Technical Meeting on Neutron-induced Reactions on Short-lived Nuclei

Monday 25 August 2025 - Friday 29 August 2025

IAEA Headquarters, Vienna

Book of Abstracts

Contents

Monday I / 1

High accuracy measurements of neutron induced cross sections on short-lived nuclei at the CERN n_TOF facility

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The n_TOF facility houses CERN's pulsed neutron source, comprising two beam lines of different flight paths (at ≈185 and ≈19 m) and one activation station. It is driven by the 20 GeV proton beam delivered by the Proto-Synchrotron accelerator impinging on a lead spallation target.
The energy resolution and the high instantaneous neutron flux are key factors to increase the signal-to-background ratio, crucial aspect when measuring radioactive isotopes.
Isotopes with half-lives higher than hundreds of days available in a sufficient amount of mass can be measured using the time-of-flight technique, while the activation technique can be applied in more challenging physics cases.
Over the last 25 years of operation of the n_TOF facility a collaboration with several laboratories (CERN-Isolde, Ill, JRC-Geel, Los Alamos, PSI) able to isolate desired isotopes has been fruitfully established.
Measurements of neutron induced reactions on short-lived isotopes are of interest of nuclear astrophysics (i- and primordial nucleosynthesis) and highly required for applications to emerging nuclear technology.
A review of past measurements (e.g on sample of 7Be, 63Ni, 78Se, 171Tm, 204Tl) and the prospects of an upgraded facility will be presented.

Wednesday I / 2

Nuclear Physics at Low-Energy Storage Rings

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Storage of freshly produced secondary particles in a storage ring is a straightforward way to achieve the most efficient use of the rare species as it allows for using the same secondary ion multiple times. Employing storage rings for nuclear reaction studies is a rapidly developing field of research. Experiments at various centre-of-mass energies spanning from a few AMeV of astrophysical interest to several hundred AMeV have been meanwhile conducted at existing Experimental Storage Ring ESR of GSI in Darmstadt and the Experimental Cooler-Storage Ring CSRe of IMPCAS in Lanzhou. Since recently, the very first nuclear reactions were addressed in the only operational dedicated low-energy storage ring CRYRING installed behind the ESR. In all those experiments, thin, pure, window-less gaseous targets are utilized, where H2, D2, He, N2 are the typical gases used. Hence, rich experience has been obtained on storing and manipulating low-energy exotic beams intersecting stable targets. Thereby, sophisticated diagnostics and detection instrumentation has been developed.
The challenge today is to explore the possibility to implement into a storage ring environment a short-lived target composed of free neutrons. If successful, the discovery potential would be enormous.
In this presentation, a summary will be given of what has been achieved by now in storage-ring-based charge-particle induced nuclear reaction studies. Finally, the ideas for a low-energy storage ring combining a free-neutron target and stored short-lived species will be discussed.

Wednesday II / 3

Study of the Neutron Capture Rate on ^{80}Ge for the r-Process

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The rapid neutron capture process (r-process), which occurs in astrophysical environments with extremely high temperatures and neutron densities, is believed to be responsible for producing roughly half of the elements heavier than iron. During the freeze-out phase of the r-process when temperatures decline and the equilibrium between neutron capture and photodisintegration breaks, individual neutron capture reactions on abundant nuclei becomes crucial, influencing the final nuclear abundance pattern. Sensitivity studies by R. Surman et al. have highlighted that nuclei near closed neutron shells, such as ^{80}Ge, play a pivotal role in determining the abundances in the (A ~ 80) region of the solar abundance pattern.

To reduce uncertainties in the neutron capture rate on ^{80}Ge, the $^{80}Ge(d,p)^{81}Ge$ neutron transfer reaction in inverse kinematics was measured at Oak Ridge National Laboratory. This experiment provided new spin assignments and spectroscopic factors for low-lying states in ^{81}Ge, resulting in more accurate reaction rate inputs for r-process simulations. As a continuation, lifetime measurements of excited states in both ^{81}Ge and ^{79}Zn have been approved at the RIKEN Nishina Center for Accelerator-Based Science (RNC), Japan. This study aim to measure the properties of low-lying intruder states in N = 49 isotones, enhancing our understanding of nuclear structure in this mass region. Further details on the experimental setup, analysis results, and future plans will be presented in the talk.

