EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum to the Proposal INTC-P-507 for the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the ^{235}U(n,f) cross section relative to n-p scattering up to 1 GeV

January 10, 2024

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Requested protons: 4×10^{18} protons on target + 7×10^{17} for a detector test
Experimental Area: n_TOF EAR1

This document is an addendum of the proposal INTC-P-507, approved in 2017 [1], concerning the measurement of the fission cross section on ^{235}U induced by fast neutrons, with kinetic energies above 10 MeV. The fission yields are measured simultaneously with the neutron flux which is, in turn, determined relative to the neutron-proton elastic scattering cross section, the main reference for reactions induced by high energy neutrons. The ^{235}U(n,f) cross section is one of the most important cross-section with the largest amount of experimental data available. In fact, it is defined as standard at the thermal neutron energy point (0.025 eV), between 0.15 MeV and 200 MeV and the integral between 7.8 eV and 11 eV [2]. In the neutron energy range from 200 MeV up to 425 MeV, the only experimental result available is from the measurement performed at n_TOF in 2018 [3–5], as outcome of INTC-P-507 (Fig. 1).

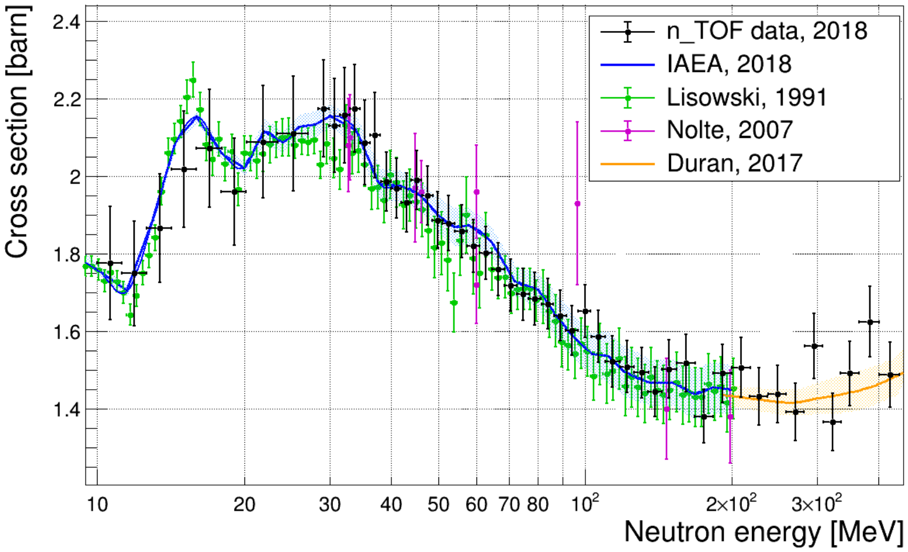

Figure 1: Final cross section obtained in 2018 at n_TOF facility, EAR-1 [5]. In addition the Lisowski [6], the Nolte [7] data together with Duran evaluation [8] and IAEA evaluation, which define the standard cross section up to 200 MeV [9], are reported.

Data on neutron induced fission cross sections at energy above 200 MeV are extremely important for understanding the interplay between collective and single particle degrees of freedom in hot nuclei, which affects the dynamics of the nuclear fission process (see, e.g., [10]). In particular, high-energy data are important for understanding the role of the transient time in fission, already observed in the proton-induced fission reaction [11, 12]. This effect reveals itself as inhibition and subsequent decrease in the probability of hot nuclei to de-excite through the fission channel in favour of other reaction processes, such as the emission of light particles.

