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Recent facility upgrades and detector developments

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Abstract. Based on an idea by Carlo Rubbia, the n_TOF facility at CERN has been operating for over 20 years. It is a neutron spallation source, driven by the 20 GeV/c proton beam from the CERN PS accelerator. Neutrons in a very wide energy range (from GeV, down to sub-eV kinetic energy) are generated by a massive Lead spallation target feeding two experimental areas. EAR1, horizonal with respect to the proton beam direction is set at 185 meters from the spallation target. EAR2, on the vertical line from the spallation source, is placed at 20 m. Neutron energies for experiments are selected by the time-of-flight technique (hence the name n_TOF), while the long flight paths ensure a very good energy resolution. Over one hundred experiments have been performed by the n_TOF Collaboration at CERN, with applications ranging from nuclear astrophysics (synthesis of the heavy elements in stars, big bang nucleosynthesis, nuclear cosmo-chronology), to advanced nuclear technologies (nuclear data for applications, nuclear safety), as well as for basic nuclear science (reaction mechanisms, structure and decay of highly excited compound states). During the planned shutdown of the CERN accelerator complex between 2019 and 2021, the facility went through a substantial upgrade with a new target-moderator assembly, refurbishing of the neutron beam lines and experimental areas. An additional measuring and irradiation station (the NEAR Station) has been envisaged and its capabilities for performing material test studies and new physics opportunities are presently explored. An overview of the facility and of the activities performed at CERN is presented in this contribution, with a particular emphasis on the most relevant experiments for nuclear astrophysics.

1. Introduction

Neutron-induced reactions play a fundamental role in different fields, such as reactor technology, astrophysics and applications. There exist several neutron time-of-flight (TOF) facilities in the world devoted to such measurements. The most active in the recent years are GELINA at JRC-Geel [1] and CERN n_TOF [2] in Europe, LANSCE [3] in the USA, ANNRI [4] at J-PARK in Japan and CSNS Back-n [5] in China. This contribution presents a brief summary and update on latest experiments at CERN n_TOF. At n_TOF neutrons are produced via spallation reactions on a Pb-target, where the Proton Synchrotron (PS) pulsed beam impinges at 20 GeV/c with a maximum duty-cycle of 0.8 Hz, a width of 7 ns RMS and a nominal intensity of 8.5×10^{12} protons/pulse. The high-energy spallation neutrons are moderated by means of a water-moderator circuit that yields a neutron spectrum spanning from thermal up to a few GeV of neutron energy. The low duty-cycle and the white neutron spectrum enable measurements in the full-energy domain every single neutron bunch. Neutrons travel along two different beam-lines for measurements based on the time-of-flight technique. EAR1 is located 185 m in the horizontal direction with respect to the proton beam-line, thus enabling very high-resolution neutron-induced reaction cross-section measurements [6]. A second experimental area, EAR2, is placed 20 m upwards from the spallation source, thus becoming suitable for measurements requiring a high resolution and a very high instantaneous neutron flux [7]. Over the last 20 years more than 135 cross-section measurements [8, 9] have been carried out at the CERN neutron-time-of-flight facility n_TOF [10] (see Fig.1). About 65% of these measurements comprise radiative neutron-

