n_TOF Experiment: Past, Present And Future

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Abstract. The neutron Time-of-Flight facility at CERN was built to measure the neutron capture and fission cross sections. A short description of the facility, the detectors and the data analysis techniques will be illustrated. A short review of the preliminary results on the fission cross sections is presented together with the implications in fundamental nuclear physics and in nuclear technologies. Future perspectives both for the experimental campaign and for the upgrade of the facility are discussed.

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INTRODUCTION

Neutron induced reactions are being the object of a renewed interest in the scientific community in several field of fundamental and applied Nuclear Physics. These reactions present several advantages both from the experimental as well as from the theoretical points of view as it is often possible to isolate and analyze the resonances characterized by different spin and parity [1]. Moreover it is possible to achieve complete information on the energy spectra, in particular γ-rays, especially below the neutron separation energy where the other experimental techniques (electron or proton scattering) are able to detect only particular transitions. These features open new horizons for the understanding of the systematic properties of the chart of the nuclides (masses and lifetimes) and the neutron reaction cross sections especially for the isotopes far from the valley of the stability.

Accurate data on neutron cross sections are also necessary in nuclear astrophysics [2] for understanding the relative contributions of the rapid and slow stellar neutron capture processes that dominate the production of heavy elements in the universe. This information should help in to define the characteristics of some stellar environments (e.g. Red Giants and or Supernovae) and calculating the age of the universe (cosmo-chronometers).

Finally, new concepts in nuclear technology for energy production and for radioactive waste transmutation [3], as well as in nuclear medicine [4] require particularly accurate neutron cross sections for a large number of isotopes since their data are scarce or contradictory. These interests have stimulated the design and the construction of pulsed spallation neutron sources at many large-scale installations.

In order to fulfil all these requests, an international collaboration neutron Time-of-flight (n_TOF) has measured the neutron capture and fission cross section at an innovative neutron facility installed at CERN in 1999. The next section will describe the facility, its performance and the experimental set-ups. Section III will illustrate the preliminary results of the fission cross section together with some details of the data analysis technique. Finally future perspectives concerning both the new measurements and the construction of a new experimental area are presented.

FACILITY AND SET-UP

The neutron beam at n_TOF is generated by the PS proton beam (7×10^{12} protons per bunch at 20 GeV) impinging a massive lead block ($80\times80\times60$ cm^3) [5] surrounded by a water container which acts at the same time as moderator and refrigerator. To minimize the in-beam background, the proton beam and the neutron beam tube are not collinear but at 10° angle. Furthermore, a magnet is installed along the flight path, to deflect the charged particles out of the experimental area (EAR-1) which is positioned 200 m from the lead target. To shape the neutron beam two collimators are positioned along the beam line. They are composed by blocks of iron, concrete and polyethylene. The first collimator has a fixed aperture while the diameter of the second varies according to the type of measurement (capture or fission) to be performed.

The neutron flux, see Fig. 1, covers a wide energy range. In the capture measurements 6.2×10^5 neutrons per pulse are available between 0.1 eV and 100 MeV neutron energy. This is among the highest instantaneous neutron flux available in the world. In the fission configuration the flux is one order of magnitude higher having the same dependence on the neutron energy. Flux measurements were performed with several detectors, particularly with a Fission Chamber, Silicon Monitors and standard neutron capture resonances (^{197}Au, ^{56}Fe).

In order to monitor the neutron flux in the experimental area and to provide the normalization of the neutron flux between different sample measurements, a Silicon Monitor was designed and installed [6]. The (n,γ) cross sections are measured with two different apparatus: two C_6D_6 [7] scintillators and the Total Absorption Calorimeter (TAC) [8]. The samples were mounted on a remotely controlled sample changer made from carbon fibre directly integrated in the vacuum tube. The design of the 4π BaF_2 detector consists of 42-element geometry including 30 hexagonal and 12 pentagonal crystals forming a closed, spherical BaF_2 shell with an inner diameter of 20 cm and a thickness of 15 cm. Given the BaF_2 density (4.88 g/cm^3), the γ-ray cascades following neutron capture can be detected with an efficiency of 95%. Other important features of this detector are a good resolution in γ-ray (6% at 6.13 MeV) and a high time resolution (~500 ps).

