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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Expression of Interest to the SPS and PS Experiments Committee

Neutron Activation Station at the SPS Beam Dump Facility (BDF)

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Abstract: The recently endorsed SPS Beam Dump Facility will produce ultra-high neutron fluxes over a wide energy range. We propose to exploit these high neutron fluxes by installation of a close target activation station with a pneumatic rabbit for measurements of neutron induced cross sections. The setup can be operated parasitically, without affecting the physics case of the SHiP experiment. The new facility will allow challenging measurements of key nuclear reactions for the first time, of urgent need in the fields of nuclear astrophysics, nuclear energy and nuclear medicine.

1 Introduction

The SPS Beam Dump Facility (BDF) is a recently endorsed infrastructure in the CERN's North Area [1] to be exploited by the "Search for Hidden Particles (SHiP)" experiment [2]. At the core of the facility, a high-Z spallation target/dump will be located to absorb proton beams at 400 GeV/c with an intensity of 4×10^{13} protons per cycle, with an average beam power of roughly 350 kW [3, 4], most of it fully deposited in the target.

The high neutron fluxes produced by the spallation process will not be employed by SHiP and will be absorbed by the target station bunker. There is therefore a unique opportunity to passively exploit these neutrons without affecting the physics case of the SHiP facility; the study of neutron - nucleus reactions via the activation technique is an excellent candidate for this.

With this Expression of Interest, the CERN n_TOF Collaboration [5] proposes the installation of a close-target activation position in combination with a pneumatic rabbit system which will transfer the activated material to the measurement station. This setup can be operated parasitically with respect to the main science programme of BDF, allowing for studies of challenging neutron capture cross sections measurements, very difficult or impossible to perform with alternative techniques, such as time-of-flight methods.

Neutron induced reaction cross sections are of high importance in nuclear astrophysics [6, 7], advanced technologies for nuclear energy [8] and nuclear medicine. Since 2001, the n_TOF Collaboration has performed world-leading research, studying neutron induced reaction cross sections with the time-of-flight technique (e.g. [9, 10, 11]). This technique allows determination of energy dependent reaction cross sections via measurement of the time of flight of the neutrons reacting with the target nuclei under investigation. However, the measurement of extremely small sample masses (often the case for radioactive samples) is challenging. The main reasons are beam induced backgrounds, the necessity to perform the measurements at considerable distance from the neutron source to optimise neutron energy resolution, and the need to pulse the neutron beam. The latter two requirements result in a reduction of the time integrated neutron flux achievable.

A complementary technique is the activation technique, which, in contrast to time-of-flight, is limited to cases where the reaction product is unstable. The activation technique consists of irradiating the samples with neutrons for a certain duration, and subsequent measurement of the reaction products either by decay counting, or high sensitivity mass spectrometry, for example Accelerator Mass Spectrometry [12]. The activation technique allows the study of smaller sample masses, since it does not require a pulsed neutron beam and measurements can be performed in close geometry. In addition, beam related backgrounds do not play a role. The BDF facility provides the unique opportunity to complement our activities at the n_TOF facility to study important neutron induced reactions that are not possible to measure via the time-of-flight technique. The high neutron fluxes will allow activation of extremely small mass samples, down to only ng of material. This is in line with the quantities that can typically be produced by implantation at a radioactive beam facility, such as nearby CERN ISOLDE, for which incidentally an improvement program is currently planned in order to increase the physics reach of the facility. Other routes to produce radioactive samples is via nuclear reactions, for example by irradiation in a thermal reactor. We also propose the installation of a pneumatic rabbit system, which will allow transfer of the irradiated material from the close target activation position, to the measurement station within a few tens of seconds. This will enable us to measure short-lived reaction products with only seconds of half life.

