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

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Since the start of its operation in 2001, based on an idea of Prof. Carlo Rubbia, the neutron time-of-flight facility of CERN, n_TOF, has become one of the most forefront neutron facilities in the world for 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 station.

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 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 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's 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.

1. 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, for a total of 127 scientists, of which 27 are PhD students.

2. 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 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.

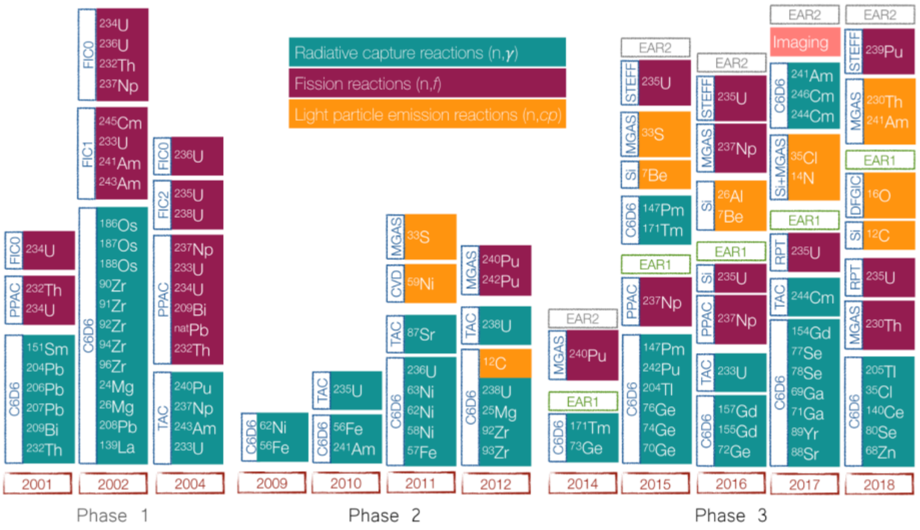

Figure 1. Experimental progamme of the n_TOF facility during its three measurement phases. The different reactions are divided in radiative capture (green), fission (purple) and charged-particle emission (orange).

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[1] database and are being adopted for cross section evaluation in the major nuclear data libraries such as JEFF[2],ENDF/B[3],and JENDL[4].

3. 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, 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 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 [2,3](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 $2x10^5$ 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 [4][5] (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

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[1] http://dx.doi.org/10.1051/epjconf/201714607003

