i-process Nucleosynthesis Workshop & School

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Libro de resúmenes

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Investigating the i-process in C-normal stars

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The so-called neutron-capture elements are, historically, thought to be produced through two main channels. They are the (rapid) r-process, happening in environments of high density of neutrons, and the (slow) s-process, in low neutron density environments like AGB stars. Recent developments have led to the proposal of the (intermediate) i-process as being responsible for the abundance pattern of stars rich in both r- and s-process elements, such as the CEMP-r/s stars, characterised by [C/Fe] > 1, [Eu/Fe] > 1 and 0 < [Ba/Eu] < 0.5 dex. In the proposed scenario, even "classic" heavy r-process species such as U and Th could be produced in the i-process. The C enhancement of the CEMP stars leads to the assumption of enrichment by a former AGB companion in the past, with AGB/post-AGB stars being proposed as sites where the i-process can occur. Following these developments, we are analysing high-resolution (R ~ 40,000), high S/N spectra in the 330-680 nm interval of r-process rich ([Eu/Fe] > 1 dex) metal-poor stars which are not C-enhanced and are mildly s-process rich ([Ba/Fe] ~ 0.5 dex). We will present a detailed abundance pattern in the heavier end of the periodic table (atomic number Z ≥ 64) for our sample of metal-poor stars. Our aim is to derive an observational counterpart to i-process modelling of the progenitors of C-normal metal-poor stars not enriched by mass transfer from a former AGB companion.

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i-process nucleosynthesis in post-AGB stars

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We present detailed calculations of neutron-capture processes during very-late thermal pulses in state-of-the-art post-AGB models. We explore the dependence of neutron-capture processes on the stellar mass and initial chemical composition.

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Constraining neutron-capture cross section for the i-process for the 151–153Nd(n,γ)152–154Nd reaction via the β Oslo method

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Nucleosynthesis of heavy elements has been traditionally attributed mainly to two neutron-capture processes, namely the *s* and *r* processes. Recent astronomical observations have revealed stars where the abundance distributions cannot be described by the aforementioned processes and for this reason, the astrophysical *i* process was introduced (*i* for intermediate between *s* and *r*). Given the proximity to stability of the i process, the main nuclear physics uncertainty is neutron-capture reaction rates. An experiment was recently run at the ATLAS facility using the low-energy beams delivered from CARIBU to constrain neutron-capture reactions of importance for the *i* process. β-decays and their corresponding γ-rays were identified using the SuN detector and the SuNTAN moving tape system. The β-decay of $^{152-154}$Pr into $^{152-154}$Nd was measured and the β-Oslo method was used to extract the nuclear level density and γ-ray strength function of $^{152-154}$Nd; preliminary results from this experiment will be presented here. From these statistical properties, $^{151-153}$Nd(n,γ)$^{152-154}$Nd reaction cross sections and reaction rates will be constrained and their significance to the i process will be identified.

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Unveiling the chemical fingerprint of phosphorus-rich stars

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Chemically peculiar stars, such as the recently discovered metal-poor ([Fe/H] ⊠ –1.0 dex) phosphorus-rich ([P/Fe] ⊠ 1.2 dex) stars, call current theories on stellar nucleosynthesis and galactic chemical evolution into questions. Given that the P-rich low-mass giants are not expected to produce their high P contents themselves, we aim at finding clues on the progenitor of these stars. On the search for the progenitor, we achieved a remarkable enlargement of the P-rich stars sample, from originally 16 to 78 stars. Based on the high resolution near-IR (H-band) spectra from the SDSS-IV/APOGEE-2 survey (DR17), we successfully performed a detailed abundance analysis of 13 elements on the enlarged sample, using the Brussels Automatic Code for Characterizing High accUracy Spectra (BACCHUS). Among other things, we report enhancements in several

elements, such as O, Al, Si and Ce, as well as strong correlations with the phosphorus abundance. In this talk, I will present the statistically reliable chemical fingerprint of the P-rich stars as well as its implications on the nature of the P-rich stars progenitor.

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The i-process in AGB stars

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The existence of the i-process is supported by the observation of metal-poor stars whose chemical compositions are intermediate between the s- and r-processes (the so called r/s-stars). The i-process is triggered when protons are mixed in a convective helium-burning zone (proton ingestion event or PIE). The astrophysical site(s) hosting PIEs and thus the i-process is (are) actively debated. Among the various possible sites, the early AGB phase of low-mass stars is a promising one. In this talk, I will focus on the development of the i-process in state-of-the-art AGB stellar models of various masses and metallicities computed with the stellar evolution code STAREVOL. I will highlight the chemical fingerprint of these stars, present i-process yields as a function of mass and metallicity, identify key reaction rates and compare model predictions with observed r/s-stars.

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Informing neutron capture for i-process nucleosynthesis via the (d,p) reaction with rare isotope beams

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The synthesis of heavy elements in stars and explosive events is dominated by processes that involve the capture of neutrons. Understanding the synthesis of A≈80 nuclei is especially challenging since the rapid neutron capture, r-process alone is unable to reproduce this abundance peak. In particular, the synthesis of 84Se probably requires a (weak) r process [1] as well as an intermediate i-process [2]. To inform neutron capture on unstable nuclei requires rare isotopes and indirect methods, such as the Surrogate Reaction Method (SRM) [3].

We have recently validated the (d,p gamma) reaction as a surrogate for (n,gamma)[4]. The (d,p) rection can also inform direct-semi-direct capture, which is important for nuclei near the N=50 shell closure.

To inform neutron capture for N≈50, A≈80 isotopes, we have mounted two measurements of the (d,p) reaction with ≈40 MeV/u beams of rare isotopes at the National Superconducting Cyclotron Laboratory (NSCL) and are approved to measure a third (d,p gamma) reaction at the Facility for Rare Isotope Beams (FRIB). For the 84Se(d,p) study [5], reaction protons were measured in the Oak Ridge Rutgers University Barrel Array (ORRUBA) of position-sensitive silicon detectors and in coincidence with heavy recoils analyzed with the S800 spectrograph. We have deduced direct-semi-direct neutron capture cross sections. In addition, we can separate the 85Se recoils from 84Se beam-like residues, data that could inform the statistical (n,gamma) rates using the SRM. We are approved to measure the 80Ge(d,p gamma) reaction with the gamma-ray detector array GRETINA coupled to ORRUBA, again with heavy recoils analyzed with the S800 to inform both direct and statistical (n,gamma) rates.