Advantages of a neutron activation station at BDF

An activation station at the BDF facility will provide a unique facility to measure neutron cross sections. Neutron fluxes are expected to be more than three orders of magnitude higher than at the existing a-NEAR station (see Fig. 3) [13], opening up opportunities for new key reaction measurements (see Sec 3). The use of neutron filters allows measurement of a range of different neutron energy spectra, which is usually needed for astrophysical and nuclear energy applications. The location at CERN is perfect. Firstly, the proximity to the n_TOF facility provides world-leading expertise in neutron reaction measurements by members of the n_TOF Collaboration. In addition, the nearby CERN ISOLDE facility will allow the production of radioactive samples and subsequent activation measurement in quick succession. The presence of the ISOLDE-MEDICIS infrastructure with the off-line separators also adds on to these capabilities. The n_TOF Collaboration has also long-standing collaboration with radio-chemists from the PSI-Villigen laboratory on the purificataion and preparation of very rare or radioactive samples. A well consolidated collaboration between n_TOF, PSI and ILL-Grenoble will also allow for the procurement of unique samples for activation experiments at the new facility. The stage of development of the Beam Dump Facility at present, still allows the flexibility of a relatively simple space reservation for a neutron activation station. The combination of all these features will result in a world-wide unique facility for the measurement of key neutron induced reactions via the activation technique.

2 Conceptual implementation at BDF

The target station of the SPS Beam Dump Facility includes a vacuum vessel that contains the production target as well as the first layer of water-cooled shielding (internal shielding). Outside the vessel, a hybrid configuration of cast iron and concrete is implemented as external shielding. A neutron activation station at the BDF would require modifying the current design of the external shielding to create space for various irradiation slots.

Specifically, four configurations of opportunistic irradiation stations have been envisaged at this stage (see Fig. 1):

- High-fluence, in-vessel, irradiation module (BHFIM)
- External activation station (BEAS)
- Internal activation/irradiation station (BIAS)
- Rabbit irradiation system (BRIS)

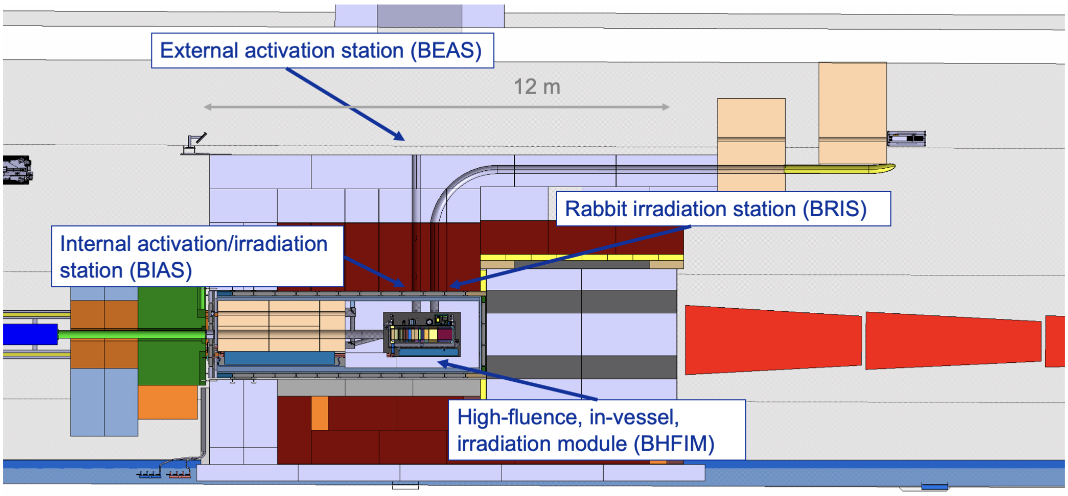

Figure 1: Top view of the BDF target station, modified in this sketch to provide a view of the potential location of the additional irradiation and activation stations.

BHFIM, located inside the vacuum vessel next to the production target, is beyond the scope of this EoI and will be discussed elsewhere. This area would provide unique neutron fluences up to 400 MGy/y for high-dose mixed field irradiation.

A measuring station at BEAS would require creating a penetration in the external shielding to extract a neutron beam from the target, similar to the method used at NEAR in n_TOF. Accessibility and irradiation conditions would be comparable to those currently available at NEAR, with a total neutron fluence of approximately 10^{13} neutrons/cm^2/h, which is at least 30 times higher than at NEAR.