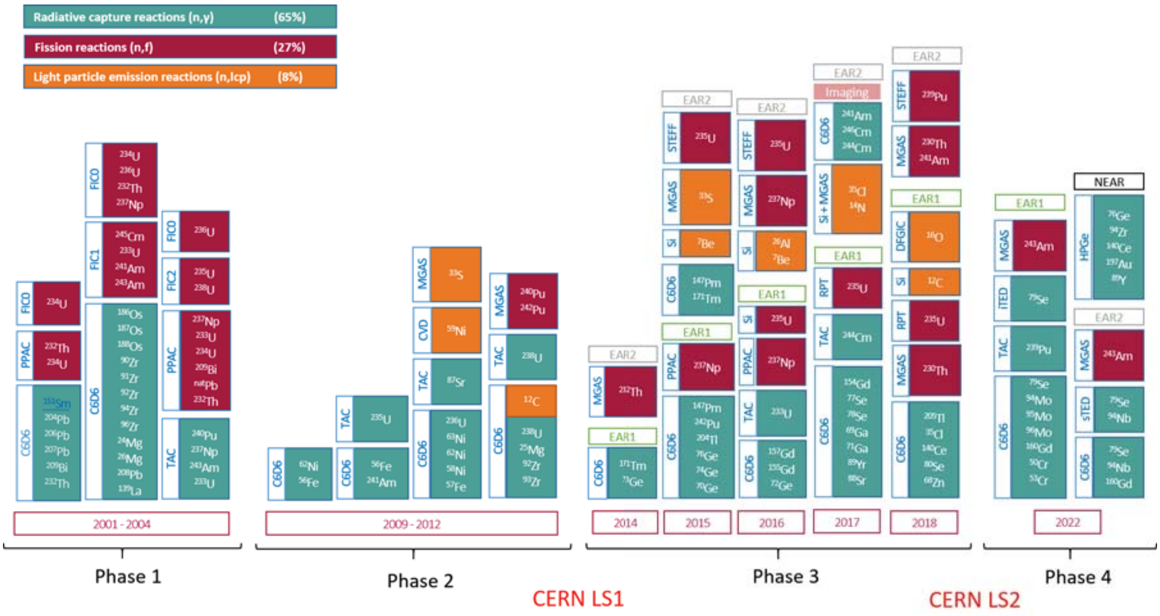

Figure 1. Graphical summary of the ∼135 experiments performed at CERN n_TOF over the last 20 years.

capture cross sections, 27% correspond to neutron-induced fission cross sections and 8% of the measurements are related to neutron-induced light charged-particle reactions. The experimental campaigns were modulated by the CERN long shut-down periods (see Fig.1), which have been used to implement progressive improvements both in the facility and in the detection systems utilized at n_TOF. Several of them are described in this contribution.

During the last CERN long shutdown LS2 (2019-2021) the facility underwent its latest major upgrade, which mainly comprised the replacement of the spallation target itself [11, 12] and the construction of the new NEAR station for neutron-activation measurements [13, 14].

The new neutron source is based on a segmented lead-target design with N_2-gas cooling (see Fig.2) [11]. This new cooling circuit avoids previous issues related to erosion-corrosion and out-diffusion effects in the water-lead interface, which led to radioactive contamination of the former water-cooling circuit [15]. Additionally, the new target comprises two independent moderator circuits, specifically designed for EAR1 and EAR2 and with the possibility of using borated- or demineralized water. The new target-moderator assembly has allowed to remarkably improve the resolution function at EAR2 [16], while increasing the neutron flux by 30-50% in both experimental areas [17], thus making it even more attractive for the measurement of unstable samples in the resolved-resonance region [18]. It is worth to remark also the improvement in the flux flatness with the reduction of neutron-absorption dips thanks to the optimized target cladding design (see Fig.2).