The present talk would summarize how the SRM can inform (n,gamma) rates and describe the experimental setup and prospects for measuring (d,p gamma) reactions with ≈40 MeV/u A≈80 beams important for nucleosynthesis, including the i process.

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[2] J.E .McKay, et al., MNRAS 491, 5179 (2019) and references therein.
[3] J. E. Escher, et al., Phys. Rev. Lett. 121, 052501 (2018).
[4] A. Ratkiewicz, et al., Phys. Rev. Lett. 122, 052502 (2019).
[5] H.E. Sims, PhD dissertation Rutgers University (2021) and to be published.

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Exploring nucleosynthetic processes in a large sample of Barium stars

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Barium (Ba) stars belong to binary systems where a former asymptotic giant branch (AGB) star polluted the less evolved companion, which became enriched with material produced through the slow neutron capture process (s process). While the AGB has evolved to a white dwarf, the currently observed Ba star preserves the abundance pattern of the AGB, allowing us to test the imprints of the s process. Comparing different AGB nucleosynthetic models and Ba star abundances, we are able to constrain, for example, the effect of the initial rotation velocity and the nature of the neutron source. When comparing AGB models to the extended list of heavy element abundances available for a large homogeneous observational sample of 169 Ba stars, we found good agreement and confirmation that the polluting AGBs are of low mass (< 4 $M_{\odot}$). However, 43 stars (equivalent to 25% of the total sample) show anomalous abundance patterns, mainly at the first s-process peak, with Nb, Mo and Ru values higher than the model predictions. We hypothesize that these anomalies carry the signature of the i-process. If confirmed, this would represent first evidence that the i process is widespread also at the metallicities around solar represented by the Ba star sample.

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Spectroscopic follow-up of metal-poor stars with anomalous neutron capture element abundances in the GALAH survey

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Old metal-poor stars offer valuable information for understanding the formation and evolution of our Galaxy. These stars have been enriched with material coming from only one or maybe just a few nucleosynthetic sources. Thus, they can provide unique insight into the early history of Galactic chemical enrichment. Interestingly, a fraction of these old stars has been found to be enriched in r-process elements. The r-process is a neutron capture nucleosynthetic mechanism that produces the

heaviest elements in the periodic table, alongside the s-process and to a lesser extent the i-process. The astrophysical sources of the r-process elements are, however, still a mystery. Recently, neutron star mergers (NSM) have been confirmed as one such source, but the long timescale for their coalescence suggests that NSM may not be the only r-process site. The current era of large stellar surveys, such as Gaia, APOGEE, and GALAH, offers the opportunity for the identification and study of large samples of metal-poor stars. This is thus a unique chance to obtain a holistic view on all the possible sources of the r-process. In this work, we report preliminary results of an observational campaign to follow up chemically peculiar metal-poor stars identified in the GALAH survey. We selected 34 stars with [Fe/H] $\leq$ -2 and relative [Ba/Fe] and [Eu/Fe] abundances that deviate by more than three standard deviations from the mean of the sample. As a pilot study, we obtained data for two stars (TYC 9219-2422-1 and BPS CS 29529-0089) with the UVES spectrograph of the VLT. We present the atmospheric parameters and chemical abundances for a series of neutron capture elements for which the r-, s-, or i-process might contribute. We also analyze the orbits and dynamic properties of these stars to understand whether they were formed in situ in the Galactic halo or were accreted from external galaxies.

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Measurement of proton-induced reaction cross-sections on germanium isotopes relevant for the p-process

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Most of the heavy nuclei in the Universe (Z $>$ 26) are formed by neutron captures during the so-called s- or r-processes. However, 35 proton-rich nuclei imply the existence of another process of nucleosynthesis, the p-process, which takes place in explosive stellar events [1-4]. The modeling of this process relies on theoretical calculations of nuclear reaction rates. One of the main uncertainties for light nuclei comes from the (γ,p) photodisintegration reactions occurring in this process [5].
To improve the reliability of the calculations, it is necessary to increase the amount of nuclear data at energies as close as possible to the astrophysically relevant ones. Our collaboration has performed cross-section measurements of proton-induced reactions on several germanium isotopes, using the activation method. The obtained results will be discussed in this presentation. The main purpose was to measure the ^{70}Ge$(p,\gamma)^{71}$As, ^{72}Ge$(p,\gamma)^{73}$As, ^{73}Ge$(p,\gamma)^{74}$As cross sections at 2.5 MeV since these reaction have been identified as crucial for the production of the lightest p-nucleus $^{74}\mathrm{Se}$.

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Modeling and nuclear uncertainties of the i process

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Heavy-element abundance distributions in some of the CEMP-r/s stars can be reproduced by those predicted for the i-process nucleosynthesis that occurred at neutron densities intermediate between the values characteristic for the slow and rapid neutron-capture processes. Given that the abundances of the second-peak elements, beyond Ba, are relatively high, even after being strongly diluted in these CEMP-i stars, we can assume that the abundance ratios for pairs of neighboring elements are mainly determined by the neutron density at which they were produced. This allows us to use a simple one-zone model with constant temperature and neutron density to calculate such elemental abundance ratios for the i process and compare them with observed ones. The one-zone i-process model can also be employed in Monte Carlo simulations in which neutron-capture rates for unstable isotopes participating in the i process are randomly varied within their uncertainties estimated with the Hauser-Feshbach method to study the impact of these uncertainties on the predicted elemental and isotopic abundances. I will describe details of these simulations and present their results. I will also discuss multi-zone evolutionary models of the rapidly accreting white dwarfs and low-mass metal-poor asymptotic giant branch stars that were proposed as possible sites of the i process and I will compare elemental abundances predicted by the multi-zone and one-zone models.

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Nucleosynthesis in AGB Binaries

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Around half the heavy elements are formed through slow neutron captures taking place in evolved asymptotic giant branch (AGB) stars, in the mass range $\sim 1-6\ M_{\odot}$. Depending on the temperature, neutrons are produced through different reaction channels - via the $^{13}C(a,n)$ reaction at lower temperatures or at higher temperatures via $^{22}Ne(a,n)$.

The nucleosynthetic imprint of these reactions can be studied by observing the material present on the surface of the AGB star. The surface chemical composition therefore provides insight into the internal production rates (of, e.g., Rb, Sr, Y, Zr, Nb, Mo, Tc, Ba, La, Ce, Nd, Pb). With with high-resolution spectroscopy, we study these elements directly by observing the AGB star, or indirectly by studying the companions of binary systems that have been polluted by mass transfer from an AGB star that has faded away.

