EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of (n,cp) reactions in EAR1 and EAR2 for characterization and validation of new detection systems and techniques

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Abstract

We propose to characterize in EAR1 and EAR2 two detectors now being developed for the measurement of (n,cp) reactions: a GEMpix and an annular silicon detector Neutron Transmutation Doped (NTD). Both systems are intended to cover a large solid angle, have a low sensitivity to the γ-flash, provide good timing information, and especially, allow particle identification with a low threshold. Also, the silicon detector is segmented, thus providing information on the angular distribution of the emitted charged particles.

Preliminary tests of both GEMpix and annular silicon detectors have been performed with sources, and with the neutron beam in the dump area of EAR1 in 2021. The results were up to expectations, showing that the performances needed for the (n,cp) physics program are within reach, with both detectors able to collect data up to hundreds of MeV. More dedicated and complete tests are necessary to optimize the operating parameters of the detectors and determine the main characteristics energy resolution, energy and particle identification thresholds, neutron energy range, etc. We plan to use samples of polyethylene, pure Carbon, and Aluminum, whose cross-sections are relatively well known or have been already studied at n_TOF. Moreover, we propose to measure the ^{12}C(n,p)^{12}B reaction with the annular silicon detector, to

compare the results with those of a measurement already performed at n_TOF with ΔE-E technique and thus validate this technique.

Further tests with Aluminum Oxide (Al_2O_3) will help to characterize the identification capability and the energy threshold for the alpha particles.

Requested protons: 2×10^{18} protons on target

Experimental Area: EAR1 and EAR2

Introduction

Studies of (n,cp) reactions are important for a variety of fields, such as Nuclear Astro-Physics, Nuclear Medicine (dosimetry, neutron therapy, radioisotope production), and nuclear energy applications. In this last application, a large set of neutron cross sections are needed for the design, construction, and operation of fusion reactors. Nuclear fusion is one of the long-term sustainable energy sources currently subject to intense Research and Development activity. The most important project being carried out in the field of nuclear fusion is ITER (International Thermonuclear Experimental Reactor), under construction in France, a large international effort aiming at verifying the viability of this source for energy production. One of the most important issues on the roadmap toward exploitation of nuclear fusion regards the effect of radiation damage on structural materials in the inner part of the tokamak [1], such as the mantle and the divertor, that are subject to extremely large fluxes of neutrons produced in the fusion reaction, with energy up to 14 MeV. Among the different types of neutron interaction with structural material, (n,cp) reactions leading to the emission of charged particles, in particular protons and α-particles, are particularly important as they are responsible for the production of hydrogen and helium gas inside the material, with consequent substantial modification of the thermo-mechanical properties of the structural elements, such as ductility and deformability. Furthermore, because of the bubble formation, gas production can lead to severe problems of embrittlement of the structures, limiting their lifetime [2].

The radiation damage produced by neutrons in fusion reactors can be assessed experimentally at neutron irradiation facilities whose beam presents spectral features and a flux similar to the ones of a fusion reactor. To this end, an International Fusion Material Irradiation Facility (IFMIF) has been proposed, with an intermediate step represented by the DONES facility, now under construction in Granada, Spain [3]. However, the interpretation of the results at these facilities is complicated by the presence of a high-energy tail in the neutron spectrum, extending at energies well above 14 MeV, due to the relatively high energy of the primary beam. The contribution of high-energy neutrons to the radiation damage has to be properly estimated and accounted for when determining the irradiation effects in fusion reactors, where the high-energy component is absent. This contribution can only be estimated using suitable calculations, Monte Carlo simulations and theoretical models, that in turn rely on neutron interaction cross-section as input. Reaction data for fusion are available in a dedicated library (Fusion Evaluated Nuclear Data Library, FENDL), complemented by the European Activation File (EAF) for activation cross-sections, which are also needed to address safety, licensing, decommissioning, and waste management issues [4]. A large effort, at the European and worldwide level, is currently devoted to increase the reliability of these libraries, possibly based on new measurements on transmutation and gas production, whose data are often scarce or discrepant, and extend the maximum energy above the current 20 MeV limit.