[2] http://www.nea.fr/dbdata/nds_jefreports/

[3] http://dx.doi.org/10.1016/j.nds.2018.02.001

[4] http://dx.doi.org/10.3327/jnst.48.1

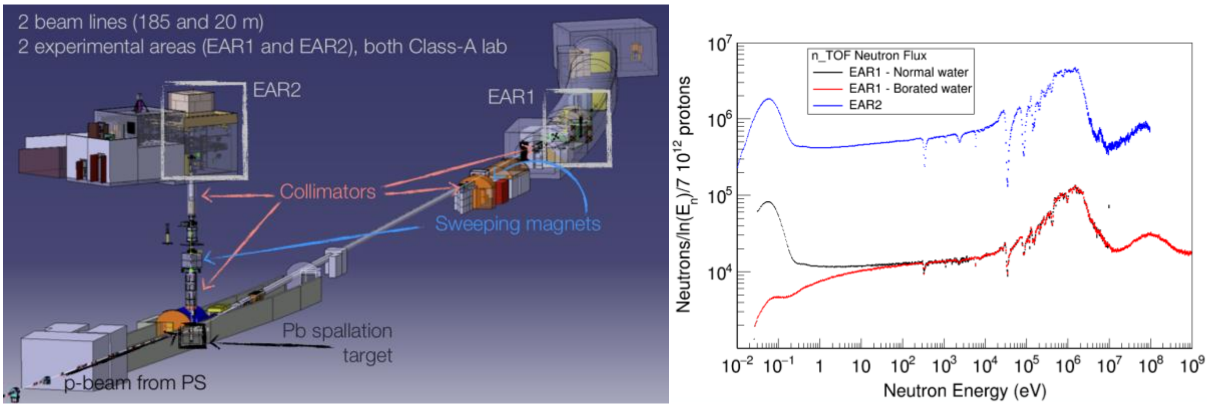

Figure 2. (Left) Scheme of the n TOF facility as in 2018. (Right) Neutron flux in EAR1 (black and red lines) and EAR2 (blue line) as a function of the neutron energy. In the low neutron energy region the difference resulting in using normal (black) or borated (red) water can be seen.

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). Recently, the high intensity neutron beam of EAR2 has been exploited to perform neutron radiography on highly activated targets, successfully proving the feasibility of the technique (Fig.3).

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 optimized 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.

4. Nuclear Astrophysics at n_TOF: the importance of neutron cross section data for modelling stellar evolution and nucleosynthesis

In the framework of nuclear astrophysics, neutron data are of fundamental importance for understanding the origin of both the lightest and the heavy chemical elements, i.e. where and how the nuclei present in the Universe have been synthesized. While nuclear fusion reactions in stars are responsible for the synthesis of nuclei up to the Fe–Ni region, neutron-induced reactions play a role in the primordial nucleosynthesis of light elements shortly after the Big Bang [6], and are at the basis of the production of the majority of nuclei heavier than Fe during the He and C burning phases of stellar evolution [7,8], in the final supernova explosion of massive stars, and in neutron star mergers.

Therefore, in order to properly assess the validity of the different stellar and nucleosynthesis models, neutron-induced reaction cross-sections as accurate and precise as possible are needed, being the fundamental nuclear data inputs in model calculations [9]].

4.1. *Stellar nucleosynthesis.* – Approximately half of the elemental abundances between iron and bismuth are produced by the slow neutron capture process ("s process") while the other half is contributed by the rapid neutron capture process ("r process"). Generally speaking, the s process can be associated with the quiet, slow burning phases of stellar evolution while the r process can be assigned to explosive scenarios such as supernovae and/or peculiar events such as merging of neutron stars. Both, the s and r process, are based on neutron capture reactions.

In particular, for the s process there is a direct correlation between the neutron capture cross section, $\sigma(n,\gamma)$, and the observed abundance of a given isotope. This correlation makes it necessary to obtain neutron capture cross section data of all isotopes along the valley of β-stability, a program which has been going on since the early days of nuclear astrophysics. Particularly unique features of s process nucleosynthesis are branching points in the reaction path. Despite the majority of unstable isotopes decays so fast that neutron capture becomes negligible, a number of isotopes exhibist half-lives comparable with the neutron capture time (typically of the order of one year), and the resulting competition gives rise to a branching of the reaction path. A detailed analysis of such branching isotopes is at the same time important and fascinating, since the evolving abundance patterns reflect the physical, thermodynamic conditions of the stellar site in which the s process takes place. In the simplest case, the s-process branchings depend on the stellar neutron flux, but some branching ratios are strongly influenced by temperature, pressure, or even by the convective motions in the deep stellar interior.

Recently, this classic picture describing the s process nucleosynthesis chain has been enriched by the enormous progress made by astronomical observations, as well as by important developments in understanding and modelling stellar evolution. Not only the need for neutron capture cross sections is enhanced by these recent developments, but the necessity of high accuracy is evident. For instance, the accuracy at the level of a few percent is mandatory for studying the details of the s process taking place in AGB stars in a realistic fashion. In addition, a huge step forward in this matter has resulted from the recent multi-messenger observation of a Neutron Star Merger (NSM) in August 2017. The simultaneous detection of gravitation waves, gamma-ray burst and electromagnetic radiation in the optical and near-optical range has unequivocally demonstrated that NSM are an important, if not the most important, site for r process nucleosynthesis, and has provided a wealth of data, that will open the way to a refinement of current r process models. Once again, the importance of assessing reliably the r process abundance distribution, points to the necessity of a reliable determination of s process abundance components, hence, of accurate neutron capture cross section data.