Bianrity in stellar systems is revealed through radial velocity measurements from the spectral observations, and by observing cyclical variations in the velocities over time. Orbital motion reveals information about the mass of the stars in the system, and in concert with the abundance measurements provides a relation between the production of the heavy elements and the mass of the star that produced them.

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Constraining the 75Zn neutron capture reaction via the β-Oslo method for the weak r-process

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Many questions remain about the neutron capture processes responsible for creating the majority of the neutron-rich heavy elements. The i-process and the weak r-process are two lesser understood neutron capture processes whose resulting abundance patterns and required astrophysical environments deviate from those traditionally ascribed to the r-process. Because of a lack of nuclear data in this region due to the difficulty in creating both neutron and exotic radioactive ion beams and targets, the weak r-process is not yet fully understood. To constrain the nuclear properties in this region, we turn to novel techniques. One of these indirect methods is the β-Oslo method, which uses β decay to populate highly-excited nuclear states in the compound nucleus of interest. The decay of these states is then used to extract the nuclear level densities (NLD) and γ-ray strength functions (γSF). By implementing these experimentally-determined statistical properties in the calculation of theoretical neutron-capture cross-section, uncertainties in the reaction rates can be greatly reduced. Here I will present results from the β decay of 76Cu in the calculation of the 75Zn(n,γ)76Zn reaction, in which the uncertainty in the reaction rate has been reduced from over an order of magnitude to a factor of just 2.5. The reaction rate will be presented, as well as its impact on the modeling of weak r-process abundances in the A ~ 80 region.

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Production of actinides by the i-process in AGB stars

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The intermediate neutron capture process (i-process) operates at neutron densities in between the slow and rapid neutron-capture processes. It is believed to be triggered by the ingestion of protons in a convective helium-burning region. One possible astrophysical site is the early thermally-pulsing phase of low-mass low-metallicity Asymptotic Giant Branch (AGB) stars.
Although it has been widely believed that actinides, and most particularly Th and U, are exclusively produced by the explosive r-process nucleosynthesis, we explore here the possibility that actinides may also be significantly synthesized through the i-process nucleosynthesis in such quiescent astrophysical objects.

The i-process nucleosynthesis is modelled in a 1Mo [Fe/H]=-2.5 AGB star, with the stellar evolution code STAREVOL. A detailed reaction nuclear network including 1160 species from H to Cf and 2247 reactions coupled to the transport processes is used to compute the i-process nucleosynthesis. During the proton ingestion event, the neutron density reaches typical densities of about 1e15cm-3 that are high enough to give rise to the production of actinides. While a significant part of the nuclear flow cycles in the neutron-rich Pb-Bi-Po region, a non-negligible fraction leaks towards heavier elements and eventually synthesizes actinides. Specific Pb, Bi and Po isotopes are important branching points where neutron capture competes with beta-decay and may hinder the flow towards the production of actinides. A specific attention is consequently paid to a detailed analysis of the systematic and statistical uncertainties affecting the prediction of the reaction rates and their impact on the production of actinides.

One stellar candidate that may confirm the production of actinides by the i-process is the carbon-enhanced metal-poor (CEMP) r/s-star RAVE J094921.8-161722 that shows Th lines in its spectrum.

Its surface abundance is shown to be reasonably well reproduced by our AGB model, though abundances of light N~ 50 elements remain underestimated. Such a finding also opens the way to a possible estimate of the time since the i-process event, through actinide-based cosmochronometry, which would provide a lower limit on the age of the CEMP r/s star. Such a cosmochronometry is expected to be accurate only if surface abundances of Th and U can be observationally derived simultaneously and if astrophysical and nuclear uncertainties can be reduced in the future.

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Constraining the Neutron Capture Rate for 90Sr through beta-Decay into the Short-Lived 91Sr Nucleus

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The slow (s) and rapid (r) neutron capture processes have long been considered to produce nearly the entirety of elements above Fe. Under further scrutiny, when comparing expected s-process and r-process yields with spectroscopic data, inconsistencies in abundance arise in the Z=40 region. These differences are expected to be attributable to the intermediate (i) neutron capture process. Operating between the environmental neutron densities of the r process and s process, ranging from 10^{13} – 10^{15} neutrons/cm^3, this process has been documented since the late 70's, but has recently gained significant traction in resolving differences between models and observations.

Sensitivity studies have shown that the intermediate neutron-capture process follows reaction pathways through experimentally accessible neutron-rich nuclei, providing opportunities to constrain the neutron capture rates that define them. Of these exotic nuclei, ^{90}Sr provides a strong case in providing new information on i-process abundances. Working in weak i-process neutron densities on the order of 10^{13} neutrons/cm^3, the ^{90}Sr(n,γ)^{91}Sr capture reaction has a negative correlation to the production of Zr, possibly explaining the discrepancy between the observed and predicted elemental abundances of Zr in i-process environments such as CEMP-i stars.

I will discuss the β-Oslo analysis of ^{91}Sr to reduce uncertainties in the ^{90}Sr(n,γ)^{91}Sr reaction, measured via the β-decay of ^{91}Rb into ^{91}Sr with the SuN total absorption spectrometer at the NSCL in

2018. By simultaneously measuring both γ-ray and excitation energies, a coincidence matrix was produced to perform the Oslo analysis, providing experimental information on the Nuclear Level Density (NLD) and γ-ray Strength Functions (γSF), two critical components in limiting the uncertainty of the neutron capture cross section when it cannot be directly measured. This constrained uncertainty will allow us to better characterize the contribution of ^{90}Sr to the i process and make progress in explaining observed abundances in suspected i-process stellar environments.

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Astronomical observations: signature of the i process at low metallicity

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Indications of the i-process have been found in various places and components of the Galaxy, from the central parts of the bulge to the remote parts of the Milky Way halo. As the i-process is intermediate in, e.g., neutron density compared to the r- and the s-process, how do we find good observational tracers of this process, and furthermore, how do we tie formation site(s) to this nucleosynthetic event? I will focus on old, metal-poor stars and explore how we can map the i-process in these indirect stellar tracers.

