EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the ^{235}U(n, f) cross section relative to the H(n, n)H reaction up to 1 GeV: test of a Proton Recoil Telescope

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Abstract

Fission cross sections are typically measured relative to ^{235}U(n, f), since the neutron-induced fission cross section of ^{235}U is a standard cross section at thermal energy and between 0.15 MeV and 200 MeV. Above this energy, no data are available, so that evaluations can only be based on theoretical calculations. The n_TOF facility offers the opportunity to measure the ^{235}U(n, f) cross section relative to the H(n, n)H reaction up to 1 GeV, provided that a Proton Recoil Telescope (PRT) is available for detecting the recoil protons. To this aim, we are currently building a PRT based on fast scintillation detectors and solid-state detectors, which would allow to reach the GeV energy region, in combination with the Parallel Plate Avalanche Counters (PPAC) system. We propose here to perform a test of the PRT at the n_TOF neutron beam in order to determine the optimal configuration for the setup.

Requested protons: 1×10^{18} protons on target, split into 2 runs over 1 year.
Experimental Area: EAR1

The ^{235}U(n, f) cross section is one of the most important cross section standards for measurements of neutron-induced reaction cross-sections. As such, it is typically used in a wide range of applications. At n_TOF, fission detectors equipped with a ^{235}U sample are used for the measurement of the neutron flux. In addition, as in most other neutron facilities, the ^{235}U(n, f) cross section is used at n_TOF as a reference for all other fission cross section measurements.

The cross section for ^{235}U(n, f) is adopted as a standard at thermal neutron energy and between 0.15 MeV and 200 MeV [1]. Recently, the n_TOF Collaboration has provided very accurate and high-resolution data collected with different detection systems (Fission Ionization Chamber, MicroMegas detectors and especially Parallel Plate Avalanche Counters (PPAC)), from thermal neutron energy to 10 keV. Furthermore, a dedicated measurement is scheduled in the near future at n_TOF to solve a discrepancy in this cross section in the 10 keV to 30 keV energy region. All measurements are performed relative to the standard ^{6}Li(n, t) and ^{10}B(n, α) cross sections. The n_TOF data collected so far on ^{235}U(n, f) will contribute to improve substantially the accuracy of this cross section in a region where it is not a standard, with the aim of making it a reference in a broader energy region.

In the energy range between 20 MeV and 200 MeV the ^{235}U(n, f) reaction is extensively used as a reference for neutron fluence measurements for various applications, ranging from the investigation of the biological effectiveness of high-energy neutrons to the measurement of high-energy neutron cross sections of relevance for accelerator-driven nuclear systems. This is mainly due to the fact that fission ionization chambers are rather rugged and easily useable instruments. Despite its widespread use, however, the recommended ^{235}U(n, f) cross section data at energies above 20 MeV are based on a small set of measurements performed relative to the differential np scattering cross section, which is the primary standard for neutron measurements. Hence, there is a clear and long-standing demand from the International Atomic Energy Agency (IAEA) to improve this situation.

At energies above 200 MeV, the ^{235}U(n, f) cross section plays an important role for several applications, as well as for fundamental nuclear physics. In particular, data on proton-induced fission have recently indicated that at high excitation energy (several hundred MeV) fission may be hindered, relative to particle emission, due to the longer time-scale of the process. The time delay of fission at high excitation energy is an important topic, as it is related to fundamental quantities, such as the viscosity, of excited nuclear matter.

