Informing neutron capture with surrogate (d,p) reactions

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Informing neutron capture on rare isotopes is important to understand the synthesis of the elements in stars and their explosions and mergers, as well as nuclear energy and stewardship science. Andrew Ratkiewicz et al., validated neutron transfer (d,p) as a surrogate for (n, γ) reactions. The coupling of an array of γ-ray detectors to the Oak Ridge Rutgers University Barrel Array (ORRUBA) of position sensitive silicon strip detectors forms GODDESS – Gamma-array ORRUBA: Dual Detectors for Experimental Structure Studies. ORRUBA has been coupled to Gammasphere and GRETINA arrays and prepared to couple to GRETA. Ionization chambers or the S800 spectrograph are deployed for heavy recoil detection. Both near Coulomb barrier (at ATLAS) and fast ($\sim$ 40 MeV/u) (at NSCL and FRIB) (d,p) measurements with rare isotope beams have been realized. For a surrogate analysis, the γ-decay probabilities as a function of excitation energy need to be extracted, requiring high efficiency for detecting the γ cascades and good resolution for charged-particle detection. High level density, limited resolution of charged particle detectors, and limited efficiency of γ detector arrays challenges informing (n, γ) cross sections via a surrogate (d,p) reaction. Recently we have demonstrated that measuring the heavy recoil of the (d,p) reaction with the S800 spectrograph can increase the efficiency of deducing the γ-decay probabilities as a function of excitation energy. Therefore, we do not need to understand the complicated decay pattern from discrete γ rays, especially important for nuclei away from closed shells and odd-odd nuclei with high level density. The present talk would summarize the (n, γ) surrogate reaction method with the (d,p) reaction and the realization of GODDESS at NSCL and FRIB with the S800. Preliminary results from recent measurements and proposed experiments to inform (n, γ) rates would be presented. This work is supported in part by the U.S. Department of Energy National Nuclear Security Administrator and Office of Nuclear Physics and the National Science Foundation.

Reaching for the stars: Next-generation neutron reaction experiments with the Neutron Target Demonstrator and the ASTRA Facility at LANSCE

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The capability to directly measure neutron reactions on unstable isotopes would grant access to many reactions of interest to the mission science and nuclear astrophysics communities. However, precision measurements in forward kinematics are currently prohibited because the stationary target radiation fields overwhelm the detection system, target sample sizes are too small, or target lifetimes are too short. We are pursuing a neutron target facility at the Los Alamos Neutron Science Center (LANSCE) to overcome these experimental challenges by circulating a radioactive sample within an ion beam storage ring and through a thermal neutron field to induce reactions in inverse kinematics. A first experiment with the Neutron Target Demonstrator (NTD) at LANSCE is underway to validate this concept. The NTD project is collaborating with the new Facility for Applications of Special Technologies for Research with Accelerators in Area A (ASTRA) to develop the high-intensity Low-Energy Heavy Ion Source (LEHIS), downstream beam transport elements, and target systems required to execute this experiment. Results from recent simulations and experimental tests of the NTD subsystems will be presented, along with an overview of the collaborative ASTRA Facility and LEHIS system.

Development of Platforms at NIF to measure (n,2n) Cross Sections

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The incredibly large neutron flux generated by a DT-fusion capsule fielded at NIF can be used to induce neutron capture reactions in materials added to the inner surface of the capsule shell in order to measure nuclear reaction rates in a plasma environment. The advantage of using NIF over traditional neutron facilities is that much less material is required, which lowers the overall radioactivity of the target material for reactions on unstable isotopes. The short burn time of a NIF shot also opens the possibility of reactions on excited nuclear states with lifetimes longer than the NIF burn. In cases where there is an insufficient quantity of target material, or the radioactivity of a traditional accelerator target is too large to handle safely, performing neutron activation at NIF may be the only viable path to measuring nuclear reaction rates on unstable nuclei when the data is unknown. In the absence of this data, nuclear reaction rates rely on models, which may have very large uncertainties. In an effort to begin measuring neutron activation rates on rare earth nuclei, two sets of NIF capsules were doped. The first set contained 91Y, 171Tm, and 152Eu, and were shot without DT fuel in an effort to determine if rare earth isotopes would fractionate from one another as they condensed out of the plasma onto the debris collectors. The second set contained 89Y, 169Tm, and 152Eu for an initial measurement of the 89Y(n,2n)88Y cross section using a cryo-layered DT capsule fill. Future efforts will focus on measuring unknown quantities such as 88Y(n,2n)87Y. Results from the fractionation shots and initial results from the layered shot will be presented.