For this reason, there exists a pressing need for new neutron data, for a variety of reactions and isotopes, and in a wide energy range, extending up to several tens of MeV. The lack of neutron data related to fusion can be addressed at n_TOF at CERN. In fact, the main features of the neutron beam at n_TOF, in particular the high flux and the wide energy range, extending up to 1 GeV, could be very conveniently exploited for measurements related to fusion.

The goal of this proposal is to investigate the possibility to measure at n_TOF (n,cp) reactions needed for the estimate of radiation damage on structural material of future fusion reactors, as well as for other applications (in particular in nuclear medicine), for astrophysics and for fundamental neutron physics. In particular, we aim at measuring the energy-dependent cross-section of (n,cp) reactions, responsible for gas production, up to at least 60 MeV neutron energy, to account for the high-energy tail in the neutron spectrum of material irradiation facilities. A pressing need for (n,cp) data exists for a variety of elements, such as Be, Fe, Mo, and W, relevant for the assessment of the damage of structural material under neutron irradiation in ITER and DEMO. Figure 1 shows the current status of available data (symbols) and evaluated cross-sections (curves) for reactions on isotopes that could in principle be measured at n_TOF. The lack of data, the discrepancy between different data sets, and between data and evaluations are evident in the figure and clearly demonstrate the need for new measurements.

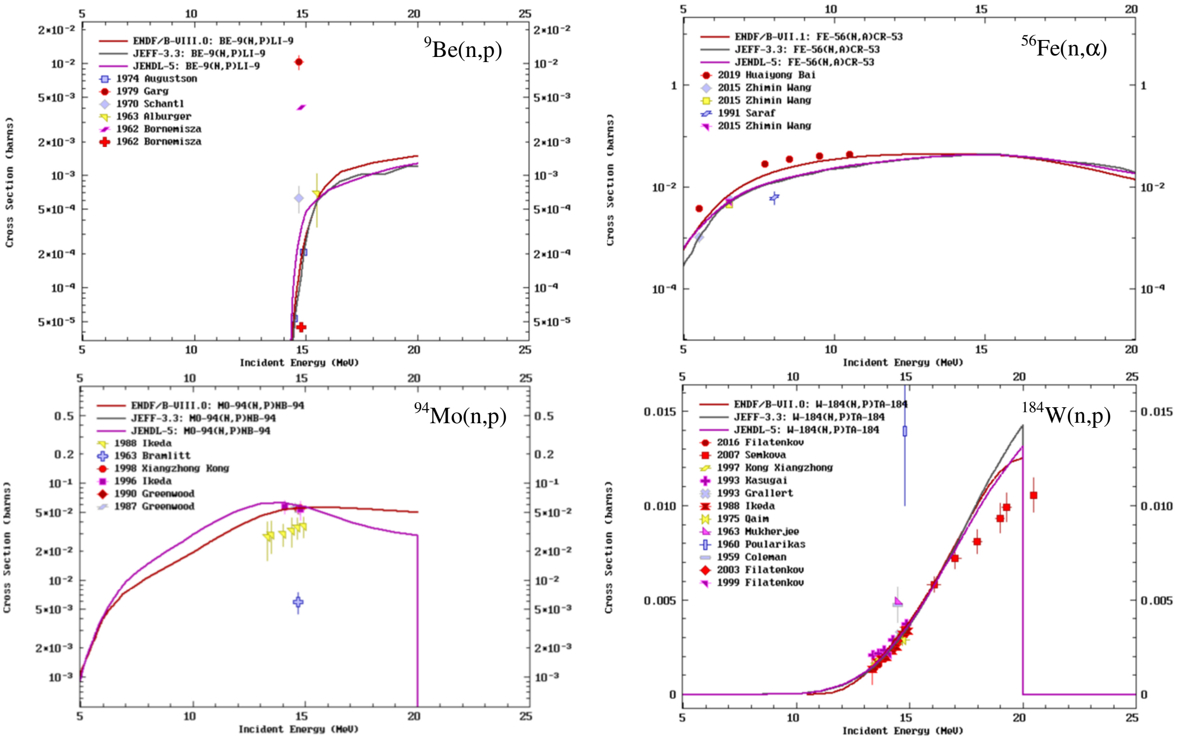

Figure 1: Cross section data (symbol) and evaluations (curves) for reactions involved in gas production for some of the main constituents of structural material in fusion reactors: ^{9}Be (upper left corner), ^{56}Fe (upper right), ^{94}Mo (lower left) and ^{184}W (lower right).