Despite the importance of the high-energy region, at present no data exist on neutron-induced fission above 200 MeV, and one has to rely on theoretical estimates. Until a few years ago, JENDL/HE [2] evaluations were thought to be the most reliable ones and were used as reference, for example to extract the neutron flux at n_TOF up to 1 GeV. However, new theoretical calculations [3], using for example the intranuclear cascade model INCL++ [4] coupled to the de-excitation model GEMINI++ [5], have indicated that the ^{235}U(n, f) cross section at high energy may be substantially different from what was previously thought. Furthermore, in a new evaluation [6], recently released by the International Atomic Energy Agency (IAEA) Nuclear Data Section, it is stated that new absolute measurements of the neutron induced fission cross sections (*e. g.* relative to n-p scattering) on uranium, bismuth, lead and plutonium have the highest priority in establishing neutron induced fission reaction standards above 200 MeV. Figure 1 shows a comparison between the JENDL/HE evaluation of the ^{235}U(n, f) cross section, the new IAEA evaluation [6], and the predictions based on INCL++/GEMINI++ model [3].

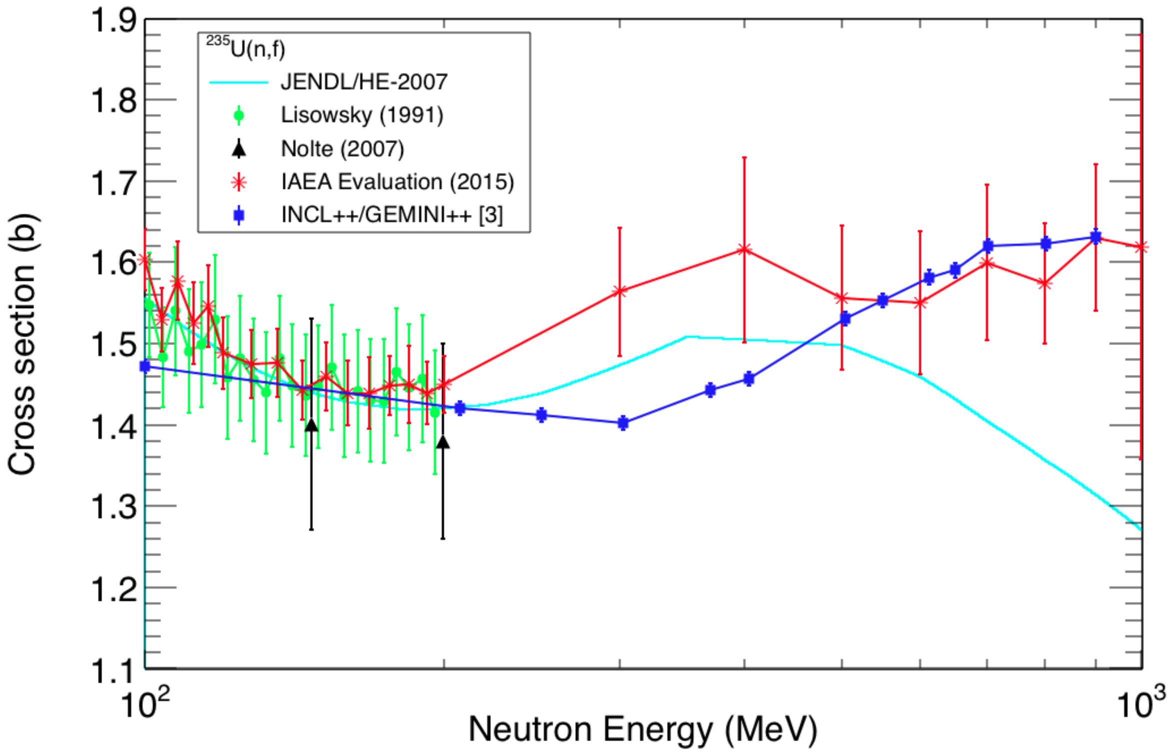

Figure 1: The ^{235}U(n, f) cross section from the JENDL/HE evaluation, the recent IAEA evaluation and the calculation based on INCL++ and GEMINI++ from ref. [3]. Experimental data retrieved from the Experimental Nuclear Reaction Data (EXFOR) database are shown as well.

The comparison clearly shows the need to measure the ^{235}U(n, f) cross section above 200 MeV, relative to the H(n, n)H elastic scattering reaction.