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CEMP-i stars in the Carina dwarf spheroidal galaxy

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Carbon Enhanced Metal-Poor (CEMP) stars ([C/Fe] > 0.7) are known to exist in large numbers at low metallicity in the Milky Way halo and are essential tracers of early Galactic chemical evolution. However, very few such stars have been identified in the classical dwarf spheroidal (dSph) galaxies, and detailed abundances, including neutron-capture element abundances, have only been reported for 12 stars. I will present the results of a detailed abundance analysis of six CEMP stars identified in the Carina dSph. The analysis reveals that five stars show enhancements in neutron-capture elements in addition to their carbon enhancement. Comparing the neutron-capture element abundances of these stars to recent i-process yields suggest an i-process enriched the majority. Exploring the absolute carbon abundances (A(C)) of CEMP stars with a likely i-process signature in dwarf galaxies and the Milky Way halo furthermore suggest that these stars generally have higher A(C) values than other CEMP stars.

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Constraining neutron-capture reaction rates on Kr isotopes for the i-process

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The majority of elements heavier than iron are produced via neutron capture processes, primarily the s process and the r process. However, certain astrophysical observations, such as Sakurai's object and several CEMP stars that show enhancement of s- and r-elements, cannot be described by either process or a combination of the two. The intermediate i process was proposed as a neutron capture process that proceeds at neutron densities between those of the s and r processes, in a region several neutrons away from stability. Models to determine the final abundance pattern of astrophysical environments depend on nuclear physics input, including β-decay rates, nuclear masses, and neutron capture rates. Denissenkov et al. performed a sensitivity study on the neutron capture rates of 52 unstable isotopes and determined eight reactions that had the largest impact on the final abundance pattern of an i process model. Measurements of the neutron capture rates on 85-86Br, 87-89Kr, 89Rb, and 89-92Sr, would significantly reduce the uncertainties. The preliminary results of an experiment performed at Argonne National Lab using the SuN detector, its associated tape station (SuNTAN), and beams from the CARIBU facility will be presented for the indirect study of 87-89Kr(n,γ)88-90Kr.
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Nuclear level densities and γ-ray strength functions from charged-particle induced reactions

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The rate of radiative capture-reactions such as (n, γ), (p, γ) and (α, γ) are affected by the nuclear level density and γ-ray strength function in the reaction product. Many of the astrophysical relevant rates cannot be obtained from experiments but are obtained from theoretical models [1, 2]. Therefore, systematic investigations both on the experimental and theoretical side are necessary. Among the numerous methods that have been established in the last decades, radiative proton capture reactions are a well-suited tool to obtain insights into these two nuclear properties [3]. From the intensity of prompt γ-ray transitions information about the dipole strength function can be extracted. This can be done either via detecting the prompt γ rays directly or by detecting γγ coincidences and applying the ratio method [4,5]. In the last years, several proton-induced experiments have been used at the University of Cologne to access these two properties and constrain their models. In this

contribution, the underlying reaction mechanism of radiative capture reactions will be presented as well as a detailed description of how they can be used to study statistical nuclear properties. In addition, the particle-γ spectrometer SONIC [6] is presented, that is available at the University of Cologne to perform Oslo-type experiments and study the deexcitation behavior of nuclei away from the valley of stability.

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39

Stellar hydrodynamics of the i-process engine

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The i process is characterized by a specific astrophysics engine in which H-rich and unprocessed material is mixed or entrained into a He-convection zone. The resulting nucleosynthesis is a result of the interplay of hydrodynamic feedback to rapid nuclear energy release and the neutron producing and consuming reactions. Hydrodynamic feedback can terminate the i-process engine by creating a split between the layers that produce the neutron source ^{13}N/^{13}C and those where the neutrons are released, or secondary instabilities, such as internal gravity wave mixing across the split may extend or modify the properties of the convective engine. In the different proposed astrophysical sites (RAWDs, low-Z AGB, super-AGB, low-Z massive stars) the hydrodynamic feedback and thus the properties of the i-process engine are now being revealed through large-scale 3D simulations. In this talk I will report on such simulations for three potential sites: low-Z AGB stars, rapidly accreting white dwards and zero metallicity (Pop III) massive stars. I will discuss the implications of these simulations for the i-process nucleosynthesis, and outline the most urgent research steps ahead, in modelling and in nuclear physics.

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Shell model nuclear level densities

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Elements heavier than iron are mainly produced by neutron capture processes, such as the s- and r-processes. Lately, the i-process has been gaining a lot of attention, as it can possibly explain the abundances of r/s-stars which cannot be reproduced by the former processes. Understanding the neutron capture rates plays a crucial role for these studies. The direct experimental calculation of i-process neutron capture rates is challenging, and instead experimentally derived nuclear level densities and gamma ray strength functions are used to predict neutron capture rates. In this talk we are presenting a method for calculating spin- and parity- dependent nuclear level densities using methods of statistical spectroscopy. This method is based on ideas of a complicated structure of the excited many-body states. The predicted nuclear level densities are compared to nuclear level densities from other models and available experimental data.

5

The study of the ^{7}Li$(\gamma, t)^{4}$He reaction with mono-energetic gamma-ray beams

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The abundances of the light elements produced in the early stages of the Universe are accurately predicted by Big Bang Nucleosynthesis (BBN). However, following the observations on low-metallicity stars, the measured ^{7}Li abundance is 3-4 times lower than expected. Due to this discrepancy, known as "cosmological Li problem", it can be assumed that either the measurements are leading to anomalous results, or an error is present in the theoretical models. Since two main reactions are responsible for the production of mass 7 elements, ^{3}H$(\alpha, \gamma)^{7}$Li and especially
^{3}He$(\alpha, \gamma)^{7}$Be , the error can be related to the WMAP baryonic density. A lower value for this quantity corresponds to a higher effect of the ^{3}H$(\alpha, \gamma)^{7}$Li reaction. While ^{3}He$(\alpha, \gamma)^{7}$Be reaction have been well studied, only a few experiments were performed over the ^{3}H$(\alpha, \gamma)^{7}$Li reaction. However, the ^{3}H$(\alpha, \gamma)^{7}$Li reaction can still be studied by its inverse reaction: ^{7}Li$(\gamma, t)^{4}$He . A measurement of the photodisintegration of ^{7}Li was performed in 2017 by our team at High Intensity γ-ray Source (HIγS) Laboratory at Duke University (USA). The detection of the alpha-triton coincidences was performed using an array of segmented silicon detectors. The considered energies of the gamma beam were between 4.4 and 10 MeV, but the coincidences have been clearly separated only for energies higher than 6 MeV and especially in the thinner detectors. As a continuation, a similar experimental campaign will take place at HIγS in the first part of April 2023, to measure the cross section and the angular distributions of ^{7}Li$(\gamma, t)^{4}$He reaction at energies lower than 6 MeV. The study is using a LiF target and an improved array of segmented silicon detectors with a similar arrangement but thinner than in the previous set-up such as the coincidences to be properly separated for those lower energies. Besides the main objective regarding ^{7}Li$(\gamma, t)^{4}$He reaction measurement the same experimental campaign has as additional porpoise the measurement of photonuclear reactions (γ,p) and (γ,α) on different targets as Sn-112 and Pd-102. Such photodisintegration reactions have been rarely reported, but can be properly used to study the corresponding capture reactions involved in the p-process. However, the photodisintegration reaction measurement for such medium-heavy mass targets by charged particles detection has never been reported before.
The preliminary results of the experimental campaign performed at HIγS in the beginning of April 2023 relevant to the "cosmological Li problem" and p-process problem will be presented.