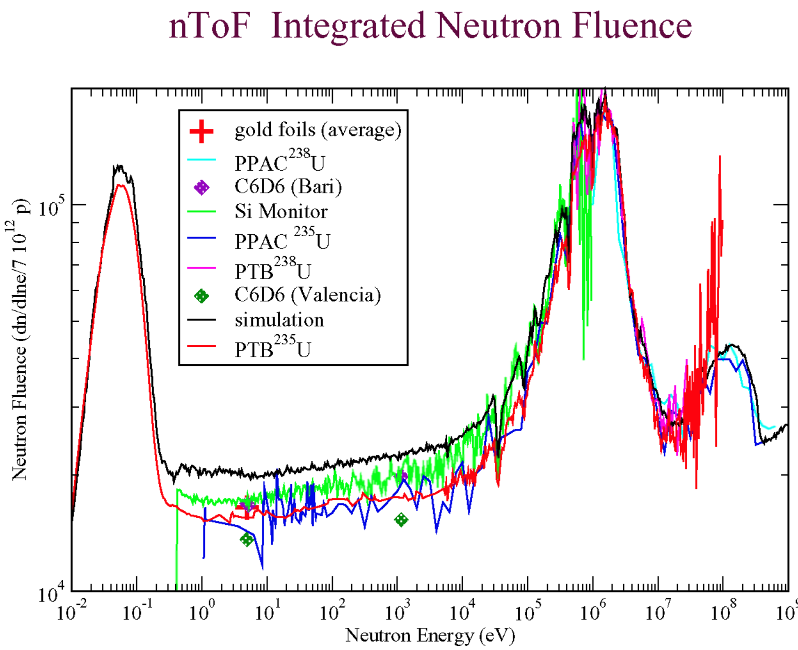

FIGURE 1. Neutron Flux of the n_TOF beam measured and simulated in the capture configuration. The legend indicates the different detectors used for those measurements.

For the fission measurements, two detectors are used: Parallel Plate Avalanche Counter (PPAC) and the Fission Ionization Chamber (FIC) [9]. A PPAC consists of two thin parallel stretched foils with gas at very low pressure in between. The principle of operation is the same as a multiwire proportional chamber. PPACs can be built in large dimensions, are not sensitive to radiation damage, have a high rate capability as position detectors (more than 2 MHz frequency) and have a good time resolution. The Fission Chamber, see Fig. 2, consists of electrodes which detect the fission products. The targets directly exposed to the neutron beam are stacked on the supports together with the electrodes. A total of 16 targets and 18 electrodes could be mounted together in our detector.

Due to the high instantaneous neutron flux, several events are generally recorded for a single neutron bunch. In order to avoid pile up and dead time problems, a data acquisition system based on high-frequency flash analogue to digital converters (FADC) has been developed [10]. The FADC modules can be operated with sampling rates up to 1 GSample/s and are equipped with 8 MByte of buffer memory for each channel. The raw data are recorded signal by signal for detailed off-line analysis by implementing a routine based on the ROOT package [11]. A dedicated routine is used to extract the information on timing, charge, amplitude, and particle identification. This information is recorded on the Data Stream Tapes (DST) which are later processed for the final extraction of the experimental yields.

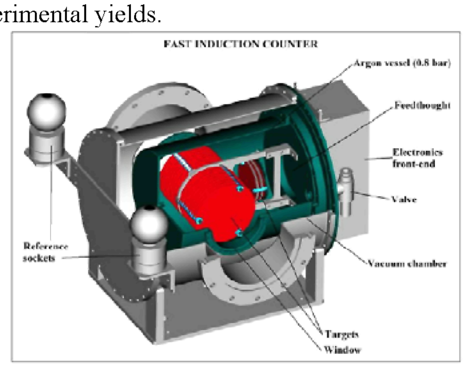

FIGURE 2. Schematic draw of the Fission Ionization Chamber used at n_TOF.

FISSION RESULTS

The list of samples measured in the FIC detectors is indicated in Table 1. The information needed for their data analysis is: the signal amplitude, total charge, time of flight and the baseline value determined for each signal. Additionally, for each proton bunch, the beam intensity and the peak of the initial flash corresponding to ultrarelativistic particles are extracted: this last information is used as a reference for extraction of the absolute neutron time of flight.

TABLE 1. Characteristics of the samples measured in FIC. The samples have a very high purity.

SAMPLE	Total Mass in mg (Number of Samples)	Half-life yr	Activity kBq
^{235}U	31.8 (2)	7.04 10^8	0.2
^{233}U	28.8 (4)	1.6 10^5	5 10^3
^{241}Am	2.26 (8)	432	7.6 10^4
^{243}Am	4.8 (8)	7370	7.4 10^3
^{245}Cm	1.71 (4)	8500	2 10^5

In Fig. 3 the amplitude distributions for the measured isotopes are presented: it is clear that, in the case of ^{235}U and ^{235}U, a simple amplitude threshold is sufficient to discriminate well between fission fragments and α-particles; for the ^{245}Cm sample, the presence of a large pileup between α-particle complicates the analysis, since a higher threshold has to be applied, which cuts also a large fraction of fission fragments. A subsequent normalization of the cross section has to be performed.

