s, i & r Element Nucleosynthesis (sirEN) Conference

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Book of Abstracts

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Exploring the Galactic halo neutron-capture enrichment through the MINCE project

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The chemo-kinematical properties of the Milky Way stellar halo contain the fossil records of our galaxy assembly history.
The Measuring at Intermediate Metallicity Neutron-Capture Elements (MINCE) project aims to provide high quality measurements of n-capture elements in halo stars at intermediate metallicity.
In the metallicity range -2.5 < [Fe/H] < -1.5, only 20% of the stars with available chemical abundances have n-capture elements
measurements.
Thus, the MINCE project represents an opportunity to shed light on the origin of n-capture elements, the early interstellar medium pollution
processes and the timescales of the Galactic halo formation.
This talk shows our recent results for about 70 Galactic halo stars observed with worldwide facilities.
In particular, the chemical abundances of 27 species (Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Rb, Sr, Y,
Zr, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu) will be presented.
The kinematical analysis revealed that a sub-sample of stars has been accreted from Gaia Sausage Enceladus (GSE) and Sequoia.
Finally, the comparison of our results with stochastic chemical evolution models provides clues on the Milky Way, GSE and Sequoia evolution.

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Ab Initio Simulations of Electroweak Decay Spectra in astrophysical scenarios: the role of the electronic structure

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We present two recently developed ab initio methods for the calculation of beta decay spectra of light to heavy nuclei in astrophysical contexts.
The first method uses a variational approach with trial wave functions expanded in multidimensional Gaussian basis sets to accurately account for the electron-electron correlation in order to calculate bound and scattering states of few-body systems. We apply this approach to compute the photodetachment cross section and resonances of the positronium ion (Ps^-) and the electron capture of ^{7}Be, considering its ionisation state and excitation level to determine the configuration-dependent EC decay rate.
Furthermore, we discuss a theoretical approach based on the numerical solution of the electroweak Hamiltonian using a mean-field Dirac-Hartree-Fock method. This method is applied to calculate the beta decay of ^{134,135}Cs, crucial production channels for Ba isotopes in asymptotic giant branch (AGB) stars. By including multiple nuclear and electronic excited states (ES) above $\simeq$ 10 keV for both the parent and daughter nuclei, we find that the half-lives for $T > 10^8$ K for ^{134}Cs increase by more than a factor of 3 compared to previous works based on systematics. These new rates enable nucleosynthesis models to better explain the isotopic composition of Ba in presolar SiC grains and the Sun. We also demonstrate the applicability of our method to calculate beta decay in astrophysical scenarios with ^{176}Lu, ^{63}Ni, ^{87}Rb, ^{93}Zr and ^{79}Se.

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The Role of Carbon-Oxygen Shell Interactions in the Nucleosynthesis and Final Fate of Massive Stars

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Abstract: Carbon-oxygen (C-O) shell interactions in the late evolutionary stages of massive stars play a crucial role in determining their final fate and have a significant impact on the pre-supernova and explosive nucleosynthesis. In this talk, I will explore the complex dynamics within C-O shells, and how these interactions drive the production of intermediate and heavy elements. Recent advancements in theoretical models and observational data provide new insights into how C-O shell interactions influence the synthesis of elements, shaping the chemical evolution of the star and the broader universe.

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Chemical Fingerprints of AGB Mass Transfer in Open Clusters

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Blue straggler stars (BSSs) are thought to form from binary interactions, particularly mass transfer, mergers, and collisions. If a BSS forms from mass accreted from a thermally-pulsing asymptotic-giant-branch (AGB) star, it can bear distinctive surface abundance markers as a result of s-process nucleosynthesis that occurred in the evolved donor star. We present an abundance study of BSSs in two open clusters, NGC 7789 (1.6 Gyr) and M67 (4 Gyr), looking for signatures of AGB mass transfer, using high-resolution optical spectra obtained at the WIYN 3.5m Observatory. We place them in the context of the previously studied open clusters NGC 6819 (2.5 Gyr) and NGC 188 (7 Gyr). We find remarkable similarities in the positions on the color-magnitude diagram of barium-enriched BSSs in NGC 7789, M67, and NGC 6819, and we find an anticorrelation between the degree of Ba enhancement in the BSSs with respect to cluster age. We also find that 40±16% of the Ba-enriched BSSs are in spectroscopic binary systems with orbital periods less than 10,000 days, indicative of the frequent occurrence of wind mass transfer or wind Roche-lobe overflow. It is probable that AGB mass transfer is the dominant mechanism of BSS formation in open clusters older than about 1 Gyr.

The authors acknowledge funding from the National Science Foundation grant AST-1714506, Sigma Xi grant G20201001111059492, and the Wisconsin Alumni Research Foundation.

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The origin of weak r-process nucleosynthesis

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The origin of the rapid neutron-capture (r-) process is a major question in astrophysics. The clue to answer this question is the chemical abundance patterns of extremely metal-poor (EMP) stars with [Fe/H] < -3, which are believed to reflect the nucleosynthesis yields of a single event. Recent high-resolution spectroscopic observations have shown that the abundance patterns of neutron-capture elements in many metal-poor stars are consistent with the solar r-process abundance pattern, indicating the universality of the r-process (e.g. Sneden et al. 2008). On the other hand, it has also been confirmed that some metal-poor stars (e.g. HD 122563; Honda et al. 2006) have an excess of light neutron-capture elements such as strontium (Sr, Z = 38) compared to heavy neutron-capture elements such as barium (Ba, Z = 56), and thus the other process that mainly produces light neutron capture elements, the weak r-process, has been proposed.

To clarify the origin of the weak r-process, we study the extremely metal-poor star SMSS J022423.27−573705.1, which has an extremely high lower limit on the [Sr/Ba] ratio as reported by Jacobson et al. (2015). Analyzing the near-ultraviolet and visible spectra obtained with VLT/UVES. we measured 26 elemental abundances. High signal-to-noise ratio observation allow us to determine the abundances of nitrogen, oxygen, zinc and barium for the first time. The abundances of neutron-capture elements were compared with the abundances of solar r-process and metal-poor stars from previous studies, and it was confirmed that the [Sr/Ba] ratio in SMSS J022423.27−573705.1 is the highest among metal-poor stars observed. We also compare the chemical abundance in SMSS J022423.27−573705.1 with theoretical nucleosynthesis models. In this talk, we summarize these results and discuss the origin of weak r-process.

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Cobalt and copper in bulge moderately metal-poor stars

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The trans-iron elements with atomic numbers 27 < Z < 52 are still not well
understood (Peterson et al. 2020, A&A, 638, A64). There is some evidence
for Ge to be classified rather as an iron-peak element than a neutron-capture
element. In particular, abundances of
Cobalt and Copper are of interest to elucidate their origin as
neutron capture elements on iron-group nuclei during He burning and later
burning stages, also called the weak-s component
(Limongi & Chieffi 2003, ApJ, 592, 404), and the alpha-rich freeze-out
in the deepest
layers (Sukhbold et al. 2016, ApJ, 821, 38).
Abundances in old stars of the Galactic bulge tend to show that
conclude that both Co and Cu appear to be more dominantly produced rather by
a weak s-process than by alpha-rich freeze-out.

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The Contribution Path Picture of Flows for the s, i, and r Processes

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The s, i, and r processes are neutron-capture nucleosynthetic channels that occur at different neutron densities. Modern reaction network calculations follow these processes in great detail in models of stellar environments, but those calculations do not necessarily provide a full but straightforward quantitative accounting of the flow of abundance from one species to another. This talk will present the matrix-tree and matrix-forest theorems from graph theory and apply them to the question of network flows. Under the often useful assumption of constant neutron density and temperature, the theorems lead to elegant analytic solutions of the contribution of the abundance of one species to another in s and i process nucleosynthesis. Such solutions give a valuable picture of network flows and provide a quantitative estimate of the role of individual reactions in final abundance yields. For the r process, the theorems lead to quantitative analysis of network flows over a time step throughout r-process evolution from the $(n, \gamma) - (\gamma, n)$ equilibrium phase through freeze out. This permits a detailed analysis of the evolution of particular abundance features in r-process calculations such as freeze-out smoothing and formation of the rare-element peak.

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Astrophysical and Nuclear Uncertainties of the r-Process

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The rapid neutron capture (r-) process is responsible for producing half of the elements heavier than iron in the Universe. Significant uncertainties remain in understanding the astrophysical environments capable of generating the necessary intense neutron fluxes. Detailed hydrodynamical simulations of proposed astrophysical scenarios (e.g. binary neutron star mergers, magneto-hydrodynamical supernovae, and collapsars) are computationally intensive and subject to various uncertainties, including the nuclear equation of state, neutrino interactions, and initial conditions.
To address these challenges, we adopt an alternative approach that is instead based on a site-independent parametric density profile. Our nuclear network calculations explore a wide range of initial electron fractions, entropies, and expansion timescales. The results align well with those of simulations and extend beyond conditions currently found in them.
Another important source of uncertainties arises from poorly constrained nuclear properties: Most nuclei along the r-process path are currently not experimentally accessible, making theoretical predictions essential, e.g. for nuclear masses, reaction rates, and fission properties. Here we show the impact of nuclear masses on r-process predictions and compare the results to observational data.

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Future telescopes and instruments for the study of heavy elements.

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Recent large spectroscopic surveys have yielded significant new insights on heavy elements, their distribution in the Galaxy, and their evolution over time. However, these discoveries have also raised new questions that require investigation using even larger samples of stars, more precise abundance measurements, and data on key, yet challenging-to measure, elements.
Following an overview of these findings, I will present future telescopes and instruments that have the potential to substantially advance the study of neutron capture elements. In particular, I will focus on: the Wide-field Spectroscopic Telescope, a facility under study that will be proposed as the next ESO initiative, after the completion of the ELT; HRMOS, a high resolution multi-object spectrograph that will be proposed at the upcoming ESO call for VLT instrumentation.

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r, i & s Nucleosynthesis Sites in Multi-messenger Era of Galactic Chemical Evolution

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GW170817 and SN1987A were the events of the century which opened a window to multi-messenger astronomy and astrophysics. There is a growing consensus that the MHD-Jet supernova and collapsar dominate the heavy r-element production over the entire history of cosmic evolution, and the neutron-star merger contribution delays due to cosmologically long time-delay for slow GW radiation [1,2]. We will first discuss when and how these astrophysical events contribute to the element production in Galactic chemical evolution [3]. We have recently found that the i- and s-processes could occur in the r-process site of collapsar nucleosynthesis [2]. We will propose nuclear experiments to measure the neutron-capture cross sections relevant for the collapsar i-process [4]. These explosive phenomena emit extremely large flux of energetic neutrinos that provide unique nucleosynthetic signals for flavor conversions at high density. We will discuss the neutrino-flavor conversions induced by collective and MSW effects at high density and propose a new astrophysical method to constrain still unknown neutrino mass hierarchy [5,6]. If our theoretical prediction would be verified by precise meteorite analysis of SiC X grains, this could be a piece of evidence constraining still unknown neutrino mass hierarchy, which is complementary to laboratory experiments on vacuum oscillation [7].

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[7] X. Yao, T. Kajino, Y. Luo, et al., to be published in ApJ (2025).

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The early chemical evolution of the Sagittarius dwarf galaxy

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The Sagittarius (Sgr) dwarf galaxy experienced its first in-fall into the Milky Way (MW) about 5 Gyr ago. As it is being tidally stripped by the MW, its core and two stellar streams are now visible in the Sky, as well as various associated globular clusters. Given its proximity, it is an ideal test-bed for galactic chemo-dynamical models. So far, studies have typically focussed on metal-rich and relatively young stars, given that they are the prevalent population. Further complicating the study of the oldest/metal-poor stars is the strong overlap in the colour-magnitude diagram between the Milky Way bulge population and stars in Sgr. However, the most metal-poor stars are key to understand the early chemical evolution of Sgr.
My talk will focus on the nucleosynthetic channels that are responsible for the production of s-, i- and r-process elements in Sgr, especially during its chemical evolution at early times. I will present the most extensive chemical abundance analysis at the lowest metallicities and connect it to the more studied metal-rich regime, also providing a complete panoramic of the system's chemical evolution. I will show that the interstellar medium of Sgr may have retained yields from more energetic Population III and II supernovae than those imprinted in the stars accreted from the Milky Way's building block. Additionally, the lack of a particular population of Carbon-enhanced stars, linked to the first supernovae, would suggest the need for a new definition for this class of stars, which should be calibrated on the average [C/Fe] of a given system.