In general, fission reaction data sets are used in important applications such as energy production with accelerator driven systems, radioactive waste transmutation, radiation shield design for accelerators and the dose received by aircrew. Neutron induced fission is also relevant in nuclear astrophysics, in particular in the nucleosynthesis of the heavy elements, where fission recycling is responsible for a modification of the r-process yields

as well as for the neutron balance in explosive scenarios [13].
The upper energy limit of the results obtained with the previous n_TOF campaign of 2018, set at 420 MeV, was determined by the setup used for the reconstruction of the incident neutron flux. In particular, this limitation was caused its inability to discriminate elastically scattered protons from those produced by inelastic channel with pion creation, which from 300 MeV upwards competes with the purely elastic n-p scattering process. In fact, the main n-p inelastic reaction, from 300 MeV up to 3 GeV, is:

$$n + p \longrightarrow n + p + \pi^0.$$

As long as this reaction, above 300 MeV, passes by the creation of the short-lived Δ baryon [14], the kinematics of the outgoing nucleons becomes different from that of the elastic channel. The contribution of the inelastic reaction to the total cross section increases with energy: it is a few percent at 400 MeV, reaching about 45% of the total scattering cross section at 1 GeV. As dynamic effects in fission are expected to take place above 600 MeV, it is desirable to extend the energy range up to 1 GeV by developing a more advanced detector setup.

A new setup with the Re-TOF telescope

In the new setup we intend to correlate the proton energy with the energy of the incident neutron, to select the elastic channel. The proton energy will be measured by time-of-flight over a length of 2 m with a plastic scintillator as a start and a TOF-wall covering an area of 60 cm × 60 cm for the stop (Re-TOF telescope). The plastic wall is divided in 3-cm-wide bars, each one coupled with 2 PMTs placed at its opposite ends, in order to ensure x- and y-localisation of the recorded events. An additional advantage of the proposed setup will be a better time resolution and a minimization of background events. The Re-TOF telescope will point to a polyethylene sample (5 mm thick) and will be placed at 25° with respect to the neutron beam direction.
Considering the least-favourable scenario, at 1 GeV, when the nucleons take the full kinetic energy after creation of the pion, the difference in time of flight between elastic and inelastic protons is 440 ps, so that a time resolution of 300 ps should be sufficient to disentangle the two reaction channels.
One or two RPTs (Recoil Proton Telescopes), with a dedicated polyethylene sample, as in the 2018 measurement, will be used as well in the new setup. These RPTs are mostly suitable for measuring in the low energy region from about 30 MeV. They are also a strong benchmark for the flux measurement in the energy region from 100 MeV and above, thanks to their accurate characterisation.
As in the 2018 setup, in parallel to the measurement of the neutron flux, we propose to use two detectors to measure the fission yields: a stack of 10 parallel plate avalanche counters (PPAC) with 9 uranium deposits and a parallel plate ionization chamber (PPFC), with 8 uranium deposits. The PPAC is operated at low gas pressure and can be made almost massless and photon insensitive [15]. Therefore, it is well suited for the measurement of fission cross sections at neutron energies of several hundred MeV, [3]. The PPAC setup detects only fission fragments emitted into a forward cone with

