Abstracts of the conference

# Nuclear Physics in Astrophysics IX

September 15-20, 2019

Castle Waldthausen, Mainz/Frankfurt area, Germany

# Exploring Stars from Deep Underground: Status and Perspectives at LUNA

Marialuisa Aliotta[1] and the LUNA Collaboration[2]

[1]*SUPA, School of Physics and Astrophysics,*
*Peter Guthrie Tait Road, Edinburgh EH9 3FD, United Kingdom*
[2]*https://luna.lngs.infn.it*

For almost three decades, the Laboratory for Underground Nuclear Astrophysics (LUNA) under the Gran Sasso mountain in Italy has provided the ideal site for pioneering measurements of key nuclear reactions for astrophysics. Here, experimental studies of hydrogen burning reactions in the pp-chain, the CNO cycles, and NeNa-MgAl cycles have led to major advances in our understanding of nucleosynthesis processes in various environments, from the Big Bang, to our Sun, to Asymptotic Giant Branch stars and classical novae (see [1] for a recent review). Now, a new phase has just begun devoted to the study of helium burning processes, with the investigation of the $^{13}$C($\alpha$,n)$^{16}$O and the $^{22}$Ne($\alpha,\gamma$)$^{26}$Mg reactions currently underway.

In this talk, I will review some recent results obtained by the LUNA Collaboration and present exciting opportunities that will soon open up with the installation of a new 3.5MV accelerator underground.

[1] C. Broggini *et al.*, Progress in Particle and Nuclear Physics 98 (2018) 55-84.

# Indirect, experimental constraints of $(n, \gamma)$ reaction rates for the $i$- and $r$-process

Ann-Cecilie Larsen,[1] Artemis Spyrou,[2,3,4] Magne Guttormsen,[1] and Sean N. Liddick[2,5]

[1] *Department of Physics, University of Oslo, Oslo, Norway*

[2] *NSCL, Michigan State University, East Lansing, USA*

[3] *Department of Physics and Astronomy, Michigan State University, USA*

[4] *JINA-CEE, Michigan State University, USA*

[5] *Department of Chemistry, Michigan State University, USA*

The element distribution we observe in the Universe, and in particular the diverse abundances of atomic nuclei, tells a fascinating story of nucleosynthesis events that have taken place throughout the 13.7-billion-year-long history starting with the Big Bang. Since the groundbreaking works of Burbidge, Burbidge, Fowler and Hoyle [1] and Cameron [2], it is known that radiative neutron-capture reactions play a major role in synthesizing elements heavier than iron. However, many questions remain when it comes to our understanding of neutron-capture processes in various stellar environments. In this respect, the intermediate and rapid neutron-capture processes are perhaps the most challenging to describe, as they involve neutron-rich nuclei for which there exist little or no data on the much-needed neutron-capture rates. In this contribution, possibilities to obtain indirect, experimental constraints of these rates by means of the Oslo method and the beta-Oslo method will be discussed [3].

[1] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).

[2] A. G. W. Cameron, Pub. Astron. Soc. Pac. **69**, 201 (1957).

[3] A. C. Larsen, A. Spyrou, S. N. Liddick, and M. Guttormsen, Prog. Part. Nucl. Phys. (2019). doi:https://doi.org/10.1016/j.ppnp.2019.04.002

# High Precision Mass Measurements of Nuclei and the Neutron Star Merger

Ani Aprahamian[1,2]

[1] *University of Notre Dame, Notre Dame, IN, USA*

[2] *Alikhanyan National Laboratory of Armenia, Yerevan, Armenia*

The origin of the synthesis of the heavy elements from Fe to U have emerged as important questions in all of physics for this century. Most of the elements above Fe in the periodic table are thought to have been produced by either the slow (s-process) or rapid (r-process) capture of neutrons in astrophysical environments. The s-process proceeds close to stability and astrophysical sites have been identified, while the r-process allows the production of nuclei much further from stability and potential sites remain mostly unresolved.

The recent observation of gravitational waves from two neutron star mergers simultaneously with the spectroscopy indicated that rare earth elements were made in this kilo nova event. The questions remain, are there enough such mergers? are mergers the only source of r-process elements ? How can precision mass measurements contribute to the discussion?

I will discuss some of our new results from the measurements of neutron rich nuclear masses and their implications towards a better understanding of the r-process and the synthesis of the heavy elements.

Invited contribution

# The Origin of the Elements from Nuclear Physics to Galaxy-Scale Simulations

Benoit Côté[1,2]

[1]*Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Konkoly Thege Miklos ut 15-17, H-1121 Budapest, Hungary*

[2]*Joint Institute for Nuclear AstrophysicsCenter for the Evolution of the Elements, USA*

Following the evolution of chemical elements across cosmic time is a multidisciplinary challenge that involves nuclear physics, stellar evolution, galaxy evolution, and cosmology. Observations, experiments, and theories need to work together in order to build a comprehensive understanding of how the chemical elements synthesized in astronomical events are spread inside and around galaxies and recycled into new generations of stars. In this talk, I will present our efforts to create permanent connections between the different fields of research involved in the process of chemical evolution. In particular, I will highlight the impact of nuclear physics and galaxy evolution uncertainties on our interpretation of the origin of the elements and isotopes. To do so, I will discuss a variety of topics including the r-process and gravitational waves, the i-process and the Solar composition, and the radioactive composition of the early Solar System, as inferred from meteorite data analysis.

# Stable beam experiments in wide energy ranges serving low energy nuclear astrophysics

Gy. Gyürky[1]

[1] *Institute for Nuclear Research (Atomki), Debrecen, Hungary*

(Dated: June 7, 2019)

It is common knowledge in nuclear astrophysics that reaction cross section measurements need to be carried out at energies as low as possible, ideally reaching the astrophysically relevant energies. This latter requirement is unfortunately fulfilled only very rarely, therefore the rates of reactions are obtained from extrapolated or calculated cross sections. The extrapolation definitely needs higher energy cross sections but the validity of calculations should also be supported by experimental data at higher energies where the measurements are possible. This is especially true in the present era of high precision astrophysics when the reaction rate uncertainties often represent the most important uncertainty in stellar models.

In this talk I will use several examples for demonstrating the usefulness of cross section measurements of alpha- and proton-induced reactions in wide energy ranges above the astrophysically relevant ones. The examples will include reactions of hydrogen burning as well as of heavy element nucleosynthesis in the p-process studied recently in Atomki. The benefits of the activation method [1], a powerful technique for cross section measurements, will also be highlighted.

---

[1] Gy. Gyürky et al., Eur. Phys. J. A **55**, 41 (2019).

# Traces of the early Universe from metal-poor stars

Camilla Juul Hansen[1]

[1]*MPIA, Heidelberg*

The elements locked up in old, metal-poor stars carry a wealth of information on the properties of the early Universe and how it evolved. Stellar abundances are fossil records of the physical conditions in the interstellar medium and of the progenitors that created the material the low-mass stars formed from. All heavy elements show a large star-to-star abundance scatter at low metallicities, which typically hides the fact that several processes and formation sites at early times created different amounts of a given element of under different conditions. Using stellar abundances, we can explore the neutron-capture processes and learn about the origin of the heavy elements from a number of formation sites that host these processes. I will discuss two groups of old metal-poor stars in which we have explored the behaviour of a large number of heavy elements, namely the Carbon Enhanced Metal-Poor (CEMP) stars and old halo stars belonging to the Sagittarius stream, in which we have detected thorium. In the latter case we found indications of early massive star enrichment in contrast with previous literature studies.

# Recent experimental progress for measurements of reaction rates involving radioactive nuclei

Christoph Langer[1]

[1] *Goethe University, Frankfurt am Main*

Many astrophysical scenarios include reactions on radioactive short-lived nuclei, such as the rapid proton-capture process during X-ray bursts and the $\gamma$-process. It is still a challenge to constrain these reaction rates, that might have an impact on the output of the overall process. This also involves reactions on nuclei that have short-lived isomeric states, which is of potential relevance also for the s process. To overcome this problem, new techniques and experimental approaches need to be developed, e.g. by using surrogate reactions as an indirect measurement, as well as using heavy-ion storage rings for direct reaction studies.

This talk will give an overview of recent experimental progress and results of astrophysically relevant reactions studies like e.g. the important $^{23}$Al(p,$\gamma$) reaction rate important for X-ray bursts.

# Meteoritic Stardust Grains

Maria Lugaro[1]

[1] *Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Konkoly Thege Miklos ut 15-17, H-1121 Budapest, Hungary*

Stardust grains represented a significant fraction (∼10%) of the the original inventory of interstellar medium dust carrying most of the metals into the early Solar System. These grains were distinguished from the rest of the dust by their anomalous isotopic compositions, reflecting the signature of nucleosynthesis in their astrophysical site of origin. These anomalies also allow us today to recognise these grains and extract them from primitive meteorites. The vast majority of recovered stardust originated in AGB stars, and the most studied, the mainstream SiC grains, came from C-rich AGB stars of metallicity roughly twice than solar. Thermal processing of dust by the young Sun resulted in this SiC stardust leaving its signature in different Solar System bodies in terms of variations in the abundances of isotopes produced by the *s* process in AGB stars. For example, it is now well established that the Earth is *s*-process rich, relative to bodies that formed further away from the Sun. Some stardust grains originated from core-collapse supernovae and left their signatures in the protoplanetary disk by producing two different reservoirs: one enriched and one depleted in supernova dust, which were separated by the formation of Jupiter. However, the relationship between the composition of the supernova-enriched reservoir and that of the fraction of supernova stardust extracted from meteorites is not straightforward and further efforts are required to understand the origin of the observed dichotomy.