Overview of Isotope Harvesting Efforts at FRIB

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At the Facility for Rare Isotope Beams (FRIB), exotic secondary beams are created by the fragmentation of a high-power primary beam. In this process only a small fraction of the beam products are selected and co-produced fragments are intercepted by accelerator components, while the unreacted primary beam will be stopped in a water-traversed beam dump. The accumulated radionuclides in all these components represent an invaluable resource and can be collected through targeted isotope harvesting.

I will give an overview of the aqueous isotope harvesting process, focusing on the collection of ^{62}Zn from a stopped ^{78}Kr beam. The ^{62}Zn decays to the short-lived ^{62}Cu ($t_{1/2}$= 9.7 min) and currently, both find collective application in nuclear medicine for the ^{62}Zn/^{62}Cu PET generator. The developed purification method facilitated the successful isolation of ^{62}Zn. Furthermore, we have started to develop the chemistry required to set up a ^{62}Zn/^{62}Cu generator.

Isotope collection from the solid phase is another possible isotope harvesting mode. Recently, we have begun exploring the radioisotopes ^{189}Pt and ^{197}Pt, which are relevant for nuclear medicine, especially in the form of radio-cisplatin. We developed a separation process to extract Pt from the collector material and impurities. Preparations are underway for a beam experiment to isolate the Pt radioisotopes and validate our method with radioactive materials.

Isotope harvesting is generally non-selective towards the production of a particular isotope, often yielding mixed samples rather than radioisotopically pure ones. Introducing a mass-separation step could expand the availability of pure isotopes. FRIB's infrastructure includes a suitable mass analyzer, enabling the development of a prototype mass separator. This talk will overview our initial mass-separation experiment where we investigated the release and extraction of stable ^{61}Ni, and provide an outlook on possible extensions to the isotope harvesting program.

Intense short pulse (n,x) reaction studies on stable and radionuclei using ATHENA at NIF

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Understanding the production of radionuclei produced by intense short neutron pulse environments is important for nuclear science applications. In a short pulse high instantaneous neutron flux environment, these radionuclei are produced through an often-complex network of completing reaction channels which may occur not only on ground states but also excited states. Reconstruction of neutron energy spectra from fluence monitors or predicting fallout debris, for example, require knowledge of these reaction networks to properly determine the neutron environment. The ATHENA experimental platform at NIF provides a unique capability for investigating these reaction networks through integral measurements under controlled laboratory conditions. At the heart of the ATHENA platform is an energy tuning assembly which modifies the DT thermonuclear NIF spectrum into a desired spectral shape. This results in a tunable neutron energy spectrum rather than monoenergetic neutrons from DT fusion. In this talk, an overview of the experimental capabilities of the ATHENA platform will be discussed as well as recent results from a NIF ATHENA shot on iridium will be presented.

Direct Neutron Capture Measurement of Zirconium-88 at CERN n_TOF

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We report the first direct measurement of zirconium-88 neutron capture cross section from 0.015 eV to 0.75 eV at the CERN n_TOF experiment. Zirconium-88 was measured in 2019 to have the second largest thermal neutron cross section of any isotope and orders of magnitude above expectation. The DICER experiment recently published a transmission-based cross section and evidence of a sub-eV resonance. This work confirms a sub-eV resonance at an energy of 0.173±0.008 eV, in agreement with DICER, and provides a Single-Level Breit-Wigner best fit.

