Status and perspectives of the neutron time-of-flight facility n_TOF at CERN

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Abstract. Since the start of its operation in 2001, based on an idea of Prof. Carlo Rubbia [1], the neutron time of-flight facility of CERN, n_TOF, has become one of the most forefront neutron facilities in the world for wide-energy spectrum neutron cross section measurements. Thanks to the combination of excellent neutron energy resolution and high instantaneous neutron flux available in the two experimental areas, the second of which has been constructed in 2014, n_TOF is providing a wealth of new data on neutron-induced reactions of interest for nuclear astrophysics, advanced nuclear technologies and medical applications. The unique features of the facility will continue to be exploited in the future, to perform challenging new measurements addressing the still open issues and long-standing quests in the field of neutron physics. In this document the main characteristics of the n_TOF facility and their relevance for neutron studies in the different areas of research will be outlined, addressing the possible future contribution of n_TOF in the fields of nuclear astrophysics, nuclear technologies and medical applications. In addition, the future perspectives of the facility will be described including the upgrade of the spallation target, the setup of an imaging installation and the construction of a new irradiation area.

1 Introduction

Neutron-induced reactions play a fundamental role for a number of research fields, from the origin of chemical elements in stars, to basic nuclear physics, to applications in advanced nuclear technology for energy, dosimetry, medicine and space science [1]. Thanks to the time-of-flight technique coupled with the characteristics of the CERN n_TOF beam-lines and neutron source, reaction cross-sections can be measured with a very high energy-resolution and in a broad neutron energy range from thermal up to GeV. During the operation of the n_TOF facility, cross-sections have been measured for almost a hundred different reactions and made public, representing key nuclear data inputs for a variety of calculations and simulations; these data are exploited, for example, in the design of new nuclear reactors, in modelling stellar and primordial nucleosynthesis, and in optimizing nuclear medicine techniques such as the Neutron Capture Therapy. The required goals of precision and accuracy are achievable also thanks to the high-performance detectors and data acquisition systems equipping the two experimental areas. The combination of the innovative features of the neutron beam line and state-of-the-art experimental setups have allowed the n_TOF Collaboration to perform high accuracy, high resolution (n,γ), (n,f) and, more recently, (n, charged particle) cross sections measurements.
During the CERN Long Shutdown 2 (LS2) several upgrades are planned to ameliorate the facility performances and further exploit its potential. In particular, three macro areas of development have been identified. Firstly, the proton beam - target assembly: a new target is under development and will be installed during LS2. It will be able to withstand a higher proton beam intensity - and therefore the instantaneous neutron flux - up to 10^{13} proton per pulse. Secondly, the neutron beam-lines will be optimized to enable additional applications, beyond neutron-induced cross section measurements, such as neutron imaging and neutron irradiation studies. Lastly, a diversity of detection techniques is under development, in particular Ge detectors for γ-spectrometry, gaseous targets, and position sensitive detectors for (n,γ) measurements to minimize beam-related background.

2 The n_TOF International Collaboration

n_TOF has been a key facility in the framework of the European Atomic Energy Community (EURATOM), actively participating in its funded nuclear data projects IP-EUROTRANS/NUDATRA, ANDES and CHANDA. The facility will continue to maintain its leading role within the upcoming SANDA project.
The n_TOF International Collaboration has been founded in 2001 with the starting of the facility, and at present it counts 42 research institutes and Universities from EU, India, Japan, Russia and Australia, and CERN for a total of 127 scientists, of which 27 are PhD students.

3 Summary of n_TOF measurements

The features of the neutron beam, combined with state-of-the-art experimental setups and data acquisition systems, make n_TOF a unique world-class facility, in particular for measurements using radioactive isotopes samples, that strongly benefit from the high instantaneous flux, with a large improvement in the signal-to-noise ratio compared to similar facilities. The important results obtained so far have already gained n_TOF a widely recognized role of excellence among the time-of-flight facilities. The forefront interdisciplinary research being carried out at n_TOF has an important impact on different fields in Science and