Invited contribution

# Mapping the Nuclear Mass Surface

Zach Meisel[1]

[1] *Institute of Nuclear & Particle Physics,*

*Department of Physics & Astronomy,*

*Ohio University, Athens, OH, 45701 USA*

Nuclear masses play a central role in nuclear astrophysics, significantly impacting the origin of the elements and observables used to constrain ultradense matter. A variety of techniques are available to meet this need, varying in their emphasis on precision and reach from stability. I will discuss recent advances in nuclear mass measurement techniques that push the frontiers of precision and exoticity, including examples which significantly impact the results and interpretation of astrophysical model calculations.

# Neutron capture and beta-decay rates under stellar conditions: theoretical approaches and perspectives for their experimental determination

Alberto Mengoni[1]

[1]*ENEA, Bologna and INFN, Sezione di Bologna, ITALY*

Under stellar conditions, nuclear reaction rates are different from those measured in laboratory. A notable example of this situation is the stellar rate for neutron capture, when nuclear excited states are thermally populated. Capture can then proceed not only for nuclei in their ground states, but also from nuclear excited states. While, the composite nucleus of a capture process is the same, different excited compound states can be populated from different target nuclear states with different spin and parity. In addition, inelastic scattering channels can be open for these states, in which the neutron is scattered out with kinetic energy higher than kinetic energy of the entrance channel (the so-called super-elastic scattering).

An additional example of the modification of stellar rates with respect to laboratory rates is provided by the beta decay. Here, the different degree of ionization of the nuclei involved imply a modification of the phase-space factor in the decay probability. In addition, here again, excited parent decaying states can be populated in a stellar plasma and additional transitions, with different degrees of forbidness, become possible. A dramatic change in the beta-decay rates under stellar conditions have been predicted and observed in a number of cases.

A review of these two rates evaluations, from the theoretical point of view as well as from the perspectives of their experimental determination will be presented with some relevant examples for both, neutron capture and beta-decay processes.

# Nucleosynthesis in Multi-Dimensional Core-Collapse Supernova Explosion Models

Bernhard Müller[1]

[1]*School of Physics and Astronomy, Monash University, Clayton, Australia*

Over the last few years, multi-dimensional simulations of core-collapse supernovae (CCSNe) have become sufficiently mature to study the nucleosynthesis in the innermost CCSN ejecta using self-consistent models. In particular, we already have quite robust explosion models for the low-mass end of the progenitor spectrum, namely for super-AGB progenitors and the lightest iron-core progenitors, which explode readily by the neutrino-driven mechanism with generically low explosion energies of 0.1Bethe and small nickel masses of a few 0.001 solar masses. Multi-dimensional simulations of these events have shown that convective overturn shortly after the onset of the explosion leads to the ejection of neutron-rich bubbles with interesting nucleosynthesis outcomes, notably high production factors for light trans-iron elements from zinc up to strontium and zirconium. Sizeable amounts of $^{48}$Ca and $^{60}$Fe are also produced in the neutron-rich bubbles. Variations in the electron fraction in these neutrino-processed bubbles, for example by a global asymmetry in the electron neutrino and antineutrino fluxes known as LESA ("Lepton-number Emission Self-sustained Asymmetry"), could even lead to a "weak r-process" in the ejecta from these events. By contrast, the innermost ejecta in more massive stars are more proton-rich according to recent simulations. Few trans-iron elements are made in the early neutrino-processed ejecta aside from some light p-nuclei, although more substantial $\nu p$-process nucleosynthesis can occur later during the neutrino-driven wind phase.

# Theory advances in reactions relevant for astrophysics

F.M. Nunes[1]

[1] *National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824*

Indirect reaction techniques is very important in astrophysics as they provide information that are complementary to direct measurements or that otherwise cannot be obtained directly. It is then critical to have a reliable reaction theory that can connect the reaction measurement with the astrophysical information desired. This is a brief report on the progress made in the theory for transfer reactions when used to determine neutron capture rates for r-process and rp-process nuclei. We first discuss the different types of experiments and their connection to astrophysics. An overview of the current status of the theory will be provided, with emphasis on several recent theory developments, including transfer to continuum, the improvement of the optical potential and uncertainty quantification. Applications to a couple of neutron rich and proton rich cases will be discussed.

# The slow neutron capture process in stars

Marco Pignatari[1,2,3,4] and NuGrid collaborators[4]

[1]*E.A. Milne Centre for Astrophysics, Dept of Physics & Mathematics, University of Hull, HU6 7RX, United Kingdom*

[2]*Konkoly Observatory, Hungarian Academy of Sciences, Konkoly Thege Miklos ut 15-17, H-1121 Budapest, Hungary*

[3]*Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements, USA*

[4]*The NuGrid collaboration, http://www.nugridstars.org*

The s process is responsible for the production of about half of the solar abundances beyond iron, and its products can be directly observed in different types of stars at different metallicities. Clear isotopic patterns enriched in s-process can be also measured in presolar grains found in meteorites, as made by the stellar conditions and nucleosynthesis of their parent stars. Thanks to this extensive source of observational data, stellar simulations and galactical chemical evolution allow to test the physics used in theoretical stellar models, and the nuclear data relevant for the s-process nucleosynthesis. In this contribution I provide an overview of the s-process nucleosynthesis in different types of stars, discussing recent results and present challenges that need to be addressed.

Invited contribution

# r-process nucleosynthesis and binary neutron star mergers

Tsvi Piran[1]

[1] *Racah Institute for Physics, The Hebrew University, Jerusalem, Israel*

# The nuclear chart and equation of state from nuclear forces

Achim Schwenk[1,2,3]

[1] *Institut für Kernphysik, Technische Universität Darmstadt*

[2] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH*

[3] *Max-Planck-Institut für Kernphysik, Heidelberg*

This talk will discuss ab initio calculations of the nuclear chart and predictions for the drip lines from light through medium-mass nuclei. Starting from a chiral two- and three-nucleon interaction with good saturation properties, we have calculated ground-state and separation energies for all nuclei from helium to iron, nearly 700 in total. From a systematic comparison, we find that the deviation of separation energies from experiment yields an approximately Gaussian distribution. We use this to provide theoretical uncertainties for our ab initio calculations towards the drip lines. Where the drip lines are known experimentally, our predictions are consistent within the estimated uncertainty. For the neutron-rich fluorine to titanium isotopes, we provide predictions to be tested at rare-isotope beam facilities. This work demonstrates that ab initio calculations are advancing to global theories. In the second part of this talk, we will discuss ab initio calculations of the nuclear equation of state based on the same chiral effective field theory interactions, with a focus on constraints for neutron star properties, thermal effects on the equation of state, and comparisons to astrophysical observations.

This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Projektnummer 279384907 – SFB 1245, the BMBF under Contract No. 05P18RDFN1, and the Max-Planck Society.

# Merger of neutron-star binaries

Masaru Shibata[1]

[1] *Max Planck Institute for Gravitational Physics at Potsdam and Yukawa Institute for Theoretical Physics, Kyoto University*

Mergers of neutron-star binaries (binary neutron stars and black hole-neutron star binaries) are among the promising sources for ground-based gravitational wave detectors. They are also a promising site for nucleosynthesis of heavy elements and an invaluable experimental field for high-density nuclear matter. I will talk on our current understanding on the process of the neutron-star mergers, emphasizing the mass ejection processes, the resulting electromagnetic counterparts, and r-process nucleosynthesis.

# Kilonova: Electromagnetic Signature of r-process Nucleosynthesis

Masaomi Tanaka[1]

[1]*Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan*

The first gravitational wave observation from a neutron star merger was successfully made for GW170817. The detection triggered electromagnetic wave observations over the entire wavelength range, which enabled the first identification of an electromagnetic counterpart of a gravitaional wave source. In the ultraviolet, optical, and infrared wavelengths, the counterpart shows characteristic properties of "kilonova", electromagnetic emission powered by radioactive decays of newly synthesized r-process elements.

In this talk, I introduce basic physics involved in kilonovae and summarize what we have learned about r-process nucleosynthesis by neutron star mergers through the observations of GW170817 (and possible events during LIGO/Virgo O3). Then, I highlight open questions and future prospects toward understanding the origin of r-process elements in the Universe.

# Indirect methods constraining nuclear capture - the Trojan Horse Method

A. Tumino[1]

[1]*Facoltà di Ingegneria e Architettura, Università degli Studi di Enna "Kore", Enna & INFN-Laboratori Nazionali del Sud, Catania, Italy*

Understanding energy production and nucleosynthesis in stars requires a precise knowledge of the nuclear reaction rates at the energies of interest. To overcome the experimental difficulties arising from the small cross sections at those energies and from the presence of the electron screening, the Trojan Horse Method has been introduced [1]. The method represents one of the most powerful tools for experimental nuclear astrophysics because of its advantage to measure unscreened low-energy cross sections of reactions between charged particles, and to retrieve information on the electron screening potential when ultra-low energy direct measurements are available. This is done by selecting the quasi-free (QF) contribution of an appropriate three-body reaction $A + a \to c + C + s$, where $a$ is described in terms of clusters $x \oplus s$. The QF reaction is performed at energies well above the Coulomb barrier, such that cluster $x$ is brought already in the nuclear field of $A$, leaving $s$ as spectator to the $A+x$ interaction. The THM has been successfully applied to several reactions connected with fundamental astrophysical problems as well as with industrial energy production. I will recall the basic ideas of the THM and show some recent results. Particular emphasis will be given to those related to the $^{12}$C+$^{12}$C fusion channel, whose reaction rate was found to be strongly enhanced at the relevant astrophysical temperatures [2].