Keywords: Big Bang Nucleosynthesis, cosmological Li problem, photodisintegration, photonuclear reactions, array of segmented silicon detectors, p-process.

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Resolving discrepancies in helium burning

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Understanding stellar nucleosynthesis remains one of the forefront challenges in physics and requires detailed knowledge of helium burning, which is composed of the astrophysically pivotal triple-alpha and $^{12}\mathrm{C}(\alpha,\gamma)$ reactions. Helium burning plays a crucial role in the life cycles of AGB and massive stars; the former being a possible site of the i-process. Since slight variations in the triple-alpha and $^{12}\mathrm{C}(\alpha,\gamma)$ reaction rates can alter the stellar model, accurate studies on the nucleosynthesis of heavier elements require helium burning to be on firm ground. However, the current understanding of the triple-alpha reaction, previously thought to be relatively well established, has been thrown into disarray by recent measurements. In addition, the $^{12}\mathrm{C}(\alpha,\gamma)$ reaction, dubbed the "Holy Grail of nuclear astrophysics" requires constraining with completely novel methods. This talk will present current and upcoming studies on the triple-alpha reaction at both medium and high temperatures, as well as the development of a novel method for indirectly studying the $^{12}\mathrm{C}(\alpha,\gamma)$ reaction.

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Identifying and characterizing nuclear isomers with potential relevance toward nucleosynthesis

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Nuclear isomers are metastable excited states with half-lives that can range over orders of magnitude from nanoseconds to billions of years. The states owe their long half-lives to a hindered transition to the ground state which arise due to a mismatch between starting and final states. Isomeric states impact multiple nuclear science applications including nucleosynthesis. The decay modes of isomeric states are varied leading to the potential emission of charged particles, photons, and (potentially) neutrons.

In astrophysical scenarios, predicting nucleosynthetic pathways using large-scale reaction networks requires information on the properties of many neutron-rich species and their decay modes. Reaction networks can assume either the properties of the ground state or use a thermally equilibrated distribution of excited states. The presence of a nuclear isomeric state can invalidate either of these assumptions and such states are distributed unevenly across the nuclear chart. Further, despite the significant role that nuclear isomers play in nucleosynthesis and other nuclear science applications, predicting their presence or absence in a specific nucleus is not a straightforward endeavor. Therefore, experimental efforts are required to identify and characterize the properties of isomeric states.

I will describe existing isomer search techniques that can be performed in neutron-rich regions and the tools available to perform them. The focus will be on large surveys performed on many nuclei simultaneously at high-energy fragmentation facilities. Examples of expected and unexpected isomeric states will be provided.

38

i-Process Isotopic Signatures in Presolar Grains

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The chemical makeup of our solar system reflects Galactic chemical evolution in the local interstellar medium (ISM) over the past ~9 Ga. While the incorporated ISM dust was mostly destroyed during the solar system formation, a small fraction of the ISM dust, known as presolar dust, is preserved in pristine extraterrestrial materials and identified by their exotic isotopic compositions, pointing to their formation in stellar winds or explosions of ancient stars. Since their stellar birth at more than 4.6 Ga, presolar grains have borne witness to a huge array of astrophysical processes. Presolar grain analysis has become an important component of the study of nuclear astrophysics as it allows for isotope analysis of bona fide stellar material in the laboratory at a precision that far exceeds what can be achieved by spectrographic measurements using state-of-the-art telescopes.

It is, however, not an easy task to link presolar grains to their parent stars. Although low-mass asymptotic giant branch (AGB) stars and core-collapse Type II supernovae are believed to be the dominant contributors to the presolar grain reservoir in the solar system, multi-element isotope data have provided clues that could support other stellar sources, e.g., novae, born-again AGB stars. For instance, large 134Ba depletions were observed in two mainstream SiC grains (Liu et al. 2014, ApJ, 786), and anomalous Ca isotopic anomalies were observed in 13C-rich graphite grains (Jadhav et al. 2013, ApJL, 777), both of which could point to intermediate neutron-capture (i-process) nucleosynthesis in their parent stars and thus argue against their commonly believed stellar origins.

In this talk, I will provide an overview of the current status of presolar grain studies, including the inventory of presolar grains that we have identified and state-of-the-art analytical capabilities for isotope analyses of presolar grains. Given our current understanding of the i-process and their stellar sites, I will discuss how likely we could unambiguously identify i-process isotopic signatures in presolar grains and the challenges.

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Astrophysical implications of the low-lying electric dipole strength in Sn isotopes

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Among different features in the total dipole response of nuclei, the low-lying electric dipole strength, sometimes referred as the pygmy dipole resonance (PDR), plays an important role for various nuclear structure studies as well as in the field of the astrophysical research. For example, the potential link of the PDR strength to the neutron skin thickness might shed a new light on approaches to constraining different parameters of neutron stars. Moreover, the PDR additionally enhances the total electric dipole strength close to the neutron threshold, thus, resulting in increased radiative neutron capture (n,γ) cross sections and abundances of elements produced via this process. As the PDR is expected to be more prominent in heavy, neutron rich nuclei, this plays a noticeable role for the astrophysical s, i, and r processes. Systematic studies of the PDR evolution in different chains of isotopes are, therefore, highly desired.