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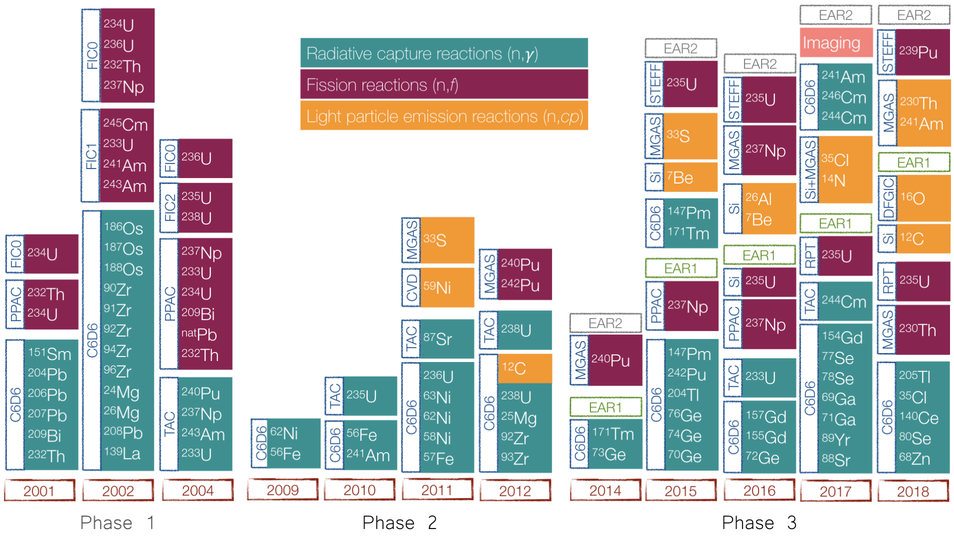
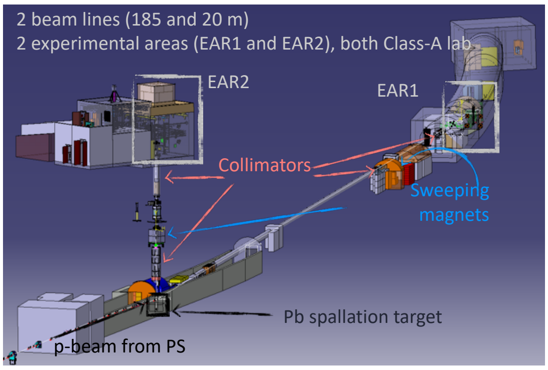


Figure 1. Experimental progamme of the n_TOF facility during its three measurement phases. The different reactions are divided in radiative capture (green), fission (purple) and charged-particle emission (orange).

Technology. In particular, as already mentioned, the Collaboration has performed several measurements of interest for Nuclear Astrophysics, addressing long-standing questions, in some cases for the first time ever, as well as measurements of relevance for Environmental and Energy problems, which list among the top-ranked in terms of interest and social impact.
In Figure 1 all isotopes measured at n_TOF are listed, divided by type of reaction - radiative capture, fission and light charged particle emission. Almost all measured reactions have led to specific publications, in many cases in journals of high impact factor (such as Physical Review Letters, Physics Letters, Energy and Environmental Science, etc..). Furthermore, the results of the measurements are being disseminated to the scientific community through the EXFOR database and are being adopted for cross section evaluation in the major public nuclear data libraries such as JEFF ,ENDF/B ,and JENDL .