---

[1] R.E. Tribble et al., Rep. Prog. Phys. **76**, 106901 (2014).

[2] A. Tumino, Nature **557**, 687 (2018).

# Neutrinos and dark matter in astrophysics

Christian Weinheimer[1]

[1]*Institut für Kernphysik, University of Münster,Germany*

There is strong evidence on very different astrophysical and cosmological scales that normal baryonic matter contribute only to one part out of six to the matter of our universe. The remaining part is called dark matter. Struture formation in the universe requires the majority of the dark matter to be cold or warm at least, i.e. non-relativistic during structure formation. Neutrinos are the only known, but subdominant part, all the rest of the dark matter has to be exotic, i.e. particles beyond the Standard Model of particle physics. Still neutrinos with there tiny but non-zero masses and mixings play a vital role in astrophysical processes, e.g. in supernova explosions. The possible Majorana character of neutrinos might also be connected to the observed baryon asymmetry of the universe.

After an introduction into the evidences for dark matter and the properties of neutrinos the search for the neutrino mass as well as the search for neutrinoless double beta decay (and the Majorana character of neutrinos) will be presented. The search for various candidates of dark matter will be described in the second part. These searches will be explained in more detail at the examples of the current experiments KATRIN, GERDA and XENON1T.

# NICE- Neutron Induced Charged particle Emission

Kafa Al-Khasawneh,[1] Benjamin Brückner,[1] Philipp Erbacher,[1] Stefan Fiebiger,[1] Roman Gernhäuser,[2] Kathrin Göbel,[1] Deniz Kurtulgil,[1] Christoph Langer,[1] René Reifarth,[1] Benedikt Thomas,[1] Meiko Volknandt,[1] and Mario Weigand[1]

[1] *Goethe University, Frankfurt*

[2] *Technical University, Munich*

Neutron-induced nuclear reactions with the charged particle in the exit channel play an essential role in the s-process nucleosynthesis, but are also important for medical and nuclear reactor technologies. Despite this importance, cross-section data for such reactions are still scarce because of the short range of charged particles ($\mu$m), which hampers their detection. Only very thin samples in the range of micrometers can therefore be used. New approaches are required in particular for the time-of-flight technique to overcome the low reaction rates.

A new detector setup (NICE-detector) based on an organic plastic scintillator was proposed and tested at the Goethe University Frankfurt. One of the test cases was the capture cross-section of $^{209}$Bi at different astrophysically important energies. In this talk, the performance of the adapted detector setup as well as the results of calculated cross-section values will be presented. This project is supported by the DFG project NICE (RE 3461/3-1).

# Convective-reactive processes in evolved massive stars

Robert Andrassy,[1] Falk Herwig,[2,3,4] Paul Woodward,[5,3] and Christian Ritter[6]

[1]*Heidelberger Institut für Theoretische Studien,*

*Schloss-Wolfsbrunnenweg 35, 69118 Heidelberg, Germany*

[2]*Department of Physics and Astronomy,*

*University of Victoria, Victoria, BC, V8P5C2, Canada*

[3]*Joint Institute for Nuclear Astrophysics,*

*Center for the Evolution of the Elements, Michigan State University, USA*

[4]*NuGrid Collaboration*

[5]*LCSE and Department of Astronomy,*

*University of Minnesota, Minneapolis, MN 55455, USA*

[6]

One-dimensional simulations show that violent mergers of convective O- and C-burning shells in massive stars can open new nucleosynthesis pathways to the production of the odd-Z elements P, Cl, P, and Sc, which are underproduced in current chemical evolution models of the Galaxy. Such mergers would likely be strongly aspherical with further implications for supernova explosion models. I will present the results of high-resolution 3D hydrodynamic simulations performed in Falk Herwig's group at the University of Victoria in collaboration with Paul Woodward, which quantify the dynamic feedback from the burning of C-rich material convectively entrained into an O-burning shell. Although most of our numerical experiments lead to quasi-stationary C burning, one shows markedly different behaviour with a convective-reactive instability causing large-scale oscillations with Mach numbers Ma $> 0.2$.

# Precision mass measurements at ISOLTRAP for nucleosynthesis studies

D. Atanasov,[1] P. Ascher,[2] K. Blaum,[3] R. B. Cakirli,[4] T. E. Cocolios,[5] F. Herfurth,[6] A. Herlert,[7] W. Huang,[8] J. Karthein,[1,3] I. Kulikov,[9] Yu. A. Litvinov,[6] D. Lunney,[8] V. Manea,[1] M. Mougeot,[8] D. Neidherr,[6] L. Schweikhard,[10] T. P. Steinsberger,[9] A. Welker,[11] F. Wienholtz,[1,10] and K. Zuber[11]

[1] *CERN, CH-1211 Geneva, Switzerland*
[2] *CENBG-IN2P3-CNRS, Université Bordeaux 1, 33175 Gradignan, France*
[3] *Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*
[4] *Department of Physics, University of Istanbul, 34134 Istanbul, Turkey*
[5] *Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium*
[6] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[7] *FAIR GmbH, 64291 Darmstadt, Germany*
[8] *CSNSM-IN2P3-CNRS, Université Paris-Sud, 91406 Orsay, France*
[9] *Universität Heidelberg, 69117 Heidelberg, Germany*
[10] *Universität Greifswald, Institut für Physik, 17487 Greifswald, Germany*
[11] *Technische Universität Dresden, 01069 Dresden, Germany*

(Dated: June 11, 2019)

The evolution of binding energies in isotopes found far from stability provides important input not only to nuclear theory, but also to astrophysics simulations. Despite the enormous progress made during the last 80 years in the description of nucleosynthesis, there are still many problems left to be solved e.g. the astrophysical site of rapid neutron-capture process ($r$-process). In this context, experiments in nuclear physics continue to develop and extend the boundaries of determined ground state properties of isotopes within the paths of the relevant astrophysical processes. Furthermore, nuclides around the shell closures are of the utmost importance for the correct understanding and description of the main observed features of the nucleosynthesis, such as the elemental abundances and light curves, and have been targeted by many experiments worldwide.

In the last years at ISOLDE/CERN, the Penning-trap mass spectrometer ISOLTRAP focused efforts in the mass region at $N = 82$ below the tin isotopic chain. Mass measurements of cadmium isotopes are now revealing for the first time the strength of the shell gap encountered by the $r$-process. Furthermore, precision mass measurements in the region below doubly-magic $^{100}$Sn were performed. Atomic masses of $^{99-101}$In allow the study of the $Z = N = 50$ shell closure and its impact on the rapid proton-capture process. In this contribution, new developments, results from both measurement campaigns as well as physics discussion will be presented.

## Mass measurements of neutron-rich Ga isotopes performed at TITAN and their impact on the nucleosynthesis of the first r-process abundance peak

S. Ayet San Andrés,[1,2] M.P. Reiter,[1,3] J. Lippuner,[4,5,6] S. Nikas,[2,7] C. Andreoiu,[8] C. Babcock,[3] B.R. Barquest,[3] J. Bollig,[3,9] T. Brunner,[3,10] T. Dickel,[1,2] J. Dilling,[3,11] I. Dillmann,[3,12,13] E. Dunling,[3,14] G. Gwinner,[15] L. Graham,[3] C. Hornung,[1] R. Klawitter,[3,16] B. Kootte,[3,15] A.A. Kwiatkowski,[3,12] Y. Lan,[3,11] D. Lascar,[3,17] K.G. Leach,[18] E. Leistenschneider,[3,11] G. Martínez-Pinedo,[2,7] J.E. McKay,[3,12] S.F. Paul,[3,9] W.R. Plaß,[1,2] L. Roberts,[19] H. Schatz,[6,19,20] C. Scheidenberger,[1,2] A. Sieverding,[2,7,21] R. Steinbrügge,[3] R. Thompson,[22] M.E. Wieser,[22] C. Will,[1] and D. Welch[19]

[1] *II. Physikalisches Institut, Justus-Liebig-Universität, 35392 Gießen, Germany*
[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany*
[3] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[4] *CCS-2, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA*
[5] *Center for Theoretical Astrophysics, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA*
[6] *Joint Institute for Nuclear Astrophysics, Center for the Evolution of the Elements*
[7] *Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[8] *Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[9] *Ruprecht-Karls-Universität Heidelberg, 69117 Heidelberg, Germany*
[10] *Physics Department, McGill University, H3A 2T8 Montréal, Québec, Canada*
[11] *Department of Physics & Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[12] *Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 5C2, Canada*
[13] *JINA-CEE, 640 S Shaw Lane, East Lansing, Michigan 48824, USA*
[14] *Department of Physics, University of York, York, YO10 5DD, United Kingdom*
[15] *Department of Physics & Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*
[16] *Max-Planck-Institut für Kernphysik, Heidelberg 69117, Germany*
[17] *Center for Fundamental Physics, Northwestern University, Evanston, IL 60208, USA*
[18] *Department of Physics, Colorado School of Mines, Golden, Colorado, 80401, USA*
[19] *National Superconducting Cyclotron Laboratory, Michigan State University, 640 South Shaw Lane, East Lansing, Michigan 48824, USA*
[20] *Department of Physics and Astronomy, Michigan State University, 567 Wilson Road, East Lansing, Michigan 48824, USA*
[21] *School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis 55455, USA*
[22] *Department of Physics and Astronomy, University of Calgary, Calgary, Alberta T2N 1N4, Canada*

Some of the nuclei involved in the formation of the first abundance peak of the r-process can be produced with the current rare isotope beam (RIB) facilities to measure their nuclear properties. The main challenges faced by the measurement techniques in this region are the low production rates together with a strong isobaric background from the N = 50 closed neutron shell. Multiple-Reflection Time-of-Flight Mass Spectrometers (MR-TOF-MS) are powerful devices which enable mass measurements of the most exotic nuclei under extreme background conditions thanks to their high accuracy, sensitivity, short cycle times and the possibility to be their own high-rate isobar separator.