Unresolved resonance region cross sections by random-matrix approach

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The random-matrix approach has been employed to calculate cross sections in the unresolved resonance region (URR) theoretically [1]. In current Monte-Carlo approaches, the URR parameters are employed for constructing a probability table, and Wigner and chi-square distributions are assumed for calculating the cross sections. However, the random-matrix approach allows us to calculate these cross sections without such assumptions. This approach employs the Gaussian orthogonal ensemble (GOE), which is a real symmetric matrix, and the elements are random numbers that follow the Gaussian distribution. The eigenvalue and its spacing distributions of GOE resemble the distribution of the actual resonance. These statistical properties of GOE are incorporated into the scattering matrix with neutron and gamma-ray transmission coefficients, which are model parameters in this model. We demonstrate that the calculated resonance spacing does not reproduce the Wigner distribution exactly. Moreover, we present the parameter dependence on the cross sections of ^{238}U.

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Numerical simulations of dynamic i-process nucleosynthesis in stars constrained by nuclear physics experiments and astrophysical observations

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Carbon-enhanced metal-poor (CEMP) stars carry the signature of neutron-capture processes in the early universe. It has been thought so far that many of the CEMP stars show slow-neutron capture products. However, new simulations that take into account the the time-dependent hydrodynamic nature of convective-reactive He-burning convection with dynamic H ingestion and nuclear-hydro feedback show that the intermediate n-capture processes with time-dependent termination may be the origin of heavy-element abundances observed in most CEMP stars. The i-process path proceeds through unstable species about two to six masses away from stability. Understanding the astrophysical, hydrodynamic processes of the intermediate n-capture process depends critically on the highly uncertain n-capture cross sections of unstable species. The astrophysical context of the i process and its astronomical manifestation in CEMP stars provides a rich testbed for nuclear data validation. Based on our Monte Carlo simulations, in which all rates are varied within a range estimated from Hauser-Feshbach models and parameter variations and comparison with observed CEMP star abundances we predicted corrections to Hauser-Feshbach n-capture rates for ^{139}Ba, ^{88}Kr, and ^{75}Ga, which have already been experimentally verified for the first two isotopes. A scheduled experiment on constraining the neutron-capture rate for ^{75}Ga will be a key test for the hypothesis that its reduced value is responsible for the high As to Ge i-process abundance ratio in the star HD94028.

The (weighted) Levenberg-Marquardt algorithm for curve-fitting problems in nuclear physics

M. Imbrišak, A. E. Lovell, M. R. Mumpower, T. Kawano
(Dated: October 25, 2024)

The current methodologies for assessing nuclear reaction data, particularly for medium to heavy nuclei, utilizes the Hauser-Feshbach (HF) statistical model [1]. This model is often used to calculate an energy-averaged nuclear reaction cross section, where resonances overlap significantly. The HF model incorporates width fluctuation correction to account for these overlaps.

The CoH_3 code [2,3] implements the coupled-channels optical model in the HF framework and is designed to address reactions within the keV to tens of MeV energy range. Due to its dependence on optical potentials, single particle densities, level densities and strength functions, the CoH_3 code contains 30 different parameters which should be determined by minimization techniques for each nucleus independently. The minimization problem is exacerbated by the fact that the measurements are not (or cannot be) performed for every reaction channel and excitation energy of interest.

We compare the minimization obtained via the standard Levenberg-Marquardt[4,5] (LM) algorithm to the extended weighted Levenberg-Marquardt (wLM) algorithm that is weighted over different reaction channels and data sets from available experiments. The weighting method that was first developed to jointly analyze different cosmological data sets [6] was employed to address the systematics arising from utilizing multiple different reaction channels measured by different research groups. The collected parameters of the fitted isotopic chains will later be used to make uncertainty quantification by extrapolating their values for the nuclei that have no data.