While quasi-monoenergetic neutron sources up to 400 MeV are available [7], it is difficult to carry out measurements at a sufficiently large number of energies to resolve fine structures in the ^{235}U(n, f) cross section. On the contrary, thanks to its very wide neutron energy spectrum, which extends from thermal energies up to more than 1 GeV, the n_TOF facility offers the opportunity to perform such a measurement with a good accuracy. The prerequisite for this measurement is the availability of a Proton Recoil Telescope (PRT) suitable for the special conditions at a spallation source, *i.e.* presence of an intense γ-flash and a continuous neutron energy distribution extending from thermal energies to the GeV energy range. The PRT exploits the elastic scattering on hydrogen, whose cross section is used as reference, by detecting the recoil proton. The measurement is typically performed using a polyethylene target. The measurement would be performed by combining a PRT with Parallel Plate Avalanche Counters (PPAC), operated in coincidence mode and equipped with a sample of ^{235}U. These detectors have already been successfully used at n_TOF to measure the fission cross section (relative to ^{235}U) of a large number of actinides up to 1 GeV neutron energy. The n_TOF data would improve the knowledge of this cross section all the way to 1 GeV, discriminating between various theoretical models on high-energy neutron-induced fission reactions, and establishing a reliable reference cross section above 200 MeV. In addition, it is worth noticing that the measurement of the neutron fluence with respect to the elastic scattering on hydrogen can improve the knowledge of the n_TOF neutron flux for neutron energies higher than 200 MeV and can improve the accuracy of other neutron induced fission cross sections measured or to be measured at n_TOF at these energies. On the low energy side, it will be important to provide improved data for the ^{235}U(n, f) cross section relative to the differential n-p scattering cross section for neutron energies down to about 20 MeV to allow a smooth match with the energy region where more data with small uncertainties are already available.

We are planning to build a PRT similar to the one used so far, for such a measurement [8], introducing some modifications. The PRT will consist of several slabs of solid state, plastic or inorganic scintillators, all read-out independently, to discriminate recoil protons from other light charged particles, *e.g.* deuterons and tritons emitted in the interaction of the neutrons with the polyethylene target, and possibly to determine its energy (an information that would be very useful for background rejection). A feasibility test of the measurement has been performed at n_TOF in 2015, with a detector made of a very fast BC408 plastic scintillator, characterized by a decay time of 2.1 ns. The detector, 5 mm thick, read out by a Hamamatsu R1924A photomultiplier with a voltage divider custom made at Laboratori Nazionali del Sud, Catania, Italy, was mounted outside the neutron beam in the first experimental area (EAR1) for a few hours, with the aim of determining its response to the γ-flash, and the maximum neutron energy at which n-p scattering could be measured. Figure 2 shows the recorded γ-flash, without any sample in the beam, for both dedicated (7×10^{12} p/bunch) and parasitic (4×10^{12} p/bunch) beam pulses. The duration of the γ-flash is such that a proton signal can be reconstructed if it occurs 40 ns after the γ-flash. Similar results were obtained for thicker plastic scintillators, as well as for LaBr and CeBr scintillators. In EAR1, a total time-of-flight (ToF) of 667 ns corresponds to a neutron energy of more than 1.5 GeV, while the ToF of the γ-flash is about 617 ns at 185 m from the neutron-producing target. Therefore, from the test it was concluded that the presence of the γ-flash does not pose particular problems if fast scintillators are used.

The final configuration of the PRT is presently being investigated, with the help of Monte Carlo simulations. The most important question to be answered is whether the full energy region between 20 MeV and 1 GeV could be covered with a single PRT consisting of several elements. In addition, the precise definition of the effective solid angle covered by the PRT, the uncertainty induced by modeling the energy and angular straggling of charged particles in the detector elements and the cross talk between detector elements induced by scattered neutrons and charged particles will be investigated. Another task is the selection of suitable target (radiator) thicknesses for different energy ranges.