Based on these considerations, an experimental program to be performed at n_TOF has been defined. This program includes capture cross section measurements on the stable isotopes of Fe, Ni, Zn, and Se, which are produced by s-process nucleosynthesis in massive stars and, in a number of cases, the respective neutron capture cross sections act as bottle-necks in the s-process reaction flow strongly affecting the production of the elements with higher masses. In addition to the stable isotopes, measurements on some radioactive targets in the same mass region have to be performed at n_TOF. Examples of branchings related to the weak s process are ^{63}Ni ($t_{1/2}$ = 100 years) and ^{79}Se ($t_{1/2}$ = 6.3x10^4 years). New data on nuclei acting as bottleneck in the s-process flow and on key branching isotopes are required, now more than ever, to improve our knowledge of the heavy element production in the Universe and its chemical evolution.

4.2. *Big Bang nucleosynthesis.* – Nuclear reactions responsible for the ^{7}Be creation and destruction during Big 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 [10]. 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 [11].

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.

4.3. *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. As a consequence, neutron-induced fission reactions and spontaneous fission play a fundamental role in the process, by recycling matter during neutron irradiation. Such process, referred to as "fission recycling" has an important effect on shaping the abundance distribution of r-nuclei in the mass region between A=110 and 170, as well as in determining the residual production of heavy nuclei, in particular Pb, Bi, Th and U. Finally, fission processes during r-process nucleosynthesis are expected to contribute to the heating of the material, due to the large energy released. The effect of fission recycling depends on the fission probabilities of a large number of, mostly neutron-rich, nuclei. For the vast majority of these nuclei one can only rely on model prediction to estimate fission cross sections and fission yields (i.e. the mass distribution of fission fragments), which at presently are highly uncertain and show discrepancies up to a factor of ten relative to the reference experimental cross sections. More work is therefore necessary to improve the situation towards more coherent and reliable fission models, and to this end a great help could come from new experimental data on actinides that have not been measured so far, or whose experimental cross section is affected by a large uncertainty. 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.

In addition, a second group of isotopes of interest consists of the stable isotopes of Mo, Ru, and Pd. Their neutron capture cross sections are required for two main objectives: for the interpretation of the isotopic patterns in pre-solar SiC grains, which represents the most direct information on the s-process efficiency of individual stars, and for the reliable determination of the r-process abundances (r-process residuals) in the critical mass region between Zr and Ba.

5. Scientific program related to 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)[5] of the International Atomic Energy Agency, and by the Nuclear Energy Agency of the OECD with its Nuclear Data High Priority Request List (HPRL)[6], a compilation of the most important nuclear data requirements.

5.1. *Fission reactors.* – Neutron-induced reaction cross-sections are key nuclear data inputs for a variety of calculations and simulations exploited in the design of critical and subcritical nuclear systems. In particular, the prediction of the behavior of the reactor cores depends strongly on capture and fission cross-section data, and crucial parameters such as the multiplication factor k_{eff}, the power peak (i.e. the ratio between the maximum and the average peak density), the reactivity coefficients (i.e. the deviation of reactors from critical state), the nuclear density variation of isotopes due to transmutation and the decay heat strongly depend on the Nuclear Data (ND) used in calculations and projections.

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.

5.2. *New nuclear data needs.* – Despite the clear effort of the community in providing high-quality nuclear data, new measurements are still advisable 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. [12], 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

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[5] https://www-nds.iaea.org/indc/

[6] https://www.oecd-nea.org/dbdata/hprl/

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.

5.3. *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 [13], 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 [14].

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[7] factors, gas production and radiation damage are another important area for cross-section measurements in fusion research.

6. 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.

6.1. *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) [15], or Fast Neutron Therapy [16], but also the widespread Proton and Heavy Ion therapies [17]. 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.