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The CoGNAC Neutron Scattering, (n,2n), and (n,3n) Measurement Capabilities at Los Alamos National Laboratory

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The Correlated Gamma-Neutron Array for sCattering (CoGNAC) experimental campaign at Los Alamos National Laboratory is a new capability for the physics community capable of measuring neutron elastic and inelastic cross sections and emitted particle angular distributions. Uncertainties in neutron scattering nuclear data represent a dominant source of potential error in a wide variety of applications, and the CoGNAC team aims to minimize these errors through high-precision measurements with active engagement with the subsequent nuclear data evaluation process. Recent results from this measurement program were published in [1], [5], [2], and [3], with multiple additional forthcoming results. The neutron detection abilities of the CoGNAC array are also currently being expanded to include an series of large-volume CLYC-7 scintillators to enable angle-differential, spectroscopic neutron-only (i.e., no γ-ray detection requirement) measurements of (n,2n) and (n,3n) reactions with the Los Alamos Neutron Science Center (LANSCE) white neutron source, funded by a recent Department of Energy Early Career Research Award. These measurements are central to reduce potential errors in fusion reactor design and operation and historical radiochemical diagnostics data. The CoGNAC approach to measurements of this collection of neutron-induced neutron-emitting reactions will be described along with current results and future measurement plans.

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Challenges of the neutron-capture measurement on radioactive ^{204}Tl with the DANCE detector

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Radiative neutron capture is one of the main reaction channels responsible for production of heavy elements in stars. The so-called slow neutron capture or s-process involves a chain of neutron captures followed by beta decays. ^{204}Tl is a branching point in the reaction chain and therefore its neutron-capture cross section is of crucial importance for astrophysical calculations.

A measurement of neutron capture on ^{204}Tl was carried out with Detector for Advanced Neutron Capture Experiments (DANCE) at Los Alamos Neutron Science Center (LANSCE). This highly efficient and highly segmented detector array is designed for detection of total γ-ray energy and individual γ rays emitted after the neutron capture. However, this was a very challenging measurement due to the large amount of background, as ^{204}Tl undergoes beta decay with 3.8-year half-life.

This talk will present experimental data from this measurement and describe complications related to the analysis, which include high count rates, very small abundance of ^{204}Tl in the sample and significant background contribution. Despite these difficulties, new resonances - identified as ^{204}Tl - are observed in the experimental data.

Neutron induced charged particle emitting reactions on radioactive isotopes at LANSCE

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o further enhance our understanding of nuclear reactions on radioactive isotopes relevant for applications such as nuclear astrophysics and national missions, we need to extend our capability of accessing radionuclides from today's reach. The Isotope Production Facility at the Los Alamos Neutron Science Center (LANSCE) provides short-lived isotopes such as ^{56}Ni with a half life of 6 days, which was used for directly measuring (n,p) and (n,α) reactions with the hotLENZ (radioactive Low Energy NZ) instrument at LANSCE. The summary of astrophysical impacts on the ^{56}Ni reaction study will be discussed as potential constrains of nuclear physics input in network calculations to improve explanations of the heavy element production puzzles. Based on the current limitations on directly accessing radionuclides and measuring nuclear reactions with them, I will present the feasibility, the future optimizations, and additional capabilities that will enhance this effort on improving our fidelity on direct measurements on neutron reactions on radionuclides.

Astrophysics impacts/needs of neutron induced reactions and related topic

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During CERN's accelerator shutdown (2019-2021), n_TOF received a significant upgrade, including a new target-moderator assembly, refurbished beam lines, experimental areas, and the creation of the NEAR Station. This new station offers exciting possibilities for neutron activation studies and novel physics research. This presentation will provide an overview of the n_TOF facility and its activities at CERN, with a particular emphasis on recent groundbreaking experiments and exciting plans for future endeavors.

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Probing nuclear structure with thermal neutrons

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Among the different approaches to study the structure of nuclei, thermal neutron-induced reactions can be used to probe different phenomena. Capture reactions on (rare) stable or radioactive targets populate low-spin states below the neutron separation energy. With thermal neutron-induced fission on actinides, neutron-rich nuclei are populated at moderately high spin. Those reactions are used at the Institut Laue-Langevin (ILL, Grenoble), at a high-resolution gamma-ray spectroscopy setup. FIPPS (Fission Product Prompt gamma-ray Spectrometer) has been used to study the structure of nuclei in different region of the nuclear chart, addressing phenomena as nuclear shape coexistence. After a general introduction about the nuclear physics activities at the Institut Laue-Langevin, recent results obtained in different experiments at FIPPS will be reported. Details of experiments involving radioactive/rare targets will be given. Particular focus will be dedicated to the first fission campaigns, showing the innovative technique of fission tagging and first results. The novel use of this device for the measurement of lifetimes of medium-high spin states in neutron-rich nuclei will be shown. The future perspectives for the coupling of the existing FIPPS setup to a fission-fragment identification system will also be outlined.