Recently, an MR-TOF-MS was installed at TRIUMFs Ion Trap for Atomic and Nuclear science (TITAN), enabling high-precision mass measurements of neutron-rich Ga isotopes up to A = 85. The impact of the newly measured masses on the formation of the first r-process abundance peak was studied under similar conditions found in the ejecta of the blue kilonova seen after the GW170817 binary neutron star merger event. Large-scale nuclear reaction calculations were performed using two state-of-the-art reaction codes and a detailed investigation of the formation of the maximum abundance at A = 80 and A = 84 was carried out.

# Stellar Modelling for Nuclear Astrophysics: Constraining the Astrophysical Origin of the p-nuclei

Umberto Battino,[1] Claudia Travaglio,[2] Claudia Lederer-Woods,[1] and Marco Pignatari[3,4,5]

[1] *School of Physics and Astronomy, University of Edinburgh, UK*

[2] *INFN-Istituto Nazionale Fisica Nucleare, Turin, Italy*

[3] *E.A. Milne Centre for Astrophysics, University of Hull, HU6 7RX, UK*

[4] *Konkoly Observatory, Hungarian Academy of Sciences, Budapest, Hungary*

[5] *Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements, USA*

The production of the p-process nuclides that we observe today in the Solar System is still uncertain. Recent Galactic Chemical Evolution (GCE) calculations, showed that explaining the inventory of the p-nuclides by the contribution from Core collapse supernovae (ccSNe) alone is challenging, thus requiring a complementary contribution from thermonuclear supernovae (SNe Ia), assuming in this last case an s-process rich pre-explosive seeds distribution, built by neutron captures during the accretion phase. Presently there are no complete stellar models calculating these abundances. We calculate accreting white dwarfs (WDs) models with five different initial masses using the stellar code MESA. We then focus on the nucleosynthesis calculating the full abundance distribution. In these models the dominant neutron source are $^{22}$Ne($\alpha$,n)$^{25}$Mg, activated at the bottom of the convective thermal pulse driven by the Helium flashes along the accretion phase, for WD masses lower than 1.26 $M_\odot$, and $^{13}$C($\alpha$,n)$^{16}$O for WD masses equal or higher than 1.26 $M_\odot$. We found neutron densities up to few $10^{15}$ cm$^{-3}$ in the most massive WDs. In particular, we obtain a strong production by neutron captures up to the Pb region, showing how the classic assumption of a neutron-capture rich pre-explosive seeds distribution is justified. Using these results, we compute the resulting explosive nucleosynthesis of proton rich heavy stable isotopes using a multi-D SNe Ia model, and discuss the uncertainties affecting our results, focusing in particular on the nuclear reaction-rates which provide the dominant contribution to the production uncertainty, highlighting which of the identified key reactions are realistic candidates for future experiments.

# First light from the Felsenkeller 5 MV underground accelerator

Daniel Bemmerer,[1] Roland Beyer,[1] Thomas E. Cowan,[1,2] Marcel Grieger,[1,2] Sebastian Hammer,[1,2] Arnd R. Junghans,[1] Felix Ludwig,[1,2] Conrad Möckel,[1,2] Simon Rümmler,[1,2] Konrad Schmidt,[2] Franziska Schoger,[1,2] Ronald Schwengner,[1] Klaus Stöckel,[1,2] Tamás Szücs,[1] Steffen Turkat,[2] Andreas Wagner,[1] and Kai Zuber[2]

[1] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01328 Dresden, Germany*

[2] *Technische Universität Dresden, 01062 Dresden, Germany*

## Abstract

The study of astrophysically important nuclear reactions between stable ions requires the use of low-background, underground accelerator laboratories. The Felsenkeller underground site in Dresden, shielded by a 45 m thick rock cover, hosts a 5 MV Pelletron ion accelerator with an external sputter ion source (for $^{12}$C and other beams) and an internal radio-frequency ion source (for noble-gas and hydrogen beams). The remaining no-beam background in muons, neutrons, and $\gamma$-rays at Felsenkeller has been completely characterized. The measured $\gamma$-background is sufficiently low to enter the Gamow peak for the so-called Holy Grail reaction $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$. The accelerator has recently been commissioned at the underground site and will soon offer a significant amount of beam time for external users, free of charge. The contribution will report on status and characteristics of the new accelerator lab, as well as on the envisaged scientific program.

# Low energy cross section of $^{18}O(p,\gamma)^{19}F$

Andreas Best[1,2] and Francesca Pantaleo[3,4]

[1] *University of Naples "Federico II", Italy*

[2] *INFN, Sezione di Napoli, Italy*

[3] *University of Bari "Aldo Moro", Italy*

[4] *INFN, Sezione di Bari, Italy*

For the LUNA collaboration

The observation of oxygen isotopes in giant stars sheds light on mixing processes operating in their interiors. Due to the very strong correlation between nuclear burning and mixing processes it is very important to reduce the uncertainty on the cross sections of the nuclear reactions that are involved. In this paper we focus our attention on the reaction $^{18}O(p,\gamma)^{19}F$. While the $^{18}O(p, \alpha)^{15}N$ channel is thought to be dominant, the $(p,\gamma)$ channel can still be an important component in stellar burning in giants, depending on the low energy cross section. So far only extrapolations from higher-energy measurements exist and recent estimates vary by orders of magnitude. These large uncertainties call for an experimental reinvestigation of this reaction. We present a direct measurement of the $^{18}O(p,\gamma)^{19}F$ cross section using a high-efficiency $4\pi$ BGO summing detector at the Laboratory for Underground Nuclear Astrophysics (LUNA). The reaction cross section has been directly determined for the first time from 140 keV down to 85 keV and the different cross section components have been obtained individually. The previously highly uncertain strength of the 90 keV resonance was found to be three orders of magnitude lower than an indirect estimate based on nuclear properties of the resonant state and a factor of 20 lower than a recently established upper limit. This result excludes the possibility that the 90 keV resonance can contribute significantly to the stellar reaction rate. In addition the strengths and branching ratios of resonances between 150 and 400 keV have been determined with much improved precision and sensitivity using a HPGe detector, including a first measurement of branching ratios of the 216 keV resonance.

# Cross Section Measurements of $^{23}$Na(p,$\gamma$)$^{24}$Mg

A. Boeltzig,[1,2,3] A. Best,[4] R. J. deBoer,[2] A. DiLeva,[4]
G. Imbriani,[4] M. Junker,[3] and M. Wiescher[2]
(for the LUNA collaboration)

[1] *Gran Sasso Science Institute, L'Aquila, Italy*

[2] *Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, USA*

[3] *INFN Gran Sasso National Laboratory, Assergi, Italy*

[4] *University of Naples and INFN Section of Naples, Naples, Italy*

The reaction $^{23}$Na(p, $\gamma$)$^{24}$Mg links the NeNa and MgAl cycles in stellar hydrogen burning. Non-resonant capture and three narrow resonance are believed to be the main contributions to the astrophysical reaction rate up to temperatures of 1 GK. For one of these resonances ($E^{\mathrm{c.\,m.}} = 138\,\mathrm{keV}$) only an upper limit on its strength has been established [1], resulting in large reaction rate uncertainties.

Cross section measurements were performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) and the Nuclear Science Laboratory (NSL) at the University of Notre Dame, in an effort to reduce the uncertainty of the $^{23}$Na(p, $\gamma$)$^{24}$Mg reaction rate. The underground location of the LUNA400 accelerator allowed for sensitive studies of the low-energy resonances, and the Sta. ANA accelerator at the NSL was used for measurements at higher beam energies. In measurements deep underground we established the existence of the $E^{\mathrm{c.\,m.}} = 138\,\mathrm{keV}$ resonance, and determined the strength of another narrow resonance with an improved uncertainty. With these new results, the astrophysical reaction rate at $T = 0.05 - 0.10\,\mathrm{GK}$, relevant for hydrogen shell burning in Asymptotic Giant Branch (AGB) stars, is reduced significantly. The analysis of the data taken on surface is ongoing.

We will present the measurements, with a focus on the results of the underground experiments, and the state of the analysis of the data taken on surface.