This work focuses on studying such evolution in Sn isotopes in terms of the $\gamma-$ray strength functions (GSFs) and its effect on (n,γ) cross sections for the heaviest Sn isotopes. The $^{111-113,116-122,124}$Sn isotopes were studied in various proton-, deuteron-, and ^{3}He-induced reactions. The so-called Oslo method was applied to the extracted particle-γ coincidence data to simultaneously extract of the nuclear level densities (NLDs) and the GSFs of studied nuclei. The derived strengths were additionally compared to Coulomb excitation data for even-even isotopes and were found to be in excellent agreement with them within the experimental error bands in the regions where the data overlap. The decomposition of the total M1+E1 response yields the evolution of the PDR in these nuclei, which, indeed, demonstrates some increase in strength of the PDR, being the largest in the heaviest studied ^{120,122,124}Sn isotopes ($\approx 2-3\%$ of the energy weighted sum rule for E1 transitions).

The experimental NLDs and GSFs were further used as inputs for the reaction code TALYS, proving the estimates of Maxwellian-averaged (n,γ) cross sections for these nuclei. The cross-sections are in good agreement with KADoNiS data (if available), JINA REACLIB and BRUSLIB libraries in most of isotopes. The PDRs in the heaviest nuclei were found to contribute with up to $5-8\%$ to the total cross-section values. All of the above-mentioned results will be demonstrated for the first time together with the study of the PDR evolution impact on them. The observed trend of the increasing PDR strength may be expected to be the case for even heavier nuclei and result in even more even larger contribution to the (n,γ) cross sections in various astrophysical scenarios.

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The impact of systematic and statistical nuclear uncertainties on the i-process nucleosynthesis

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The observed surface abundance distribution of Carbon-enhanced metal-poor (CEMP) r/s-stars suggests that these stars have been polluted by an intermediate neutron-capture process (the so-called i-process) occurring at intermediate neutron densities between the r- and s-processes. Triggered by the ingestion of protons inside a convective He-burning zone, the i-process could be hosted in several sites, a promising one being the early AGB phase of low-mass low-metallicity stars. The i-process remains however affected by many uncertainties including those of nuclear origin since it involves hundreds of nuclei for which reaction rates have not yet been determined experimentally.
We investigate both the systematic and statistical uncertainties associated with theoretical nuclear reaction rates of relevance during the i-process and explore their impact on the i-process elemental production, and subsequently on the surface enrichment, for low-mass low-metallicity stars during the early AGB phase.
We use the TALYS reaction code (Koning et al. 2023) to estimate both the model and parameter uncertainties affecting the photon strength function and the nuclear level densities, hence the radiative neutron capture rates. The impact of correlated systematic uncertainties is estimated by considering different nuclear models, as detailed in Goriely et al. (2022). In contrast, the uncorrelated uncertainties associated with local variation of model parameters are estimated using a variant of the backward-forward Monte Carlo method to constrain the parameter changes to experimentally known cross sections before propagating them consistently to the neutron capture rates of nuclei of i-process interest.
On such a basis, the STAREVOL code (Siess et al. 2006) is used to determine the impact of nuclear uncertainties on the i-process nucleosynthesis in a 1 $M_\odot$ [Fe/H] = - 2.5 model star during the proton ingestion event in the early AGB phase. A large nuclear network of 1160 species coherently coupled to the transport processes is solved to follow the i-process nucleosynthesis. This study allows us to quantify the relative importance of statistical versus systematic uncertainties with respect to the surface abundances in AGB stars and to identify the reaction rates that would need to be better constrained in the future in order to improve our understanding of the i-process.

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Looking for light elements i-process abundances in metal-poor stars

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In the present work, chemical abundance analysis were done at high-resolution spectroscopy (R ~ 48000) for a sample of extrinsic Carbon stars. These stars were expected to have high carbon abundance as also an enrichment in the neutron capture process elements. Two out of these stars have peculiar abundances for light neutron capture elements which is in-between the predicted abundances for s- and r-process elements. This may be related to the occurrence of the intermediate neutron capture process. In this talk, we will present our results in comparison with known i-process stars and discuss the extended analysis to a large sample of metal-poor stars. Furthermore, we will also give a suggestion on how the light and i-process elements (CNO, Rb, Sr, Y, Zr) in metal-poor stars can give clues on i-process.

4

β-feeding intensities from 133Sn using the Summing NaI (SuN) Total Absorption Spectrometer

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Coautor(es): Andrea Richard [2] ; Stephanie Lyons [3] ; Sean Liddick [4] ; Erin Good [5]

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Nuclear data inputs are necessary for generating and improving models of heavy element nucleosynthesis in the universe. β-decay properties such as decay rates and branching ratios, along with detailed level schemes of neutron-rich nuclei are critical for informing nucleosynthesis simulations involving processes such as the astrophysical i- and r- processes [1-2]. While β-decay rates are known for many neutron-rich nuclei, the branching ratios, otherwise referred to as feeding intensities, are often not well characterized due to the pandemonium effect [3]. To overcome this effect, the technique of Total Absorption Spectroscopy (TAS) can be used to obtain β-feeding intensities using a dedicated detector such as the Summing NaI (SuN) detector [4] based at FRIB/MSU. In this presentation, the TAS analysis of the β-decay of 133Sn will be presented. 133Sn ions were generated by the CARIBU 252Cf spontaneous fission source at Argonne National Lab. The beam was implanted onto the SuNTAN setup which includes a movable magnetic tape for ion implantation and subsequent removal of radioactive decay products. A plastic scintillator barrel placed at the center of SuN was used for β-particle detection while β-delayed gamma-rays were detected in the SuN detector. The β-feeding intensities to be presented were determined using a chi2 minimization procedure between experimental data and simulated data using a combination of the RAINIER and Geant4 software packages.

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Constraining Neutron Capture Rates in Unstable Nuclei

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In this contribution we present the first model-independent measurement of the absolute partial nuclear level density (NLD) for a short-lived nucleus. For this purpose we adapt the recently introduced "Shape method" for β-decay experiments, providing the shape of the γ-ray strength function for exotic nuclei. In this work, we show that combining the Shape method with the β-Oslo technique allows for the extraction of the nuclear level density without the need for theoretical input. This development opens the way for more precise constrains of neutron capture rates for unstable nuclei. We discuss our benchmarking results for the unstable 88Kr nucleus. We then provide the first experimental constraints on the 139Ba(n,g)140Ba reaction rate, which is the dominant source of uncertainty for the production of La within the i process. Based on our results we can show that some of the observed abundance patterns are produced with a neutron density of 10^13 n/cm^3.