Tuesday II / **4**

Predicting neutron-induced reactions on short-lived nuclei

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The present talk will critically review the enormous theoretical challenges in nuclear physics faced by astrophysical applications and more specifically by neutron-induced reactions for nucleosynthesis applications. These include, in particular, the theoretical determination of radiative neutron capture and neutron-induced fission cross sections of exotic short-lived neutron-rich nuclei. To do so, the various nuclear ingredients, namely nuclear masses, level densities, photon strength functions, as well as fission properties, need to be estimated on the basis of accurate and reliable models.
New progress based on mean-field models (and beyond) will be described, namely
- Masses obtained from the BSkG3 Skyrme-HFB calculations using a 3D coordinate-space representation, allowing for axial, triaxial and octupole deformations;
- Fission probabilities based on the same BSkG3 Skyrme-HFB calculations taking into account both triaxial and octupole deformations simultanously to estimate the fission path;
- Nuclear level densities obtained (i) within the combinatorial approach on the basis of the triaxial BSkG3 ground state and fission isomers, and (ii) within the conceptually new approach based on the boson expansion of QRPA excitations;
- Photon strength functions for both E1 and M1 de-excitation modes within the QRPA approach
All these new predictions are compared with available experimental data as well as predictions from other competing models. They are used to estimate radiative neutron capture and fission probabilities.

Monday I / **5**

Surrogate reactions in inverse kinematics at heavy-ion storage rings

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In this contribution, I will present the NECTAR project, which uses for the first time surrogate reactions in inverse kinematics at a heavy-ion storage ring. This allows one to measure all the de-excitation probabilities as a function of the excitation energy of the nuclei formed through the surrogate reaction with unrivaled efficiency and precision, and to indirectly determine neutron-induced cross sections of short-lived nuclei, which are currently not measurable.

I will describe our new methodology and the results of the first two surrogate-reaction experiments, which we have successfully performed at the ESR storage ring of the GSI/FAIR facility in Darmstadt, Germany. In these experiments we have investigated the (p,p'), (d,p) and (d,d') surrogate reactions and have achieved a significant breakthrough by measuring for the first time the fission, gamma-ray, neutron and even two- and three-neutron emission probabilities simultaneously. The measurement of all competing decay channels makes it possible to determine fundamental quantities, including fission barriers, particle transmission coefficients, gamma-ray strength functions, and nuclear level densities, and to employ them to infer (n,f), (n,gamma), (n,n'), (n,2n), and (n,3n) cross sections.

Tuesday IV / 6

Advancing the Measurement of Short-Lived Nuclei via Flowing Sample Neutron Activation for Elemental Analysis and Fission Yield Studies

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Neutron activation analysis of short-lived radionuclides offers numerous advantages including high sensitivity, rapid turnaround, and minimal sample handling, making it an invaluable tool for various applications. To leverage these strengths, our team at ETRR-2 has developed Flowing Sample Neutron Activation Analysis (FS-NAA), a continuous-flow system that circulates liquid samples between a neutron irradiation port and a high-purity germanium detector, enabling in-line measurement of radionuclides with half-lives from seconds to hours.

Key achievements of FS-NAA include:
•Detection of short-lived isotopes (e.g., In-116m2, F-20, Al-28, Na-24, V-52, Se-77m) using 252Cf source.
•Enhanced sensitivity under reactor irradiation, enabling measurement of low-cross-section nuclides such as O-19 (via O-18(n,γ)O-19).

Operational advantages of FS-NAA:
Simplicity: It relies on a straightforward pump and tubing loop with standard irradiation and detection components, where no complex pneumatic lines, motorized changers, or specialized shielding. This arrangement minimize the installation time, cost, and maintenance.