4 The CERN n_TOF facility: characteristics and future plans

Neutrons at n_TOF are produced by spallation induced by a pulsed proton beam of 20 GeV/c momentum from the Proton Synchrotron (PS) impinging on a water-cooled Pb target. The high peak current of the PS proton beam(some 7 10^{12} proton per pulse ≈25 ns long), combined with the high energy, results in a very intense neutron source, and in a very wide energy spectrum reaching up to 1 GeV neutron energy. The lead spallation target is equipped with a moderator circuit that can host normal or borated water, with the purpose of widening the neutron energy spectrum down to the epithermal and thermal region, and leading to an almost isolethargic spectrum [2](Figure 2,right). For the first thirteen years of operation, only one neutron beam line in the horizontal direction was available, with the experimental area (EAR1) located at 185 m distance from the spallation target. In this area, the neutron beam is characterized by an instantaneous intensity of about 2 10^5 neutrons/proton-bunch/cm^2, an energy spectrum extending over almost eleven orders of magnitude, from 25 meV to 1 GeV, and a high energy resolution ($\Delta E/E < 10^{-3}$ in most of the energy range). In 2014, a second beam line in the vertical direction with respect to the impinging proton beam was completed. The corresponding experimental area (EAR2) is located at 20 m distance from the spallation target [3][4] (Figure 2,left). Compared with EAR1, the neutron beam in the new area has a much higher intensity (>10^6 neutrons/bunch/cm^2), at the expenses of a slightly worse energy resolution and narrower energy range (from thermal up to 250 MeV). The two experimental areas are somewhat complementary: while the characteristics of the neutron beam in EAR1 are ideal for high resolution measurements of neutron capture reactions on stable or long-lived radioactive isotopes ($t_{1/2}$>100 y), the much higher flux in EAR2 allows one to perform measurements on radioisotopes with short half-life, on samples available in small (sub-mg) mass, on reactions with low cross section, or on all of these at the same time. In fact, for radioactive isotopes the combination of the higher flux and shorter time-of-flight results in an increase of the signal-to-background ratio of more than two orders of magnitude, relative to EAR1, when considering the background related to the radioactivity of the sample. As a consequence, the neutron beam in EAR2 allows challenging measurements on isotopes with half-life as short as a few months. This was indeed the case for the measurement of neutron-induced reactions on ^{7}Be of interest for Big Bang Nucleosynthesis (the Cosmological Lithium Problem discussed in a different section). The replacement of the n_TOF spallation target is foreseen within the next two years. The new target and related systems will have a geometry better op-



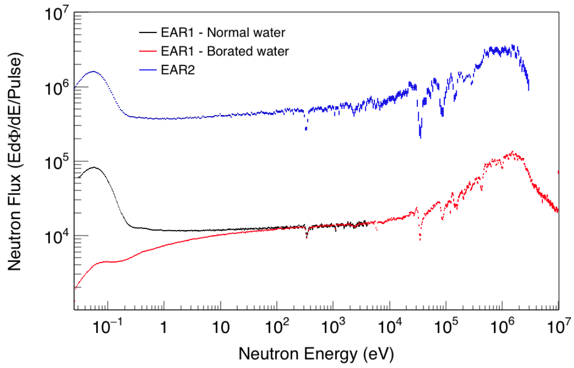
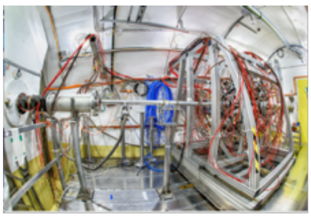


Figure 2. (Left) Scheme of the n_TOF facility as in 2018. (Right) Neutron flux in EAR1 (black and red lines) and EAR2 (blue line) as a function of the neutron energy. In the low neutron energy region the difference resulting in using normal (black) or borated (red) water for the neutron moderator can be seen.

timized for EAR2, resulting for the second experimental area in an expected increase of the neutron flux of about a factor of 2 in the neutron energy region above a few keV, and in a much improved energy resolution with respect to the current generation target. This enhancement in the luminosity of the neutron beam in EAR2 is particularly convenient for measurements of neutron-induced fission cross sections on short-lived actinides. Such measurements are of key importance for nuclear reactor calculations and for the correct modelling of the fission recycling in r process nucleosynthesis, a topic that has become of great interest in particular after the recent multi-messenger observation of a neutron star merger event. In addition, infrastructure civil engineering works are foreseen to adapt the target/beam-line configuration in order to exploit other applications such as neutron imaging and neutron irradiation. The latter, in particular, could open the way to cross-section measurements by the activation technique, taking advantage of the extremely high neutron intensity expected also for the high energy region of the neutron spectrum.



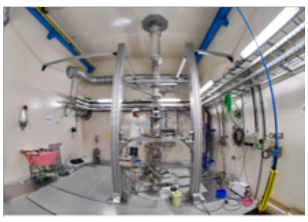


Figure 3. The two n_TOF experimental areas: left EAR1, right EAR2.