For the time to energy calibration, in order to consider the effective neutron flight path (sum of the geometrical length and of the moderator distance), a method developed in Ref. [12] have been employed. Additionally in the resolved resonance region $^{235}U(n,f)$ resonances were used for the energy calibration procedure. An example of the results for a limited energy interval is reported in Fig. 4. A very good agreement with known experimental data and with ENDF/B-VII.0 is observed.

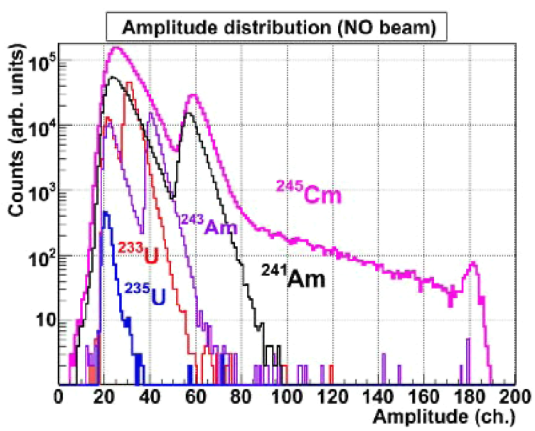

FIGURE 3. Amplitude distribution of the signals for the samples under measurement in the FIC.

For the determination of the absolute value of the cross sections of the actinide targets, the ^{235}U isotope was used for the extraction of the n_TOF neutron flux in the fission configuration (that is with the 4 cm diameter collimator, see [5]). The energy behaviour of the neutron flux can be derived from the ratio between the ^{235}U fission rate and evaluated cross sections. In detail Fig. 4 shows the energy distribution measured for the ^{235}U sample, normalized to the nominal bunch of 7×10^{12} protons. The red line in the figure shows the predictions based on the tabulated cross-sections from the ENDF-B/VII database. For comparison with the experimental data, the evaluated cross-sections were scaled by an arbitrary factor so to match the first resonance. Typically, a very good agreement is observed for most resonances. However, some differences can be observed in restricted energy regions, mostly in correspondence of valleys between resonances. Although typically of the order of a few up to 20% percent, such discrepancies propagate to the extracted neutron flux and, as a consequence, affect the measured cross-sections for all other isotopes. However the general good agreement in the whole energy range between the n_TOF and the evaluated data ensures about the correctness of the data taking and of the data analysis procedures.

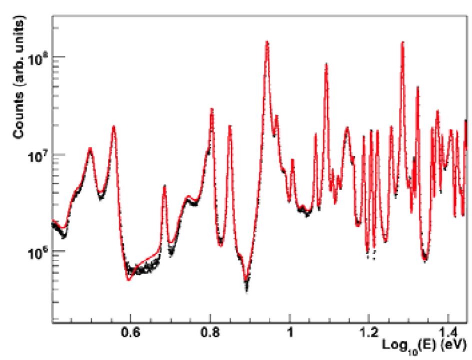

FIGURE 4. Experimental yield of the $^{235}U(n,f)$ measured at n_TOF (black dots) compared to the ENDF/B-VII.0 data (red curves).

The first analysis of the fission data completed at n_TOF is for the ^{233}U(n,f) reaction [13]. This cross section has been measured from thermal to 1 MeV neutron energy. It is important to stress that the data here shown are not normalized to any previous result but rely purely on the standard ^{235}U(n,f) cross sections. A further noteworthy aspect is that, for the first time, the whole energy range from thermal to 1 MeV is covered in a unique measurement, thus minimizing possible systematic uncertainties. Fig. 5 shows the n_TOF data (in black) compared with the evaluated cross-sections and with the most recent measurements reported in EXFOR database. In the unresolved resonance region the n_TOF cross-sections are affected by a very low statistical error. A reasonable agreement is observed with this last data set, and with the ENDF/B-VII.0 database as well as with JEFF-3.1, not shown in the figure. In the resolved region previous data show sizable discrepancies between themselves, both in terms of resonance strength and energy, and differences are also observed between the two databases ENDF/B-VII.0 and JEFF-3.1. Finally, the high energy resolution of the neutron beam allows to resolve resonances for neutron energies above 600 eV while the previous limit reported in the ENDF/B.VII.0 is 600 eV (150 eV for JEFF-3.1). In a preliminary analysis from 0.6 eV to 1 keV, it was possible to resolve 200 pseudo resonances. Taking into account the recommended average spacing of 0.52 eV [14] for the mixed spin group it would be possible to conclude that 569 resonances would be missed.