Preparation of highly radioactive targets for nuclear data measurements

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Nuclear data for neutron induced reactions on short-lived radioisotopes are critical for a wide range of applications spanning from radiochemical diagnostics, nuclear reactor designs to nuclear astrophysics. In this contribution, fabrication of two different targets: (1) ^{56}Ni electroplated on gold foil and (2) ^{88}Zr-filled tungsten canister within a hot cell will be described. Tools developed to accomplish these unique experiments by remote handling techniques will be highlighted. Nickel-56 ($t_{1/2}$ = 6.075 days) was produced by medium energy proton-induced reaction on natural cobalt target at Isotope Production Facility (IPF) at Los Alamos Neutron Science Center (LANSCE). After target dissolution, approximately 100 mCi of ^{56}Ni was separated from bulk of cobalt by cation-exchange chromatography. The final step involved electroplating of isolated and purified ^{56}Ni on a 6 μm-thick gold foil mounted on a metal frame. This sample was studied using the fast neutron beams available at the Weapons Neutron Research (WNR) facility at LANSCE [1, 2]. The second project involved production of ^{88}Zr ($t_{1/2}$ = 83.4 days) via low-energy proton irradiation of natural yttrium target at IPF. The yttrium target was dissolved and several curies of ^{88}Zr were isolated utilizing hydroxamate-based extraction chromatography resin. Zirconium-88 was concentrated to very small volume in hydrochloric acid. An automated dispensing unit was designed and installed inside a hot cell to dispense samples of ^{88}Zr ranging from 4 to 8 microliters into tungsten canisters and enclosed using lead plugs. Neutron transmission measurements were performed on these ^{88}Zr-filled samples at LANSCE utilizing the Device for Indirect Capture Experiments on Radionuclides (DICER) [3, 4].

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Overview of needs and capabilities for radionuclide reaction physics

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Constraining Neutron-Induced Reactions on Unstable Nuclei

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Neutron-induced reactions on unstable nuclei are important. However, their cross sections are hard to measure directly. I will discuss the currently-available data in various evaluations and libraries for neutron-induced reactions on unstable nuclei (there is very little) and talk about what would be required to constrain or directly measure some of these reactions. I will also discuss some applications of these cross sections.

A neutron target for measurements in inverse kinematics

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Virtually all of the isotopes heavier than iron would not exist without neutron-induced reactions. Despite there importance in many different astrophysical scenarios, there are almost no direct measurements for isotopes with half-lives shorter than a few years. A radically new approach is necessary to overcome this constraint.

Ion storage rings offer unprecedented possibilities to investigate radioactive isotopes of astrophysical importance in inverse kinematics. During the last years, a series of pioneering experiments proofed the feasibility of this concept for the fusion of charged paricles at the Experimental Storage Ring (ESR) at GSI. In the future, a combination of a free-neutron target and an ion storage ring can bring the half-life limit for direct neutron-induced reactions down to fractions of a minute.

The Neutron Target Demonstrator project at the Los Alamos National Laboratory is the first step towards such a facility. The goal of the project is to prove that a neutron capture cross section can indeed be directly measured in inverse kinematics.

Measurements of the Radio-production Cross Section of ^{193}Ir$(n, n')^{193m}$Ir between 0.5 and 9 MeV

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Iridium has historically served as a useful neutron fluence monitor due to its ability to probe the thermal, fission, and fusion energy regimes through (n, γ), (n, n'), and $(n, 2n)$ reactions. ^{193}Ir has a J^{π}=11/2- metastable state ($t_{1/2}$=10.5 days) that can be induced from (n, n') reactions and emits a 9.18 keV x-ray via internal conversion. The effectiveness of iridium as a neutron fluence monitor is dependent on the accuracy the (n, n') cross section. Recent measurements of the ^{193}Ir$(n, n')^{193m}$Ir radio-production cross section indicate a discrepancy between ENDF, model predictions, and previous measurements. Further measurements are needed to address this discrepancy. An experiment to measure the ^{193m}Ir radio-production cross section was conducted at the University of Notre Dame St.ANA 5U accelerator laboratory. Neutrons from ^{7}Li$(p, n)^{7}$Be and ^{13}C$(\alpha, n)^{16}$O was used to bombard iridium foils from 0.5-9 MeV. Measurements were normalized to Gold, Nickel, Iron, and Indium reference foils. Results from this measurement will be presented.