# Aluminium-26 from massive binary stars

Hannah E. Brinkman,[1] C. L. Doherty,[1,2] O. R. Pols,[3] E. T. Li,[4] B. Côté,[1,5] and M. Lugaro[1,2]

[1] *Konkoly Observatory, MTA CSFK, Konkoly Thege Miklos ut 15-17, H-1121 Budapest, Hungary*

[2] *Monash Center for Astrophysics, Monash University, VIC3800, Australia*

[3] *Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, 6500 GL Nijmegen, The Netherlands*

[4] *College of Physics & Energy, Shenzhen University, China*

[5] *Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements, USA*

Aluminium-26 is a short-lived radionuclide with a half-life of 0.72 Myr, which is observed today in the Milky Way Galaxy via $\gamma$-ray spectroscopy and is inferred to have been present in the early Solar System via analysis of meteorites. The main contributors to the cosmic abundance of $^{26}$Al are considered to be massive stars, and the yields of $^{26}$Al from single, massive stars, both the stellar winds and the supernova explosions, are widely available in the literature. Massive stars, however, are often found in binary systems, and the effect of binary interactions on the $^{26}$Al yields have not been investigated since Braun & Langer (1995)[1]. We present our work aimed to fill this gap. We have used the MESA stellar evolution code to compute massive ($10\,M_\odot \leq M \leq 80\,M_\odot$), non-rotating, single and binary stars of solar metallicity (Z=0.014). From these simulations we have computed the wind yields for the single stars and for the binary systems where mass transfer plays a major role. We found that, depending on the initial mass of the primary star, in a binary system the $^{26}$Al yield can either increase or decrease. For binary systems with primary masses up to $\sim$35-40 $M_\odot$, the yield can increase by up to two orders of magnitude, while above $\sim$45 $M_\odot$ the yield becomes similar to the single star yield or even decreases. Our preliminary results show that the effect of winds in binary systems on the total abundance of $^{26}$Al produced by a stellar population is still minor compared to that of the supernova explosions. On the other hand, if massive star winds are the origin of $^{26}$Al in the early Solar System, our results will have significant implications on the identification of the potential stellar, or stellar population, source.

# Study of the $^{22}$Ne(p,$\gamma$)$^{23}$Na at LUNA

A. Caciolli on behalf of the LUNA collaboration[1]

[1] *University and INFN of Padua, Padua, Italy*

The $^{22}$Ne(p,$\gamma$)$^{23}$Na reaction, part of the neon-sodium cycle of hydrogen burning, may explain the observed anticorrelation between sodium and oxygen abundances in globular cluster stars. At astrophysical energies, the presence of many resonances dominates the rate. The LUNA collaboration measured for the first time three of them: $E_p = 156.2$, 189.5, and 259.7 keV. Recently, by using an high efficiency setup, made of a $4\pi$-BGO detector and a windowless gas target, the uncertainties related to those three states have been lowered drastically and the direct component of the cross section was also measured at four different energies below 300 keV, in the center of mass. In addition, the two suggested resonances at $E_p = 71$ and 105 keV have been studied and new upper limits were established, leading to a negligible contribution of these two states in the thermonuclear reaction rate. As a result, at a temperature of 0.1 GK the error bar of the $^{22}$Ne(p,$\gamma$)$^{23}$Na rate is now reduced by three orders of magnitude. Here, new $^{22}$Ne(p,$\gamma$)$^{23}$Nadata and the LUNA recommend reaction rate are reported. The new high efficiency setup provides also the possibility to investigate the branching cascades, despite the limited resolution of the BGO detector. This way new branchings have been found for the above mentioned resonances and the direct component of the cross section.

# On the $^{12}$C hoyle state gamma decay

G. Cardella,[1] F. Favela,[1] N.S. Martorana,[2,3,4] L. Acosta,[5,1] L. Auditore,[6,1] A. Camaiani,[7] E. De Filippo,[1] S. De Luca,[6,1] N. Gelli,[7] B. Gnoffo,[1,3] D.J. Marin-Lambarri,[5] G. Lanzalone,[2,8] C. Maiolino,[2] A. Nannini,[7] A. Pagano,[1] E.V. Pagano,[2] M. Papa,[1] S. Pirrone,[1] G. Politi,[3,1] E. Pollacco,[9] L. Quattrocchi,[1,6] F. Rizzo,[3,2] P. Russotto,[2] A. Trifiró,[6,1] and M. Trimarchi[6,1]

[1] *INFN- Sezione di Catania, Italy*
[2] *INFN-LNS, Italy*
[3] *Dipartimento di Fisica e Astronomia, Universitá di Catania, Italy*
[4] *CSFNSM Catania, Italy*
[5] *Instituto de Fsica, Universidad Nacional Autónoma de México*
[6] *Dipartimento di Scienze MIFT, Universitá di Messina, Italy*
[7] *INFN sezione di Firenze and Dip. di Fisica Universitá di Firenze, Italy*
[8] *Facoltá di Ingegneria e Architettura, Universitá Kore, Italy*
[9] *CEA IRFU Saclay, Gif sur Yvette, France*

The $\gamma$-decays of $^{12}$C excited levels (the Hoyle state at 7.6 MeV and in some cases the 9.64 MeV) are very important for its production in universe. We present here a new attempt to precisely measure such gamma decay probabilities. The one of the Hoyle state is known to be of the order of $4 \times 10^{-4}$ [1], while for the one of the 9.64 MeV $3^-$ only a lower limit decay probability is known, of the order of $10^{-7}$ [2]. The measurement was performed at INFN-LNS in Catania using the $4\pi$ CHIMERA multidetector [3]. In order to measure such low probability decay-channels we performed a 4-fold coincidence measurement. The target $^{12}$C nucleus was excited by using a beam of 64 MeV $\alpha$-particles produced by the superconducting cyclotron (CS) of INFN-LNS. The scattered $\alpha$-particles, and the recoiling $^{12}$C were detected and identified by E-E and ToF methods [3] performed by two stages Si-CsI(Tl) CHIMERA telescopes and the Timing of the Pulsed CS . The emitted $\gamma$-rays were detected and identified by using the second stage of the telescopes, CsI(Tl) scintillators, using fast-slow techniques [4]. Kinematical rules and energy momentum conservation laws were used to constraint the data analysis. In the experiment also the 3-$\alpha$ decay of highly excited nuclei was measured. The contemporary measurement of all decay channels is useful to reduce the systematic errors. Preliminary results of the data analysis will be shown.

[1] R.G. Markham et al., Nucl. Phys. **A 270**, 489 (1976).
[2] D. Chamberlin et al., Phys. Rev. **C10**, 909 (1974).
[3] A. Pagano et al., Nucl.Phys. **A734**, 504 (2004).
[4] G. Cardella et al., NIM **A799**, 64 (2015).

# New measurement of the neutron capture cross section of the thallium isotopes $^{203}$Tl, $^{204}$Tl and $^{205}$Tl

A. Casanovas,[1] C. Domingo-Pardo,[2] C. Guerrero,[3] A. Tarifeño-Saldivia,[1]
F. Calviño,[1] J. Lerendegui-Marco,[3] and the n_TOF Collaboration[4]

[1] *Universitat Politècnica de Catalunya, Spain*

[2] *Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Spain*

[3] *Universidad de Sevilla, Spain*

[4] *CERN, Switzerland*

Neutron capture cross sections are one of the key input parameters for an accurate description of the s-process of stellar nucleosynthesis, which is responsible for the production of about half of the elemental solar abundances between Fe and Bi in AGB stars. In this talk we will present the new measurement of the capture cross section of the thallium isotopes $^{203}$Tl, $^{204}$Tl, and $^{205}$Tl, performed at the n_TOF facility (CERN) between 2015 and 2018.

During s-proces conditions, for a nucleus of radioactive $^{204}$Tl ($T_{1/2} = 2.78\,y$, $\beta$-decays to $^{204}$Pb), the probability of decaying is similar than that of capturing a neutron, thus acting as what is called a branching point. Concerning $^{205}$Tl, this terrestrially stable nucleus becomes unstable by bound-state beta decay, decaying to $^{205}$Pb. In the end, both cross sections play an important role in fixing the final abundances of the lead isotopes. What is more, they are necessary for and accurate determination of the primordial ratio $^{205}$Pb/$^{204}$Pb, which has a potential use as an s-process cosmo-chronometer thanks to the long half-life ($T_{1/2} = 1.5\times10^7\,y$) of $^{205}$Pb.

This is the first time the $^{204}$Tl$(n,\gamma)$ cross section has been measured, using a sample of 260 mg of $^{203}$Tl enriched to 4% (9 mg) in $^{204}$Tl and a detectopm setup of four $C_6D_6$ gamma detectors. The overall content of 96% of $^{203}$Tl made an ancillary measurement of $^{203}$Tl$(n,\gamma)$ alone necessary, which has yielded updated cross section data for this reaction, as well.

The measuring technique, the stellar cross section calculation, and the implications for the s-process of the new nuclear data will all be covered in this talk.

