Modernization in development and dissemination of EXFOR library and its application to evaluation of fast neutron fission cross sections

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The fission cross section is an important ingredient of neutron reaction data libraries because of its impact on fission energy system application. Experimental fission cross sections measured with both white neutron and monoenergetic neutron sources have been compiled in the EXFOR library [1], and utilized in evaluation of general and special purpose libraries.

The fast neutron fission cross sections have been evaluated by us by analysing the experimental datasets accumulated in the EXFOR library by using the simultaneous least-squares analysis code SOK [2]. We applied this approach to six U and Pu nuclides (^{233,235,238}U, ^{239,240,241}Pu) for the JENDL-5 library [3]. We also performed new evaluation for two additional nuclides ^{242}Pu and ^{232}Th after release of the JENDL-5 library [4-5]. These evaluations as well as our ongoing evaluation on ^{237}Np will be discussed.

We try to rely on the experimental knowledge received from the experimentalists as much as possible, and utilize it in a traceable manner. That is, we first review each EXFOR entry against the source documents including discussion with the experimentalist when needs arise. Then we update the EXFOR entry and use it as a direct input to SOK. We often add information on the partial uncertainties and correlations during this procedure, and it improves the covariance of the evaluated fission cross sections. Finally, this EXFOR entry will be shared with the nuclear data community by its submission to the International Network of Nuclear Reaction Data Centres for inclusion in the EXFOR library.

The network is modernizing the EXFOR library development and dissemination process with new code packages. We found the EXFOR library translated in JSON (JavaScript Object Notation) is useful for loading into evaluator's code such as SOK, and we introduce our recent attempt.

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Cross section measurements for the proton-induced production of the theranostic ^{47}Sc radionuclide*

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^{47}Sc is an interesting radionuclide from the medical application point of view, due to its favorable decay characteristics (β^- particles of 162.0 keV mean energy, γ rays of about 159 keV energy, half-life of 3.3492 d [1]) which allow to define ^{47}Sc as theranostic, and to its possibility to be matched to ^{43}Sc or ^{44g}Sc to constitute a theranostic pair. Currently, the scientific research concerning this radionuclide is facing the challenge to identify the optimal production route which can provide the largest amount of ^{47}Sc with an appropriate purity for medical applications. For this purpose, at the INFN-LNL, in the framework of LARAMED (LAboratory of RADionuclides for MEDicine), the proton-induced production of ^{47}Sc has been investigated through two dedicated projects funded by INFN CSN5: PASTA (Production with Accelerator of Sc-47 for Theranostic Applications) in 2017-2018, and REMIX (Research on Emerging Medical radIonuclides from the X-sections) in 2021-2023 [2, 3].

In the context of these two projects, nuclear cross sections of ^{47}Sc and its contaminants from metallic ^{nat}V and enriched ^{48,49,50}Ti targets were measured up to 70 MeV. The enriched targets were manufactured with the HIVIPP (HIgh energy VIbration Powders Plating) technique [4, 5] and characterized through the EBS (Elastic Back Scattering) method at the INFN-LNL. The irradiation runs of all the targets were performed at the GIP ARRONAX facility [6], where a cyclotron able to deliver a tunable 30 to 70 MeV proton beam is available, while waiting for the start, scheduled for this year, of the similar one located at INFN-LNL.

The experimental results of all the produced radionuclides were analyzed and compared to figure out if a valid proton-induced production route for the medical employment of ^{47}Sc is feasible. From this investigation, ^{nat}V and enriched ^{50}Ti targets have shown to be the most promising target materials for ^{47}Sc production with adequate purity for targeted therapy.

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Characterizing Nuclear Fragmentation Reactions for Nuclear Physics Applications with the FOOT Experiment

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The cross section measurement of nuclear fragmentation reactions of light nuclei (A < 20) in the energy range between 100 and 800 MeV/u is of great interest in current applied physics research. As a matter of fact, a complete understanding of such interactions would lead to an improvement in both Particle Therapy treatment planning and in risk-assessment for radiation exposure in long-term human Space missions. However, as of today, nuclear reaction databases lack the experimental measurements needed to accurately model nuclear fragmentation. A phenomenological description of such processes is inherently subject to significant uncertainties, which could become too large for an acceptable evaluation of risks related to hadrontherapy treatment and radiation exposure.