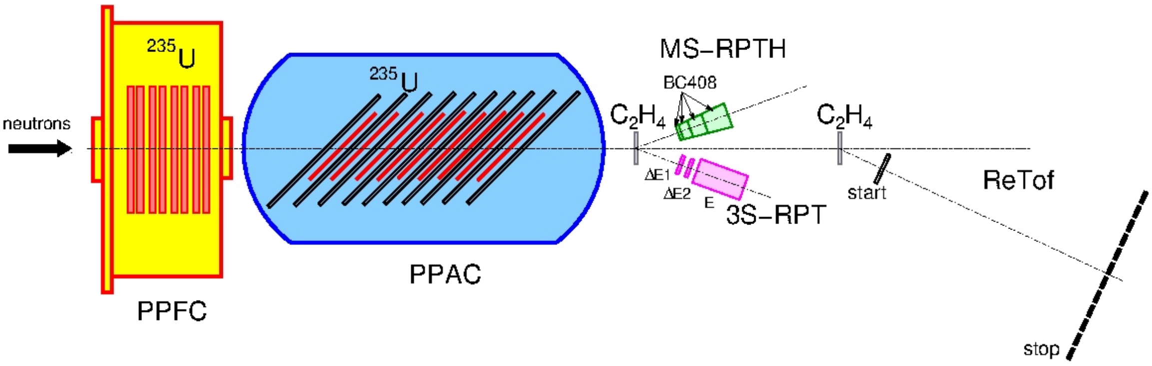

Figure 2: Schematic setup of the ^{235}U(n,f)/^{1}H(n,n)^{1}H cross section ratio measurement to be carried out at EAR-1.The neutron beam will be shaped by the capture collimator. Two fission detectors, a Parallel Plate ionization chamber and a stack of parallel plate avalanche counters, and two C_2H_4 samples are placed along the neutron beam. One or two RPTs at a fixed angle (25°) facing the same C_2H_4 and a Re-TOF telescope pointing at a second C_2H_4 sample, are also shown here.

an opening angle of about 60° and its fragment-detection efficiency must be accurately evaluated. In contrast, the fragment-detection efficiency of a PPFC is about 97% for 300 µg/cm^2 thick samples. However, the increased photon sensitivity due to the operation at ambient gas pressure can prevent the use of a PPFC close to the γ-flash. Therefore, the PPFC can be used to calibrate the PPAC fragment-detection efficiency in the energy range below 100 MeV. The combination of the two fission yield detection systems are therefore the best option for a full characterization and detection of fission events, in the full energy range. A sketch of the complete setup for the contemporary measurement of the neutron flux and the fission yield is shown in Fig 2.

Test of Re-TOF detector performance in EAR-1

Since one of the detectors used for flux measurement, the Re-TOF telescope, has never been used at n_TOF, we propose to do a one-week test to verify the performance of the detector in EAR-1. The first step is to verify how the detector deals with the intense γ-flash, one of the main challenge of this measurement as neutrons of 1 GeV will only be separated by about 90 ns from the flash. As described before, the key point of the Re-TOF telescope is the time resolution we will be able to achieve with the detector in EAR-1. This will be verified during a one-week test (i.e. $7 \cdot 10^{17}$ protons on target) together with the possibility of discriminating protons produced by the elastic and the inelastic channel for neutron-induced reactions up to 1 GeV. A good time-resolution, coupled with the correlation between the neutrons TOF and the protons TOF, could also allow the elimination of background events produced by the ^{12}C(n,lcp) reaction without the need of a dedicated measurement with a carbon target on beam.
The setup for the test foresees the Re-TOF telescope at a 25° with respect to the neutron beam direction, facing a polyethylene sample at a distance of about 20 cm. At the same time, we will acquire data also with a RPT already used in the experimental campaign

of 2018. To assess the background rejection performance, a C sample will be placed on beam instead of the PE sample for about $2 \cdot 10^{17}$.

Beam request

The experiment is to be carried out in EAR-1 because here the neutron spectrum extends up to the GeV region. We request the same number of protons as in the original proposal INTC-P-507 [1]: $4 \cdot 10^{18}$ protons on target. As visible in Fig. 1 the result of the 2018 measurement suffers from statistical fluctuations from 150 MeV upwards. With the setup proposed in this addendum we expect an increase of a factor 4 in the fission yield (from 2 to 9 ^{235}U samples) and a factor two in the neutron flux measurement since with Re-TOF telescope there is no need to perform a dedicated background measurement with a carbon sample on beam.

Summary of requested protons: $4 \cdot 10^{18}$ protons on target + $7 \cdot 10^{17}$ for a detector test.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The setup consists of two fission gas chambers: a stack of 10 parallel plate avalanche counters (PPAC) with 9 ^{235}U deposits and a Parallel Plate Ionization Chamber (PPFC), with 8 ^{235}U deposits. In addition we will use 3 telescope composed of plastic scintillators.

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using: Capture collimator	☒ To be used without any modification ☐ To be modified
PPAC - ISD Form: 3006565 v.1	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
PPFC	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
Plastic scintillators	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☒	PPAC: 0.004 bar, 100 l PPFC: 1 bar, 11 l
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☒	PPAC: 650 V PPFC: 200 V Plastic scintillators: 700 V
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]

	Dangerous for the environment	☒	C_3F_8 gas, 5 kg
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards	Use of radioactive material	☒	^{235}U sample 150 mg 12 kBq