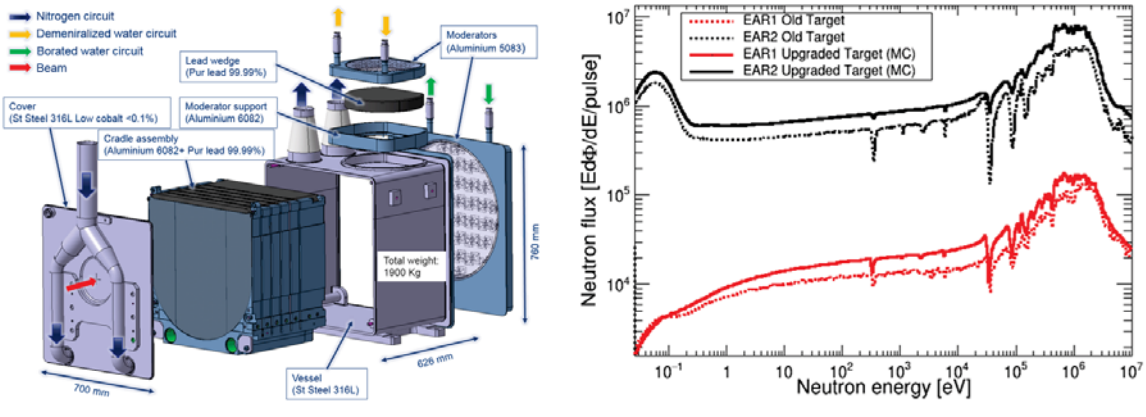

Figure 2. New segmented spallation-target design with N_2-gas cooling [11] (Left). Neutron-flux versus neutron-energy for EAR1 and EAR2 before (dotted line) and after (solid line) target upgrade (Right) [16].

Improvements in the facility have been accompanied also by concomitant developments on detection systems. This statement will be illustrated with a few selected examples on each one of the main neutron-reaction channels shown in Fig.1. Thus, Sec.2 summarizes the recent measurement of the $^{235}\mathrm{U}(n, f)$ cross section from thermal up to 170 keV with very high resolution and improved accuracy using a customized setup of samples and Si-detectors placed in-beam [19, 20]. Detection systems customized for the measurement of neutron-induced light-particle emission are briefly discussed in Sec.3 on the basis of the $^{7}\mathrm{Be}(n,p)$ and $^{7}\mathrm{Be}(n,\alpha)$ reactions. These measurements were carried out at EAR2 using highly radioactive ^{7}Be-samples and they were of relevance for Big-Bang nucleosynthesis studies [21, 22]. The measurement of the key s-process branching nucleus ^{79}Se is discussed in Sec.4 together with recent developments on total-energy detection systems aimed at enhanced detection sensitivity [16]. Finally, Sec.5 summarizes future prospects of the new NEAR station [13, 14, 23, 24] for measurements of astrophysical interest.

2. Fission measurements for reactor technology

Neutron-induced fission cross sections are fundamental for the design of future Generation-IV reactors, nuclear-waste transmutation and new fuel cycles [25, 26]. More than 30 neutron-induced fission cross section measurements have been carried out so far at n_TOF using a variety of detection systems and covering different neutron-energy ranges (see Fig.1). Most relevant isotopes of U, Pu, Np, Th, Cm and Am have been investigated. A recent example is the measurement of the $^{235}\mathrm{U}(n,f)$ cross section in a wide neutron energy range (25 meV-170 keV) and with an improved systematic uncertainty of 1.5% [19, 20]. This accuracy could be achieved thanks to a very high-resolution and redundant measurement at n_TOF EAR1 relative to the standard reactions $^{6}\mathrm{Li}(n,t)$ and $^{10}\mathrm{B}(n,\alpha)$. The measurement was performed with a customized setup, consisting of six samples, two for each target material ^{235}U, ^{6}Li and ^{10}B, and six silicon detectors, each one facing one sample (see Fig.2 in [19]). Thus, each reaction was measured with a separate sample-detector pair in the forward and in the backward direction with respect to the neutron beam. This redundancy allowed us to minimize systematic effects related to the asymmetry in the angular distributions of the standard reactions used as reference. These new cross-section results may help to solve discrepancies in previous experiments and improve future evaluations, as requested by the NEA in the framework of the Collaborative International Evaluation Library Organization (CIELO) project [27].