The main features of the n_TOF neutron beam can be very conveniently exploited for measurements of neutron-induced reactions related to fusion. In particular, the wide energy spectrum of the beam will allow collecting data above 20 MeV, currently lacking for most of the elements that constitute structural elements in fusion reactors. At the same time, the high flux will allow us to collect data even on reactions with low cross-sections, that can hardly be measured anywhere else. Measurements of (n,cp) reactions have been performed or attempted in the past at n_TOF. Measurements of the ^{7}Be(n,p) and (n,α) relevant for Nuclear Astrophysics (Cosmological Lithium problems), performed with Si-based detection systems, were successfully completed in EAR2 [14,15]. Si-based telescopes were also used for the measurement of the ^{12}C(n,p) reaction, and the data are currently being analyzed [12,13]. An attempt was also performed to measure the ^{16}O(n,α) reaction, with a high-pressure gas detector, but the presence of a high proton-recoil background hindered the detection of the emitted α-particles. However, a more ambitious experimental program on these reactions at n_TOF requires a dedicated and optimized experimental setup.

The (n,cp) detectors

The present proposal aims to characterize two innovative approaches, that present the right features for the proposed measurements, based on i) Timepix detectors and ii) NTD silicon detectors with particle identification capability. These could be efficiently used for the measurement of various (n,cp) reactions of interest for fusion energy as well as for other fields in fundamental and applied Nuclear Physics. To this aim, we propose to perform measurements of (n,p) and (n,α) reactions whose cross-sections are relatively well known.

The GEMpix detector

The Timepix ASIC family are highly compact Front-End Electronics, with pixels dimension of 55x55 μm^2 and an active area of 14x14 mm^2. These ASICS can be coupled with different types of sensors (silicon, CdTe, diamond, gas chamber, etc.) that can provide deposited energy, timing, and position information with good accuracy [5,6]. A typical time resolution that can be achieved with Timepix is of the order of ns, making this detector suitable for time-of-flight measurements. Furthermore, it can also provide particle identification, performed by analysing the morphological structure of the cluster of pixels in which a charge is recorded. This device, with solid-state sensors or in combination with gas detectors like the GEM, has been successfully used in many applications, ranging from measurements of the cosmic ray flux in the International Space Station, to dosimetry and microdosimetry with proton or Carbon beams. A Timepix detector has already been successfully used at n_TOF to measure the spatial profile of the neutron beam, in combination with a ^{10}B converter, for low energy neutrons, and a polyethylene one for fast neutrons. Figure 2 shows a Timepix mounted in the neutron beamline, for alignment purposes.

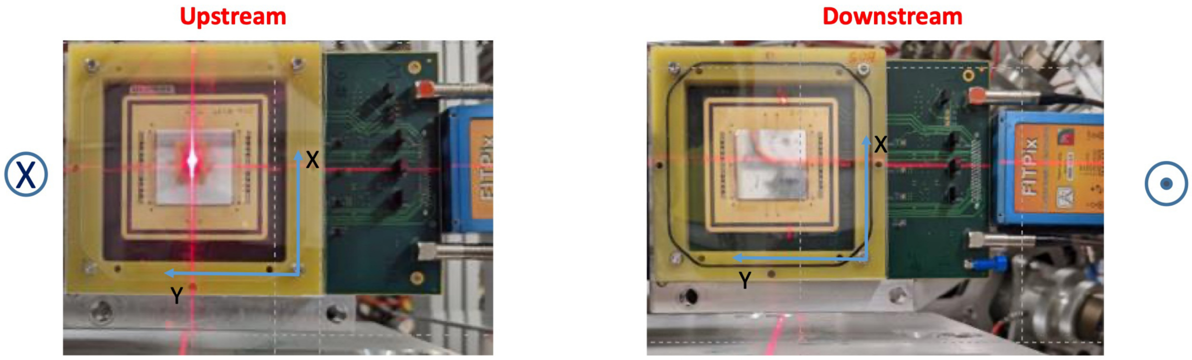

Figure 2: The Timepix detectors used at n_TOF for beam alignment purposes. The detector has been used in conjunction with a ^{10}B deposit for the detection of low-energy neutrons and with a polyethylene n/p converter foil for the high-energy ones.