# Cross section of the $^{13}C(\alpha,n)^{16}O$ reaction at low energies

Giovanni Francesco Ciani*,[1] Andreas Best,[2,3] J. Balibrea-Correa,[2,3] and L. Csedreki[4,5]
(for the LUNA collaboration)

[1] *MTA Atomki, 4023 Debrecen, Hungary*

[2] *INFN, Sezione di Napoli, 80126 Napoli, Italy*

[3] *Università degli Studi di Napoli "Federico II", Italy*

[4] *Gran Sasso Science Institute, INFN, 67100 L'Aquila, Italy*

[5] *INFN Laboratori Nazionali del Gran Sasso (LNGS), 67100 Assergi, Italy*

(Dated: June 11, 2019)

The $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source for the s process, which is responsible for the production of about half of the heavy elements in the universe. It operates in thermally pulsing low mass AGB stars at temperatures of about 90 MK. This translates to a Gamow window between 140 - 230 keV, far below the Coulomb barrier. Several direct measurements of the low energy cross section of $^{13}C(\alpha,n)^{16}O$ have been performed in the past, and while remarkable results have been achieved, ultimately the Earth surface environmental background has been a limiting factor. The LUNA collaboration has performed a measurement of $^{13}C(\alpha,n)^{16}O$ cross section in the low-background environment of the Laboratori Nazionali del Gran Sasso (LNGS), where the environmental neutron flux is reduced by over three orders of magnitude with respect to the surface. This unique location, combined with a high-efficiency low background detector based on $^3He$ counters, a highly stable intense alpha beam ($< I >= 200\ \mu A$) and a pulse shape discrimination technique for the suppression of the detector intrinsic background, permitted us to push the low-energy limit of cross section measurements 50 keV below the lowest point in literature, reaching the high energy edge of the Gamow window. Thanks to a novel and detailed analysis on the target modification during the beam irradiation and an experimental campaign on the detector efficiency, unprecedented overall uncertainties lower than 15% have been achieved.

An update on status of the analysis and cross sections results will be presented.

# The CEMP star SDSS J02220313: the first evidence for proton ingestions in very low-metallicity AGB stars?

Sergio Cristallo,[1,2] Elisabetta Caffau,[3] Piercarlo Bonifacio,[3] and Gabriele Cescutti[4]

[1] *INAF - Osservatorio Astronomico d'Abruzzo, Teramo, Italy*

[2] *INFN - Sezione di Perugia, Perugia, Italy*

[3] *GEPI, Observatoire de Paris, Paris, France*

[4] *INAF - Osservatorio Astronomico di Trieste, Trieste, Italy*

Carbon-enhanced metal-poor (CEMP) stars are common objects at metal-poor regime. We present observations of a CEMP star, SDSS J02220313, with a known high carbon abundance and a strong enhancement in neutron-capture elements of the first peak (Sr and Y) and of the second peak (Ba) of the slow neutron capture process (the s-process). Therefore, this star can be classified as a CEMP-s star.
However, SDSS J02220313 presents some peculiarities: a larger overabundance (with respect to iron) of the first s-process peak than the second s-process peak and an extremely large Ba/La ratio (more than a factor 10) [1]. Both features do not match with a standard s-process, nor with a pollution typical of the intermediate neutron capture process (i-process).
The enhancement in heavy elements suggests that the evolved companion had a low main sequence mass and that the latter experienced a proton ingestion episode at the beginning of the AGB phase [2]. We identify a transient phase of that peculiar mixing episode which shows the nucleosynthesis features characterizing SDSS J02220313. We speculate on the possible theoretical scenario.

[1] E. Caffau et al., A&A, submitted (2019).

[2] S. Cristallo et al., PASA **26**, 139 (2009).

# Global $R$-matrix analysis of the $^{11}B(\alpha, n)^{14}N$ reaction

R.J. deBoer,[1,2] Q. Liu,[1,2] Y. Chen,[1,2] M. Couder,[1,2] G. Gilardy,[1,2] J. Görres,[1,2] E. Lamere,[1,2] K. Manukyan,[1,2] L. Morales,[1,2] D. Robertson,[1,2] C. Seymour,[1,2] E. Stech,[1,2] B. Vande Kolk,[1,2] and M. Wiescher[1,2]

[1] *The Joint Institute for Nuclear Astrophysics, Notre Dame, Indiana 46556, USA*

[2] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

Nucleosynthesis in the first generation of massive stars offers a unique setting to explore the creation of the first heavier nuclei in an environment that lacks any heavier nuclei impurities from earlier stellar generations. In later generations of massive stars, hydrogen burning occurs predominantly through the CNO cycles, but without the carbon, nitrogen, and oxygen that allow this catalytic reaction sequence, these stars would have to rely on the inefficient *pp*-chains for their energy production. However, there may be other reaction chain sequences that utilize only light elements that act as alternative pathways around masses 5 and 8 that activate under these special conditions. One such reaction chain could be $^{10}$B(p,$\alpha$)$^{7}$Be($\beta\nu$)$^{7}$Li($\alpha,\gamma$)$^{11}$C($\beta\nu$)$^{11}$B($\alpha$,n)$^{14}$N, which would also provide a neutron source to this early stellar environment. In this work, improved measurements are reported for the $^{11}$B($\alpha$,n)$^{14}$N reaction made at the University of Notre Dame Nuclear Science Laboratory. A multichannel $R$-matrix analysis is presented that includes not only $^{11}$B+$\alpha$ data, but also additional data sets from $^{14}$C+$p$ and $^{14}$N+$n$ measurements, in order to facilitate a comparison of the underlying nuclear structure and to better understand the systematic uncertainties of the different measurements. Additional measurements are underway at the CASPAR underground facility.

# The s process production in rotating low-mass AGB stars

Jacqueline den Hartogh,[1,2,3] R. Hirschi,[2,4,3] M. Lugaro,[5,6] C.L. Doherty,[5,6] U. Battino,[7,3] F. Herwig,[8,9,3] M. Pignatari,[10,5,9,3] and P. Eggenberger[11]

[1]*Konkoly observatory, MTA CSFK, Budapest, Hungary*

[2]*Astrophysics group, Keele University, UK*

[3]*NuGrid Collaboration,* `http://www.NuGridstars.org`

[4]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Japan*

[5]*MTA CSFK Konkoly observatory, Budapest, Hungary*

[6]*Monash Centre for Astrophysics (MoCA), Monash University, Australia*

[7]*School of Physics and Astronomy, University of Edinburgh, UK*

[8]*Department of Physics and Astronomy, University of Victoria, Canada*

[9]*JINA-CEE, Michigan State University, USA*

[10]*E. A. Milne Centre for Astrophysics, University of Hull, UK*

[11]*Observatoire de Genève, Université de Genève, Switserland*

The slow neutron capture process (s-process) is responsible for about half of all elements heavier than iron in the universe, and is therefore important for galactic chemical evolution. Its main production site is the Asymptotic Giant Branch (AGB) phase, a late evolutionary phase in stars with an initial mass between about 0.8 and 8 $M_{\odot}$. Since stars rotate, it is important to calculate stellar evolution models including rotation. However, the implementation of rotation and rotation-induced mixing in stars is uncertain and does not reproduce all observables. Specifically, recent observables obtained by asteroseismic surveys show a process of angular momentum transport is missing in stellar evolution theory. We will present new AGB models including rotation that do match the observed rotation rates from large scale asteroseismic surveys. The s-process production of these rotating AGB models and their uncertainties will be presented and discussed in detail.

# Impact of rotation on heavy element production within stars on the low-mass/high-mass star divide

Carolyn Doherty,[1] Simon W. Campbell,[2] Jacqueline den Hartogh,[1]
Alexander Heger,[2] Projjwal Banerjee,[3] and Pilar Gil-Pons[4]

[1]*Konkoly Observatory, Hungarian Academy of Sciences, 1121 Budapest*

[2]*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Australia*

[3]*Department of Astronomy, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240*

[4]*Polytechnical University of Catalonia, Barcelona, Spain*

Super-AGB stars reside in the mass range ≈ 6-10 $M_\odot$ and bridge the divide between low/intermediate-mass and massive stars. They undergo off-centre carbon ignition prior to a thermally pulsing phase which can consist of many 10-1000s of thermal pulses. With their high luminosities and very large, cool, red stellar envelopes, these stars may appear seemingly identical to their slightly more massive red supergiant (RSG) counterparts and may act as massive star imposters. Important for both of these classes of star is rotation, and in particular its impact to the surface composition relative to the process of second dredge up. The chemical surface enrichment may result in a clear nucleosynthetic signature to differentiate between super-AGB stars and (massive star) RSGs. Rotation also acts to reduce the lowest initial mass for core collapse supernovae, with the refinement of this mass boundary having important implications for the energetics and chemical enrichment of galaxies. Here we present detailed heavy element nucleosynthesis predictions for a grid of rotating and non-rotating super-AGB star and low-mass massive star models.

# Review and new concepts for neutron-capture measurements of astrophysical interest

C. Domingo-Pardo,[1] V. Babiano-Suarez,[1] L. Caballero,[1] I. Ladarescu,[1] J.L. Tain,[1] F. Calviño,[2] A. Casanovas,[2] A. Segarra,[2] A. Tarifeño Saldivia,[2] C. Guerrero,[3] , J. Lerendegui-Marco,[3] M.A. Millan-Callado,[3] J.M. Quesada,[3] M.T. Rodríguez-González,[3] S. Heinitz,[4] E.A. Mauregui,[4] R. Dressler,[4] N. Kivel,[4] D. Schumann,[4] U. Köster[5],[5] and The CERN n_TOF Collaboration

[1] *IFIC (CSIC-University of Valencia), Spain*

[2] *UPC-Barcelona, Spain*

[3] *University of Seville, Spain*

[4] *Paul Scherrer Institut (PSI), Villigen, Switzerland*

[5] *Institut Laue-Langevin (ILL), Grenoble, France*

The idea of slow-neutron capture nucleosynthesis formulated in 1957[1, 2] triggered a tremendous experimental effort in different laboratories worldwide to measure the relevant nuclear physics input quantities, namely $(n, \gamma)$ cross sections over the stellar temperature range (from few eV up to several hundred keV) for most of the isotopes involved from Fe up to Bi. A brief historical review will be presented to illustrate how, advances in the instrumentation have led, over the years, to the discovery of many new aspects of $s$-process nucleosynthesis and to the progressive refinement of theoretical models of stellar evolution. A summary will be presented on current efforts to develop new detection concepts, such as the Total-Energy Detector with $\gamma$-ray imaging capability (i-TED). The latter is based on the simultaneous combination of Compton imaging with neutron time-of-flight (TOF) techniques, in order to achieve a superior level of sensitivity and selectivity in the measurement of stellar neutron capture rates.