3. Neutron-induced charged-particle emission experiments for Big-Bang nucleosynthesis

In the last years an increasing number of neutron-induced charged-particle emission measurements have been carried out at n_TOF, with a focus on astrophysics and medical applications [28]. These are very challenging measurements owing to the very small cross sections involved, the reduced Q-values and other experimental effects. At variance with fission and radiative neutron-capture reactions, light-charged particle emission experiments commonly require of detection systems specifically designed for each particular measurement. Thus, two different detection set-ups were developed to measure (n,p) and (n,α) reactions on ^{7}Be, which are of interest for the cosmological lithium problem [29]. Both experiments were carried out at the high-flux EAR2 station owing to the very high sample activities. The $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$ cross section was measured from thermal up to 325 keV using a Si telescope and a high-purity sample. The highly radioactive sample (1 GBq) was produced by implantation of a ^{7}Be ion beam at the neighbouring ISOLDE facility [22]. The $^{7}\mathrm{Be}(n,\alpha)^{4}\mathrm{He}$ cross section was measured in the 10 meV to 10 keV neutron energy range using two ^{7}Be samples with an even larger total activity of 36 GBq. Each sample was set-up in a sandwich configuration with two 140 μm-thick Si-detectors placed directly in-beam [21]. Although significant discrepancies were found between both cross-section measurements and the scarce previous data available, the results helped to rule-out a significant contribution of uncertainties in these two nuclear reactions into the long-standing cosmological lithium problem.

4. Neutron-capture reactions for heavy-element nucleosynthesis

Neutron-capture reactions play a fundamental role in understanding the nucleosynthesis of heavy elements in the universe [30]. In this respect, the measurement of the so-called *s*-process branching nuclei represents one of the main fronts of experimental research at CERN n_TOF [31]. These radioactive nuclei split the *s*-process path and produce variations in the local isotopic-abundance pattern, which reflects the physical conditions of the stellar environment. However, in many cases the measurement of branching nuclei is hindered by the difficulty of producing a suitable sample with the sufficient mass and enrichment for the radioactive nucleus [32], and by the experimental difficulty ascribed to the measurement of a very small quantity of atoms combined with a very high γ-ray background from the sample-decay activity.

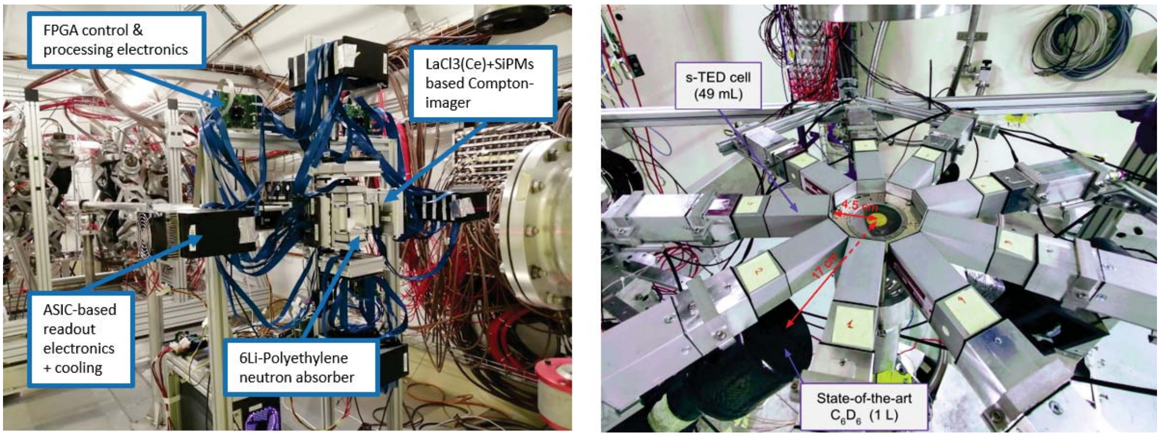

Figure 3. New total-energy detection system with imaging capability i-TED installed at EAR1 (Left). New segmented total-energy detector (s-TED) for capture measurements in EAR2 (Right).