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First measurement of the r-process abundance at the Galactic Center using a hyper velocity star

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The Galactic-Center (GC) region of the Milky Way has been a focal point for astronomers for many years, yet its formation history remains a subject of debate. So far, thanks to near-infrared spectroscopic observations, which suffer least from interstellar extinction, abundances of Fe-peak, alpha, and s-process elements have been determined for dozens of stars residing within the GC region. However, the r-process elemental abundances have not yet been determined for any stars in the GC region because r-process elements do not show detectable absorption lines in the near-infrared.

To address this limitation, here we present optical high-resolution spectroscopic measurement of [Eu/Fe] of a hyper-velocity star (HVS) originating from the GC region. Leveraging the very mild extinction towards the HVS, optical spectroscopy offers an unprecedented opportunity to access absorption lines from a wide range of elements, including r-process elements for the first time. We find that the star has enhanced [Eu/Fe] along with mildly enriched [alpha/Fe]. These chemical signatures indicate an enhanced contribution of neutron-star mergers to the chemical enrichment at the Galactic Center.

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High Precision Optical Follow-up of APOGEE-Identified Chemical Doppelgangers: Implications for Neutron-Capture Element Mixing in the ISM

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Recent work using APOGEE stellar abundances have suggested that the Milky Way disk is well-mixed and chemically simple, with age, [Fe/H], and [Mg/Fe] predicting a star's detailed chemical profile to high precision. APOGEE notably lacks access to strong lines of neutron-capture elements which may experience a distinct trajectory of chemical evolution that can not be traced by the aforementioned parameters. To test this, we obtain optical, R~60,000 spectroscopy of 27 APOGEE "chemical doppelgangers," random pairs of disk field giants that APOGEE indicates are as chemically similar as stars within open clusters, and investigate whether they are also "doppelgangers" in the neutron-capture elements. Selected doppelgangers are also required to have nearly identical stellar parameters and C/N ratios, a tracer of stellar age in giants. We perform line-by-line differential abundance analysis of doppelgangers' optical spectra and confirm that all are are indeed doppelgangers in the elements accessible by APOGEE with occasional exceptions of Al. We find that 20 of 27 pairs, however, are not doppelgangers in the neutron-capture elements. Additionally, we find apparent correlations between pairs' similarity in neutron-capture elemental abundances and their similarity in dynamical parameters. If we assume that stars in each doppelganger pair were born at relatively similar times and positions in the disk, then these results could point to a) azimuthal neutron-capture element variations in the interstellar medium that exceed those of the lighter elements, b) radial neutron-capture abundance gradients that are steeper than the gradients of lighter elements, and/or c) random neutron capture abundance variations in the radial direction that act independently of the lighter elements. These results emphasize the value of neutron-capture elements in identifying stars with similar chemical compositions and Galactic origins.

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Unlocking stellar ages with s-process elements: Calibrating chemical clocks using Kepler data

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S-process elements (Y, Zr, Ba, Ce), produced via slow neutron-capture processes in stars, are key tracers of stellar and Galactic evolution. When paired with alpha-elements (Mg, Ca, Si, Ti) in abundance ratios, they serve as chemical clocks, providing a powerful tool for estimating stellar ages. In this talk, I present a detailed spectroscopic analysis of 68 Kepler red giant stars, offering high-precision abundances of s-process elements and asteroseismic ages with better than 10% precision from individual mode frequencies.

This sample is used to calibrate chemical clock-age relations, which are fundamental for estimating "chemical ages" of field stars in large spectroscopic surveys. By applying these calibrations to the APOGEE and Gaia-ESO surveys, I derived "chemical ages" for ~270,000 stars, uncovering significant age trends across stellar populations. The results reveal critical insights, such as the age separation of low- and high-alpha sequences, the age-metallicity relation, the flaring of the Galactic disc, and the presence of old metal-rich stars.

This work underlines the importance of s-process elements in reconstructing the chemical and temporal evolution of the Milky Way, highlighting their role in age-dating tools for the Galactic archaeology.

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Identifying r-process Elements in Kilonova Infrared Spectra

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Binary Neutron Star mergers are a promising site for the nucleosynthesis of heavy elements via the r-process. This has been observationally confirmed with the detection of the kilonova AT2017gfo and the investigation of its light curves and spectra. While much work has been done to decode AT2017gfo signatures, the specific identifications of elements responsible for each spectral feature is still challenging, particularly in the infrared range. In our study (Rahmouni et al. 2024, arXiv:2412.14597), we conducted a systematic selection of heavy elements most likely to exhibit strong transitions in the infrared range, using their experimentally calibrated energy levels. Our analysis reveals that most elements with strong absorption lines are lanthanides (Z=57-71) and actinides (Z=89-103). This is due to their complex atomic structures with many low-lying energy levels, resulting in strong infrared lines. Previous studies (Domoto et al. 2022, ApJ 939, 8) have shown that La III and Ce III account for the absorption features at $\lambda \sim 12{,}000$ - $15{,}000$ Å. While our results support these findings, we further identify Gd III as the next most promising species. Due to its unique atomic structure involving the half-filled 4f and the outer 5d orbitals, Gd III has one of the lowest-lying energy levels, between which relatively strong transitions occur. By performing radiative transfer simulations, we confirm that Gd III affect the feature at $\lambda \sim 12{,}000$ Å previously attributed to La III. Future space-based time-series observations of kilonova spectra will allow the identification of Gd III lines.

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Effects of multiple spiral arm patterns on O, Eu, Fe, and Ba abundance gradients

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According to observations and numerical simulations, the Milky Way could exhibit several spiral arm modes with multiple pattern speeds,
wherein the slower patterns are located at larger Galactocentric distances. Our aim is to quantify the effects of the spiral arms on the azimuthal variations of the chemical abundances for oxygen, iron and for the first time for neutron-capture elements (europium and barium) in the Galactic disc. We assume a model based on multiple spiral arm modes with different pattern speeds.
We apply new analytical prescriptions for the spiral arms in a 2D Galactic disc chemical evolution model, exploring the possibility that the spiral structure is formed by the overlap of chunks with different pattern speeds and spatial extent. The predicted azimuthal variations in abundance gradients are dependent on the considered chemical element. Elements synthesised on short time scales (i.e.,

oxygen and europium in this study) exhibit larger abundance fluctuations. In fact, for progenitors with short lifetimes, the chemical elements restored into the ISM perfectly trace the star formation perturbed by the passage of the spiral arms. The map of the star formation rate predicted by our chemical evolution model with multiple patterns of spiral arms presents arcs and arms compatible with those revealed by multiple tracers (young upper main sequence stars, Cepheids, and distribution of stars with low radial actions). Finally, our model predictions are in good agreement with the azimuthal variations that emerged from the analysis of Gaia DR3 GSP-Spec [M/H] abundance ratios, if at most recent times the pattern speeds match the Galactic rotational curve at all radii.

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Spectral analysis and plasma ejecta opacity of the early-stage kilonova

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In the context of the multi-messenger astronomy, the observation of an electromagnetic counterpart of the GW170817 event, known as kilonova (KN), provided evidence that the coalescence of binary neutron stars systems is a favourable stellar site hosting the rapid neutron capture process (r-process). Critical information related to the KN plasma composition can be derived through the analysis of spectra. In this framework, we present numerical results of selected light r-process nuclei at different ionisation states of interest for the early-stage KN ejecta, which have been performed using the relativistic atomic code package grasp2018 to estimate plasma opacity values. Moreover, these opacity results were used as input to the radiative transfer code POSSIS (Bulla M., $MNRAS$, 2019) to recreate and study spectral features and bolometric KN light curves, in order to provide useful constraints with the observed data and to improve our understanding of nuclear processes involved. Finally, we highlight the importance of having more and accurate atomic inputs to better address the opacity estimation and KN light curves modelling.

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Barium isotope ratio in very metal-poor stars as a key to a puzzle of light neutron-capture element synthesis at the earliest epoch.

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Aim. We determine r- to s-process contributions to Ba isotope mixture along with Ba, Eu, and Sr NLTE abundances in a sample of very metal-poor (VMP) stars. The selected stars have [Ba/H] < -2.2 and, thus, formed before the contribution from the main s-process in low and intermediate stars became significant. Some of our sample stars are enhanced in Sr with [Sr/Ba] up to 0.7. These stars

gained their high Sr abundance from a poorly known process, phenomenologically called in the literature as a light element primary process (LEPP, Travaglio et al. 2004) that may appear to be, for example, a weak s-process or a weak r-process. We aim to uncover the nature of this extra Sr source via Ba r- to s- isotope ratio determinations.
Method. The abundances from the resonance Ba II 4554 and 4934 A lines are affected by the adopted Ba isotope mixture. We compute Ba isotope mixtures that correspond to different r- to s- process contributions (pure r-process, 80%/20%, 50%/50% and 20%/80%, i. e. solar ratio) and determine the corresponding abundances from the Ba II resonance lines in each sample star. In addition to that, we determine Ba abundances from weak subordinate Ba II lines, which are immune to the adopted Ba isotope mixture. After that we compare Ba abundance from the subordinate lines with those from the Ba II resonance lines.
Results. Three of our sample stars are strongly r-process enhanced, and consistent within the error bars abundances from the resonance lines and subordinate lines can be achieved with pure r-process Ba isotope mixture, while including the s-process contribution results in a larger abundance discrepancy between the subordinate and resonance lines.
We found higher s-process contribution in stars with higher [Sr/Ba] overabundance, arguing that extra Sr synthesis was due to the early s-process occurring in massive stars. Using stars with high [Sr/Ba] we estimated the [Sr/Ba] ratio produced in the early s-process and found [Sr/Ba]_earlyS = 1.1 +- 0.2. Our result suggests that variations in [Sr/Ba] ratios in VMP stars can be explained by different contributions of the r-process and the early s-process to their chemical composition.

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Development of the Charge-Exchange Oslo Method and its First Application to Constrain (n,γ) Cross Sections

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Charge-Exchange (CE) reactions are an important tool for studying the spin-isopin response of nuclei. They can be utilized to obtain information about interactions mediated by the weak nuclear force, such as β and electron capture decay. Using the proportionality between Gamow-Teller strength (B(GT)) and the CE differential cross section, B(GT) distributions can be extracted indirectly. Since CE reactions are not limited to a narrow Q value window, they provide information that is complementary to information obtained from β and electron capture decay. Such data are necessary for constraining reaction rates that happen in dense and hot astrophysical environments. The main goal is to combine measurements in which GT strengths are extracted with γ-decay measurements, utilizing the Charge-Exchange Oslo (CE-Oslo) method to extract level densities and γ-ray strength functions, which are also important for constraining astrophysical reaction rates. As an initial test, the CE-Oslo method is being tested on 93Nb(t,3He+γ) data taken previously with the S800 spectrometer in coincidence with the GRETINA γ-ray detector at FRIB. The γ-coincidence data for 93Zr was applied with the Oslo method to develop the CE-Oslo method, and nuclear level densities (NLDs) and γ-ray strength functions (γSFs) of 93Zr were then extracted. These NLDs and γSFs were then used as inputs for the Hauser-Feshbach calculations using the TALYS to indirectly constrain the 92Zr(n,γ) cross sections, and hence 92Zr(n,γ) Maxwellian-averaged cross sections, which are crucial for understanding the astrophysical s-process nucleosynthesis. The results of this analysis will be published soon as the first publication of the CE-Oslo method. It is also planned to measure the 92Zr(3He,t+γ) reactions in RCNP, as well as 93Nb(p,d+γ) reactions in the Oslo-Cyclotron laboratory

to independently apply the CE-Oslo method and Oslo Method, respectively, and extract reaction rates for the nucleosynthesis of cosmochronometer 92Nb. This high-precision study will lay a solid foundation for using the CE-Oslo method in future (p,n+γ) experiments in inverse kinematics with rare isotopes and make it possible to simultaneously extract NLDs, γSFs, β-decay strengths, and (β-delayed) neutron decay probabilities (Pn) on neutron-rich unstable nuclei, which are important for several nucleosynthesis processes, including the r, i, γ, and ν processes. The high resolution available for (3He,t) experiments at RCNP will also make it possible to extract level densities in two independent manners: by using the CE-Oslo technique and by using the fine-structure analysis. From the measurement on 92Zr, it will be possible to extract level densities and γ-ray strength functions which are relevant for the γ-process in type Ia supernovae and Gamow-Teller strength distributions of relevance for the ν-process in core-collapse supernovae. These astrophysical phenomena are the possible sites for the production of long-lived 92Nb, which can serve as a cosmochronometer.