The aim of the FOOT experiment is to improve and expand the knowledge on nuclear fragmentation processes by performing a set of high accuracy cross section measurements. The experiment foresees an extensive program of data acquisition campaigns with light ion beams (^{4}He, ^{12}C and ^{16}O) at 200-800 MeV/u impinging on targets with different chemical composition representative of human tissues and spacecraft shielding materials. The final goal of FOOT is the measurement of double differential cross sections in kinetic energy and emission angle with a maximum uncertainty of 5% and 10% for projectile and target fragmentation reactions, respectively. To reach this goal, FOOT has been designed as a fixed target experiment with the ability to detect, track and identify both the primary beam and the nuclear fragments produced in beam-target interactions, measuring all their kinematic properties. Since the needed ion beams are available in different facilities, the experiment comprehends two portable and complementary setups: one based on nuclear emulsion films and mainly focused on light fragments ($Z \leq 3$) and one made of several electronic detectors and optimized for heavier fragments ($3 \leq Z \leq 8$), which includes a magnetic spectrometer, a Time-Of-Flight system and a calorimeter. This latter is currently being completed and will be fully operational by the end of 2024.

As of today, both setups of FOOT have been employed in a series of data acquistion campaigns with ^{16}O, ^{12}C and ^{4}He beams at the GSI (Darmstadt, Germany), HIT (Heidelberg, Germany) and CNAO (Pavia, Italy) facilities. In these occasions, fragmentation measurements were performed using graphite and polyethylene targets.

In this contribution, after an overview of the current status of the FOOT experiment, the first results on cross section measurements obtained from data acquisitions are presented. Future perspectives and developments will also be addressed, with a particular focus on the future cross section measurement capabilities through particle tracking in the electronic setup of FOOT.

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Bilayer target for an efficient production of ^{47}Sc from proton-induced irradiation*

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Currently, various methods for the production of ^{47}Sc are under study, both using nuclear reactors and particle accelerators, but there is not yet an established optimal method that allows the production of ^{47}Sc with yield and purity suitable for medical purposes [1-3]. We proposed a method [4] for the production of ^{47}Sc, optimized for irradiating a target with a proton beam up to 35 MeV. The target consists of a double layer of materials: the first layer is made of ^{nat}V, and the second is made of enriched ^{50}Ti.

Using a target made of two different materials for the production of ^{47}Sc offers several evident advantages: *1. Optimized Yield*: Different materials may have different cross-sections for the nuclear reactions that produce ^{47}Sc. By selecting materials with high cross-sections, the yield can be maximized. *2. Purity Control*: The presence of impurities like ^{46}Sc and ^{48}Sc can be minimized. Each target material can be chosen based on its propensity to produce fewer unwanted radionuclides, thus improving the purity of ^{47}Sc. *3. Energy Efficiency*: The reaction energy (up to 35 MeV) can be more effectively utilized with materials that are better performing at different energy ranges, leading to a more efficient production process. *4. Material Availability*: Using two different materials can alleviate the issue of scarcity or cost of a single material, making the process more feasible and economical. *5. Tailored Production*: The method can be tailored for specific applications, such as medical use, by adjusting the proportion and type of target materials to suit the required ^{47}Sc specifications. *6. Industrial Application*: It encourages the industrial development of specialized targets and automated modules for extraction and purification, which can lead to advancements in medical technology and treatment options. These advantages contribute to a more effective and practical approach to producing medical-grade ^{47}Sc, which is used in radiopharmaceuticals for diagnostic, therapeutic, and theranostic purposes. In this communication, we discuss the nuclear-data issues and nuclear-reaction simulations that have led to this invention.