An irradiation position at BIAS would enable an increase in hourly neutron fluence by about a factor of 150 compared to BEAS, reaching up to 1.6×10^{15} neutrons/cm^2/h and 4 kGy/h. Handling of samples would be possible using a dedicated handling tool, allowing for installation and removal from the transport side.

Both BEAS and BIAS are accessible only during periods of beam absence from BDF/SHiP, or during Technical Stops or Year-end Technical Stops. This limited access could pose challenges for activation measurements, as the required cooldown times to access the BDF target station would prevent the measurement of isotopes with very short half-lives. To overcome this limitation, the target station could be equipped with a rabbit system (BRIS), which—with similar fluences as BIAS—would allow for the insertion and removal of samples independently of the operational status of BDF/SHiP. An irradiation capsule could then be transported via an ad-hoc system to the target surface building in a dedicated receiving station within a few tens of seconds, enabling the measurement of isotopes with very short half-lives. A conceptual implementation of such a system is shown in Fig. 2, based on a study conducted with an external contractor. The rabbit will be designed in order to never endanger at any time the operation of BDF/SHiP.

This technology already exists and is derived from systems used in reactors for the production of radioisotopes for medical applications.

The various neutron spectra for the proposed station are reported in Fig. 3

The installation of a fixed moderator on the target assembly is possible and compatible

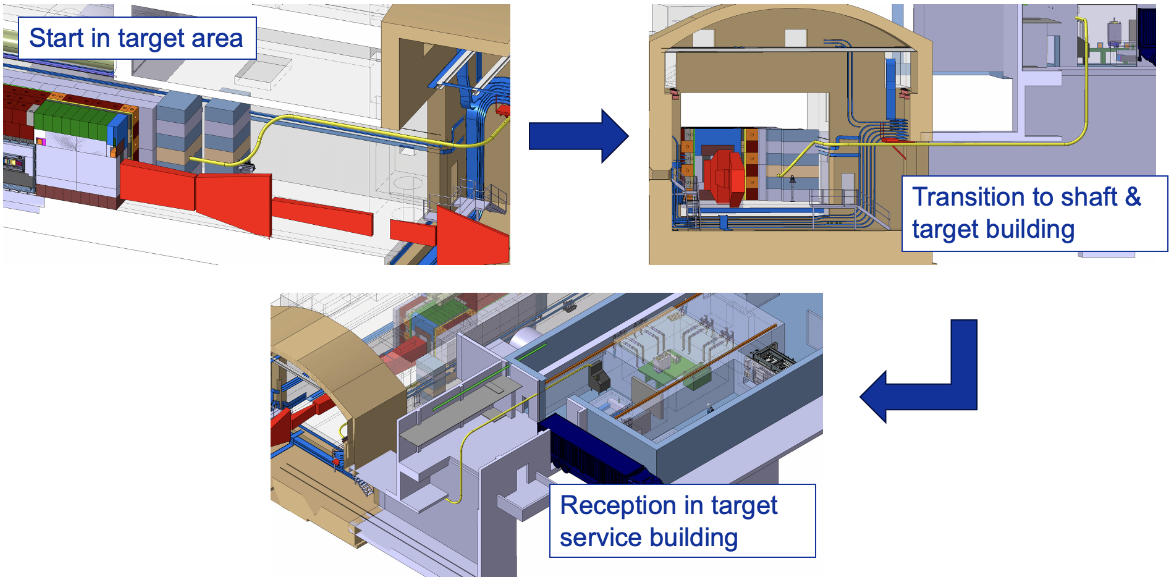

Figure 2: Conceptual design of the transport path for BRIS from the BDF Target station to the surface building, where a dedicated receiving station would be realized.

with the main physics case of the BDF/SHiP facility. In order to simplify handling in target systems, it is suggested to consider inert moderator systems.

2.1 Neutron Spectral Shaping

The neutron energy distribution at BDF spans over several orders of magnitude (see Fig. 4), a unique case amongst neutron facilities, and available thanks to the high energy proton beam. The use of neutron B_4C filters of different thicknesses allows shaping of the neutron flux to neutron spectra which resemble Maxwellian neutron energy distributions of different stellar temperatures. This makes the methodology ideal for nuclear astrophysics studies since the stellar cross section can be determined from the spectrum averaged cross section by only applying a small correction. The quality of the spectra could possibly be further improved by installation of a permanent moderator, which would shift the neutron spectrum towards lower neutron energies. This will be investigated in detail in the development phase, but is in principle compatible with the design for BDF (see Sec 2).