Stability of Detector Dead Time: Continuous sample renewal maintains a nearly constant count rate, virtually eliminating dead-time fluctuations and reducing the need for post-acquisition corrections, thus improving quantitative accuracy and reproducibility.
Flow-Rate Adjustability: Tunable pump speed optimizes the irradiation and counting times: high flow-rates minimize decay losses for ultrashort-lived nuclides, while slower flow maximizes buildup for longer-lived species, making FS-NAA adaptable across a broad half-life spectrum.

Concurrently, we are conducting an evaluation of U-235 fission yields under the IAEA CRP F42007 project; our findings are under review at Physical Review C. Building on FS-NAA's versatility, future work will apply this technique to the real-time measurement of very short-lived fission fragments in aqueous media, opening a novel experimental pathway for characterizing neutron-induced reactions on isotopes with sub-minute half-lives.

Wednesday I / 8

A new approach for measuring direct neutron capture reactions in storage rings

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Storage rings coupled to radioactive beam facilities have allowed to access experiments of astrophysical interested that cannot be carried out otherwise. If such a storage ring could be coupled to a "neutron target", this would allow for the first time the direct measurement of neutron capture cross sections of short-lived radionuclides down to seconds of half-lives.

The creation of elements heavier than iron in stars is almost completely driven by three neutron capture processes: the "slow" (s) and "rapid" (r) process are responsible for ~99% of the observed stable abundances, while the intermediate (i) process can account for some abundance patterns in so-called "carbon-enhanced metal-poor stars" enhanced with elements associated with the s- and the r-process (CEMP r/s stars).
The most important missing puzzle piece for all of these three neutron capture processes are experimental neutron capture cross sections on short-lived nuclei with half-lives below 100 d. The vast majority of the cross sections of stable and longer-lived nuclei at astrophysically relevant energies (keV) have been measured in the past 50 years and used to benchmark and improve theoretical models, leading to an agreement within a factor of 2-3 with the statistical Hauser-Feshbach model at and close to stability.

However, once one moves away from stability, these predictions become unreliable and show variations up to a factor of 100-1000 between different models with different input parameters. This uncertainty directly translates into large uncertainties in the modelling of astrophysical abundances, especially in the i- and r-process.

To overcome these limitations, neutron capture cross sections for shorter-lived nuclei have to be directly measured and used to benchmark theoretical predictions far off stability. So far the direct measurement of neutron capture cross sections of shorter-lived nuclei is impossible due to the unavailability of macroscopic amounts (sample sizes larger than 1e15 atoms) of the "target" material for neutron activations at astrophysical energies.

In "inverse kinematics" a radioactive beam could be used to impinge on a "neutron" target. I will summarize a path forward for the construction of such a pioneering "neutron capture storage ring" at the TRIUMF-ISAC facility and outline the limitations of such a facility of the "first generation".

Wednesday III / 9

Advancing reaction theory to enable predictions and indirect measurements of cross sections for neutron-induced reactions on short-lived nuclei

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Reliable nuclear data with quantified uncertainties are essential for basic and applied science. When measurements are not possible, evaluators rely on systematics, theory predictions, and indirect observables. This is particularly relevant for applications involving reactions with short-lived nuclei, such as simulations undertaken to understand stellar evolution and the synthesis of the elements. Integrated nuclear structure and reaction descriptions provide the basis for reliable reaction predictions, for achieving consistent evaluations across multiple isotopes, and for enabling indirect (surrogate) measurements of cross sections. This talk will focus on advances in incorporating state-of-the-art nuclear structure theory, newly-developed optical-model potentials, and improved approaches to uncertainty quantification into reaction calculations. I will discuss strategies for predicting neutron capture reactions and progress in extracting cross sections from indirect measurements with both stable and radioactive beams.