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Estimates for the nebular emission from r-process elements

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The origin of heavy r-process elements in the universe is still a matter of great debate, with a confirmed scenario being neutron star (NS) mergers. Additional relevant sites could be specific classes of supernovae (SNe), such as Type Ib/c, where a central engine pushes neutron-rich material outwards, contributing to the ejecta of the massive exploding star. We investigate our ability to infer the production of heavy elements in such events, on the basis of the observed electromagnetic (EM) nebular emission.
We solve the steady-state ionization, level population, and thermal balance, for ejecta in non-local thermodynamic equilibrium (NLTE), in order to explore the role of heavy elements in cooling the gas, and in the emergent spectrum. We find that heavy elements can dominate the cooling process of the nebula if they constitute more than ~10% of the total ejected mass, especially for kinetic temperatures above ~5000 K. While such an amount seems unlikely to be produced in many Type Ib/c SNe, already a few 0.1% of the total mass could be instead sufficient to leave a detectable imprint in the late infrared (IR) spectrum, which would be relatively clean from emission from lighter elements.

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The production of heavy elements from rotating massive stars in the Galaxy

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Massive stars play a crucial role in the chemical evolution of galaxies, particularly enriching the interstellar medium with heavy elements. Recent stellar modelling studies have highlighted the beneficial effects of rotation in massive stars, enhancing their nucleosynthesis especially at low metallicies, where stars are expected to rotate faster. Indeed, once rotation is taken into account heavy elements are importantly synthetized in massive stars through s-process during their lifetime, and possibly through r-process upon their death. In this way, the yields from rotating massive stars become a valuable ingredient for Galactic chemical evolution models to explain the abundances measured in stars.
In this talk, I will present the results coming from the GEMS chemical evolution model, which includes the nucleosynthesis of massive stars with a distribution of rotation velocities. The model reproduces the scatter visible in the observations, and is able to explain the evolution of key heavy elements. This approach allows us to derive significant constraints on the production sites of heavy elements.

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Neutron-capture processes revealed by dwarf galaxies

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The Milky Way is an environment rich with satellite galaxies, stellar streams and accreted systems. Looking at detailed chemical abundance patterns of individual stars in these systems allows us to trace back different nucleosynthetic sources, such as the slow (s), intermediate (i) and rapid (r) neutron-processes. Recent observations of these systems suggest that the i-process might have been more important at low metallicities, compared to higher metallicities. With spectroscopic observations of individual stars in the Milky Way and the dwarf galaxy satellites, it becomes clear that (at least) two distinct r-process sites are needed to explain the data: a quick source with timescales comparable to core-collapse supernovae, and a delayed source with characteristic timescales of a few ~Gyr, most probably originating in neutron star mergers. In this talk I will go over the data and the arguments leading to these result sand show that only by looking at all the available data in many galaxies will we be able to solve the puzzle that is the neutron-capture processes.

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Diverse Stellar Neutron-Capture Isotopic Signatures Recorded in Presolar Silicon Carbide Grains

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Presolar grains are submicron- to micron-sized meteoritic grains that originate from stellar winds lost from the surfaces of multiple stars and from the ejecta produced by stellar explosions. Among the best-studied presolar phases is SiC. Multielement isotope analyses of presolar SiC grains indicate that most have origins in AGB stars and core-collapse Type II supernovae (CCSNe). AGB dust constitutes the majority of presolar SiC grains (>90%), including mainstream (MS), Y, and Z grains, while CCSN dust contributes a smaller fraction, including X, C, and D grains. Isotopic analyses of presolar SiC grains, therefore, enable detailed examination of AGB and CCSN nucleosynthesis at the level of isotopes.

We conducted a survey of Ni isotope ratios in presolar SiC grains using secondary ion mass spectrometry. We chose Ni isotopes for several reasons: (i) Ni is highly enriched in presolar SiC grains; (ii) the most neutron-rich isotope, 64Ni, is primarily produced by the s-process in AGB stars and is minimally affected by the initial stellar composition, making it a reliable proxy for probing s-process efficiency; (iii) the least neutron-rich isotope, 60Ni, is poorly produced by the s-process, largely reflecting the initial composition that indicates galactic chemical evolution (GCE); and (iv) under different neutron exposures, a variety of Ni isotope patterns are predicted for neutron bursts, a neutron-capture process driven by the 22Ne(α,n)25Mg reaction during CCSNe.

We selected a suite of presolar SiC grains based on their C, N, and Si isotope ratios for subsequent Mg-Al, Ti, and Fe-Ni isotope analyses. Statistically meaningful Ni isotope data were obtained for 56 new MS grains, 26 Y grains, 15 Z grains, 1 C grain, 1 D grain, and 17 X grains.
Our new Ni isotope data reveal several key observations: (i) Compared to existing data [1], we observed more extreme Ni isotope anomalies in MS grains, likely resulting from our methodology for suppressing Ni contamination. Our Ni isotope data align more closely with AGB models that have been calibrated against the Sr, Zr, Mo, and Ba isotopic compositions of MS grains [2]. (ii) By mitigating contamination, we robustly constrained the s-process efficiency in the parent AGB stars of MS, Y, and Z grains, following the order of Y > Z > MS. This contrasts with previous inferences based on Si and Ti isotope data [3]. (iii) The 60Ni/58Ni ratios of MS/Y and Z data are influenced by homogeneous and heterogeneous GCE effects, respectively. (iv) C and X CCSN grains exhibit distinct Ni isotopic patterns, indicating a wide range of neutron exposures experienced by the grains in their parent CCSN ejecta. Notably, the C grain recorded the highest neutron exposure, providing stringent constraints on the exposure condition during the explosion and relevant neutron-capture cross-sections, such as 63Ni(n,γ)64Ni. Detailed data-model comparisons will be presented at the meeting.

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The Stellar Precursors of the Solar System? Constraints from quantitative relations between genetic anomalies and NRLEE ejecta

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The stellar precursors of the protoplanetary disk defined the Solar System's composition, a fundamental property that influenced the nature of the subsequent planetary system. The identity of the dominant stellar precursors, however, remains under investigation. Partial constraints have been inferred from nucleosynthetic isotope (i.e., genetic) anomalies in meteorites. Genetic anomalies are part per million-scale isotopic variations of a sample composition from a standard composition. These fine-scale anomalies reflect the heterogeneous distribution of isotopically variable presolar carriers throughout the disk.

Correlated genetic anomalies in neutron-rich iron group species 46Ti, 48Ca, 50Ti, and 54Cr characterize bulk rock meteorite compositions. On the Solar System scale, these genetic anomalies form two near-omnipresent groups, which are defined as the non-carbonaceous (NC)-carbonaceous chondrite (CC) isotopic dichotomy. This dichotomy is widely used as the basis of qualitative and quantitative models of Solar System formation. Using the NC-CC isotopic dichotomy for such reconstructions, however, requires an understanding of the type and stellar origin of presolar carriers whose heterogeneous distribution in the disk resulted in genetic anomalies.

The presolar carriers and stellar precursors that are responsible for the correlated anomalies of 48Ca, 46Ti, 50Ti, and 54Cr in bulk meteorites are yet to be determined. In this contribution, the approach to constraining the identity of these carriers comes from the stellar nucleosynthesis standpoint. The stellar precursors of 48Ca, 46Ti, 50Ti, and 54Cr are identified and then assessed to determine if sufficient quantities were synthesized and added to the disk to generate the observed genetic anomalies in meteorites. Given the special nucleosynthetic requirement that 48Ca be produced in neutron-rich, low-entropy matter expansions during rare astrophysical events in the Galaxy, we focus on this type of stellar precursor. The exact nature of these events is unclear, but they are likely associated with the explosion of a dense white-dwarf star, such as the deflagration of a near Chandrasekhar-mass white dwarf, an electron-capture supernova (ECSN), or a thermonuclear ECSN (t-ECSN). Due to the variety of plausible sites, they are referred to here generically as "NRLEEs"(Neutron-rich, Low-Entropy matter Ejectors).

This study quantitatively assesses the relative abundances of 48Ca, 46Ti, 50Ti, and 54Cr produced in NRLEEs by using a simple one-dimensional model of the explosion of a carbon/oxygen-dense white dwarf star with *s*-process enhanced abundances to illustrate the nucleosynthesis that could occur in NRLEEs. A multicomponent Galactic Chemical Evolution (GCE) model provides a quantitative estimate of the abundance of different dust types (processed, low-mass, SNIa, SNII, NRLEE) and their isotopic compositions in the initial Solar System. To assess if NRLEEs are the source of neutron-rich iron group species in the Solar System, mixing calculations between the average Solar System composition and calculated NRLEE compositions are performed. The results are contrasted with NC-CC meteorite compositions. Preliminary findings will be reported to provide one of the first quantitative assessments of the stellar precursors that underpin the NC-CC isotopic dichotomy and the associated constraints on the dominant stellar precursors of the Solar System.

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Collective neutrino oscillations and the heavy-element nucleosynthesis in supernovae

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In high energy astrophysical processes involving compact objects, such as core-collapse supernovae or neutron star mergers, neutrinos are likely to play an important role in the synthesis of nuclides. Neutrinos in these environments can experience collective flavor oscillations driven by neutrino-neutrino coherent forward scattering. Recently, there has been interest in exploring potential beyond-the-mean-field effects in the collective oscillations of neutrinos. Here, we seek to explore possible implications of these effects for the heavy-element nucleosynthesis yields in supernova environments with different astrophysical conditions and neutrino inputs. We find that collective oscillations can impact the operation of the νp-process and r-process nucleosynthesis in supernovae. The potential impact is particularly strong in high-entropy, proton-rich conditions, where we find that neutrino interactions can nudge an initial νp process neutron rich, resulting in a unique combination of proton-rich low-mass nuclei as well as neutron-rich high-mass nuclei or a full "intermediate neutron capture process" like path. We describe this neutrino-induced neutron capture process as the "νi process". In addition, nontrivial quantum correlations among neutrinos, if present, could lead to distinctly different nucleosynthesis results compared to the corresponding mean-field treatments, by virtue of modifying the evolution of the relevant one-body observables.

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Trans-Fe elements from Type Ia Supernovae

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A Type Ia supernova (SNIa) marks the catastrophic explosion of a white dwarf in a binary system. These events play a crucial role in galactic chemical evolution and serve as pivotal standardizable candles for measuring cosmic distances, underpinning the discovery of the Universe's accelerated expansion. However, the progenitors of SNIa remain uncertain, introducing challenges to their use in cosmology and nucleosynthesis predictions.

In this work, we present a grid of five models detailing the evolution and nucleosynthesis of slowly merging carbon-oxygen white dwarfs approaching the Chandrasekhar mass. These models test a variety of physics input settings, including accretion rates, nuclear reaction rates, convection parameters, and the composition of the accreted material. During the merger process, as the mass of the primary white dwarf approaches the Chandrasekhar limit, carbon burning is initiated first on the surface before eventually igniting explosively at the center. As a consequence, the ^{22}Ne(α,n)^{25}Mg reaction activates in the outer layers of all models, producing a weak s-process-like abundance pattern, peaking at Kr, overproduced by a factor of $\sim$1000 compared to solar. The trans-Fe elements-enriched outer layer mass varies from 0.05~$M_\odot$ to 0.11~$M_\odot$, depending on the accretion rate. Our explosion simulations of these progenitor models eject significant amount of first-peak elements (e.g., Se, Kr) and light p-nuclei (e.g., ^{74}Se).

Previous theoretical studies found that a similar nucleosynthesis process during the progenitor phase may also occur on the surface of near-Chandrasekhar white dwarfs formed through the accretion of H-rich material via the single-degenerate scenario. Therefore, these results suggest trans-Fe enrichment might be a hallmark of near-Chandrasekhar SNIa ejecta, regardless of the specific progenitor channel, and could provide a new spectral signature distinguishing them from sub-Chandrasekhar explosions.

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Chemical abundances of light neutron-capture elements in metal-poor stars

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Metal-poor stars play a key role in understanding the nucleosynthesis of heavy elements in the early Universe, as their chemical abundances reflects the composition of the gas in which they formed. High-resolution spectra show that metal-poor stars have robust chemical abundance patterns in the $60<Z<70$ region, while variations are visible in region of the lighter heavy elements ($30<Z<50$). These abundance pattern variations seem to suggest that more than one formation site is responsible for the nucleosynthesis of these elements and/or that formation occurs under different physical conditions.

In this talk, I will present the abundances of heavy elements, including the poorly studied Mo, Ru, Pd and Ag, for a sample of 52 very metal-poor stars.

The talk will focus on exploring the impact of different neutron capture processes that synthesise heavy elements at low metallicity, comparing the observed chemical abundances with those predicted by theoretical models.