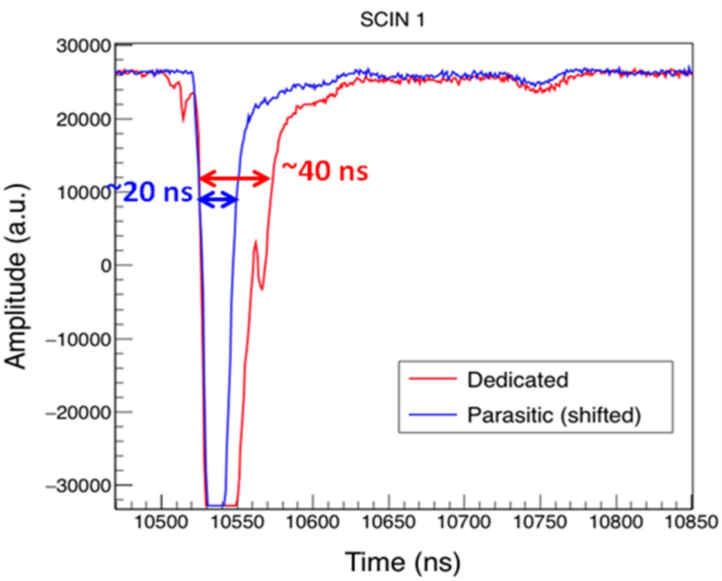

Figure 2: Response of BC408 scintillator, 0.5 cm thick, to the γ-flash in EAR1 at n_TOF for dedicated and parasitic pulses.

The results of the simulation work have to be verified by further experimental tests. Dedicated beam time at n_TOF is needed to determine the optimal configuration for the measurement. In order to achieve high-enough hydrogen density, a polyethylene CH_2 sample will be used for the H(n, n)H scattering. Although this material presents a favorable stoichiometric ratio between hydrogen and carbon, the carbon in the radiator material is a source of background and therefore it requires a dedicated measurement with a graphite sample of equivalent thickness. The PRT will be tested at a few angles relative to the neutron beam direction. Particular attention will be dedicated to the background, in particular the due to scattered neutrons reaching the PRT. In addition, the suitability of silicon diodes as an alternative to transmission detectors consisting of plastic scintillators has to be investigated to enhance the particle discrimination capability of the PRT, at lower neutron energies.

Based on previous detector tests, we have estimated that a total of 1×10^{18} protons will be needed for the present study. Based on the results of the test, we plan to build the final PRT. The PPAC fission detectors for the final measurements are already available.

Summary of requested protons: 1×10^{18}

References:

[1] A.D. Carlson, *et al.*, Nuclear Data Sheets **110** (2009) 3215

[2] Y. Watanabe, *et al.*, Journal of the Korean Physical Society **59** (2011) 1040

[3] S. Lo Meo et al., Nucl. Phys. A **933** (2015) 43

[4] A. Boudard, J. Cugnon, J.-C. David, S. Leray, D. Mancusi, Phys. Rev. C **87** (2013) 014606

[5] D. Mancusi, R.J. Charity, J. Cugnon, Phys. Rev. C **82** (2010) 044610

[6] INDC International Nuclear Data Committee, "*^{209}Bi(n, f) and ^{nat}Pb(n, f) Cross Sections as a New Reference and Extension of the ^{235}U, ^{238}U and ^{239}Pu(n, f) Standards up to 1 GeV*", INDC(NDS)-0681 Distr. ST/J/G/NM , IAEA 2015

[7] IAEA-TECDOC-1743, "*Compendium of Neutron Beam Facilities for High-Precision Nuclear Data Measurements*", IAEA 2014

[8] V. Dangendorf, R. Nolte, F. Roos, H. Schuhmacher, B.R.L. Siebert, M. Weyrauch, Nuclear Instruments and Methods A **469** (2001) 205