The collaboration gained considerable experience in neutron spectral shaping for activation studies at the n_TOF NEAR irradiation station [13, 14]. Our simulations and preliminary experimental results show that using B_4C neutron filters can shape the initial neutron spectra to resemble the stellar Maxwellian neutron distribution. The use of different thicknesses allows to access spectra corresponding to different stellar temperature. Fig. 5 shows the neutron spectrum resulting from a 1.65 mm B_4C filter compared to a Maxwellian spectrum at $kT = 8$ keV (left) and the neutron spectrum resulting from a 3.25 mm B_4C compared to a Maxwellian spectrum at $kT = 25$ keV. These temperatures (kT-values) are found for example in Red Giant stars during slow

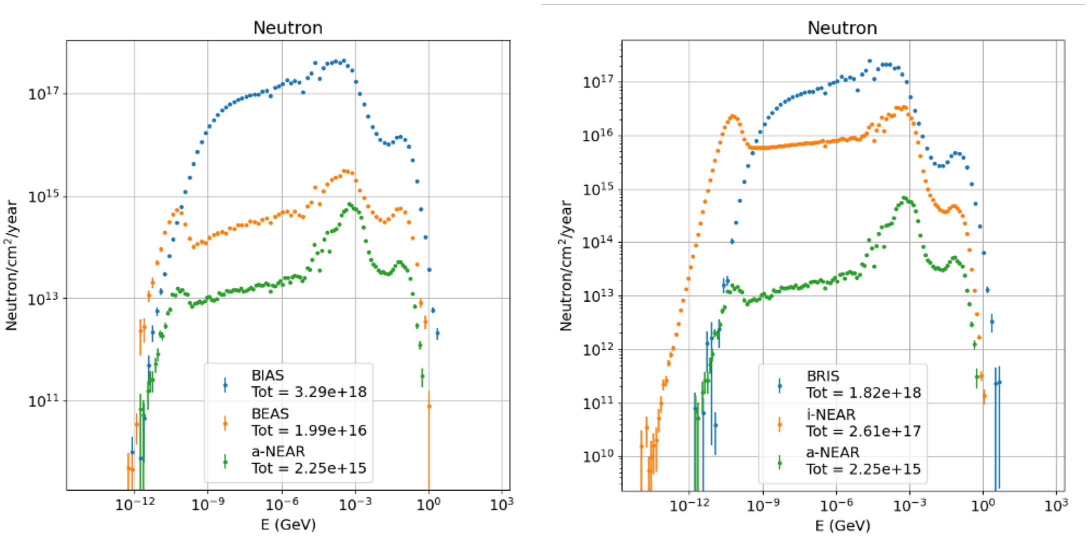

Figure 3: Neutron spectra of the various proposed irradiation/activation stations at BDF, compared with the a-NEAR and i-NEAR values [13].

neutron capture nucleosynthesis.

3 Science Cases

Neutron induced reaction cross sections are essential for studying cosmic nucleosynthesis processes and advanced nuclear technologies. The following sections list measurements that could be performed at the Activation station of BDF.

3.1 s-process branching points

The slow neutron capture process (s-process) in stars is responsible for about half of the elemental abundances heavier than iron and is characterised by a sequence of neutron captures followed by radioactive β-decays. Neutron capture cross sections on s-process branching points, i.e. radioactive isotopes where the s-process path branches due to the competition between β-decay and subsequent neutron capture, can give important clues about stellar conditions, such as neutron densities, temperatures and density [6] (see Fig 6). A number of these cross sections have been studied at n_TOF, however in some cases the in-beam background precluded a measurement of the cross section over the entire stellar neutron energy range. We propose measurement of stellar neutron capture cross sections on the radioactive ^{94}Nb, ^{147}Pm, ^{163}Ho and ^{171}Tm.