5 Scientific program of CERN n_TOF facility : Astrophysics

5.1 Big Bang nucleosynthesis

Nuclear reactions responsible for the ^{7}Be creation and destruction during ig Bang Nucleosynthesis (BBN) play a key role in the determination of the resulting primordial abundance of ^{7}Li, the third chemical element formed during the very early phase of evolution of the Universe. Current standard BBN models predict a ^{7}Li abundance which is a factor of 2-3 larger than what can be determined by astronomical observations. A neutron channel which could enhance the destruction rate of ^{7}Be during BBN has been the subject of recent research activities at n_TOF. The ^{7}Be(n,α) ^{4}He reaction has been measured for the first time in a wide incident neutron energy range, allowing to put severe constrains of one of the ^{7}Be destruction mechanisms during BBN [5]. A second reaction channel, the ^{7}Be(n,p)^{7}Li has been explored, again extending the reaction cross section data to a wider neutron energy range and therefore, allowing for an update of the related reaction rate used in standard BBN network calculations [6]. The new estimate of the ^{7}Be destruction rate based on the obtained experimental results yields a decrease of the predicted Cosmological Lithium abundance of about 10%, insufficient to provide a viable solution to the Cosmological Lithium Problem. Consequently, the two n_TOF measurements allowed to rule out neutron-induced reactions as a potential explanation of the long-standing Cosmological Lithium Problem, leaving all alternative physics and astronomical scenarios still open.

5.2 New perspectives for neutrons in astrophysics

In the scenario of Neutron Star Mergers, the large number of free neutrons per seed nuclei (of the order of a few hundred) leads to the production of heavy fissioning nuclei. A first attempt in this sense has already been successfully performed in the first experimental area, with the challenging measurement of the neutron-induced fission of ^{245}Cm. In that case, data were collected at n_TOF with an accuracy comparable to those obtained by other means, while covering a much wider energy range. A significant step forward in this respect is represented by the high-luminosity neutron beam in the second experimental area (EAR2), that will certainly offer the unique opportunity to collect precious cross section data and fission yields for short-lived actinides of interest for Nuclear Astrophysics. In view of the installation of the new spallation target, that will lead to a further increase of the neutron flux in EAR2, the possibility to perform challenging fission measurements of interest for r-process nucleosynthesis may finally become a reality. Together with fission, challenging capture measurements of relevance for nuclear astrophysics could become feasible in the forthcoming future at n_TOF. As mentioned before, in the study of the s-process nucleosynthesis the knowledge of the capture cross sections of short-lived isotopes acting as branching points is crucial. However, the measurements to date are scarce, mainly due to the difficulty in procuring enough material of the radioactive isotopes of interest and on the associated preparation of a high-quality target. Following the successful experience of recent years, enough material (milligrams) can be produced at the ILL reactor and suitable targets for n_TOF can be produced at PSI. Up to now ^{171}Tm, ^{147}Pm and ^{204}Tl have been measured, and the desirable enhancement of this collaboration between CERN, ILL and PSI could provide n_TOF with targets of isotopes never measured to date. The near-term plans include a more massive ^{147}Pm target and also ^{163}Ho that would be measured at both EAR1 and EAR2 with the improved n_TOF spallation target.

6 Scientific program of CERN n_TOF facility : Nuclear Technologies

The cross-sections of neutron-induced reactions are also key ingredients for the development of present and future nuclear technologies, in particular for safety and criticality assessments in nuclear reactors. The nuclear data needs related to nuclear technologies and other applications are being revised on a continuous way by the International Nuclear Data Committee (INDC) of the International Atomic Energy Agency, and by the Nuclear Energy Agency of the OECD with its Nuclear Data High Priority Request List (HPRL) , a compilation of the most important nuclear data requirements.

6.1 Fission reactors

A significant part of the experimental program of the n_TOF facility has regarded nuclear data needs for nuclear technologies, in particular concerning measurements of radiative capture and fission reaction cross-sections on major and minor actinides. Thanks to the high-performance detection systems available, (n,γ) and (n,f) experimental data have been collected, for example, on the most important isotopes of U, Pu, Np, Th, Cm and Am. In addition, the issue of measuring radiative capture cross-sections on ^{233,235}U fissile isotopes has been addressed, overcoming the difficulty due to the competing γ-ray background from fission reactions with a dedicated detection system allowing to measure at the same time fission and capture reactions.