Despite their importance, however, for some of the major elements composing the biological tissue as C, N, and O, there is a lack of microscopic cross-section information [4]. In particular, neutron dosimetry will greatly benefit from more accurate data in a wider energy range for neutron-induced reactions on C and O, in order to better describe the A150 tissue-equivalent plastic/muscle kerma ratio . In addition, the radiative neutron capture on N is responsible for a part of the dose delivered in BNCT treatments due to the high Q-value – and the consequent large photon emission – of the reaction. The scarcity of the existing data sets for this cross section urges new measurements to obtain the accurate and precise experimental data needed for a more truthful BNCT dose planning.

6.2. *Medical radioisotope production.* – The EU Observatory for the supply of medical radioisotopes and the International Agency for Atomic Energy (IAEA) warn about the scarce availability of ^{99}Mo (parent of ^{99m}Tc, the most used radioactive tracer in nuclear medicine) and urge the international community to investigate new alternatives for its production. In this context, a promising route is to exploit the ^{100}Mo(n,2n) reaction with high energy neutrons [8], which should

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[7] Kerma is an acronym for *kinetic energy released per unit mass*, defined as the sum of the initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation in a sample of matter, divided by the mass of the sample.

therefore be determined with high accuracy together with the collateral ^{98}Mo(n,x) reactions that can lead to impurities. Another radioisotope that is increasingly used in theranostic nuclear medicine procedures (theranostic being the combination of therapy and diagnostic) is ^{177}Lu, thanks to its chemical properties and its simultaneous emission of imageable gamma photons along with the β-electrons suitable for therapy. Recently, its production is being performed by the indirect carrier-free route ^{176}Yb(n,γ), which leads to ^{177}Yb subsequently decaying in a few hours to the longer living ^{177}Lu. In the next future, the development of compact accelerator neutron sources in the epithermal and fast range opens the possibility of ^{177}Lu production by adiabatic resonance crossing.

For a correct estimation of the production yields in massive targets for both ^{99}Mo and ^{177}Yb, there is a great need of neutron-induced reaction cross-section data in a wide energy spectrum – covering the thermal, the resolved resonance as well as the fast energy region. The same applies to the production of other commonly used medical isotopes via (n,γ) reactions on ^{124}Xe, which leads to the precursor of ^{125}I, ^{130}Te (^{131}I), ^{104}Ru (^{105}Rh), and with less importance ^{103}Rh, ^{154,155}Eu, ^{141,140}Ce and Sn (stable isotopes).

7. Spin-off of the n_TOF facility

Recently progresses have been made towards the idea of exploiting the high pulsed neutron flux of the n_TOF facility for applications beyond neutron-induced reaction measurements. In particular, two developments are envisaged for the future: a neutron irradiation station set up in the vicinity of the spallation target, and an optimal configuration to perform neutron imaging in the beam-line leading to the second experimental area, interchangeable with the configuration needed for cross section remeasurements.

7.1. *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 [18]. Neutron radiographies are obtained both by exploiting the different material densities – i.e. using neutron elastic scattering – and/or by material analysis based on their 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 in the investigation of metal-shielded samples, such as engineering components or fine art artifacts.

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 of a higher penetrability of fast neutrons, that allows to study bigger objects. In this context, the neutron time-of-flight (n_TOF) facility of CERN could join the number of facilities available worldwide for neutron radiography and inspection of materials thanks to the high instantaneous flux of the second experimental area and the possibility to measure highly radioactive or contaminated components thanks to EAR2 being a class-A laboratory.