The good timing and particle identification properties of the Timepix have proven fundamental to collect virtually background-free data, with good spatial and time resolution.
The Timepix ASIC can store charge, time, and position information with a maximum rate of about 5 MHz per pixel [7]. The detector active area can reach easily 3x3 cm^2 with the quad configuration (a matrix of 2x2 Timepix module) to exploit the full size of the neutron beam at n_TOF, of ~3 cm diameter.

For the test, we are developing a new version of the GEMpix, with three GEM layers, with the sample mounted inside the gas region, to substantially reduce the detection threshold. The main advantages of this setup are the very high detection efficiency, close to 2π, and the low threshold for particle identification, compared to a standard ΔE-E telescope. For the measurement, we plan to use a polyethylene and an Al_2O_3 sample, of 1 mm thickness. In order to characterize the maximum energy that can be reached with this device in the two experimental areas, we propose to perform the test in both experimental areas at n_TOF.

The annular silicon detector (ASD)

While the Timepix has already been used at n_TOF and its use within this proposal should be fairly straightforward for measurements of (n,cp) cross-sections, we plan to develop a new device for measuring energy-dependent angular-differential cross-sections, i.e. as a function of neutron energy and particle emission angle, that is important for determining the angular anisotropy of the emission, for fusion as well as for other applications (such as in Nuclear Medicine, for determining the directionality of dose deposition). We propose to develop a segmented annular silicon detector, Neutron-Transmutation Doped (NTD), 300 μm thick, with particle identification capability. Schematically, the detector is a disk of 96 mm diameter, with a hole in the center of 46 mm diameter, larger than the neutron beam in EAR1 (~3 cm in diameter). A photo of the detector is shown in Figure 3.

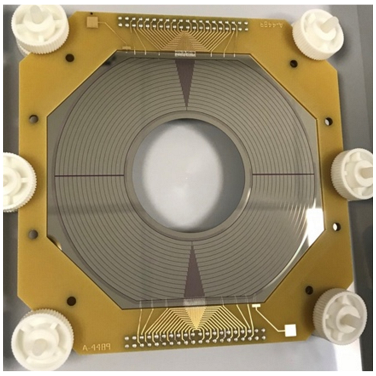

Figure 3: A photo of the annular silicon detector. The view with 4x16 strips is the junction side.

The configuration with 4x16 annular strips on the junction side and 16 azimuth sectors on the ohmic side, allows to measure the particles emission angle. The sample for the measurement will be placed on the beam axis upstream and downstream of the detector.

The particle identification in this device relies on the analysis of the signal shape, according to a method described in Ref. [8-10]. In brief, it relies on the different stopping power of different particles, that affect the shape of the pulses produced in Neutron-Transmutation Doped (NTD) silicon detectors, when the particles enter from the cathode side (the rear of the detector).

Signals are fed to suitably developed PSA software, aimed to analyze the pulses produced by the charge preamplifier reading the detector output. Although it has not been previously applied at n_TOF, this technique is well established and employed in important collaborations (e.g. FAZIA [11]), and compared to the telescope configuration it guarantees lower energy thresholds. Very preliminary tests have been performed in air for a few hours in EAR1, using a standard annular silicon detector (not NTD), the only one available at that time. The results are shown in Figure 4.