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Ab Initio Optical Potentials as Input into Astrophysical Simulations Using the Symmetry- Adapted No-Core Shell Model

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Ab initio optical potentials at low energy are of interest for nucleosynthesis studies, where experiments are difficult and data is often unavailable. In this work, we use ab initio Symmetry-Adapted No-Core Shell Model nuclear structure results to perform a Green's function evaluation of the optical potential, which in turn can inform total cross sections and phase shifts for neutron elastic scattering up to the Ca region. The method is suitable for the astrophysically relevant regime of low energies and provides ab initio descriptions of cross sections for neutron and proton elastic scattering, as well as (d, n) and (d, p) reactions, with a view toward reliable optical potentials for alpha projectiles of interest and alpha-induced reactions in stars. I will also discuss 15O + ⍰ clustering in 19Ne.

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Towards direct measurements of neutron capture rates relevant to the i process

Timm-Florian Pabst[1] ; Dennis Mücher[1] ; Markus Schiffer[1] ; Abdallah Karaka[1]

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With most quantities along the i process being well constraint experimentally, neutron capture rates are among the largest unknowns in terms of nuclear physics input. Direct measurements of neutron capture rates for i process relevant nuclei are hindered by the fact that most key nuclei are unstable. In this talk we discuss the current theoretical uncertainties of neutron capture rates of some key i process nuclei. We then discuss the possibility to measure the neutron capture rates of selected unstable nuclei two steps away from stability using a two-step approach. Future experiments at the

Cologne AMS facility are discussed, coupling two high-flux tandetron accelerators to perform these very demanding measurements.

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The i process and connections to other nucleosynthesis processes

Marco Pignatari[1]

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The interest in the intermediate neutron-capture process (or i-process) in stars grew quickly in the past decade. The main reason is the capability of the i-process to explain a number of puzzling observations in stars and in presolar grains, that the s-process and the r-process cannot do. Indeed, the typical neutron densities of the i-process in between the s-process and the r-process allows it to build distinctive elemental and isotopic patterns that can be recognized by observations. At the same time, the rediscovery of the i-process comes when consistent stellar hydrodynamics simulations are becoming accessible for the conditions relevant for the i-process, and nuclear experiments can directly measure the relevant rates defined along the i-process nucleosynthesis path. In this talk, I will give an overview of the main features of the i-process production in stars, how they compare to observations and how they compare to the production of other theoretical nucleosynthesis processes.

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The Oslo method and future experiments in the ^{135}I region at OCL

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The correct estimation of (n, γ)-rates for neutron-rich nuclei is of great importance to obtain reliable predictions of abundances in heavy-element nucleosynthesis simulations.
As the modeling of the i and r processes heavily relies on theoretical models, which at present are very uncertain, it is important to provide experimental constraints in order to increase their predictive power.
Nuclei around ^{135}I have been identified as being a possible bottleneck for the i process, making the study of (n, γ) rates in this region crucial.
Although direct measurements are presently limited to stable targets, indirect experimental techniques can be used to investigate the properties of neutron-rich, unstable nuclei. One such technique is the Oslo method coupled with the Hauser-Feshbach theory. Using ^{126}Sb(n, γ) as a case study, future experimental possibilities at OCL using the newly acquired targets of ^{116}Cd, ^{128}Te and ^{130}Te will be discussed.
The new data will hopefully provide more insights on the evolution of the pygmy resonance in the region, and its impact on the i-process nucleosynthesis.

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Towards direct reaction rate measurements for the i process

Rene Reifarth[1]

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Neutron capture rates on nuclei with half lives between seconds and hours determine the mass flow during the i process. The currently largely used activation and time of flight techniques allow the investigation of isotopes with half lives longer than approximately 1 year.

Improvements of the techniques are still possible and might bring this limit down to months. The required large step towards investigating minute-half-lives is only possible with a completely different approach. As with charged-particle-fusion reaction of astrophysical interest, also neutron capture reactions on short-lived nuclei need to be investigated in inverse kinematics. This, however, requires a neutron target, which has to be constantly renewed. A combination of a storage ring and a spallation neutron target can be the solution.

6

Impact of the Experimentally Constrained ^{102,103}Mo(n,γ) Reaction Rates on the Mo, Ru and Rh Abundances Predicted for the i-Process

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A longstanding question in Nuclear Astrophysics is how elements are synthesized in stars. Observations of carbon-enhanced metal poor stars (CEMP) show that observed abundance patterns cannot be reproduced by the traditional neutron-capture processes (s and r), and indicate that an additional process known as the intermediate neutron-capture process (i-process) is needed to describe these abundances. Occurring at intermediate neutron densities, the majority of nuclear physics properties (mass, half-life, etc.) are well constrained, however the neutron-capture cross sections and reaction rates remain largely unmeasured. Using the β-Oslo method, an indirect technique in which the nuclear level density (NLD) and γ-strength function (γSF) are extracted following the β-decay of a neutron-rich parent, the neutron-capture cross section can be experimentally determined. In this work, ^{103,104}Mo were studied at the National Superconducting Cyclotron Laboratory via the β-decay of ^{103,104}Nb and detected using the Summing NaI (SuN) total absorption spectrometer. Results on the NLD, γSF, neutron-capture cross sections, and reaction rates of ^{102}Mo(n,γ)^{103}Mo and ^{103}Mo(n,γ)^{104}Mo using the β-Oslo method will be presented. These new rates were used in Nucleosynthesis Grid (NuGrid) extended network calculations to determine their impact on Mo, Ru, and Rh abundances predicted in the i-process. Results from this study show [Ru/Mo] abundance ratios that are substantially lower than those observed in stars polluted by products of either s or r process, indicating that this abundance ratio is a new characteristic for the i-process.

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Proton ingestions in massive stars at very low metallicity

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At zero and very low metallicity, H and He burning in massive stars occur close in temperature, due to the lack of CNO nuclei in the pristine material they are made of. The metal-poor composition and the low difference in temperature both contribute to lower entropy barrier between the H and He burning shells and this may lead to proton ingestion events in the He shell. During a H-He shell interaction, the hot CNO cycle is triggered and $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ neutron source is activated. The very high neutron density reached during these episodes is typical of the i-process nucleosynthesis. Here I will present models of a 25Msun star, analysing how the proton ingestion events depend on the initial metallicity and possibly on the stellar rotation. I will discuss the activation of the i-process during H-He convective shell interactions.