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Tuesday III / 10

Nuclear Input Parameters in Neutron-Induced Reactions on Short-Lived Nuclei

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Neutron-induced reactions on short-lived nuclei are of critical importance in both fundamental and applied nuclear science, with implications for nucleosynthesis processes, next-generation reactor systems, and the transmutation of long-lived radioactive waste. Given the experimental challenges associated with studying unstable isotopes, theoretical modeling becomes indispensable. The Hauser-Feshbach statistical model remains a cornerstone for describing compound nuclear reactions; however, its predictive reliability hinges on key nuclear input parameters—such as level densities (NLD), optical model potentials (OMP), and gamma-ray strength functions (γSF)—which are often poorly constrained for nuclei far from stability.
In this presentation, selected hypotheses and experimental results that probe NLD and OMP behavior away from the valley of stability will be reviewed. These results might reveal significant deviations from commonly used global parameterizations, underscoring the limitations of standard models in exotic regions of the nuclear chart. The findings highlight the necessity for localized or microscopic adjustments to input parameters to ensure accurate modeling. Ultimately, this emphasizes the critical role of targeted experimental investigations and parameter studies in enabling reliable Hauser-Feshbach predictions for neutron-induced reactions on short-lived nuclei.

Monday II / 11

Microscopic Modeling of Inelastic Scattering: Applications to Surrogate Reactions and Exotic Nuclei

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Accurate modeling of neutron-induced inelastic scattering is essential for enhancing the predictive capabilities of nuclear reaction codes, particularly for short-lived nuclei where experimental data are limited. Inelastic scattering can proceed through multiple mechanisms, including compound nucleus formation and decay, as well as direct and pre-equilibrium emissions. We have developed a unified microscopic framework integrating the Jeukenne–Lejeune–Mahaux (JLM) folding optical potential with quasiparticle random phase approximation (QRPA) excitations, employing coupled-channels or distorted-wave Born approximation formalisms.

The microscopic model has undergone rigorous validation against extensive experimental data on stable nuclei, both structurally and reaction-wise. Neutron and proton elastic and direct inelastic scattering on spherical and deformed targets have been benchmarked for numerous stable nuclei, including Pb, Bi [1], and actinide [2]. Additionally, recent analyses of neutron-induced inelastic scattering with gamma emission (n,n'γ) on isotopes such as W (182,184,186W) [3], 232Th [4], and 238U [5] at GELINA to further showcase the versatility of our approach.

Importantly, our microscopic model, based on an effective nucleon-nucleon interaction, allows its application to both neutron and proton projectiles, and potentiallycomposite projectiles via double-folding potentials. For example, the same framework was successfully applied to proton inelastic scattering on neutron-rich Ni isotopes [6] and neutron-deficient Sn isotopes [7] in inverse kinematics. These studies highlight the complementarity between neutron-induced and proton-induced reactions, as proton probes predominantly sense neutron densities, providing constraints complementary to electromagnetic observables. Comparison of calculated and measured (p,p') cross sections allowed extraction of neutron-to-proton excitation ratios, validating QRPA predictions and nuclear structure models [6, 7]. The study of the pygmy dipole resonance in 140Ce via the (n, n′γ) reaction at NFS-SPIRAL2 [6] further illustrates the versatility and interest of our microscopic approach for nuclear structure studies.

Additionally, the model has proven effective in surrogate reaction studies, exemplified by the (α, α′)reaction on 240Pu to constrain neutron-induced reactions on short-lived 239Pu [9]. Recent pioneering inverse-kinematics experiments using heavy-ion storage rings, such as (p, p′) on 208Pb as a surrogate for neutron capture on 207Pb [10], further underscore its capability in extracting neutron-induced reaction observables indirectly.

Thus, our microscopic model demonstrates broad applicability and predictive power, particularly suited for reactions involving exotic nuclei. We will review its foundations and validations, discuss recent
progress, and explore future applications, particularly emphasizing neutron-induced reactions on short-lived nuclei.