Neutron-induced measurements at TUNL's tandem lab

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Constraining neutron capture rates on radionuclides: the DICER instrument at LANSCE

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Neutron capture data essential for applications such as astrophysics, criticality safety and defense applications, however, challenging to acquire for short-lived radionuclides. A technique has been recently developed at the Los Alamos Neutron Science CEnter (LANSCE), that can provide accurate data on a plethora of radionuclides relevant to these applications, by performing neutron transmission measurements. The Device for Indirect Neutron Capture Experiments on Radionuclides (DICER) is a capability that was developed to address the aforementioned challenge. DICER performed its first measurement on a radioactive sample recently, by irradiating liquid ^{88}Zr samples that were produced in collaboration with the Isotope Production Facility (IPF) at LANSCE. This measurement resulted in the discovery of a nuclear level near the neutron separation energy. Other recent efforts include the measurements of ^{239}Pu and ^{88}Y. A description of the new apparatus as well as preliminary data on a few stable and radio-isotopes will be presented.

Microscopic approach to nuclear reactions

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The dynamics of quantum systems, and in particular nuclear systems, is very di¿icult to describe as it involves many degrees of freedom. In the last years, we have made progress in description of nuclear dynamics due to (i) the development of density functional theory, and its time dependent extension, and (ii) the extreme advances in computing capabilities, and particularly the use of graphics processing units. This has had implications for fission modeling, as it showed that the usual adiabatic approximation used to calculate fission fragments mass and charge distributions is inadequate, as most of the potential energy from saddle to scission dissipates into internal degrees of freedom, thus heating up the compound nucleus with consequences for neutron emission from excited fragments. In this talk, I will summarize the latest advances in describing the dynamics of nuclei and discuss future improvements and directions.

Neutron poisons and neutron storage in steller environment

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Neutron capture reactions on light nuclei are labeled as neutron poison since they can reduce the overall neutron flux in stellar environment. However, these kind of reactions may also serve as neutron storage until a subsequent process triggers a release of neutrons. Some examples, in particular in the context of tritium will be discussed.

NG-Trap: Trap System for Measuring Neutron Capture Cross Section of Short-lived Neutron Rich Isotopes

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Neutron-capture cross-sections of radioactive neutron-rich isotopes have a wide impact on nuclear astrophysics, nuclear reactions and nuclear structure studies. Measurement of these cross-sections is currently considered impossible due to the instability of the targets and projectile. We propose a method to overcome this limitation. We plan to stop and thermalise fission fragments in a cryogenic stopping cell. These fragments will then form a cooled low-energy beam transported into an RF trap system (coined 'NG-Trap' [1]). An intense neutron beam will then irradiate this trapped 'cloud target'. The reacted ions will be mass-selected, identified and counted using a multiple-reflection time-of-flight mass-spectrometer (MR-TOFMS), thus extracting (n,γ) cross-sections.

This talk will present preliminary results towards the goal of generating the required 'cloud target'. A demonstrator system based on a triple-RFQ system[2] with an ion capacity of more than 10^{10} ions will be presented. This system is a major milestone of the plan to install a high-capacity trap at the Soreq Applied Research Accelerator Facility (SARAF), currently under construction in Yavne, Israel.

[1] T. Dickel *et al.*, EPJ Web of Conferences **260**, 11021 (2022).

[2] E. Haettner *et al.*, Nucl. Instr. Meth. A **880**, 138 (2018).

[3] I. Mardor *et al.*, Eur. Phys. Jour. A **54**, 91 (2018).