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The time evolution of the s-process elements as traced by Galactic open clusters

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In recent years, the spectroscopic analysis of stars in Galactic open clusters showed a peculiar behavior regarding the slow neutron capture processes. On one hand, clusters at ages younger than 200 Myr display an unexpected over-abundance of Ba, reaching values up to ~0.7 dex at 30 Myr. On the other hand, regarding the other s-process elements such as Y, Zr, La and Ce, there is a general disagreement in the literature. Some authors claim that these other elements, in particular La and Ce that are produced in the same way as Ba, are found solar at all ages. Others instead claim they show a slight increase in abundance with age. This is commonly referred to as the Ba puzzle.
In this talk, I will present the latest results obtained by the analysis of FGK dwarfs stars belonging to six open clusters observed within the Gaia-ESO large spectroscopic survey. From our deep investigation, we found that stellar activity (more intense at these ages) might be responsible for the Ba enrichment. Nevertheless, the hypothesis of a nucleosynthesis origin (activation of the intermediate process) cannot be discarded yet.

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I-Process nucleosynthesis in AM CVn Systems

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It is common opinion that AM CVn systems end their life as peculiar SNe Ia events due to detonation of a massive He layer piled up via mass transfer onto the CO WD component.
However, it has been shown that, if the effects of rotation are properly taken into account in modeling the evolution of the accretor in these systems, the accreting WD experiences recurrent very strong He-flashes during which all the accreted mass as well as part of the underlying CO core is lost via Roche lobe overflow episodes.
Moreover, it has been found that during the flashes the temperature at the base of the He-rich layer largely exceeds 350 Mk, so that alpha-captures onto 22Ne become possible and a neutron flux (of the order of 10^15 cm^(-3)) typical of the I-process nucleosynthesis is delivered. The 22Ne mass fraction abundance in the He-rich layer is almost equal to the initial metallicity of the progenitor star, as it is produced via double alpha captures onto 14N, the ashes of H-burning via CNO cycle.
In this talk we discuss the nucleosynthesis produced during He-flashes by studying the future evolution of the PTF J2238+743015.1 system. We extend our analysis by investigating the dependence of the obtained results on the physical conditions in the He-burning shell and on the initial metallicity of the progenitor system. At the end we estimate the expected contribution of rotating AM CVn systems to the evolution of the interstellar medium.

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New results on AGB stars and meteoritic data

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We run *slow* neutron-capture process (*s* process) nucleosynthesis calculations with the *Monash* post-processing code for seven stellar structure evolution models of low-mass asymptotic giant branch (AGB) stars with new sets of nuclear input. We present our new nucleosynthesis predictions of a selection of isotopic ratios and compare them to the corresponding ratios measured in presolar stardust grains from AGB stars. Our new models quantitatively reproduce the minor *s*-process production of the classical p-only ^{94}Mo observed in stardust silicon carbide (SiC) grains (around 3-4%) and match the ^{64}Ni/^{58}Ni values from the SiC grain data. The predictions for the He intershell ratios of ^{80}Kr/^{82}Kr and surface ratios of ^{137}Ba/^{136}Ba ratios are better fitted to SiC grains than for the previous *Monash* models. The ^{186}W produced by our new models still does not match the tungsten isotopic composition of large SiC stardust grains but does match the tungsten composition observed in other types of meteoritic materials well.

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A Prototype Neutron Detector Array for s-process Measurements

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Neutron detection sometimes plays a vital role in direct studies of astrophysically important reactions. In particular, the reaction 22Ne(a,n)25Mg is undergoing study using the SHADES array at the Belotti Ion Beam facility at Laboratori Nazionali del Gran Sasso. This reaction, and 13C(a,n)16O, is widely regarded to serve as a neutron fuel for the slow neutron capture (s-) process occurring in massive stars and asymptotic giant branch stars, which synthesise elements above A = 60 –90 and 90 –209, respectively. Prior to constructing the full SHADES array, the neutron detection capabilities of its detectors were tested using a scaled-down prototype array and a neutron beam produced at the Goethe University Frankfurt's Van de Graaf accelerator facility "FRANZ". The prototype consisted of an EJ-309 liquid scintillator surrounded by six 3He proportional counters. Under study was the neutron / gamma-ray discrimination performance of the EJ-309 using traditional and machine-learning techniques, the lower detection limit of the neutron energy, and the timing coincidence features between the EJ-309 and counters. In future, such coincidence is expected to improve the sensitivity of the full SHADES array via a novel anti-coincidence gate on background neutrons. This talk will summarise the measurement performed at Frankfurt and the determined characteristics of the prototype array.

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22Ne(α, n)25Mg at the INFN Bellotti Ion Beam Facility

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Neutron capture reactions are the main contributors to the synthesis of the heavy elements through the s-process. 22Ne(α, n)25Mg is the main neutron source in stars together with 13C(α, n)16O. In the

relevant stellar energy (450 keV < Ecm < 750 keV) few data ara available, I.e. reaction cross section upper limits from direct experiments and highly uncertain estimates from indirect sources exist. The ERC project SHADES (UniNa/INFN) is currently performing direct cross section measurements at these energies. We will present details on the ongoing experiment and discuss target characteristics, experimental backgrounds and preliminary analyses on the detector efficiency and the 832 keV resonance.

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Exploring Nuclear Formation Processes at Intermediate Metallicity: The MINCE Project's Insights into Neutron-Capture Element Abundances

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The abundances of neutron-capture elements in metal-poor stars are crucial for understanding the astrophysical sites and mechanisms responsible for heavy-element nucleosynthesis. While the very metal-poor regime ([Fe/H] < -2.5) has been extensively studied, the intermediate metallicity range (-2.5 \leq [Fe/H] \leq -1.5) remains poorly explored, leaving a significant gap in our understanding of nucleosynthesis. This transitional epoch in the Galaxy marks the interaction of slow (s-process), rapid (r-process), and intermediate (i-process) neutron capture mechanisms, shaping the chemical composition of the interstellar medium.

My work focuses on analyzing high-resolution spectra of about 90 stars, observed using FEROS, achieving high quality spectra (signal-to-noise ratio S/N ~ 50). This dataset enables a detailed investigation of star-to-star abundance scatter of neutron-capture elements, including ~ 20 key elements (e.g., Sr, Ba, Eu), as well as lighter elements such as CNO, \alpha-elements, and Fe-peak elements. We will reveal distinct abundance patterns among neutron-capture elements, which could indicate the relative contributions of s-, r-, and i-process nucleosynthesis. To further explore the s- and r-process, I focus on the rarely studied elements Mo and Lu, which provide unique insights into the mechanisms shaping neutron-capture nucleosynthesis and Galactic chemical evolution. Additionally, I will identify and examine stars displaying peculiar abundance signatures to gain deeper insights into their origins and nucleosynthetic history, thereby uncovering new dimensions of the Galaxy's nucleosynthetic history and its chemical evolution.

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Constraining the neutron-capture nucleosynthesis from surface chemical composition of chemically peculiar stars: some highlights from our recent studies

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Among the chemically peculiar metal-poor stars, the two sub-classes of carbon-enhanced metal-poor (CEMP) stars, the so called CEMP-s and CEMP-r/s stars are powerful tracers of slow (s) and intermediate (i) neutron-capture nucleosynthesis, evolution of binary systems and mechanisms of mass-transfer. The epoch of the earliest s-process nucleosynthesis that influenced the chemical enrichment, as well as questions related to production sites and production mechanisms of i-process nucleosynthesis, that are currently far from being clearly understood can be investigated using these and related stars through accurate and precise measurements of elemental abundances of heavy elements covering a wide range of masses and metallicity. However, to understand the complex

mechanisms underlying the nucleosynthesis and evolution of heavy elements a holistic approach integrating observation, theories and simulations is necessary. Some recent results obtained from our chemodynamical studies of a sample of chemically peculiar stars will be presented in the light of companion low-mass,
low-metallicity AGB stars'contribution to the chemical enrichment of heavy elements. Many details associated with the early nucleosynthetic enrichment events that remain poorly understood can be probed with the newly discovered rare pristine objects, the oldest stars believed to be associated with the first supernovae. In this context, some areas where follow-up spectroscopic studies would make an impact will be discussed.

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22Ne(,)26Mg with EAS

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The reaction 22Ne(,)26Mg is associated with several questions in nuclear astrophysics, such as the Mg isotope ratio in stellar atmospheres and the nucleosynthesis of element beyond Fe through its competition with the neutron source 22Ne(,)25Mg.
Due to very low stellar energies and therefore very low cross section, direct experiments have been only able to provide upper limits below a strong resonance at 832 keV.
The purpose of the EAS project is to perform the first direct measurement of the 22Ne(,)26Mg in the range of astrophysical interest below 600-800 and the remeasurement of the well-known 832 keV resonance.
The measurement will be performed at Laboratori Nazionali del Gran Sasso and will be carried out using a high and stable α particle current delivered by the newly commissioned LUNA MV accelerator.
Moreover, its position underground and additional passive shielding will reduce the γ-background.
The γ-rays produced in the reaction will be detected by a NaI scintillator array surrounding a windowless, recirculating gas target.
I will present the current status of the project and the preliminary results of NaI detector array simulations.

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N-capture elements in GCs using the Gaia-ESO data

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Globular clusters (GCs) are important stellar objects for understanding the formation and evolution of our Galaxy, providing crucial constraints to the chemical evolution and assembly history of the Galactic halo. Although there have been many individual efforts to characterise GCs in terms of heavy elements chemically, there is a lack of a global analysis with a homogeneous method. I present the most extensive study of neutron-capture elements in GCs using the Gaia-ESO survey data to provide clues about the contribution of different stellar processes and events, such as supernovae,

AGB stars, or neutron star mergers. I show, from the observational point of view, the neutron-capture elements (Y, Zr, Ba, La, Ce, Pr, Nd, and Eu) distribution within GCs, as well as the relative contributions of s- and r-process to the chemical abundances in this objects.

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The Principal Components of Metal-poor Stars

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The nuclear mechanism responsible for roughly half of the heavy-elements (Z>30) abundances in our Solar system—the rapid neutron capture (r) process—was long thought to produce a "universal" abundance pattern. However, recent studies have challenged r-process universality by identifying significant variations between the elemental abundances patterns of metal-poor ([Fe/H]<-1.0), r-process-enhanced stars. In particular, r-process-rich ([Eu/Fe]>+0.3) stars show a signature that may possibly only be explained by fission. In this work, we construct a method of decomposing stellar abundance patterns into a basis set of patterns from which each star can be constructed as a linear combination, akin to a principal component decomposition. We use this method to uncover the underlying signature that is present in the r-process-rich stars in order to derive an empirical record of fission in the r-process. This talk will present the "pure" fission pattern is that is recovered from these metal-poor stars.

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Neutron capture and total cross-section measurements on ^{94,95,96}Mo at n_TOF and GELINA

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Cross-sections for neutron-induced interactions with molybdenum, in particular the neutron capture cross sections, play a significant role in various fields ranging from nuclear astrophysics to nuclear power plants and the development of innovative nuclear technologies. Molybdenum is found in pre-solar silicon carbide (SiC) grains and an accurate knowledge of its neutron capture cross section

has a crucial role in stellar nucleosynthesis models, in particular in Asymptotic Giant Branch (AGB) stars. From the work of Liu et al., a deviation on the model predictions has been observed when using Mo cross section data from the two main KADoNiS versions, with KADoNiS 1.0 providing the better agreement with the grains data. In addition to its astrophysical role, molybdenum isotopes can be found as a fission product in fission power plants and the use of this material is under study for future improved reactors. This shows the importance of an accurate knowledge of the total and capture cross-section for molybdenum isotopes.

Experimental data in the literature for the capture cross-section of Mo isotopes suffer from large uncertainties. This is also reflected in the large uncertainties of the cross-sections recommended in the ENDF/B-VIII.0 library. Below 1 eV the relative uncertainty of the capture cross-section is above 18% for ^{94}Mo and around 40% for ^{96}Mo, while above 2 keV the uncertainties are in the order of 10-20% for ^{94,95,96}Mo. The uncertainty on the capture cross section data in the libraires is also reflected in the uncertainty of the MACS (Maxwellian Averaged Cross Section) found in the latest version of KADoNiS. The presents uncertainties are on the level of 10% in the MACS at 30 keV for all the molybdenum isotopes, while an uncertainty below 5% would be needed to disentangle the observed discrepancies. One of the reasons for these large uncertainties is related to the absence of transmission data for enriched samples.

In this contribution the preliminary results of transmission and radiative capture measurements performed at n_TOF (CERN, Switzerland) and GELINA (EC-JRC Geel, Belgium) will be presented. Moreover, the updated values of the MACS for ^{94,95,96}Mo will be shown. The effect of these new preliminary values of the cross section in stellar nucleosynthesis calculations for AGB stars will be presented.