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Wednesday II / 13

Measurement of Neutron-Induced Reactions on Radioactive Isotopes via Surrogate Reactions at RIBF

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Measuring neutron-induced reactions on radioactive isotopes is a significant challenge, as both the projectile (neutron)
and the target nuclei are often unstable. Surrogate reactions offer a promising alternative for evaluating these nuclear
reaction rates. At the RIBF facility in RIKEN, radioactive isotope beams can be slowed down and focused using a novel device called OEDO.

We employ the (d,p) reaction as a surrogate for neutron-induced reactions. A distinctive feature of our experimental
setup is the use of a magnetic spectrometer located downstream of the target. This allows for unambiguous
identification of the reaction residues in coincidence with the recoiled protons, enabling us to determine the decay
channels above the separation energy as a function of excitation energy.

Our first experiment focused on the 79Se(n,γ) reaction. Subsequent measurements targeted surrogate reactions for
130Sn(n,γ) and 56Ni(n,p). In this talk, we will primarily present results from the 79Se case and introduce preliminary
findings from the 130Sn measurement.

Monday II / 14

indirect Constraints of Neutron-Induced Reactions

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Neutron-induced reactions on radioactive nuclei are important for a variety of applications. However, these reactions are often difficult to measure directly due to the unstable nature of the reactants. A variety of indirect methods have been developed in which experimental measurements are used to constrain the statistical calculations of these reactions. I will discuss the epistemological uncertainties inherent in these approaches and share some results from a recent experimental campaign in which we gathered data for several indirect constraints.

Tuesday I / 15

Constraining capture rates on radionuclides through neutron transmission with the DICER instrument at LANSCE

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With very few exceptions, direct measurements of neutron capture rates on radionuclides have not been possible. A number of indirect methods have been pursued, however, substantial effort has been devoted to quantify the usually large systematic errors that accompany the results from these techniques. A new instrument has been developed at the Los Alamos Neutron Science CEnter (LANSCE) to provide more accurate data on several radionuclides relevant to nuclear criticality safety, radiochemical diagnostics, astrophysics, nuclear forensics and nuclear security, by measuring the transmission of neutrons through radioactive samples and studying resonance properties. The Device for Indirect Capture on Radionuclides (DICER) and associated radionuclide production at the Isotope Production Facility (IPF), both at LANSCE, as well radioactive sample fabrication, have been under development the last few years. A description of the apparatus and two cases studies on 88Zr and 88Y will be presented.

Wednesday III / 16

Realistic Reaction Evaluations for Fission Products Off Stability

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Nuclear applications such nonproliferation, post-detonation forensics, spent-fuel assay, reactor burnup and design, as well as astrophysics, rely on the accurate description of the neutron interaction with unstable fission products. However, current cross-section descriptions of these nuclei are either non-existent or based on simplified assumptions, leading to unquantified impacts on predicted cross-sections. In this work we will discuss a newly funded project aiming to address these issues through predictive modelling, leveraging machine-learning methods, with an experimental component to help constrain model parameters. We will discuss details of the approach as well as project status and plans. We will present preliminary results, focusing on the most produced nuclei off stability in the fission process of 235U. In particular, we will discuss coupled-channels mechanisms

with different models for nuclear deformation. When completed, assuming the methods are well-established, the project should be able to provide realistic evaluated files for the whole isotopic chain of all off-stability fission products of 235U, 239Pu, and 252Cf. The evaluated files will be submitted to ENDF/B for consideration in the future ENDF/B-IX release.

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Tuesday II / 17

The predictive power of TALYS

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An attempt is made to quantify the predictive power of the TALYS nuclear reaction model code for neutron-induced reactions up to 30 MeV. Special emphasis is put on the neutron capture channel in the fast energy range, but all other reaction channels up to 30 MeV will be covered as well. This uncertainty analysis is based on several prerequisites:

Modern descriptions of the nuclear level density and photon strength function,

An outlier-cleaned and computationally accessible version of the EXFOR database,

Sensitivity profiles for TALYS nuclear model parameters and their use in automated parameter optimization.

