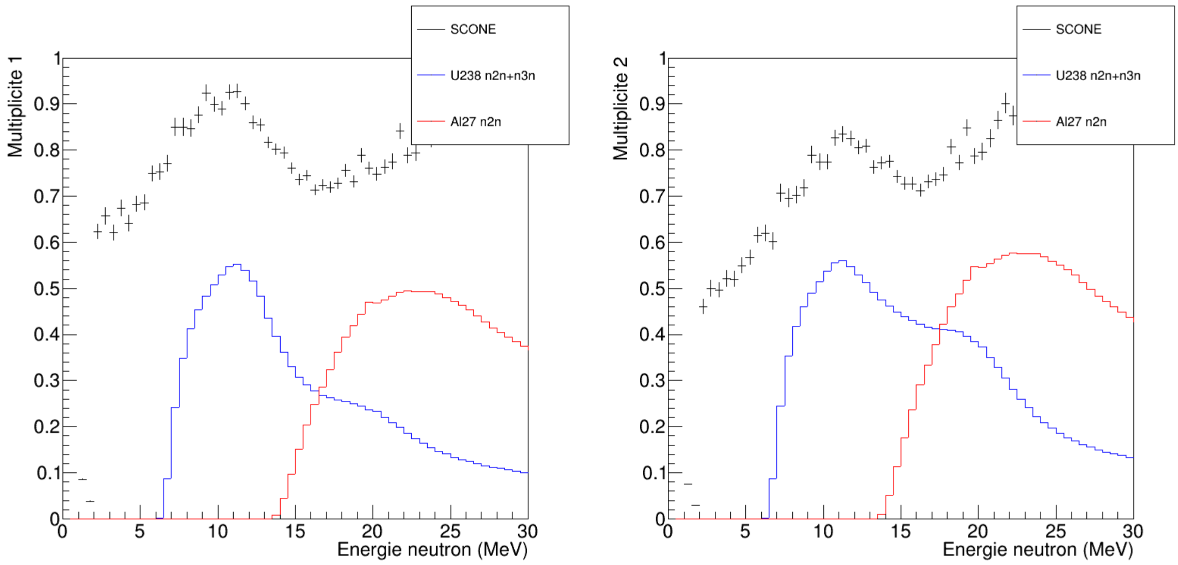

Figure 9 Identical to Figure 8 but for an averaged beam current of 1 µA.

Figure 8 shows the raw spectra for neutron multiplicities of 1 and 2 obtained with the SCONE detector. They are compared to the expected contributions from (n,2n) and (n,3n) reactions on ^{238}U (blue curve) and from the (n,2n) reaction on Al. These expected contributions were calculated from the JEFF3.3 evaluated cross-sections convoluted with the SCONE response. The data presented in Figure 8 were obtained for a beam current of 120 nA. Figure 9 presents the same spectra but with SCONE data obtained at a 1 µA averaged beam current.

While a very small surplus is observed at a 120 nA current, a very clear signal is obtained for a 1 µA. On both figures, there are clear evidence of other contributions (residual fission events, reaction on other materials in the beam, …), that cannot be exactly subtracted in the absence of a dedicated measurement with a blank fission chamber. Although it prohibits extracting (n,xn) reaction cross-sections from this experiments, these spectra indicate that this should possible with a complete measurement including a dedicated irradiation of a blank fission chamber.

Conclusion

The first experiment with the SCONE setup took place at the GANIL/NFS neutron facility in november 2021. This was a complete successful experiment from a technical point of view. Very good results are obtained on the prompt fission neutrons and γ-rays emission. Innovative results should be obtained relative to neutron - γ-ray competition in the fission fragments de-excitation. The obtained data on the (n,xn) reactions cross-sections measurements indicate their feasibility by means of complete measurements of parasitic reactions contributions in the same experiment.

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[i] F. Reines and al. Phys. Rev. 117 (1960)159.
[ii] M. Soleilhac, J. Fréhaut et J. Gauriau, Journal of Nuclear Energy 23(1969)257.
[iii] B. Fraïsse & al., Phys. Rev. C 108, 014610 (2023).