6.2 New nuclear data needs

Despite the clear effort of the community in providing high-quality nuclear data, new measurements are still needed in order to meet the target accuracies as quoted by the CIELO (Collaborative International Evaluated Library Organization) Project, with special emphasis on data on fissile actinides, starting from ^{233,235}U, ^{239}Pu and ^{245}Cm. In this context, new data of fission yields with better uncertainty assessment (i.e. covariances) are required due to their very important role concerning, for example, safeguards and reactor decay heat. As outlined in Ref. [7], current nuclear data requests are concentrating on the determination of cross-sections relevant for the development of future Generation-IV reactors, and for the study of essential (system-dependent) structural materials, coolants, and inert fuel elements, as Na, Mg, Si, Fe, Mo, Zr, Pb, and Bi. Moreover, neutron induced gas-production reactions – i.e. where the ejectile is H, ^{3}H, ^{4}H or He – on light elements like C, N, F and O is one of the main causes of radiation damage in reactor components. In this context, having access to improved cross-sections in particular in the fast energy region of the neutron spectrum, is becoming increasingly important.

6.3 Perspectives for new nuclear technology applications

Besides the development of new and existing fission nuclear systems, the still open matter of nuclear waste transmutation via accelerator-driven systems (ADS), which consists in combining a subcritical reactor with a spallation neutron source to externally increase the neutron fluence , requires high-energy data up to the GeV energy regime. In the same line of research, further nuclear data requests are dealing with investigations of alternative Th-based nuclear fuel cycles and coolants . Special needs are related to the design and operation of future nuclear fusion devices, where neutron cross-section data must be provided for a variety of nuclides constituting the materials to be used for the breeders, neutron multipliers, coolants, shielding, magnets and insulators. Particularly accurate data around 14 MeV in connection with the production of photons and secondary neutrons are essential for neutron/photon transport calculations. Data related to tritium production, kerma factors, gas production and radiation damage are another important area for cross-section measurements in fusion research.

7 Cross section measurements for medical applications

Neutron-induced reaction data are of key importance in radiation dosimetry for defining the safety hazards related to the neutron beams and for irradiation applications. In medical hadron therapies, this quantitative aspect is particularly crucial to determine the optimum irradiation parameters in tumor treatment, be it for direct fast neutron applications or in boron neutron capture therapy. A variety of neutron data is also mandatory for the production of radioisotopes for medical applications.

7.1 Particle therapy

The accurate and precise knowledge of neutron transport is an essential ingredient for a correct treatment planning in different forms of particle therapy, including not only neutron therapies such as Boron Neutron Capture Therapy (BNCT) [8], or Fast Neutron Therapy , but also the widespread Proton and Heavy Ion therapies[9] In these latter techniques, in fact, direct reactions induced by the highly energetic charged particles generate secondary neutrons that can deliver a significative dose outside the beam active area.

8 Possible future applications

Recently it has been explored the idea to exploit the high neutron flux of the n_TOF facility for applications beyond neutron-induced reaction measurements. In particular, a neutron irradiation station will be set up in the vicinity of the spallation target, and an optimal configuration to perform neutron imaging will be studied for the beam-line going to the second experimental area, interchangeable with the configuration needed for reaction measurements [10].

8.1 Neutron imaging at n_TOF EAR2

Neutron imaging techniques are a well-known tool for non-destructive analysis, which use the peculiar interaction of neutrons with matter to penetrate thick-walled samples[19]. Neutron radiographies are obtained both exploiting the different material densities i.e. sensitive to the neutron elastic scattering and the neutron-induced reaction cross-sections. In this sense, the mass attenuation coefficient is complementary to the one proper of X-rays, making the technique a valid alternative to X-ray radiographies when metal-shielded samples as engineering parts or fine art artifacts should be investigated. Despite neutron imaging is generally performed with thermal neutrons from nuclear reactors, accelerators with spallation targets are becoming suitable sources for neutron imaging as well, offering the advantage that the better penetrability of fast neutrons allows to study bigger objects. In this context, the neutron time-of-flight (n_TOF) facility of CERN could enter in the number of facilities available for neutron radiography and inspection of materials thanks to the high instantaneous flux of the second experimental area. Once set up, there are a number of possible applications to exploit such a neutron imaging station, in particular for a material analysis point of view:

- the analysis of post-irradiated samples at the CERN HiRadMat facility, presently lacking a dedicated hot-cell for damage inspection. Experiments will profit from having a tool for non-destructive inspection to check the integrity of materials after irradiation or to evaluate corrosion;
- the inspection of equipment associated to the n_TOF target cooling and moderator station, like the device which maintains boron at a constant level (so called "pot-a-bore");
- the complementary inspection of welding with energy-selective neutron radiography in order to identify inhomogeneity due to variations in the crystals lattice properties of the material in the weld zone;
- the measurement of humidity transport in soils or concrete, due to the sensitivity of the neutron radiography to small amounts of hydrogenous compounds in a matrix.