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Evidence for r-process production by rare supernovae in the low metallicity environment

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The decreasing trend of the [Eu/Fe] feature caused by stars in the Large Magellanic Cloud (LMC) is followed by a nearly constant value; this trend is generally attributed to an onset of the delayed Fe release from type Ia supernovae (SNe), which is the same interpretation of the [α/Fe] feature. However, this feature appears in the LMC at [Fe/H] of approximately -0.7, which is significantly higher than that for the [α/Fe] case ($\approx$-2). We propose that this [Eu/Fe]-knee feature is created by a fade-out of core-collapse SNe producing r-process elements. The metallicity threshold for the occurrence rate of these r-process SNe at a subsolar is nearly identical to that for long gamma-ray bursts.

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s-process and Carbon-Enriched Low-Mass Evolved Stars as Tracers of s-process Nucleosynthesis

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Observational studies focusing on low- to intermediate-mass evolved stars, such as post-AGB stars, reveal remarkable diversity in their chemical compositions, particularly in terms of CNO abundance and *s*-process enrichment. These stars provide critical insights into AGB nucleosynthesis, dredge-up events, and hot-bottom burning. However, the mechanisms driving the observed diversity in their chemical signatures remain uncertain.
In this talk, I will explore both observational and modelling perspectives on s-process and carbon-enriched post-AGB stars. I will also discuss our recent discovery of the most carbon-rich and s-process enhanced post-AGB star in the Small Magellanic Cloud (SMC). High-resolution optical spectroscopy with VLT/UVES has revealed this star's exceptionally high C/O ratio and a significant enhancement of s-process elements, including the first-ever precise measurement of lead (Pb) abundance, the final product of the *s*-process nucleosynthesis. These results challenge existing nucleosynthesis models and set a new benchmark for understanding how mass loss rates and mixing processes shape the chemical evolution of evolved stars.

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Spectral modelling of kilonovae in 3D NLTE

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Kilonovae are the transients powered by the radioactive decay of *r*-process elements, usually associated with neutron star mergers (NSMs). The late-time spectrum of NSMs is the most important tool to investigate the origin of the heaviest elements including the actinides, their nucleosynthesis at these sites, the environments of their production, and whether or not their abundances can be sufficiently explained by NSMs alone. Spectral modelling is an essential bridge to validate the theory of *r*-process sites, as it allows the results of hydrodynamic explosion models to be compared directly with observations.

We present the first results of our work on the spectral modelling of kilonovae in three dimensions (3D) and non-local thermodynamic equilibrium (NLTE). This approach is essential since the hydrodynamical model results of NSMs are highly asymmetric, requiring 3D treatment; additionally, the elemental signatures of the bulk material in the ejecta become visible only at late times, when NLTE is a necessity.
EXTRASS is a spectral code designed for the 3D NLTE modelling of supernovae in the late-time nebular phase. It is able to generate light curves and spectra for arbitrary viewing angles by following photon packets, using explosion models as input. We are extending this code to kilonovae, with the aim of producing the first 3D NLTE synthetic light curves and spectra of NSM models.

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An open-source library for performance-portable neutrino reaction rates and Applications to neutron star mergers

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A realistic and detailed description of neutrinos in binary neutron star (BNS) mergers is essential to build reliable models of such systems. To this end, we present BNS_NURATES, a novel open-source numerical library designed for the efficient on-the-fly computation of neutrino interactions, with particular focus on regimes relevant to BNS mergers. BNS_NURATES targets a higher level of accuracy and realism in the
implementation of commonly employed reactions by accounting for relevant microphysics effects on the interactions, such as weak magnetism and mean field effects. It also includes the contributions of inelastic neutrino scattering off electrons and positrons and (inverse) nucleon decays. Finally, it offers a way to reconstruct the neutrino distribution function in the framework of moment-based transport schemes. As a first application, we compute both energy-dependent and energy-integrated neutrino emissivities and opacities for conditions extracted from a BNS merger simulation with M1 transport scheme. We find some qualitative differences in the results when considering the impact of the additional relevant reactions and of microphysics effects. For example, neutrino-electron/positron scattering reactions are important for the energy exchange of heavy-type neutrinos as they do not undergo semileptonic charged-current processes, when μ are not accounted for. Moreover, weak magnetism and mean field effects can significantly modify the contribution of β processes for electron-type (anti)neutrinos, increasing at the same time the importance of (inverse) neutron decays. The improved treatment for the reaction rates also modifies the conditions at which neutrinos decouple from matter in the system, potentially affecting their emission spectra.

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Atomic Data Requirements for Non-LTE Modeling of Kilonova

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The observation of kilonova AT2017gfo following the neutron star merger GW170817 [1] has provided compelling evidence for the production of r-process elements in these events. While recent spectral analyses have identified several elements in the ejecta [2,3,4], accurate abundance determinations remain challenging due to limitations in available atomic data, especially for modeling later epochs where non-LTE effects become crucial [5].
We present extended and improved calculations for lanthanides and actinides, including forbidden transitions, using both the Flexible Atomic Code [6] and AUTOSTRUCTURE [7], with atomic structure optimized using our recently developed sequential model-based optimization procedure [8]. Additionally, for selected elements, we benchmark electron-impact excitation cross sections and collision strengths calculated within the distorted wave approximation. We also present preliminary results extending these calculations to selected lanthanides, providing new atomic parameters necessary for non-LTE modeling of kilonova spectra.
This expanded atomic dataset, including forbidden transitions, improved energy levels, and electron-impact excitation rates, establishes the construction of a foundational atomic dataset that can be

used for more reliable modeling of late-time kilonova spectra where non-LTE effects dominate the emission features.

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Neutron-capture signatures in a large sample of Ba stars

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Barium (Ba) stars belong to binary systems where a former asymptotic giant branch (AGB, now a white dwarf) star polluted the less evolved companion, which became enriched with material produced through the slow neutron capture process (s process). 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 based on high-resolution spectra, 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 180 Ba stars, we could confirm that the polluting AGBs are of low mass (< 4 MSun). Most of the matching AGB models require low accreted mass, but a few systems with high accreted mass are needed to explain the observations. However, approximately 25% of the sample stars show anomalous abundance patterns, mainly at the first s-process peak (with higher Nb, Mo and/or Ru than the models), along with high W. The high W value is comparable to some post-AGB stars, and might indicate that we can identify different subgroups among the Ba star sample. The s-process temperatures derived with the [Zr/Fe] - [Nb/Fe] thermometer have an unrealistic value for the majority of our stars. The most likely explanation is that at least a fraction of these elements are not produced in a steady-state s process, and instead may be due to processes not included in the AGB models. Additional measurements could reveal the cause for these overabundances and can help to identify the underlying processes.

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Calculation of electron impact excitation cross-sections and collision strengths for non-LTE modelling

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The production of heavy elements beyond iron in the expanding ejecta of binary neutron star mergers (NSMs) provided evidence for the synthesis of lanthanides and possibly actinides through rapid neutron capture (r-process) nucleosynthesis. However, identifying specific atomic absorption and emission features in kilonova spectra to associate them with individual elements remains a significant challenge [1,2].
One of the primary obstacles is the lack of comprehensive atomic data for modeling the late nebular epochs (> 4 days post-merger). While it is a reasonable approximation to assume that the ejecta is in local thermodynamic equilibrium (LTE) and that atomic absorption processes dominate in the early hours (< 1 day after the NSM), it is not possible to assume LTE for nebular epochs (non-LTE). During these late stages, relevant processes include photoionization, ionization and excitation by electron impact, and electronic recombination, for which the data is very scarce [3].
In this work, we address this gap by benchmarking electron-impact excitation (EIE) cross sections and collision strengths (CS) for selected elements, including Y, Pt, and Au [4], using the Flexible Atomic Code [5] and AUTOSTRUCTURE [6]. Our results show that the approximations by van Regemorter and Axelrod underestimate collision strengths by orders of magnitude, particularly for forbidden transitions. Preliminary calculations of EIE cross-sections and CS for selected lanthanides will be also presented, providing new atomic parameters essential for advancing non-LTE spectral modeling.

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Tracing r-process nucleosynthesis in neutron star mergers with long-lived remnants: results from M1 neutrino transport simulations

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Binary neutron star (BNS) mergers eject neutron-rich matter, providing ideal conditions for the nucleosynthesis of heavy elements via the r-process. The radioactive decay of these elements powers a quasi-thermal electromagnetic transient known as kilonova (KN). Despite significant progress since the detection of GW170817, many open questions about KNe remain, such as the interpretation of the spectral features observed in AT2017gfo. On the one hand, accurate predictions of r-process yields are crucial for modeling and interpreting KN signals. On the other hand, precise modeling of microphysics in BNS merger simulations is essential to determine the properties of the merger ejecta, which provide the starting point for nucleosynthesis calculations. In my talk, I will present the results of the nucleosynthesis from BNS merger ejecta, computed for the first time using tracer particles from numerical relativity simulations performed with the M1 neutrino transport scheme. These simulations predict long-lived remnants and account for three distinct ejecta channels: dynamical ejecta, neutrino-driven wind, and spiral wave wind.

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Statistical framework for nuclear parameter uncertainties in nucleosynthesis modeling of r- and i-process

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Propagating nuclear uncertainties to nucleosynthesis simulations is key to understand the impact of theoretical uncertainties on the predictions, especially for processes far from the stability region, where nuclear properties are scarcely known. While systematic (model) uncertainties have been thoroughly studied, the statistical (parameter) ones have been more rarely explored, as constraining them is more challenging.

We present here a methodology to determine coherently parameter uncertainties by anchoring the theoretical uncertainties to the experimentally known nuclear properties through the use of the Backward Forward Monte Carlo method. We use this methodology for two nucleosynthesis processes: the intermediate neutron capture process (i-process) and the rapid neutron capture process (r-process). We determine coherently for the i-process the uncertainties from the (n,γ) rates while we explore the impact of nuclear mass uncertainties for the r-process.

The effect of parameter uncertainties on the final nucleosynthesis is in the same order as model uncertainties, suggesting the crucial need for more experimental constraints on key nuclei of interest. We show how key nuclear properties, such as relevant (n,γ) rates impacting the i-process tracers, could enhance tremendously the prediction of stellar evolution models by experimentally constraining them.

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r-process nucleosynthesis and radioactively powered transients from magnetar giant flares

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We present nucleosynthesis and light-curve calculations for a new site of the *r*-process from magnetar giant flares (GFs). Motivated by radio afterglow observations which indicate sizable baryon ejecta from GFs, Cehula et al. (2024) recently proposed a scenario whereby magnetar crustal material is ejected as a result of a shock driven into its surface layers during the reconnection-driven GF. We confirm with nucleosynthesis calculations that these ejecta can synthesize moderate yields of third-peak *r*-process nuclei and substantial yields of first- and second-peak nuclei through the alpha-rich freeze-out mechanism. We use the nucleosynthesis output to make light-curve predictions of *novae breves*, kilonova-like optical/UV transients, and the gamma-ray transients powered by the radioactive decay of the unbound debris. We show that the predicted gamma-ray emission properties (light-curve, fluence, and spectrum) match a previously unexplained hard gamma-ray signal observed in the aftermath of the famous December 2004 giant flare from the magnetar SGR 1806-20. This MeV emission component is direct observational evidence for the synthesis of $\sim 10^{-6} M_{\odot}$ of *r*-process elements. The discovery of magnetar giant flares as confirmed *r*-process sites, contributing at least $\sim$ 1-10% of the total Galactic abundances, has implications for the Galactic chemical evolution, especially at the earliest epochs probed by low-metallicity stars.

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Measurement of the neutron capture cross section of ^{64}Ni at n_TOF

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The neutron capture cross section of ^{64}Ni is an important parameter in nuclear astrophysics to accurately simulate stellar nucleosynthesis and validate stellar models. ^{64}Ni is among the seeds of the s-process and acts as an effective bottleneck for the production of the heavier nuclei in the s-process path. For this reason, its neutron capture cross section has been found to be one of the three key nuclear parameters that dominate the uncertainty on the predicted abundances of many nuclei produced by the s-process up to Lead. Moreover, a discrepancy observed in SiC presolar grains between measured ^{64}Ni isotopic ratios and predictions from a promising model for mixing in AGB stars suggests a possible incorrectness of the recommended value of the neutron capture cross section of ^{64}Ni. Experimental measurements available in literature are indeed very scarce and discrepant, especially concerning time-of-flight measurements that are ultimately needed to determine Maxwellian Average Cross Sections (MACS) at different temperatures. For these reasons, a new accurate time-of-flight measurement of the neutron capture cross section of ^{64}Ni has been performed at the n_TOF facility at CERN, taking advantage of its high instantaneous neutron flux and using a highly enriched ^{64}Ni sample. The preliminary results show interesting discrepancies with respect to the cross section recommended in the most recent releases of the evaluated nuclear data libraries. In particular, a huge resonance reported before at 9.52 keV is not observed. As a consequence, a significant impact on the currently adopted MACS in the range of astrophysical interest is expected. The astrophysical motivations, the measurement and the preliminary results will be presented in this contribution.