Despite important efforts in the past, several relevant s-process branching nuclei could not be accessed at all via TOF, like for example ^{147}Pm [15] or ^{163}Ho(n,γ) [16]. In the case of ^{94}Nb [17] and ^{171}Tm [16, 10], previous activation and TOF attempts were still rather limited, both in terms of neutron-energy range and accuracy. The only capture-data on ^{147}Pm corresponds to two activation experiments at $kT = 25$ keV [18, 19]. An attempt

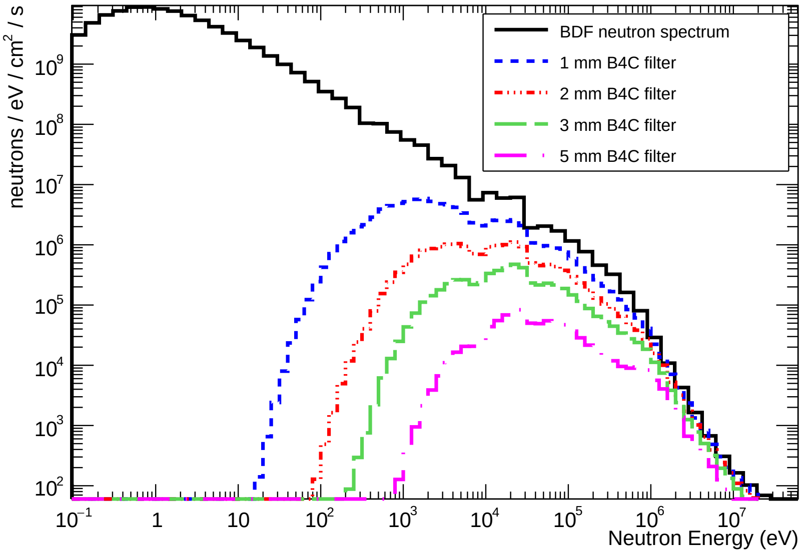

Figure 4: Expected neutron flux spectrum at the rabbit (BRIS) irradiation position of the BDF facility. The spectrum is compared to resultant spectra when B_4C filters of different thicknesses are added.

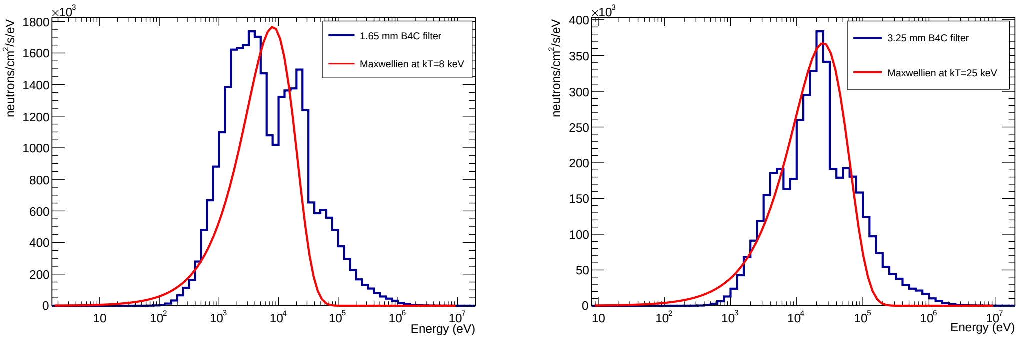

Figure 5: (left) Neutron spectrum at the BRIS position with 1.65 mm thick filters, resembling a thermal neutron spectrum at $kT = 8$ keV. (right) Neutron spectrum at the BRIS position with 3.25 mm thick filters, resembling a thermal neutron spectrum at $kT = 25$ keV.