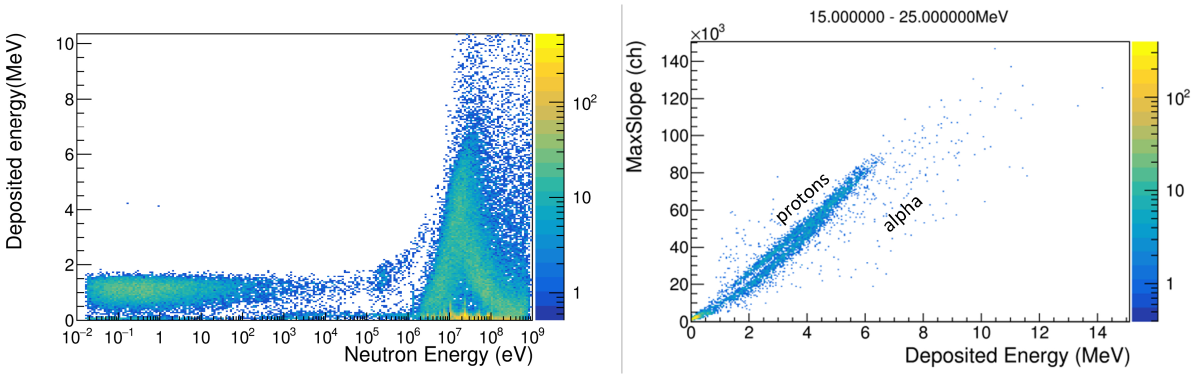

Figure 4: (Left) Deposited energy vs Neutron energy for events collected in air at n_TOF (EAR1), with a ^{6}LiF plus CH_2 sample (left panel) at a distance of 3 cm from the detector (not NTD). The structures at lower energy are related to tritium from the ^{6}Li(n,t)^{4}He reaction, while the one higher energy is due to protons and other light charged particles from the polyethylene sample. The right panel shows the maximum slope vs deposited energy, in the neutron energy range 15 MeV – 25 MeV. An attempt of discrimination between protons and α-particles could be achieved.

In these tests, the standard n_TOF Data Acquisition system has been utilized for the sampling and recording of the full pulse shape. The off-line analysis with PSA provides relevant information on the charge signal, in particular time-of-flight, amplitude, rise time, and maximum slope of the rising edge, needed for particle identification. The test also demonstrated that the device in combination with the PSA is essentially insensitive to the γ-flash, thus allowing us to collect data on (n,cp) reactions up to several hundred MeV. This is an important progress, as there are essentially no data available on these reactions above a few tens of MeV. The measurement of the already studied reaction ^{12}C(n,p)^{12}B [12,13] will allow us to validate the proposed approach by comparing the results. Further measurements with other targets and at higher neutron energy, will provide for the first time the possibility to test and improve nuclear models (such as TALYS, INCL++, and other high-energy models) currently used in Monte Carlo simulations.

The use of NTD detectors, the optimization of the front-end electronics and data analysis will substantially improve the resolution with a subsequent decrease of the identification threshold, to a much lower value compared with standard ΔE-E telescopes. This could represent a very significant progress for alpha particle detection, and for such a reason we will investigate also the response to an Al_2O_3 target, to measure the lowest achievable energy threshold.

It needs to be pointed out that if the results of the measurements validate the use of such a technique, combinations of annular detectors and squared detectors can be properly arranged, in order to increase the coverage of the solid angle for more challenging and/or higher accuracy measurements of (n,cp) reactions.

Summary of requested protons:

A total of **0.3×10^{18}** protons on target is needed to test the annular detector in EAR1, using different samples. This test is also required to optimize the setup and the PSA software. The reaction $^{12}C(n,p)^{12}B$ will be measured in EAR1 in a second step, once everything is well settled. It requires a total amount of **10^{18}** protons, estimated by considering a ^{12}C sample of thickness 0.3 mm, placed at 5 cm from the detector as a tradeoff between detection efficiency, angular coverage and angular resolution. Applying the Binary cascade model, the simulated expected rate in the neutron energy range 15 MeV - 25 MeV is about 0.014 counts/pulse (assuming 7x10^{12} protons per pulse). With 10^{18} protons on target, the foreseen total number of counts is around 2000, enough to obtain a significant trend of the cross section as a function of the neutron energy. Further **0.2x10^{18}** protons on target are needed to measure the background with an empty sample.

The tests of GEMpix in EAR1 require a total of 0.5x10^{18} protons on target, and can be performed in combination with the measurements of the annular detector.

For EAR2 the requests for the measurement with the two detectors amount to **0.5x10^{18}**. We plan to mount and operate the two detection systems in parallel, one downstream of the other, so to minimize the proton request.

To summarize, our request is:

- EAR1 = **1.5x10^{18}** protons on target
- EAR2 = **0.5x10^{18}** protons on target

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