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Homogeneous abundances in the LMS-1 dwarf galaxy stream and its globular clusters: extreme Ba spreads in the galaxy and remarkable chemical consistency in Eu

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The LMS-1/Wukong stream represents the only chance locally to study a low-mass dwarf galaxy and globular cluster system. As a low mass dwarf galaxy, it also offers insight into the extreme chemical abundances and rare nucleosynthesis now synonymous with these objects. Currently on a polar orbit, just north of the Galactic Bulge, LMS-1 was likely a major contributor to the build up of the inner Milky Way at early times and given the close proximity in phase space and metallicity to the globular clusters, NGC 5024 and NGC 5053, it is likely these clusters were accreted alongside LMS-1. For the first time, we have performed homogeneous abundance measurements of stars in LMS-1, NGC 5024 and NGC 5053 using high resolution spectroscopy to understand the chemical similarities and differences between the galaxy and its clusters. We find a large >1 dex spread in Ba in LMS-1 driven by two extremely s- and r-process deficient stars. This spread is not seen in the two clusters. Neglecting these two stars, we see excellent consistency in the r-process element Eu between the two clusters and the dwarf galaxy, suggesting that Eu remains a promising tag linking clusters to their host galaxies. The nucleosynthetic implications of this finding and further results from this remarkable system will be presented in this talk, linking back to the formation of low-mass dwarf galaxy/globular cluster systems and extreme nucleosynthesis at early times.

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Modeling Mass Transfer in AGB Binaries

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The nucleosynthetic s-process occurring in AGB stars from ~ $1–6 M_\odot$ is responsible for creating half of the heavy elements in the universe, the chemical imprint of which can be studied by observing the material on the surface of binary barium (Ba), CH, and carbon-enhanced metal-poor (CEMP) stars. We simulate the results of AGB mass transfer in binaries by computing a grid of binary stellar evolution models using the STARS code (Pols et al. 1995), using stellar yields from the FUll-Network Repository of Updated Isotopic Tables & Yields (FRUITY) database (Cristallo et al. 2011). We compare 1D-LTE abundance patterns (including C, Sr, Y, Zr, Mo, (Ru), Ba, La, Ce, Nd, (Sm), Pb, Eu) and surface parameters of Ba stars from de Castro et al. (2016); Roriz et al. (2021, 2024), and a small number of Ba, CH, and CEMP-s from Dimoff et al. (2024) to the grid. We find correlations between AGB masses and the abundance patterns of their polluted companions, and we estimate accretion masses. We find the most frequently chosen scenario to explain heavy element enhancement in Ba stars is a small amount of material ($\leq 0.2 M_\odot$) accreted onto a $\geq 2.3 M_\odot$ binary companion to a $2.50 M_\odot$ AGB star near the onset of core He burning. We compute mass-transfer efficiencies, and find overall agreement with the slow AGB wind regime. We also find scenarios with higher efficiencies, which may indicate other mass-transfer mechanisms.

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Solar abundances for nuclei beyond Sr: s, i or r element nucleosynthesis

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We provide an update on nucleosynthesis beyond strontium, utilizing the latest nuclear data for both the slow (s-process) and rapid (r-process) neutron capture processes. A significant portion of the r-process abundance distribution is associated with neutron star mergers (NSMs).
At the state of the art, precise observational constraints on their nucleosynthesis are not yet available, and the uncertainties on the models of r-processe abundances do not depend only on the knowledge of the astrophysical site where they occur, but also on the nuclear physics input.

We estimate the contributions from the r-process to Solar System abundances by adopting the largely site-independent waiting-point concept through a superposition of neutron density components normalized to the r-abundance peaks and the s-process contributions using recent models of asymptotic giant branch stars, acknowledging that uncertainties in these estimates are dominated by nuclear physics. The results from both approaches are critically compared to verify wether the (few) discrepancies revealed hint to an i-process contribution or can be solved by providing more precise nuclear physics input.

Beside the remaining challenges in the nucleosynthesis models, new measurements in ionized plasmas, particularly β-decays from unstable cesium isotopes, could help refine these estimates. For heavier nuclei, the situation is more complicated, as r-process progenitors are beyond current experimental reach and uncertain branching ratios influence the s-process. This particularly concerns nuclei with long half-lives in the lab, such as Lu-176 and Re-187, whose decay rates in stars are not well understood. New measurements for these isotopes are urgently needed.

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Exploring Neutron Capture Elements in Globular Clusters with the GALAH Survey

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Contrary to the traditional view of globular clusters as single stellar populations, some ancient star clusters exhibit remarkable diversity in their neutron capture process element abundances. The Galactic Archaeology with HERMES (GALAH) Survey provides detailed measurements of key neutron capture process elements, including Sr, Y, Zr, Mo, Ru, Ba, La, Ce, Nd, Sm, and Eu. Recent observational campaigns have expanded the number of globular cluster stars included in the survey, providing an opportunity to significantly enhance our understanding of these relics of the early Universe. In this talk, I will present the quantity, quality, and scientific potential of the globular cluster spectra obtained by the GALAH survey. I will also address critical caveats and limitations in interpreting GALAH-derived neutron capture element abundances, informed by insights from globular cluster analyses. Lastly, I will highlight ongoing efforts to investigate the third s-process peak in anomalous star clusters, focusing on lead (Pb) abundances, through high-resolution observations with the Magellan MIKE spectrograph.

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Correlation between nuclear capture rates and abundances in r-process nucleosynthesis

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Neutron star mergers eject dense neutron rich material which are understood to be the primary sites for the production of many of the heavy elements in the universe via rapid neutron capture process, the r-process. There are several competing processes and reactions that determine the amount of heavy nuclei produced during this process, including the cooling of the material, neutron captures, compound nucleus formation followed by gamma emission, beta decays when free neutrons become scarce, fission, and the complexities associated with forming nuclei away from stability in the form of favorable shell closures for nucleons. In this talk we will discuss our work on exploring the impact of correlation in nuclear reactions on astrophysical observations such as the abundance patterns and the heating rates. We investigate the impact of correlations in neutron capture rates which have not been studied in the past and conduct a reaction theory-consistent Monte Carlo study to assess the full impact of rate uncertainties.

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[Y/Mg] as a Stellar Chronometer: Combining Asteroseismic and Chemical Data

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The determination of stellar ages remains one of the greatest challenges in astrophysics, as age cannot be directly measured. Advances over the last decade highlight the great potential of chemical clocks, particularly abundance ratios involving s-process and α- elements to estimate stellar ages with improved precision. For a sample of ~200 stars observed with the high-resolution spectrograph and 1.65 m telescope at the Molėtai Astronomical Observatory in Lithuania, we determined Y and Mg abundances and derived new asteroseismic ages from TESS observations. Our results reveal a strong dependence of the [Y/Mg]-age relationship on the Galactic birthplaces of thin-disc stars, while confirming previous results on negligible correlations for thick-disc stars. This study highlights the importance of integrating chemical compositions, asteroseismic data, and precise astrometric measurements from Gaia to refine the applicability of chemical clocks and enhance our understanding of Galactic chemical evolution.

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The r, s, and p-process record in presolar grains

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The isotopic compositions of Sr, Zr, Mo, Ru, and Ba in presolar SiC and graphite have much to tell us about nucleosynthesis in stars. We highlight here two examples from recent simultaneous measurements on multiple elements in single presolar grains. (1) From their Mo and Ru isotopic compositions, the mainstream, Y-, and Z-type SiC grains have remarkably constant and solar-like ratios of *r*- to *p*-process isotopes, implying that their parental AGB stars had near-solar initial isotopic compositions. (2) Graphite grains contain Mo and Ru, but suffer from some solar system Mo contamination. Ruthenium, on the other hand, seems pristine. One Ru-rich area within a graphite grain has a more pure s-process component than any AGB star model is capable of producing in well-mixed envelope. This implies that grain formation around AGB stars can occur before the envelope is thoroughly mixed after a third dredge-up event. We will summarize recent data on heavy elements and the constraints they place on nucleosynthesis mechanisms.

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Neutron capture rates in the i and r process

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The rapid (r) and intermediate (i) neutron capture processes are critical for explaining the observed abundance patterns in stars. Both processes rely on neutron-capture rates, which remain largely unconstrained, experimentally.

For the i process, we report the first experimental constraint on the ^{139}Ba(n,γ)^{140}Ba reaction rate using radioactive ion beams (RIBs) from CARIBU at Argonne National Laboratory and the newly developed Shape method [1]. Our results reduce the dominant uncertainty in lanthanum production, a key i-process indicator, and confirm that elemental abundances in metal-poor stars are consistent with an i-process scenario at neutron densities of 10^{13} n/cm^3 [2].

For the r process, we present new measurements of neutron capture rates in neutron-rich Cs [3] isotopes, almost 10 neutrons away from the last stable Cs isotope, probing nucleosynthesis pathways "north-east" of the doubly magic Sn-132 nucleus. These data provide critical inputs for statistical Hauser-Feshbach models, enabling improved predictions of neutron-capture rates in this key r-process region.

Finally, we discuss ongoing efforts at RIB facilities such as TRIUMF (Canada) and FAIR (Germany) to further expand the experimental neutron-capture rate database for both the r and i processes.

[1] Muecher, Spyrou et al., Phys. Rev. C 107, L011602, 2023
[2] Spyrou, Muecher et al., Phys. Rev. Lett. 132, 202701, 2024
[3] Greaves, Muecher et al., in preparation

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New and precise data of the possible i-process star J094921.8-161722

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Several Carbon Enhanced Metal-Poor (CEMP) stars have been categorized as CEMP-rs, denoting that their spectra show overabundances both slow (s-) and rapid (r-) process elements. The nature of these stars is not yet explained, but hypotheses such as the "double pollution"and the intermediate (i-) process nucleosynthesis have been proposed. Two groups of authors have studied the stars GIU J190734.24-315102.1 and J094921.8-161722, and provided observation-based abundances that support the double pollution hypothesis. However, using the same observation-based data of J094921.8-161722, that shows a non-negligible enhancement of thorium, another group of researchers sup-

ported the possibility of the i-process to be the source of enrichment, invoking a parsimonious argument. Here we show element abundances, including Th and U, and Ba and Eu isotopic ratio determinations, from new ESO UVES spectra of optimal quality in the blue. Our approach is dedicated to re-derive stellar properties and abundances from revised methods that use state-of-the-art 3D NLTE and 1D NLTE models, which have been scrutinized and proven to minimize model and data processing biases. We discuss the compatibility with i-, and r- + s-process nucleosynthesis models. Further, we evaluate the possibility of dating the star based on cosmochronometry from Th and U.

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Galactic Chemical Evolution with r-process elements

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The origin of the heaviest elements is still a matter of debate. For the rapid neutron capture process (r-process), multiple sites have been proposed, e.g., neutron star mergers and (sub-classes) of supernovae. R -process elements have been measured in a large fraction of metal-poor stars. Galactic archaeology studies show that the r-process abundances among these stars vary by over 2 orders of magnitude. On the other hand, abundances in stars with solar-like metallicity do not differ greatly. While the large scatter at low metallicities might point to a rare production site, why is there barely any scatter at solar metallicities? In this talk, I will discuss chemical evolution scenarios that provide an explanation for the observed abundance features of r-process elements in our Galaxy, especially at the lowest metallicities. Further, I will explain how adding short lived radioisotopes to the model can help to further constrain the r-process and other processes, and explain why certain short lived radioisotopes arrive conjointly on Earth, even though they were produced at different nucleosynthesis sites.

83

Chemical clocks and their time zones: exploring the cosmic time evolution of [s/Mg] in the Milky Way

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A linear relation between [s/alpha] and age has been found for stars with near solar metallicity. However, this "chemical clock" relationship has been shown to be non-universal, with dependencies on metallicity and position in the Galaxy. Using a novel empirical technique for recovering stellar birth radii (Rbirth) in observations, I will show the cosmic time evolution of [Ce/Mg], [Ba/Mg], and [Y/Mg] for different birth radii using APOGEE DR17 and GALAH DR3 data. The age-[s/Mg] relation is strongly dependent on birth location in the Milky Way, with stars born in the inner disc having the weakest correlation. The non-universal relations of chemical clocks is caused by their fundamental trends with Rbirth over time, and suggest that the tight age-[s/Mg] relation obtained with solar-like stars is due to similar Rbirth for a given age.