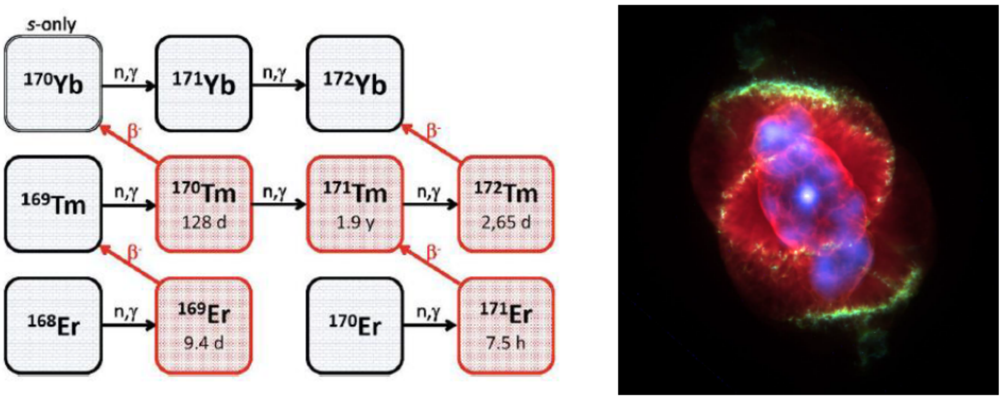

Figure 6: (left) s-process nucleosynthesis path around the branching ^{171}Tm. (right) The Cats Eye Nebula, example of a Planetary Nebula formed by a dying Red Giant, enriched in heavy elements produced in the s-process.

to extend the cross-section measurement down to 8 keV via TOF at n_TOF [15] was not successful owing to the reduced sample-mass available and the limited sensitivity of the TOF method. In the case of ^{171}Tm the only existing TOF data was obtained at n_TOF, but resonances could be identified only up to ∼700 eV, well below the 8 keV to 30 keV thermal conditions for nucleosynthesis in AGB stars. For ^{94}Nb(n, γ) there exist only a TOF experiment carried out at n_TOF EAR2 with the fully-optimized s-TED setup. This data is still under analysis [17] but resonances have been observed only up to neutron energies of about 300 eV [17]. The high neutron-flux at BDF, as well as the possibility to experimentally tailor the neutron-distribution at several energies, will allow one to obtain accurate data for these *s*-process branching isotopes in the full stellar-energy regime, thus enabling a fully consistent and reliable astrophysical interpretation of the results.
In summary, a large neutron-flux activation facility like the one proposed at BDF, represents in most cases the only possibility to tackle long-standing remaining *s*-process branching nuclei and, in other cases, an invaluable complementary information to previous TOF experiments, mostly limited in sensitivity and attainable energy range.

3.2 i-process nucleosynthesis

The so-called i-process involves neutron capture at neutron densities of 10^{13}–10^{16} cm^{-3}, which are several orders of magnitudes higher than in the s-process. Recently, the i-process attracted significant interest because it might explain the abundance pattern of a special kind of Carbon-Enhanced Metal-Poor stars (CEMPs), called CEMP-s/r [20]. The path of the *i*-process comprises radioactive nuclei 4-5 mass-units away from the stability valley. Therefore, no experimental capture-data exists yet on any of the relevant *i*-process isotopes. The high neutron fluences expected at BDF represent a unique opportunity to tackle several relevant cross sections for the first time and thus obtain experimental information that otherwise would not be accessible. Furthermore, the possibility to produce some of these nuclei at nearby ISOLDE represents a unique advantage for conducting i-process activation experiments at the new activation station. From an experimental standpoint, the requirement of target-nuclei with short half-lives, such as some of those involved in the i process, leading after neutron capture to product nuclei with even shorter half-lives, of the order of 1-100 minutes, offers a unique opportunity to perform cyclic activation experiments, where a sample is irradiated and measured several times in a row. Although the *i* process was already proposed in 1977 by Cowan and Rose [21], the recent renewed interest on this nucleosynthesis mechanism has triggered many dedicated sensitivity studies [22, 23, 24]. For example, it has been found that in the i-process conditions variations in the neutron-capture rates of some specific isotopes could affect the observable elemental ratio predictions involving Ba, La and Eu in i-process conditions [22]. Some of the reactions that could be studied include $^{125}\mathrm{Sb}(n,\gamma)$, $^{137}\mathrm{Cs}(n,\gamma)$ and $^{144}\mathrm{Ce}(n,\gamma)$. New sensitivity studies of the i process will provide additional candidates for direct neutron-capture experiments at BDF.