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Direct Measurements of Neutron Capture Rates in Unstable Astrophysical Nuclei: A New Frontier

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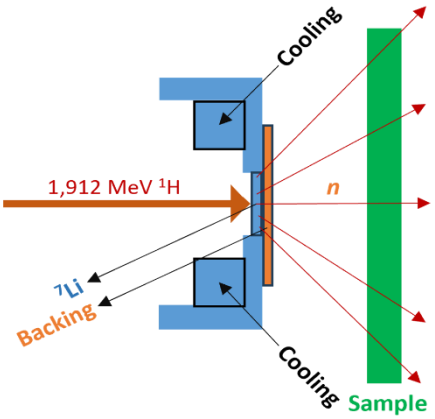
The intermediate neutron capture process (i- process) likely occurs in AGB stars and is essential for explaining the elemental abundances in certain CEMP stars. While most aspects of the i- process are experimentally well-constrained, neutron capture rates and cross sections remain a significant unknowns in the nuclear physics context. Indirect measurements are plagued by higher uncertainties while direct measurements are challenging because many key nuclei involved in the i- process are unstable.

In this poster, we will explore the current possibilities for direct measurements of neutron capture cross sections for selected long-lived nuclei to better understand the dynamics of the i- process. We will present the status and initial tests of a new beamline designed to produce a high-density secondary neutron beam at the CologneAMS 6MV tandetron. These cross sections will be measured using a novel activation technique that detects beta-decay electrons. Our first case study is the $^{137}Cs(n,\gamma)^{138}Cs$ cross section, aimed at enhancing our understanding of the observed Lanthanum and Barium abundance ratios in AGB stars.

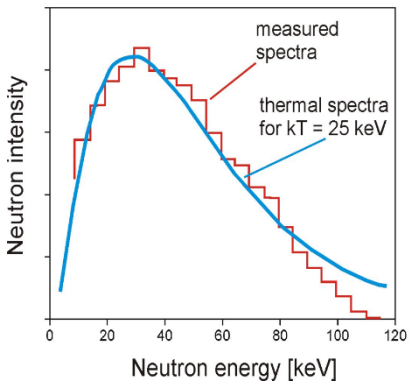


➢ *Produced neutrons:*

$^{7}Li(p,n)^{7}Be$

❖ Maxwellian spectrum with peak ~ 25 KeV

❖ Forward directed cone (~ 140° Opening angle)



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Sub-Coulomb Barrier Fusion Reaction in Multi-atom Collision Environments

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Light nuclei fusion reactions in deep sub-Coulomb barrier energy region are essential reactions in astrophysics and fusion applications. However, there are very limited experimental data. At the same time. the real reaction environments are very different from accelerator experiment. Instead simple two body fusion, the real reaction occurs in a multi-atom collision environment in high dense plasma. Electron screen of target nuclear may also affect fusion significantly in keV energy. In this work, a series of studies on light-nuclei fusion reactions *i.e.*, d-D, p-^{7}Li, d-^{6}Li, p-^{9}Be, d-^{9}Be, performed by us in recent years is presented. Combine these low-energy experimental data with the reported $S_{exp}(E_i)$ points in the higher energy region where the screening effect is almost negligible, R-matrix theory is used to fit the existing data in the full energy region and simultaneously obtain the bare astrophysical S-factors and screening energies in corresponding environments. The screening potentials obtained from various metal environments were generally higher than existing theoretical predictions, *i.e.*, ~600 eV in Liquid-Li, 545±98 eV in Be-metal.

In order to understanding the environmental screening effect in ion beam experiments, approaches on hydrogen cluster ions interacted with solids and gas targets are carried out. The stopping powers of various hydrogen cluster ions are obtained from the depth profile of implanted hydrogen. The change of fusion reaction rate caused by stopping powers difference of cluster ions is therefore discussed.

A model of cluster ion fusion in dense plasma is proposed, simulation of d-D and d-T fusion in various dense plasma environment is undergoing. A new experimental of hydrogen cluster ions fusion at low energy ion beam platform is planed.

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