1

Total Absorption Spectroscopy of Ground and Isomeric States in 70Cu

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The existence of the weak intermediate neutron-capture process (i-process) explains the observed astrophysical abundances of elements around the Z<50 region [1]. Neutron capture reactions in the A=70 mass region for Ni, Cu, and Zn isotopes are known to produce large variations in predicted i-process abundances [1]. Predicted stellar abundances of Ga are particularly affected by the ^{69}Zn(n,γ) reaction. The β-decay of ^{70}Cu offers a unique opportunity to use total absorption spectroscopy (TAS) to obtain complementary β-decay information and utilize the β-Oslo method to constrain the ^{69}Zn(n,γ) reaction rate for i-process nucleosynthesis. ^{70}Cu has three different β-decaying spin-parity states that populate different spin ranges at similar excitation energies in the daughter nucleus: the 6^- ground state, the 101 keV 3^- isomeric state, and the 242 keV 1^+ isomeric state [2]. In an experiment performed at the National Superconducting Cyclotron Laboratory ^{70}Cu was produced and delivered to the Summing NaI (SuN) Total Absorption Spectrometer [3]. Spectra from the β-decay of each spin-parity state were isolated using different beam on/off periods. Results from total absorption spectroscopy following the β-decay of each of the three β-decaying spin-parity states will be presented, along with preliminary results from β-Oslo analysis to obtain γSF and nuclear level densities to constrain the ^{69}Zn(n,γ) reaction rate for i-process nucleosynthesis.

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Determining the gamma strength function and level density in 64Fe via the beta-Oslo method

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There is a lack of information on the behavior of nuclear level densities and gamma strength functions for many regions of the nuclear landscape, especially for and not just away from stability. In some stable isotopes, for example, in the Fe-Cd region, an unexpected increase in the gamma-decay probability has been observed. This leads to an up-bend in the gamma strength function below ~4 MeV, which has a significant influence on extracted neutron-capture rates. It is unknown how the gamma strength function behaves for neutron-rich nuclei. Furthermore, nuclear level densities and gamma strength functions are critical for constraining neutron-capture rates. Rates are often crucial missing observables for models of the r and i-processes. For the i-process in particular, sensitivity

studies indicate isotopes within ~3-7 mass units of stability are often critical isotopes in determining the abundance distributions produced. Currently, facilities such as the NSCL/FRIB and ANL can produce these neutron-rich isotopes. The up-bend was first observed in iron isotopes and we populated excited states via beta-decay for the neutron-rich iron nuclei including Fe-64, a candidate for the up-bend in the gamma strength function. Gamma decays within Fe-64 were recorded with the Summing Na(I) (SuN) segmented total absorption spectrometer, which allows us to simultaneously extract the level density and strength function. We will present results for gamma strength functions and level densities in this region, and implications for capture processes.

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A systematic study of Sr isotopes \\using the β-Oslo Method

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Understanding of neutron-induced reactions on nuclei far from stability has far-reaching implications for cosmogenic nucleosynthesis and fundamental nuclear physics. Presently, direct measurement of the radiative-capture cross section is experimentally inaccessible for these short-lived nuclei; however, indirect methods such as the β-Oslo method enable the experimental constraint of key nuclear properties that are inputs for reaction-theory calculations.

In particular, reaction rates on neutron-rich Sr isotopes directly influence astrophysical abundances through processes that produce the heaviest elements present in the universe. We have performed an experiment at Argonne National Laboratory in order to determine the γ-ray strength function (γSF) and nuclear level density (NLD) for ^{93,94,95}Sr isotopes. Low-energy Rb beams were produced at the Californium Rare Isotope Breeder Upgrade (CARIBU) and transported to the Summing NaI(Tl) (SuN) detector where coincident β-γ events were observed. The γSF and NLD, properties extracted from the measured γ-ray spectra using the β-Oslo method, contribute the greatest uncertainty in Hauser-Feshbach calculations of neutron-capture reaction rates for short-lived neutron-rich nuclei. Additionally, this work on very-neutron-rich nuclei, which have low neutron separation energies and high β-delayed neutron branches, examines a smaller region of statistical decays than previous applications of the β-Oslo method.

The experimental techniques and preliminary results of this work will be presented. Furthermore, the results of this work will shed light on nuclear structure properties for Sr isotopes, leading to significantly improved predictive reaction modeling.

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New observational evidence of i-process patterns in CEMP-sr stars and in stars of higher metallicities

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In the past decade, a growing number of stars have been found to be enriched in both s- and r-process elements. These chemical peculiarities were derived from the analysis of high-resolution spectra and detailed abundance determinations sometimes using non-LTE and/or 3D corrections. Stars with an hybrid s+r abundance profile were mostly found among CEMP (Carbon-Enriched Metal-Poor) stars (and constitute the CEMP-sr subgroup) but also in some objects of higher, close-to-solar metallicities. In this talk, the available abundances of these stars will be discussed, and the diagnostics that could help to better constrain the still-debated origin of the sr-enriched objects will be reviewed.

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Theoretical study of proton-induced reaction on p-nuclei of Ruthenium

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The elements heavier than iron are mainly synthesized by the s-process (slow neutron capture process), r-process (rapid neutron capture process), and p-process. The origin of 35 stable proton-rich isotopes with a mass between 74Se and 196Hg lie near the neutron-deficient side of the valley of stability, commonly known as "p-nuclei", has been one of the major open questions in nuclear astrophysics [1, 2]. The probable site for this process is in an envelope of the supernova of Type II or the outermost part of supernova Type I. In the present study, the proton capture reactions of the stable p nuclei 96Ru and 98Ru have been calculated using the nuclear model code TALYS [3]. The reaction cross section, astrophysical S factor and reaction rates are calculated for the reactions. The results are compared with the data of the NON-SMOKER code [4], literature data taken from the EXFOR data library [5], and the available evaluated data libraries.

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Indirect neutron-capture reaction measurements for the i-process

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Understanding the origin of the heavy elements is consistently identified as a high priority challenge for nuclear physics research. It has long been understood that neutron-induced reactions on unstable nuclei are essential for driving nucleosynthesis beyond the iron peak. However, direct studies of such reactions are impractical due to the absence of a stable or long-lived target material. Therefore, theory must be combined with experiment to provide meaningful constraints on reaction cross-sections. In this talk, I will discuss recent efforts to constrain neutron capture cross-sections using indirect methods, focusing on the Surrogate Reaction Method (SRM). I will also summarize the experimental needs of SRM studies and discuss opportunities for future studies motivated by i-process nucleosynthesis.