3.3 Astrophysical Origin of rare nuclei

^{180m}Ta is the rarest stable isotope found in nature, and is unique in being the only isotope stable in the isomeric state, while its ground state is unstable. Different astrophysical scenarios, have been proposed for its production, but their different contributions remain unknown since they heavily depend on stellar parameters and reaction rates. ^{180m}Ta can be produced in Red Giants by neutron capture reactions on the unstable ^{179}Ta, however there is no data on its production channel via $^{179}\mathrm{Ta}(n,\gamma)$. The high neutron fluxes at BDF will allow to measure the stellar $^{179}\mathrm{Ta}(n,\gamma)$ for the first time, using a sample similar in mass to what has been produced before for a measurement of this cross section at a thermal reactor (well below neutron energies relevant for stellar nucleosynthesis) [25].

3.4 Cross sections for Nuclear Energy and other applications

A long list of accurate nuclear data needed for the design and operation of new generation fission reactors is still pending [26, 27]. The lack of such data is mostly related to difficulties in retrieving (or producing) samples of adequate mass for a dedicated measurement at current neutron facilities. In this respect, the very high neutron flux that would be available at the BDF station could allow to perform such measurements with samples of much smaller mass. Another issue that could be addressed at BDF is the neutron damage in structural material of future fusion reactors, leading to severe degradation, limiting reactor lifetime [28, 29]. Data on various neutron-induced reactions, in particular those leading to gas production, are mostly missing or incomplete in the pertinent energy range, hindering at present a reliable estimate of the radiation damage to structure materials operating in the extremely harsh environment of future fusion reactors. Cross sections measurements at BDF, exploiting the very convenient features of the neutron beam in terms of fluence and energy range, may allow to start addressing this issue, by providing much-needed data for the modelling and prediction of neutron damage in fusion energy applications. First measurements could be dedicated to elements present in structural materials, subject to the production of isotopes with an half life of hundreds of years, by

means of the (n, 2n) reaction channel: ^{109}Ag, ^{151,153}Eu, ^{159}Tb,^{193}Ir.
As a further prospect concerning medical applications,neutron irradiation at BDF could allow to explore and test new production routes of innovative radio-pharmaceuticals for therapy and diagnostics, or their combination in the so-called theranostics method [30]. First studies could be dedicated to the production of the ^{67}Cu therapeutic electron and X-ray emitter through the ^{67}Zn(n, p) reaction or to the production of the β-emitter ^{64}Cu through the ^{64}Zn(n, p) reaction.
An interesting application in Geophysics could relate to Burial Dating [31]. Burial Dating is a technique used to determine the time an object or sediment has been buried underground by measuring the accumulation of cosmogenic isotopes, such as ^{10}Be and ^{26}Al, produced by cosmic rays. To improve the accuracy of these measurements, precise neutron cross-section data is essential, as it helps quantify the rate at which neutrons, generated by cosmic rays, interact with various elements in the sample, affecting isotope production. The neutron spectrum can be shaped to resemble that of neutrons from cosmic rays, allowing for irradiations of rock samples to directly determine the rate of ^{10}Be and ^{26}Al production in the rock.

4 Conclusions and outlook

This document outlines a proposal to establish a worldwide unique neutron activation station at CERN's BDF facility, dedicated to cross-section measurements relevant to astrophysics and nuclear technologies.

The main aspects covered by this Expression of Interest are:

- A conceptual design for a new irradiation/activation station at BDF that enables more than three orders of magnitude higher neutron flux with respect to what is attainable at CERN n_TOF activation station aNEAR
- The possibility to tackle world-wide unique neutron-capture experiments of key interest for astrophysics and of great relevance for nuclear technologies
- The new facility will deliver invaluable complementary information for many experiments presently conducted via the TOF technique, and it will expand the synergies with ISOLDE, enabling world-wide unique activation experiments on very small radioactive samples.

According to the endorsement of this EoI for an activation station at BDF as part of the ongoing Technical Design report, the installation timeline will be reassessed to align with CERN's available resources. If CERN approves the final implementation following a Proposal, the collaboration will also seek additional matching funds to support the project's completion.

By taking advantage of the unique beam characteristics at CERN and collaborating with the on-site n_TOF, ISOLDE & CERN-MEDICIS teams, this proposed station aims to become a leading experiment in its field over the coming decades.

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