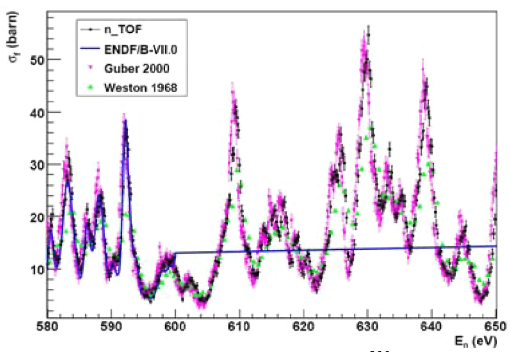

FIGURE 5. Experimental yield of the ^{233}U(n,f) measured at n_TOF compared to the ENDF/B-VII.0 data and to the most recent experimental data, see EXFOR database.

Another interesting isotope, measured at n_TOF, is ^{245}Cm since only few and discordant measurements exist. In particular no experimental result exists in the energy range between thermal and 20 eV. This isotope presents a very large α-background due to the relatively short half-life (8500 yr). For this reason, in addition to a higher amplitude threshold, the experimental data have been corrected also for the residual α-background. Due to an uncertainty in the detection efficiency, normalization to a known cross section value is required. Since at thermal energy various measurements with discrepancies on the order of 10% have been performed, we have chosen a weighted mean of those values for normalization purposes. n_TOF preliminary data are higher than ENDF/B-VII, particularly in the energy range between 0.1 eV and 8 eV, where the discrepancies rise up to 10%. A more refined analysis is however needed before indicating definitive conclusions. When compared with previous experimental results, see Fig. 6, good reproduction of the fission resonances is obtained, with discrepancies up to 20% for dips and amplitudes of some resonances.

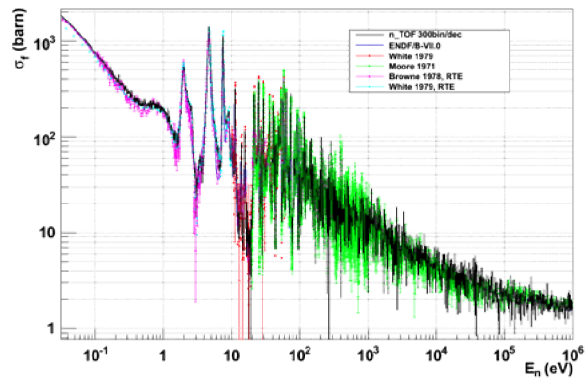

FIGURE 6. Experimental yield of the ^{235}Cm(n,f) measured at n_TOF compared to the most recent experimental data, see EXFOR database.

FUTURE PLANS

Two goals are essentially planned at n_TOF for the next years. The first is the prosecution of the experimental activities to measure the neutron cross sections and photon strength functions. Concerning this issue there is already a long list of isotopes selected whose the accurate measurements are particularly interesting like: Mo, Ru and Pd, Fe, Ni, Zn and Se, Th, U, Pu, Am, Cm [15]. As in the first phase of this project, Nuclear Astrophysics and applications in to advance Nuclear Technologies will play a fundamental role in the n_TOF scientific programme. A part of those measurements (Fe, Zn and Se) is already accepted by Isolde/n_TOF Committee at CERN and is in schedule on 2009. The neutron beam will restart on November 2008 with a new spallation target. The first runs will be devoted to the commissioning of the neutron beam, to estimate the neutron flux and the background sources. From the experimental point of view (detectors, samples, DAQ), the n_TOF collaboration is ready to take data.

The second task is the construction of a new experimental area (EAR-2). According to the simulation, the best location for the new hall is at 90° upside with respect to the proton beam direction with 20 meters of flight-path. For the new area, the spallation block and the neutron beam tube has to be redesigned and a new set of detectors has to be built. This hall will get a neutron flux ~100 times higher than in the first experimental area. At same time the background, induced by the ultrarelativistc particles and γ-rays, will be strongly reduced. EAR-2 will be able to perform measurements with small mass samples or very low cross sections so enlarging the n_TOF scientific programme.

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