8.2 n_TOF neutron irradiation station

Radiation-induced effects in structural and shielding materials, as well as in microelectronic components, represent an increasing safety issue especially for life-critical and safety-critical applications such as aviation, industrial automation, medical devices, automotive electronics, and communication infrastructure. In this respect, neutrons produced by cosmic-ray interactions in the atmosphere are one amongst the major source of malfunctions in integrated circuits due to single event upsets [11]. There is therefore a growing need for irradiation facilities able to perform quantitative measurements of neutron radiation damages, including in the high energy part of the neutron spectrum, difficult to reach at research reactors. In the context of the installation of a new spallation target in the n_TOF target pit, we are studying the possibility to modify the shielding located around the pit to install a neutron irradiation facility. That would nicely complement the suite of irradiation facilities available at CERN, with a high intensity mixed field, composed by neutrons and photons. Thanks to the cumulative dose reached, the facility would allow testing radiation effects on mechanical properties, mimic conditions expected in many installations at CERNincluding critical LHC zones in the HL-LHC era-and allowing the study of the resistance of materials to cosmic rays, as electronics on space stations, satellites, and future accelerators. Besides radiation-damage studies, the irradiation station can be used to measure neutron cross-sections measurements via the activation technique. In particular, we propose to study a set of (n,lcp) (lcp = α, p, d, etc.) cross sections of relevance in nuclear astrophysics and technology.

9 Summary

Since its start of operation, in 2001, a rich experimental program has been carried out at the n_TOF facility, resulting in a wealth of high-quality data on neutron-induced reactions of interest for Nuclear Astrophysics, advanced nuclear technologies and medical applications.
The main features of the n_TOF neutron beam in the two experimental areas, i.e. the high instantaneous neutron flux, high-resolution and wide energy range, make this installation unique in the landscape of neutron facilities worldwide. Combined with state-of-the-art detection systems, such features have finally made feasible challenging measurements of neutron-induced reactions, in particular on radioactive isotopes of relatively short half-life, of crucial importance for different fields in basic and applied nuclear physics, from stellar nucleosynthesis, to new