Given the success of the proof of concept experiment, consisting in an analysis of the inner structure of an irradiated Antiproton Decelerator (AD) target, an upgrade is needed and advisable to make the facility efficiently suited for neutron examination and material studies. On the one hand, from the facility point of view, a new collimation system needs to be designed and built to optimize the beam characteristics. This can be planned in two subsequent phases, with the first one, less invasive, consisting in testing the achievable intrinsic spatial resolution of the facility by collimating thermal neutrons with Cd filters. On the other hand, new detection systems need to be studied and developed to exploit at maximum the potentialities of the n_TOF neutron beam. Firstly, a faster and more solid scintillator should be used, as the ZnS, used for the initial test, proved inefficient for measurement with a pulsed neutron beam where the acquisition is open for few μsec. Secondly, exploiting the time-of-flight technique proper of the facility will open new possibilities. For examples, material identification could become possible by coupling the imaging system with scintillators, and – as a more challenging developments – the use of fast Micro-

Channel Plate (MCP) detectors as imaging devices could lead to material-sensitive radiographies. In addition, if equipped with neutron detectors, the facility can give information about neutron diffraction, providing material scientists with important information for engineering materials.

Once set up, a neutron imaging station could be exploited for a number of possible applications, in particular from the point of view of material analysis:

- the analysis of post-irradiated samples at the CERN's 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 inhomogeneities due to variations in the crystals lattice properties of the material in the weld zone.

7.2 *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 amongst the major source of malfunctions in integrated circuits due to single event upsets. 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 [19].

In the context of the installation of a new spallation target at n_TOF, we are studying the possibility to modify the shielding located around the target pit to install a neutron irradiation facility by means of a pneumatic rabbit-like system. This installation 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 CERN – including critical LHC zones in the HL-LHC era – and allowi the study of the resistance of materials to cosmic rays, like electronics on space stations, satellites and future accelerators. Moreover, dosimetry measurements could be foreseen, using diamond detectors that behave more similarly to human tissues compared to silicon.

Besides radiation-damage studies, the irradiation station can be used to measure neutron cross-section 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. The respective cross sections can be accurately determined by means of the common experimental techniques applied in activation studies (gamma counting or accelerator mass spectrometry). In this sense, the insertion of a high precision calorimeter for the analysis of the activated samples before the hood for the preparation of containers is under study. Moreover, the possibility of making active irradiation measurements is being explored, with the use of battery-powered Diamondpix detectors.

In addition, such an irradiation facility would possibly allow the production of radioactive isotopes, to be later measured in both n_TOF experimental areas, or to be exploited in close collaboration with ISOLDE. In the context of exploring synergies between the ISOLDE and n_TOF facilities, as it has been happening since a number of years, the construction of an irradiation station at n_TOF would in fact allow for a closer scientific program, where isotopes and regions of the nuclide chart currently inaccessible to ISOLDE via proton irradiation would be opened up due to neutron activation. This – combined with the ion source knowledge at ISOLDE – could lead to a much-improved production of neutron rich elements, paving the way to unique experiments in the domains of astrophysics and nuclear structure. In addition, the ability to irradiate with neutrons within CERN would attract significant interest from the nuclear solid state and medical community which already constitute a significant part of the ISOLDE community.

Finally the facility could be used as a tool for geologic dating. One important field of research in geology is the understanding and predictive modelling of the evolution of the continental surface, especially laterites, in response to climatic and geodynamic forcings. By revealing the record of ancient formation conditions, it is possible to quantify weathering processes as a function of time. This is done by dating minerals contained in laterites, through the decay of uranium and thorium (UTh), by measuring the helium and UTh contents. However the small size of microcrystals embedding UTh induces, already at tropical temperatures, some He loss by diffusion which has to be corrected for. The amount of He loss can be assessed from the internal profile of He4 in the crystals, which is probed by step heating degassing in vacuum.

However a reference profile is needed, preferably uniform. The purpose of the Irradiation is to create a uniform profile of He3 which has the same diffusivity as He4 and the degassing of He4 and He3 are measured. The production of He3 requires high energy particles higher than 100 MeV. Protons are an option, but the risk is the temperature rise due to the energy deposition by electronic interaction, which would result in additional He losses [20]. The other option is the neutron irradiation but energetic neutrons are needed so the n_TOF irradiation facility would be well suited.

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