The global assessment of predictive power is based on a simultaneous analysis of all cross sections, MACS, and average radiative widths in the range A=20-209 for which experimental data exists. The main discussion point will then be to which extent the predictive power is applicable to short-lived nuclides.

Tuesday III / 18

Reference Input Parameter Library updates: photon strenghts and nuclear level densities

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The updates to the RIPL Gamma and Density sections from past and ongoing IAEA CRPs will be presented.

Tuesday I / 19

Constraining Neutron Capture Rates in Exotic Nuclei

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Accurate neutron capture rates for unstable nuclei are essential for nuclear data evaluations and for improving reaction network calculations. A promising approach combines radioactive ion beams with the Oslo method, which extracts nuclear level densities and γ-ray strength functions to indirectly constrain capture rates. The β-Oslo technique extends this capability to beam intensities down to ~1 particle per second, enabling measurements on highly exotic isotopes and greatly expanding the range of nuclei accessible compared to other indirect methods. I will review the status and challenges of applying the Oslo method with exotic beams, including developments with (d,p) reactions. Specific topics include the "shape"method, absolute normalization issues, and strategies for "breeding"capture products one to two steps from stability for cross section determination via accelerator mass spectrometry (AMS). While the emphasis is on measurement techniques and data, I will briefly note the relevance of these efforts for constraining i-process and r-process nucleosynthesis models.

Monday III / 20

Neutron Activation Analysis with Short-Half-Life Radionuclides: Opportunities, Challenges, and Implementation Guidelines

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Abstract: Neutron Activation Analysis (NAA) remains a widely applied technique at research reactors worldwide, offering multielement, non-destructive analysis with high accuracy. Traditional NAA protocols, typically based on measurements performed several days to weeks post-irradiation, enable the determination of 30–40 elements but often suffer from long turnaround times. This delay has contributed to a declining interest in NAA as a commercial service, particularly in the face of faster competing analytical methods. Short half-life radionuclide NAA presents an underexploited opportunity to significantly reduce analysis times, enabling results within a single working day. This approach not only improves throughput but also extends elemental coverage to nuclides not accessible via long-lived activation products. Despite its potential, implementation has been limited due to technical and analytical constraints, particularly in research reactor environments. This work outlines the requirements for successful deployment of NAA with short-lived radionuclides, focusing on necessary adaptations to irradiation facilities, detection systems, and calibration protocols. The aim is to guide both experienced practitioners and new users in overcoming current limitations and leveraging this approach to enhance the analytical performance and competitiveness of NAA laboratories. While broadly applicable to various neutron sources, the sensitivity data presented primarily reflect research reactor-based configurations. Keywords: Neutron Activation Analysis; short half-life radionuclides; research reactors; irradiation facility design.

Monday I / 21

Direct radiative neutron captures for astrophysics - Status quo

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Neutron capture reactions play a crucial role for the understanding of the synthesis of elements heavier than iron in stars and stellar explosions via the slow (s), intermediate (i), and rapid (r) neutron

capture processes. In all three processes, the fine balance between neutron capture and beta-decay rates under the given astrophysical conditions defines how long a nucleus can accumulate material before decaying into the next isotopic chain.

Most of the s-process neutron captures on stable or long-lived nuclei (t(1/2)» 10 y) along the line of stability and have been experimentally constrained in the past 50 years [1], with satisfying precision for most astrophysical modelling. However, the direct measurement of neutron cross sections with shorter half-lives (t(1/2) <1 year) requires the use of radioactive beams in inverse kinematics and the development of new methods. Only a few measurements have been performed so far with these indirect methods. This general lack of experimentally constrained data leads to large deviations between various Hauser-Feshbach predictions for very neutron-rich nuclei [2] which also makes abundance predictions for the r-process very unreliable [3].

I will give a short introduction about the limitations of direct measurements, as well as the status of direct neutron capture reactions in the astrophysical energy range.

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Tuesday IV / 22

Capture cross section using integral data

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Presenting integral measurements directly related to capture reactions.