[1] E.M. Burbidge et al., Review of Modern Physics **29**, 547 (1957).

[2] A. Cameron, Tec.Rep. Chalk River RCL **41**, 1 (1957).

# Imprints of fission in r-process abundance patterns

Marius Eichler[1]

[1] *Institut für Kernphysik, Technische Universität Darmstadt,*

*Schlossgartenstr. 2, DE-64289 Darmstadt, Germany*

About half of the heavy elements in the universe are produced by the *rapid neutron capture process* (r-process). While recent multi-messenger detections of compact binary mergers have confirmed neutron star mergers (NSMs) as an r-process site, it is currently unclear if this scenario can account for all the enrichment of heavy r-process nuclei in the galaxy, especially at low metallicities. Theoretical models show that the heaviest r-process nuclei can possibly be produced also in other astrophysical scenarios, such as magneto-rotationally driven supernovae (MRSNe) or disks forming around collapsars. Distinguishing these scenarios by means of their nucleosynthetic signatures proves extremely challenging, since the properties of the neutron-rich nuclei involved are unknown, in addition to the uncertainties in hydrodynamical conditions of the ejecta.

Most models, however, agree that the ejecta from NSMs include components that are neutron-rich enough for fission cycling, while outflows from MRSNe are generally less neutron-rich. In our theoretical nucleosynthesis calculations, r-process abundances derived from neutron-rich conditions with the inclusion of fission cycling can be systematically distinguished from an r-process where fission is insignificant. Here we will discuss the signatures of fission in the r-process and assess their robustness against the nuclear and hydrodynamical uncertainties.

# The $^{59}$Cu(p,$\alpha$)$^{56}$Ni cross section and heavy element nucleosynthesis in core collapse supernovae

Ruchi Garg,[1] Claudia Lederer-Woods,[1] Tom Davinson,[1] Mirco Dietz,[1] Daid Kahl,[1] Massimo Barbagallo,[2] Sarah-Jane Lonsdale,[1] Alex Murphy,[1] and Phil Woods[1]

[1] *School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK*

[2] *European Organization for Nuclear Research (CERN), Switzerland*

In the research field of heavy element nucleosynthesis, the origin of p-nuclei has been a longstanding problem. They are thought to be produced in the hot environments such as supernovae via p-capture and $\gamma$-disintegration processes. But with these processes, most stellar models fail to reproduce the observed abundances of the lighter p-nuclei $^{92,94}$Mo and $^{96,98}$Ru [1]. In a study by Fröhlich et al., a new process called the $\nu$p-process was suggested as an explanation for the abundances of p-nuclei with A>64 [2]. However, the competition between (p,$\alpha$) and (p,$\gamma$) reactions on $^{59}$Cu in an end-point cycle could hinder the reaction flow to the heavier elements by cycling the material back [3]. This competition is temperature sensitive and it is crucial to measure the $^{59}$Cu(p,$\alpha$)$^{56}$Ni reaction cross section in order to obtain reliable modelling results. Additionally, this reaction is of key importance to the light curve of X-ray bursts and the ashes' composition on the surface of the neutron star [4].

We have carried out the first direct measurement of the $^{59}$Cu(p,$\alpha$)$^{56}$Ni reaction cross section. The experiment was performed at the recently upgraded HIE-ISOLDE facility at CERN in inverse kinematics bombarding a $CH_2$ target with a high intensity radioactive $^{59}$Cu beam at beam energies between 3.6 - 5.0 MeV/u. I will present the experimental procedure, data analysis and first results.

[1] M. Arnould and S. Goriely, Physics Reports **384**, 1 (2003).

[2] C. Fröhlich *et al.*, Physical Review Letters **96**, 142502 (2006).

[3] A. Arcones *et al.*, The Astrophysical Journal **750**, 18 (2012).

[4] R. Cyburt *et al.*, The Astrophysical Journal **830**, 55 (2016).

# Nuclear reaction studies on stored ions

J. Glorius,[1] C. Langer,[2] Yu. A. Litvinov,[1]
R. Reifarth,[2] for the NucAR, and SPARC collaboration

[1]*GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*

[2]*Goethe Universität Frankfurt am Main, Germany*

Explosive nucleosynthesis involves large nuclear reaction networks which evolve beyond nuclear stability. To adress the scarce data situation in this domain, radioactive ion beams can be produced and made available for reaction studies in inverse kinematics. At GSI/FAIR the unique combination of the FRagment Separator FRS and the Experimental Storage Ring ESR makes it possible to store, decelerate and cool such ion beams. This technique allows the direct measurement of reaction cross sections inside the Gamow window as has been shown recently for proton-capture reactions [1].

This talk will give an overview on the past and recent developments at the GSI storage rings towards reaction studies at low energies. This includes the first steps with the pilot experiment on $^{96}$Ru(p,$\gamma$) as well as the last beam time investigating $^{124}$Xe(p,$\gamma$) at the ESR facility.

Finally, an extended outlook to future experiments at the new low-energy storage ring CRYRING will be given, which is perfectly suited for studies inside the Gamow window.

---

[1] J. Glorius, Phys. Rev. Lett. **122**, 092701 (2019).

# Coulomb dissociation of $^{16}$O into $^{4}$He and $^{12}$C

Kathrin Göbel,[1] Michael Heil,[2] Aleksandra Kelić-Heil,[2] René Reifarth,[1]
Lukas Bott,[1] Christoph Caesar,[2] Bastian Löher,[2] Daniel Körper,[2]
Deniz Savran,[2] Haik Simon,[2] Hans Törnqvist,[3] and Stefan Typel[2]
(for the R$^3$B collaboration)

[1] *Goethe-Universität Frankfurt*

[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt*

[3] *Technische Universität Darmstadt*

The fusion reaction of carbon and helium to oxygen is the key to understanding the evolution of stars and the relative abundances of both elements. The reaction rate of $^{12}$C($\alpha$,$\gamma$)$^{16}$O has to be known with an uncertainty of lower than 10% at a center-of-mass energy of 300 keV during Helium burning conditions. So far, experiments have studied the reaction down to about 1 MeV.

We measured the Coulomb dissociation of $^{16}$O into $^{4}$He and $^{12}$C at the R$^3$B setup in a first campaign within FAIR Phase-0 at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt. The goal is to improve the accuracy of the experimental data and to reach lower center-of-mass energies.

The experiment required beam intensities of $10^9$ $^{16}$O ions per second at an energy of 500 *A*MeV. The rare case of Coulomb breakup into $^{12}$C and $^{4}$He posed another challenge: we had to detect particles with the same magnetic rigidity as the primary beam, which are not separated by the super-conducting magnet GLAD. Radical changes of the R$^3$B setup were necessary: All detectors had slits to allow the passage of the unreacted $^{16}$O ions, while $^{4}$He and $^{12}$C would hit the detectors' active areas. We developed and built detectors based on organic scintillators to track and identify the reaction products with sufficient precision.

The talk reviews the setup and the beamtime, and gives the current status of analysis.

# Stable Ion Beam Experiments with the DRAGON Recoil Separator at TRIUMF

Uwe Greife[1] and the DRAGON Collaboration[2]

[1]*Department of Physics, Colorado School of Mines, Golden, Colorado, USA*

[2]*TRIUMF, Vancouver, Canada*

The DRAGON experiment (Detector of Recoils And Gammas Of Nuclear reactions) was designed to provide a recoil separator to study radiative capture reactions, both on protons and alpha particles, using accelerated radioactive ion beams at the ISAC-I facility of the TRIUMF laboratory in Vancouver, Canada. The addition of a Supernanogam ECR source now allows for the use of stable ion beams with intensities in the 1E12 s-1 range at the beam lines connected to the ISAC-I accelerator. The DRAGON experiment consists of a windowless, recirculating gas target which is surrounded by a BGO scintillator array to capture the gamma photons emitted in the radiative capture reactions on hydrogen or helium gas. The heavy reaction recoils travel with the incident ion beam into the actual recoil separator consisting of consecutive magnetic and electrostatic dipoles. These provide beam suppression factors of order 1E8-1E13 depending on ion type and energy regime. The remaining leaky beam ions and reaction recoils are detected in the focal plane using a local time-of-flight and an energy detection system, which, either independently or together with the BGO array, provide further beam suppression. The sensitivity of the system, coupled with the now available stable heavy ion beam intensities, makes the DRAGON experiment competitive with low energy nuclear physics measurements at other facilities employing more intense proton or alpha beams in normal kinematics. This contribution will present recent results using neon (20-Ne, 21-Ne) and sulphur (34-S) beams for the measurement of radiative capture reactions relevant to nuclear astrophysics.