84

Progress on opacity measurements in laboratory plasma trap relevant for Kilonovae signals

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Kilonovae (KNe) are promising electromagnetic signals arising from compact binary mergers, which offer to nuclear astrophysicists a unique window to study the heavy-element nucleosynthesis driven by the rapid neutron capture (r-process) nucleosynthesis predicted to occur in this astrophysical environment. Deeply heterogeneous post-merging ejecta composition of both light and heavy-r process nuclei, however, implies strong effects on the KNe light-curve due to the varying opacity of the system, yet hard to be fully addressed by theoretical models. In the framework of the PANDORA project at INFN-LNS, we present a first-of-its-kind design of experimental and computational activities, aiming at measuring the opacity of magneto-plasma under laboratory-controlled conditions resembling the astrophysical scenario for KNe propagation in ejecta, as being an unsolved key variable of the problem. In this view, the results of recently performed experiments at the INFN-LNS to reproduce stable early-stage ejecta thermodynamical conditions of under-dense and low-temperature plasmas are here reported, along with preliminary results on gaseous plasma opacity.

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Nuclear Beta-decays of highly ionized heavy atoms in stellar interiors: part II

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The compilation1 of the beta-decay rates, based on the method developed in PART I,2 has been extensively used for various s-process models. Given the advent of a sophisticated modeling of the s-process associated with the thermal pulse/inter-pulse and 3rd dredge-up phase in low-mass stars, and of a possibility of the s-processing in the core/shell carbon burning phase in massive stars, it may be worth improving the beta-decay formalism in PART I on some fronts: 1) updating nuclear input data (ft-values, Q-values), 2) estimating the possible errors in the computed rates, 3) extending the temperature- and density- domains, and 4) removing various approximations and inter-/extrapolations that were necessary in PART I because of the limited computational capabilities and budget (!). This contribution mainly concerns the item 3) & 4).

1 K. Takahashi & K. Yokoi, Atomic Data and Nuclear Data Tables 36, 375-409 (1987)
2 K. Takahashi & K. Yokoi, Nuclear Physics A404, 578-598 (1983)

86

Unveiling the Mystery of Technetium-Rich M Stars: Implications for AGB Evolution

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The technetium(Tc) -rich M stars reported in the literature (Little-Marenin & Little 1979; Uttenthaler et al. 2013; Shetye et al. 2022) are puzzling objects since no isotope of technetium has a half-life longer than a few million years, and 99Tc, the longest-lived isotope along the s-process path, is expected to be detected only in thermally-pulsing stars enriched with other s-process elements (like zirconium). The anomaly deepens as carbon enrichment is anticipated in tandem with zirconium, following each thermal pulse on the asymptotic giant branch (AGB). Surprisingly, the Tc-rich M stars lack significant zirconium enhancement (which would categorise them as S-type stars) and display no substantial carbon overabundance (which would label them as carbon stars).

In my talk, I'll present a systematic high-resolution study of a large sample of Tc-rich M stars. I'll delve into the spectral properties of these stars, and its comparison with those of Tc-rich S stars. Additionally, I'll present their s-process element abundance analysis, accompanied by a comparison of their location on the HR diagram with Tc-rich S-type stars. Lastly, I will discuss the role of Tc-rich M stars as the potential tracer of the onset of the third dredge-up.

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Nucleosynthetic Yields from realistic neutrino-driven explosions of core-collapse supernovae in 1D

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Core-collapse supernovae are one of the most important sources of heavy elements in the universe. Therefore, accurate modeling of the stellar evolution and the explosion phases are crucial to obtain accurate predictions of their nucleosynthetic signature. In this talk I will present results from nucleosynthesis calculations of realistic neutrino-driven supernova explosions in spherical symmetry. I will comment on the explosive nucleosynthesis, weak r-process component calculated with realistic neutrino spectra, as well as the contribution of the pre-supernova seeds to the final yields. As a representative example, I will discuss Ti44, a radioactive isotope that powers the late-time light curve of supernovae and whose abundance has been measured in several supernova remnants. I will discuss different production mechanisms both pre- and postcollapse as well as the potential impact of multi-dimensional effects on its final abundance.

88

Copper-hydrogen collisions and implications on the Galactic evolution of copper

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The astrophysical production sites of copper and its Galactic chemical evolution remain poorly understood. Reliable copper abundances in metal-poor stellar atmospheres can provide vital clues, but these measurements are prone to modeling uncertainties due to departures from local thermodynamic equilibrium (LTE). One of the largest sources of uncertainty in non-LTE modeling of copper arises from the cross-sections for inelastic collisions with hydrogen. To address this, we present new calculations for inelastic collisions between copper and hydrogen, using a combined Linear Combination of Atomic Orbitals (LCAO) and free electron model approach, which provides improved and extended rate coefficients for non-LTE models.

By applying non-LTE corrections to LTE copper abundances in stars from the literature, we find significant changes in the [Cu/Fe] trends. Our results reduce scatter in star-to-star and line-to-line abundances and resolve previous discrepancies between dwarfs and giants. Notably, we identify, for the first time, a potential upturn in [Cu/Fe] at low metallicity and a dip around [Fe/H] = -1.7, which may hint at a Pair Instability Supernova (PISN) signature. These findings shed new light on copper's cosmic origins and highlight its potential as a tracer of nucleosynthesis in the early Galaxy.

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Fluorine Abundances in Carbon Stars

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The fragile nature of the lone stable isotope of fluorine, 19 F, makes the light, odd-Z element fluorine a useful probe of the processes occurring in stellar interiors. Fluorine enhancements have been observed in asymptotic giant branch (AGB) stars, and the observed excess of fluorine in AGB stars relies heavily on measurements of stars with a C/O ratio of ~1. We determine the abundance of fluorine in ten Galactic carbon stars (3 N-type, 6 R-type, and 2 J-type) with C/O ratios greater than 1.1 using spectra obtained with the high-resolution spectrograph iSHELL (R~75,000) on the NASA Infrared Telescope Facility (IRTF). We compare the observed fluorine abundances to theoretical models and investigate the relation between fluorine abundance and s-process element enhancement in our sample stars.

90

Plasma-induced modification of β-decay rates relevant for the s-process

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The s-process nucleosynthesis pathway is governed by the competition between neutron capture rates and β-decay lifetimes of radioisotopes. The latter are susceptible to changes in atomic configuration of the parent and daughter ions and are consequently modified inside stellar plasmas due to the ion charge state distribution and level excitation. PANDORA is an upcoming facility at INFN-LNS which aims to use an electron cyclotron resonance ion source (ECRIS) as a compact magnetoplasma to measure plasma-induced variation of β-decay rates. We report here on upgrades in the theoretical modelling of in-plasma β-decay under different thermodynamic conditions, through the examples of orbital electron capture in 7Be and bound/continuum decay in 134Cs. The
results reaffirm the impact of the electronic configuration on the decay rate and improve upon the methodology of Takahashi-Yokoi by including finer atomic effects. Using a Particle-in-Cell Monte Carlo (PIC-MC) code to model ECRIS dynamics, we extend the analysis to a realistic laboratory plasma and demonstrate expected spatial gradients of isotope decay rates in the plasma chamber.

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Chemical evolution of neutron-capture elements

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The field of chemical evolution of galaxies is key to understanding the origin and distribution of neutron-capture elements, able to provide insights into the astrophysical sites responsible for heavy-element nucleosynthesis, as well as the mechanisms that govern their dispersal throughout galaxies. In this review talk, I will present both past and recent advancements in this field. By integrating observational constraints from metal-poor stars, Galactic and extragalactic surveys, and theoretical nucleosynthesis models, I will discuss the relative contributions of different astrophysical sites to the enrichment history of heavy elements. While the s-process is generally associated with asymptotic giant branch stars and rotating massive stars, the astrophysical origin of the r-process is still debated. Neutron star mergers are considered a key site for producing heavy neutron-capture elements, but their long merger timescales and low observed rates raise questions about whether they alone can explain r-process enrichment in galaxies. Some rare classes of core-collapse supernovae, such as magneto-rotational supernovae or collapsars, have been proposed as additional sources, though their role remains uncertain. By comparing state-of-the-art Galactic Chemical Evolution models

with observational data, in this talk I will highlight key uncertainties (including the timescales and relative contributions of different nucleosynthesis sites) and future directions in the field, providing a comprehensive perspective on how neutron-capture elements shape the chemical evolution of the Universe.

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Theory of the intermediate neutron capture process (i-process)

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Despite considerable progresses during the last decades, the origin of the elements heavier than iron is not yet fully understood. In addition to the slow (s) and rapid (r) neutron capture processes, an intermediate neutron capture process (i-process) is thought to exist at neutron densities intermediate between the s- and r-processes. The astrophysical site(s) hosting the i-process is (are) actively debated. In this presentation, I will review the current understanding of the i-process and focus on its development in various sites. I will emphasize the unique chemical signature of the i-process, including the production of actinides, address nuclear uncertainties, and compare model predictions with observations of chemically peculiar stars and pre-solar grains.

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Neutron Capture Nucleosynthesis In Asymptotic Giant Branch Stars

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This paper presents a general review of the Asymptotic Giant Branch
(AGB) evolutionary stages for Low and Intermediate Mass Stars and of the
nucleosynthesis processes occurring in them, chiefly as a consequence of the activation, in their final phases, of two crucial neutron-releasing reactions, 13 C(a,n) 16 O and 22 Ne(a,n) 25 Mg. These are jointly responsible for the production of most of the heavy nuclei generated through slow neutron captures, i.e. the so-called s-process, where neutron additions on unstable isotopes close to valley of beta-stability occur on average less effectively than the corresponding weak interactions (mainly b - decays). In particular, AGB stars are recognized to produce almost entirely s-process nuclei in the range from A ~ 85 (Kr, Rb, Sr) to A ~ 208-209 (Pb, Bi), i.e. the so-called Main Component of the s-process, as observed in our Galaxy, together with variable contributions to lighter species. As this field has been active now for almost 70 years and has seen the gradual development of our knowledge of the basic nuclear mechanisms and the parallel growth in our understanding of the stellar models for those advanced evolutionary stages, part of this review is dedicated to the historical progresses in these fields.
More modern approaches encountered significant difficulties, hampered as they
were by our poor understanding of stellar (especially non-convective) mixing
mechanisms. This peculiarity will require therefore some a non-marginal mention.
Decisive improvements finally came jointly by gradually more precise
observational constraints and by increasing accuracy in the determination of neutron
capture cross sections. They both induced the understanding of 13 C(a, n) 16 O as the
dominant neutron releasing reaction for the production of heavy s-nuclei. I then
proceed to account for (some) contributions coming from various research groups to
the improvements of the present century, both on mixing mechanisms and on less-
widely parameterized approaches, which now seem to yield a rather comprehensive
view of the subject and to the establishment of the first credible constrains on the r-
(and possibly i-) processes, complementing the synthesis of heavy nuclei.

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Tracing the Origins of Elements: Insights from AGB and Post-AGB Stars

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Low- and intermediate-mass (LIM) stars are fundamental to the Universe's chemical evolution, yet their element production remains poorly understood. Recent observations of post-AGB stars reveal striking chemical diversity—some exhibit strong carbon and s-process enrichment, while others show no trace of these elements. Binary interactions further complicate this picture, with most post-AGB binaries displaying photospheric chemical depletion, though recent discoveries challenge this trend. This diversity has profound implications for Galactic Chemical Enrichment models, which rely on theoretical stellar yields to trace the origins of elements. In this talk, I will present insights from multi-wavelength observations of post-AGB stars and advanced modelling to unravel this chemical diversity, highlighting recent advances and critical gaps in our understanding of LIM stars' contributions to the cosmic chemical budget.

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The weak s-process production in massive stars: theory, uncertainties and comparison with observations

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The abundances in the Solar System are the result of the contributions from many generations of stars. Beyond the Fe-group elements, about half of the abundances were made by the slow neutron-capture process, or s-process. Stars with initial mass of the order of 9 solar masses or larger contributed a relevant fraction of the s-process elements between Fe (Z=26) and Zr (Z=40), with free neutrons mostly provided by the alpha-capture reaction on Ne22. The predictions from computational simulation of the s-process in these stars are strongly affected by nuclear and stellar uncertainties. Therefore, after decades of research, the solar s-process abundance pattern of these elements remains uncertain. In this presentation I will discuss current challenges for s-process nucleosynthesis simulations in massive stars, the main uncertainties and available observations to benchmark stellar models.