^{79}Se, with a half-life of 2×10^{5} years represents such a challenging case [33, 34]. In this case the only possibility to produce a sample of ^{79}Se required neutron-activation at ILL-Grenoble of an eutectic ^{208}Pb^{78}Se-alloy, which was produced at PSI-Villigen [35]. The resulting sample contained about 3 mg of ^{79}Se embedded into about 3 g of ^{208}Pb and 1 g of ^{78}Se. The low concentration of ^{79}Se required of a dedicated measurement at EAR1 with very high neutron-energy resolution, so that the capture-levels of ^{79}Se+n could be clearly identified and disentangled from capture-resonances from the main isotope in the sample (^{78}Se). The large amount of lead in the sample yielded a significant neutron-induced γ-ray background in the surrounding walls and materials, which could be best treated by means of a new detection system called i-TED [36, 37] shown in Fig.3-left. i-TED consists of an array of four Compton cameras specifically developed and customized for neutron-capture experiments [38]. This system allows one to obtain information on the incoming radiation direction, thereby allowing one to reject a significant portion of the surrounding background radiation [37, 16]. On the other hand, the sample radioactivity was dominated by Se- and Co- impurities activated during the neutron-irradiation at ILL, leading to 5 MBq of ^{75}Se and 1.4 MBq of ^{60}Co. This large sample-related background could be best handled at EAR2 by means of its very high instantaneous neutron flux. However, the capture measurement at EAR2 required new detectors capable of coping with very high count-rate conditions. To this aim an array of nine small (49 ml volume) C_6D_6-detectors was implemented (Fig.3-right). The new detection system, called s-TED [39, 16], permits to reliably handle the very large instantaneous and varying count-rate conditions. Owing to the small detector volume, a very short detector-sample distance becomes possible ($\lesssim$5 cm), thus remarkably enhancing signal-to-background ratio with respect to state-of-the-art C_6D_6 detectors that had to be placed further away from the neutron beam (36 cm) [40, 41]. The analysis of this experiment is in progress and preliminary results are very promising [42].

5. Outlook

As discussed in the preceding sections, upgrades in the facility and improvements in detection systems have allowed for a corresponding enhancement in detection sensitivity for the measurement of challenging neutron-induced cross sections. Regarding neutron-capture measurements, there are many isotopes whose neutron-capture cross sections are difficult to access via TOF experiments owing to the limited number of atoms that can be made available in a sample. In such cases, if applicable, the neutron-activation technique may become the only possibility to gain experimental knowledge on the cross section. Also, the combination of TOF- and activation-measurements may yield a more accurate, complete and reliable information (see e.g. [43] and table 2 in [30]). In order to perform this type of experiments a new experimental area, the NEAR station, has been recently built at a short distance (3 m) from the n_TOF spallation target [13, 9, 14]. The neutron beam is transported from the spallation target into the NEAR station by means of a collimator inserted in a hole of the shielding wall. The new area is complemented with the GEAR laboratory, which is equipped with a high-efficiency HPGe detector for measuring the γ-ray activity of the samples irradiated at the NEAR station. A moderator/filter assembly allows one to produce a neutron distribution that resembles a Maxwell-Boltzmann spectrum at different thermal energies, spanning between a few keV and several 100 keV (see Fig.11 in [14]). At present, a series of systematic measurements are being carried out in order to characterize the neutron field at NEAR [44]. In the future, one of the most interesting features will be the possibility to measure very small radioactive samples, which may be produced in the nearby ISOLDE facility and conveniently transported to NEAR for activation experiments [45]. At present, cooling-down times required to access NEAR are of the order of 4 hours, which puts a constraint on the shortest activation-product half-life accessible at NEAR. In order to access isotopes with activation products of even shorter half-lives the fast-cyclic activation technique may be used [46]. This may open the possibility to access radioactive nuclei of interest, not only for the s-process but also for the intermediate i-process of nucleosynthesis [47], such as ^{137}Cs(n,γ) or ^{144}Ce(n,γ) [45].

Further major facility upgrades will remain hindered until the next 3 years-long shutdown CERN-LS3 in 2026, with the exception of small upgrades and additions to NEAR. On the other hand, the innovative capture-detection systems, i-TED and s-TED, have delivered already very satisfactory results and they still have margin for further enhancements and improvements in the forthcoming years. Progressive refinements in readout photosensors [48], electronics and structural materials [41] may contribute further to enhanced performances and new, more accurate and complete neutron-capture measurements.

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