technological applications for energy, environmental and medical science.
The experimental program carried out so far has only partially exploited the potentialities of the n_TOF facility, that have been further expanded with the construction of the high-luminosity second experimental area in 2014. In Nuclear Astrophysics, while an important contribution has already been provided by n_TOF, much remains to be done in order to improve the knowledge of processes leading to the production of heavy elements in the Universe, namely the s-process nucleosynthesis occurring in AGB stars, and the r-process taking place in explosive scenarios like Supernovae and Neutron Star Mergers. In particular, n_TOF represents today a unique facility for studies of neutron capture reactions on unstable s-process branch point isotopes, as proven by the successful measurements of ^{151}Sm ($t_{1/2}$=90 yr) and ^{93}Zr ($t_{1/2}$=1.5E6 yr). Such studies can be extended in the future to include even more challenging cases, like ^{134}Cs ($t_{1/2}$=2.1 yr), ^{85}Kr ($t_{1/2}$=10.7 yr) or the very short-lived 185 W ($t_{1/2}$=75.4 d). In all these cases, the much larger instantaneous neutron flux of n_TOF, compared to other existing facilities, results in a greatly enhanced signal-to-background ratio, for the background related to the natural radioactivity of the sample.
Similarly, the high-luminosity and wide energy range of the n_TOF neutron beams are key features for high-accuracy measurements of neutron-induced fission cross sections, of relevance for the so-called fission recycling in r-process nucleosynthesis. This is particularly important in the scenario of Neutron Star Mergers (NSM), where the large number of free neutrons leads to the production of heavy fissioning nuclei. In that context, fission processes play an important role in shaping the abundance distribution of heavy nuclei, by recycling matter during irradiation, and are expected to contribute to the heating of the ejected material. While fission cross sections and fission yields have already been measured in the first experimental area for actinides of half-life >1000 y, the much larger signal-to-background ratio that can be achieved in the high-luminosity second experimental area is finally allowing fission studies of actinides of half-life as short as a few years. An important future goal will be to collect high-accuracy, high-resolution fission data on a complete isotopic chain, such as from ^{244}Cm to ^{247}Cm, providing for the first time much needed data for improving the modelling of fission recycling in r-process nucleosynthesis in NSM.
Neutron-induced reactions also play a key role in a variety of technological applications. In the field of nuclear energy, new cross section data are needed to improve the reliability of safety and criticality calculations for current fission reactors, as well as to estimate the production and evolution of high-level nuclear waste. New data are required for the development of advanced reactor concepts, such as future Generation IV or nuclear systems dedicated to nuclear waste transmutation. In both cases, neutron capture cross sections are needed for a number of fission fragments and actinides, while for these last ones, neutron-induced fission cross sections are also required.
Like for Nuclear Astrophysics, the n_TOF experimental program has already provided a significant contribution to the field, addressing many High Priority Nuclear Data requests and helping improving the accuracy of current evaluated cross sections, in particular those under the responsibility of the International Atomic Energy Agency. While most measurements have regarded so far long-lived fission fragments and actinides, future programs will concentrate on short-lived ones, thanks to the extremely high flux of the second experimental area, whose performances will be further optimized with the new spallation target. New measurements of capture and fission reactions will be performed on the short-lived Pu and Cm isotopes, being n_TOF currently the only place in the world were data of the required accuracy can be collected on these nuclei. We recall here that these are the very same data needed for modelling fission recycling in r-process nucleosynthesis, confirming the interdisciplinary nature that has characterized the experimental program at n_TOF since its early days of operation, and will continue to do so.
Together with capture and fission reactions, the n_TOF Collaboration has recently undertaken a new line of research, with measurements of reactions leading to charged particle emission, in particular (n,p) and (n,α) reactions, as well as inelastic reaction. The main goal of the foreseen program will be to address the pressing needs related to the development of future nuclear fusion reactors, such as ITER and DEMO, in particular the H and He gas production in structural material, due to neutron irradiation during operation. The recent measurements in EAR2 of the extremely challenging ^{7}Be(n,p) and (n,α) reaction, of interest for the Cosmological Lithium Problem, have demonstrated the great capability of the n_TOF facility for these type of measurements, paving the way towards the important area of neutron measurements in fusion research.
A final remark regards research for nuclear medicine. Measurements performed at n_TOF in this field have so far regarded radiation oncology, such as sulfur-enhanced neutron therapy, but new needs are emerging in this field. For example, the development of theranostic nuclear medicine procedures (theranostic being the combination of therapy and diagnostic) is calling for new data on new radioisotope production, such as on the ^{177}Lu precursor ^{177}Yb produced by neutron capture of ^{176}Yb.
In conclusion, in almost twenty years of operation n_TOF has been one of, if not the, most productive neutron facility in the world, with forefront research being performed thanks to the innovative features of the neutron beams and the synergy of groups with various competences and expertise. As new needs of nuclear data for fundamental and applied science are continuously emerging, the facility has all potentialities to continue play in the future a world-leading role in the field of neutron physics with accelerators.

References

[1] C. Rubbia et al., CERN/LHC/98-002-EET, 1998.

[2] E. Chiaveri et al., Nucl. Inst. Meth. A 743 (2014) 79

[3] http://public.web.cern.ch/public/en/research/NTOF-en.html

[4] C. Weiß et al., Nucl. Inst. Meth. A 799 (2015) 90

[5] M. Barbagallo,et al. Physical Review Letters 117, 152701 (2016)

[6] L. Damone et al., Physical Review Letters 121 (2018) 042701

[7] T. Ault, S. Krahn, A. Croff, Annals of Nuclear Energy 110 (2017) 726

[8] W.A.G. Sauerwein, R.L. Moss, Requirements for Boron Neutron Capture Therapy (BNCT) at a Nuclear Research Reactor, European Communities (2009) http://dx.doi.org/10.2790/11743

[9] S. Dangtip et al., Nucl. Inst. Meth. A 452 (2000) 484

[10] Mingrone, F. et al., n_TOF Collaboration, Development of a Neutron Imaging Station at the n_TOF Facility of CERN and Applications to Beam Intercepting Devices. Instruments 2019, 3, 32.

[11] M. Calviani, O. Aberle - Roadmap for the Implementation of a New Target Mobile Shielding and a NEAR Experimental Station at the n_TOF Facility – EDMS 2158356 (TOF-PM-WD-0001), CERN, May 2019