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A Black Hole and Its Metal-Poor Companion: A Full Chemical Analysis of the Red Giant in Gaia BH3

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Gaia BH3 is the third black hole that was discovered with in the early data release in Gaia DR4 due to the astrometric implication of a ~33 solar mass companion of a red giant. This red giant companion is an old metal-poor star that is likely a part of the Sequoia halo substructure. The possible production mechanisms for this binary system and the initial detection of Eu in this star (Gaia Collaboration et al. 2024) made this red giant companion a prime target to follow-up. Here we present a full chemical abundance analysis of the red giant companion in Gaia BH3 with ~40 hours of observations on the Tull Coudé Spectrograph on the 2.7 Harlan J. Smith Telescope at McDonald Observatory. We confirm the presence of neutron capture elements as well as the detection of Li. We attempt to use the r-process elements detected in this red giant to place an age on this system. The presence of these heavy elements in this ~33 solar mass black-hole and red giant binary has implications about the formation of this peculiar system and can help us constrain the environments that produce neutron-capture elements. These observations lay the groundwork for heavy element chemical analysis for subsequent black-hole and stellar binaries that will likely be found in Gaia DR4.

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The quest for r-process cosmic forges

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Despite the first direct evidence of r-process nucleosynthesis occurring in the merger of two neutron stars, the problem of the presence of one or more sites where the r-process can proceed is not settled. Depending on the merger rate and on the average ejecta amount, mergers involving neutron stars could explain the bulk of the r-process elements in the Galaxy. However, metal poor stars and galactic chemical evolution seem to require other sites in addition to compact binary mergers, especially due to the presence of heavy elements at very low metallicity. In this talk, I will review the astrophysical sites where r-process nucleosynthesis can occur, with a special emphasis on compact binaries and special classes of supernovae, focusing on their possible diversity.

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Measurements of the s process neutron sources

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The reactions 13C(a,n)16O and 22Ne(a,n)25Mg are the neutron sources for the main and (the latter) the weak s process. Their cross sections need to be known at very low energies to provide for reliable astrophysical reaction rates in the s process energy windows. In the recent years there has been a world wide effort to both directly and indirectly measure these cross sections at low energies, at experimental facilities on the surface of the earth as well as deep underground. In this talk we will gave a status update on our knowledge and the measurement of these two crucial reactions for astrophysics.

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Observations of r-process enriched stars

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About half the elements heavier than iron in the Universe, like silver and gold, are created in the rapid neutron-capture (r-)process. However, today, almost 70 years after the theoretical prediction of this process, it is still highly debated in what type of stellar explosions it can take place. One of the best places to search for answers is in ancient, metal-poor stars formed from the enriched gas. Their chemical makeup is like a time capsule, a direct fingerprint of the elements produced by the stellar generations that came before them. Since the first r-process enhanced star, CS-22892-052 was discovered more than 30 years ago, multiple projects like the Hamburg/ESO R-process enhanced star survey (HERES), Chemical Evolution of R-process Elements in Stars (CERES), and the R-Process Alliance (RPA) have searched for more r-process enriched stars in the Milky Way. At the same time, numerous r-process enriched stars have been discovered in stellar streams and dwarf galaxies. This

talk focuses on recent advances in finding r-process enriched metal-poor stars and what the detailed chemo-dynamical analysis of these stars can tell us about heavy element nucleosynthesis and the astrophysical site(s) of the r-process.

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Neutron capture reactions for the astrophysical i process

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The astrophysical i process has been proposed to explain astronomical observations that could not be explained by the traditional s and r processes. It involves nuclei that are a few steps from stability where the main missing piece of information from the nuclear physics side is neutron-capture reaction rates. In this talk I will present an experimental program that aims at constraining important neutron-capture reactions for the astrophysical i process. I will focus on the mass 90 and 140 regions, where stellar observations show sensitivity to model parameters and nuclear physics inputs. The measurements of the relevant reactions took place at the CARIBU facility at Argonne National Lab using the SuN detector. The β-Oslo method was used to extract the
nuclear level density and the γ ray strength function, which were used to constrain the relevant neutron capture reaction rates. The impact of the experimental results on the astrophysical i process will be discussed.

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Nuclear weak-interaction processes in stars

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Nuclear weak-interaction processes play an important role in nucleosynthesis processes and late-stages of the evolution of stars. These processes are often modified due to the temperature and density conditions of the environment allowing for the appearance of novel decay channels normally not found under laboratory conditions. At the moderate conditions at which the s-process operates in AGB stars atoms are partially ionized making necessary to consider both atomic and nuclear corrections to the processes. An important example is 205Tl that decays by bound-beta decay to 205Pb under stellar conditions. The evolution of the core of AGB stars is again determined by weak processes that lead phases with URCA cycles and double electron capture processes. Typically in all these cases weak processes are determined by only a few nuclear transitions whose strength should be determined experimentally whenever possible.

Weak processes are also fundamental to determine the collapse and explosion of massive stars. Electron capture processes operating in nuclei determine the collapse dynamics. However, differently to low and intermediate mass stars, they operate in a broad range of nuclei excited to rather high temperatures making an experimental determination challenging. As the density increases neutrino matter interactions become more and more important being fundamental to determine the supernova explosion.

Neutrino-nucleus reactions are also important for the nucleosynthesis of heavy nuclei. I will introduce a new nucleosynthesis process, the νr-process, that operates in ejecta subject to very strong neutrino fluxes producing p-nuclei starting from neutron-rich nuclei. It may solve a long standing problem related to the production of 92Mo and the presence of long-lived 92Nb in the early solar system.

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Nuclear theory and r-process observables

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The nucleosynthetic pathway of the rapid neutron capture process (r-process) proceeds far to the neutron-rich side of the valley of beta stability. Particularly for the heaviest species, this region of the nuclear chart lies well past where current rare isotope facilities have so far been able to reach. Thus simulations of the r-process rely on nuclear theory for key nuclear properties including masses and fission rates and yields. In this review talk, we will examine the role played by these nuclear properties in shaping r-process observables such as abundance patterns and electromagnetic signatures.

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Kilonova modeling

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Kilonovae are optical-IR transients powered by radioactive decay of r-process elements produced in neutron star merger ejecta. The nature of r-process elements is imprinted in kilonova light curves and spectra. In this talk, I review kilonova light curve modelings, opacity of heavy elements, and nebular emission. In addition, I will talk about what we learned from the first neutron star merger, GW170817 and the JWST observations of a kilonova candidate associated with a long GRB 230307A, and open issues.

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Signatures of Heavy Element Nucleosynthesis in Presolar Grains

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Presolar grains condensed around ancient dying stars that contributed dust from which our Solar System was made. Discovered in the 1980's, these sub-micron to tens of microns-sized pieces of dust are identified on the basis of their highly anomalous isotopic compositions, compared to that of objects that formed in the Solar System. The isotopic analysis of presolar grains in the laboratory provide a unique opportunity to understand the nucleosynthesis reactions that occur in stars and other stellar processes.
Multielement isotope data on individual presolar grains yield tight constraints on various parameters that are used in nucleosynthesis model calculations, such as, nuclear reaction rates etc. Traditionally, light element (C, N, O, Si, Mg-Al, K-Ca, Ti, Fe) isotopes have been used to determine the stellar origins of presolar grains and to classify them. The new generation resonance ionization mass spectrometers that have higher useful yields and improved precision allow us to carry out coordinated heavy element (Ni, Sr, Zr, Mo, Ru, Ba) isotope measurements in presolar grains, on which light element isotope data can also be obtained. The majority of presolar grains studied to date provide evidence that they condensed in either asymptotic giant branch (AGB) stars or core collapse supernovae. A small fraction of grains exhibits signatures that indicate they might originate in novae, born-again AGB stars, J-type stars, and other rare stellar objects. The capability of measuring light and heavy element isotopes in individual presolar grains provides an unprecedented opportunity to understand the various neutron capture processes in the stellar sites that produce heavy elements.

This review will discuss the important results that have stemmed from such coordinated light & heavy element isotopic studies of presolar grains.

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From Stars to the Laboratory: Exploring the (weak) r-Process with Nuclear Reactions

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Stellar explosions and colliding neutron stars are significant sources of the chemical elements found in nature. While some astrophysical processes responsible for element creation are well-understood, others, like the rapid neutron capture process (r-process), remain challenging to study. These nucleosynthesis processes often involve reactions on short-lived radioactive isotopes, which can now be produced and studied at accelerator facilities. By measuring charged-particle reactions relevant to the r-process, we can better constrain nuclear reaction rates and properties, allowing laboratory insights into how elements are forged in the cosmos. Breakthroughs in astronomical observations highlight the need for complementary advancements in nuclear experiments on rare isotopes. I will discuss the essential role that charged-particle reactions play in understanding stellar explosions, showcase recent experimental achievements, and offer an outlook on future nuclear astrophysics research, particularly as it relates to the weak r-process.

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Direct neutron capture experiments on stable and unstable isotopes

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Neutron-capture reactions drive the formation of elements heavier than iron, occurring through both the slow (s-) process in low-mass AGB and massive stars, and the rapid (r-) process in explosive stellar environments. Recently, the more exotic i-process, which involves higher neutron densities and more exotic nuclei than the s-process, is also gaining great interest.
For stable nuclei heavier than iron almost all neutrons capture cross sections at s-process temperatures have been determined. However, for cases such as the s-process bottlenecks, located at neutron shell closures, the neutron capture cross sections should be measured with improved accuracies since they directly impact the width and height of the abundance peak at these mass numbers. On the other hand, unstable isotopes acting as branching points of the s-process, offer crucial information about the physical conditions of stellar nucleosynthesis. Neutron-capture measurements on radioactive isotopes, in combination with stellar spectroscopy and isotopic analyses of primitive meteorites, can help to better understand the role of stellar mass, rotation or metallicity and to refine further our understanding of galactic chemical evolution.
One of the best suited methods to measure neutron capture (n,γ) cross sections over the full stellar range of interest is the time-of-flight (TOF) technique. However, TOF neutron capture measurements on unstable isotopes are still very challenging due to the limited mass (~mg) available and the high experimental background arising from the sample activity. The situation has improved in recent years with the combination of facilities with high instantaneous flux, such as the n_TOF-EAR2 facility, with detection systems with an enhanced detection sensitivity and high counting rate capabilities. In this context, this
contribution will present an overview of key s-process isotopes measured at the CERN neutron Time-of-Flight (n_TOF) facility over the years and their astrophysical significance and will show how recent improvements on the neutron-beam facility and state-of-the-art detector developments have led to significant advances on the measurement of radioactive nuclei.
Despite the significant breakthroughs, the TOF technique still presents limitations concerning unstable isotopes with short half-lives (smaller than a few years), restricted neutron energy ranges

(beyond a few keV), and attainable accuracy. In this context, complementing the TOF technique with activation measurements in a quasi-stellar beam, when feasible, may deliver complementary and more accurate information on a specific cross section. Moreover, the unsurpassed sensitivity of activation measurement opens the door to first-time measurements on much smaller sample quantities. Following this logic, n_TOF has recently deployed the new high-flux n_TOF-NEAR activation station. In this line, the contribution will review some of the recent advances and ambitious future projects for direct neutron capture measurements at CERN and in other facilities which will help to push the boundaries of neutron-capture measurements, overcoming current limitations and helping to unlock new frontiers in our understanding of stellar nucleosynthesis.

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Low-mass carbon-enhanced metal-poor thermally pulsing AGB star HD112869

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Some regimes of AGB evolution have not yet been studied in sufficient detail. These include the AGB stars with extremely low metallicity. This poster presents the results of contemporaneous radial velocity monitoring, broadband BVR photometry, and high-resolution spectroscopy for metal-poor star HD112869. The radial-velocity monitoring shows semiregular variations with a peak-to-peak amplitude of about 10 km/s and a dominating period of ~ 114.9 days. The velocity variations are accompanied by light and colour variations those are shifted in phase relative to the velocity curve. The reason for the velocity, light, and colour variations is obviously the pulsations in the atmosphere of HD112869. The iron abundance was found to be low in the atmosphere of HD112869, [Fe/H] = -2.3 ± 0.2 dex, on the basis of ionized lines that are almost free from NLTE effects. The carbon abundance was found to be high, log ε (C) = 8.3 ± 0.1 dex. With the adopted oxygen abundance, [O/Fe] = +0.8 dex, the carbon to-oxygen ratio was found to be very high, C/O ~ 12.6. The isotopic lines of C 2 and CN molecules are too weak to be detected in the crowded spectrum, and the lower limit of isotopic ratio was found to be extremely high, 12 C/ 13 C > 1500. The s-process elements Sr, Y, and Ba are not enhanced significantly. However, the Nd, La, Sm abundance seems to be enhanced relative to iron. The upper limit for the r-process element Eu was set, [Eu/Fe] ≤ +0.8 dex. A carbon-to-oxygen ratio above 1, a high luminosity, and pulsation instability are typical features of cool evolved AGB and post-AGB stars. During thermal pulses the photospheric C/O ratio can exceed 10. According to the current data, HD112869 seems to be a single metal-poor low-mass TP-AGB star.