# Studies of $\beta$-delayed neutron emission in neutron-rich $r$-process nuclei with the BRIKEN detector array

C.J. Griffin,[1] R. Caballero-Folch,[1] I. Dillmann,[1] and the BRIKEN Collaboration

[1] *TRIUMF, Vancouver, British Columbia, Canada*

$\beta$-delayed neutron emission probabilities of exotic nuclei, along with nuclear masses and $\beta$-decay half-lives, are of key importance in the stellar nucleosynthesis of heavy elements via the rapid neutron-capture process ($r$-process). Not only does $\beta$-delayed neutron emission lead to a redistribution of material as neutron-rich nuclei $\beta$-decay towards stability, it also acts as a source of late-time neutrons which increase the neutron-to-seed ratio and can be recaptured during the freeze-out phase. Both of these processes influence the final $r$-process abundance distribution and obtaining a more complete description of this process is vital to developing a deeper understanding of observed elemental abundances.

The $\beta$-delayed neutrons at RIKEN (BRIKEN) project [1, 2] combines the world's most efficient neutron detector array with the highly-segmented silicon implantation detector AIDA and two HPGe clover detectors for $\gamma$ spectroscopy. In operation since 2016, several experiments have already been conducted studying $\beta$n-emission in 231 nuclei from $^{64}$Cr to $^{151}$Cs and measuring many $\beta$n-emission probabilities and decay half-lives for the first time. With further experiments planned to study $A > 190$ and $A < 50$ nuclei in the coming years, the BRIKEN campaign will contribute a wealth of new results which are critical in reducing the uncertainty in $r$-process abundances obtained using astrophysical nucleosynthesis network calculations.

C.J. Griffin, R. Caballero-Folch, and I. Dillmann are funded by the Canadian NSERC and NRC.

[1] A. Tarifeño-Saldivia et al., J. Inst. **12.04**, (2017).

[2] A. Tolosa-Delgado et al., NIMA **925**, 133-147, (2019).

# Mass measurements of rare isotopes for improved rp-process modeling at the LEBIT facility

A. Hamaker,[1,2] G. Bollen,[1,3] D. Puentes,[1,2] M. Redshaw,[2,4]
R. Ringle,[2] R. Sandler,[4] S. Schwarz,[2] and I. T. Yandow[1,2]

[1]*Michigan State University, East Lansing, Michigan 48824, USA*
[2]*National Superconducting Cyclotron Laboratory, East Lansing, Michigan 48824, USA*
[3]*Facility for Rare Isotope Beams, East Lansing, Michigan 48824, USA*
[4]*Central Michigan University, Mount Pleasant, Michigan 48859, USA*

Type I X-ray bursts are frequently observed thermonuclear explosions on the surface of neutron stars that accrete matter from a nearby companion star. The bursts are powered by nuclear reaction sequences that transform accreted hydrogen and helium into heavier elements via the $3\alpha$-reaction, the $\alpha$p-process, and the rapid proton capture process (rp-process). Nuclear data on neutron deficient rare isotopes are needed to predict burst light curves that can then be compared with observations to constrain system parameters and neutron star properties. A recent sensitivity study on type-I x-ray bursts [1] has shown that the light curves and calculated final ash abundances are significantly affected by the current mass uncertainties in many proton rich nuclei. To this end, a recent experimental campaign at the Low Energy Beam and Ion Trap (LEBIT) facility at the National Superconducting Cyclotron Laboratory (NSCL) [2] has set out to measure the masses of several of these nuclei. In this talk, I will discuss recent mass measurements of importance for rp-process modeling including $^{56}$Cu [3], $^{51}$Fe [4], and $^{61}$Zn [in progress] as well as several more planned measurements of $^{27}$P, $^{24}$Si, and $^{80\text{-}82}$Zr.

---

[1] H. Schatz and W.-J. Ong, The Astrophy. J. **844**, 29 (2017).

[2] R. Ringle *et al.*, Int. J. Mass Spectrom. **349**, 87 (2013).

[3] A. A. Valverde *et al.*, Phys. Rev. Lett. **120**, 032701 (2018).

[4] W.-J. Ong *et al.*, Phys. Rev. C **98**, 065803 (2018).

# Indirect measurements of neutron-induced cross sections at storage rings

A. Henriques,[1] B. Jurado,[1] D. Denis-Petit,[2] T. Chiron,[1] L. Gaudefroy,[2] J. Glorius,[3] M. Grieser,[4] C. Langer,[5] Yu. A. Litvinov,[3] L. Mathieu,[1] V. Mot,[2] R. Prez-Snchez,[1] J. Pibernat,[1] R. Reifarth,[5] O. Roig,[2] B. Thomas,[1] B. A. Thomas,[1] J. C. Thomas,[6] and I. Tsekhanovich[1]

[1] *CENBG, CNRS/IN2P3-Université de Bordeaux, Bordeaux, France*

[2] *CEA-DAM DIF, Arpajon, France*

[3] *GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt, Germany*

[4] *Max-Planck Institut fuer Kernphysik, Heidelberg, Germany*

[5] *University of Frankfurt, Frankfurt, Germany*

[6] *GANIL, Caen, France*

The synthesis of elements from iron to uranium (heavy elements) that takes place in stars can only be understood through the knowledge of neutron-induced cross sections on very short-lived nuclei. Nevertheless, these measurements can be extremely challenging or even impossible to perform due to radioactivity of the targets involved.

The most promising way to access neutron-induced cross sections is to use surrogate reactions in inverse kinematics, where the nucleus formed in the neutron-induced re-action of interest is produced by the interaction of a radioactive beam and a light tar-get nucleus. The decay probabilities of the excited nucleus induced by the surrogate reaction are very useful to constrain model parameters and predict much more accurately the desired neutron cross sections. Storage rings offer the ideal conditions to perform high-precision decay-probability measurements.

In this contribution we will present the future plans and developments towards performing surrogate-reaction studies in inverse kinematics with radioactive-ion beams at storage rings. Such developments include the study of a new experimental set-up to be placed at the CRYRING storage ring at GSI and the investigations we have carried out regarding using solar cells as heavy ion detectors.

# A classification of CEMP stars based on neutron density that reveals the important role of the i process and the need for better nuclear physics data

Falk Herwig,[1] Pavel Denissenkov,[1] and Ondrea Clarkson[1]

[1] *University of Victoria, Victoria, Canada*

Most C-enhanced metal poor stars show simultaneously substantial enhancements of heavy n-capture elements, such as Sr, Y, Zr, Ba, La and Eu. These have been commonly classified according to the presence of the element Ba which is dominantly made by the s-process and of Eu which has an s-process production contribution of only $\sim 3\%$, and is therefore considered an r-process element. We are revisiting the classification of CEMP stars with the goal to establish more granular criteria based on the neutron-density prevailing in the stellar nuclear production site. To this end we have constructed equilibrium nucleosynthesis simulations for $6 < \log N_{\rm n} < 23$. These models are independent of any specific astrophysical site. After demonstrating how well these constant $N_{\rm n}$ simulations represent more realistic astrophysics-based nucleosynthesis simulations we compare the simulations with the JINAbase databased of CEMP stars. Most stars labeled CEMP-s in that data base cannot be reproduced by s-process neutron density models, but instead by the intermediate neutron density, demonstrating the importance of the i process for understanding the heavy-element patterns in CEMP stars. Our analysis involves elemental ratios of both first and second peak, and reveals that predictions of observational abundance ratios are severely limited by nuclear physics uncertainties, especially the $(n, \gamma)$ rate of n-rich unstable species 2 - 6 masses off the valley of stability. This new type of analysis lends itself to a systematic nuclear physics impact study approach, and we will present results from three such studies that have revealed a handful of $(n, \gamma)$ reactions that should be measured with the highest priority. We will briefly summarize the present state of simulations in 3D and 1D of the most likely astrophysical sites of the i process.

# Developing synergy between multi-dimensional and 1D simulations of stellar convection

Raphael Hirschi[1]

[1]*Keele University, Keele, ST5 5BG, UK*

Stars are complex objects involving many multi-dimensional processes like convection, rotation and magnetic fields. Ideally, we would like to model stars with 3D MHD simulations but it is unfortunately not feasible to simulate their entire evolution in 3D. We will thus always need 1D stellar evolution models to provide the necessary input for galactic chemical evolution and to study the cosmic impact of stars in general. In this talk, I will introduce a framework to develop synergy between 3D and 1D simulations, the so-called RA-ILES framework. I will end by presenting recent results obtained by applying this framework to convective boundary mixing, which is one of the most important uncertainties in the evolution of stars of all masses.

# $^{19}$F spectroscopy and implications for astrophysics

M. La Cognata[1]

[1] *Laboratori Nazionali del Sud - INFN, Catania, Italy*

In astrophysics, $^{19}$F plays a major role because of the diverse reactions where it is involved and of its abundance. This may be used as a probe of stellar nucleosynthesis, since production and destruction rates are very sensitive to the stellar interior physical conditions, especially in the case of asymptotic giant branch (AGB) stars and the s-process. In these stars, $^{19}$F is produced by the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ reaction chain, so the study of $^{15}\mathrm{N}+\alpha$ elastic scattering provides valuable clues about its synthesis, as the spectroscopic information can be used to constrain the resonance strengths and energies intervening in the calculation of the reaction rate.

$^{19}$F spectroscopy through $^{15}\mathrm{N}+\alpha$ elastic scattering is also important in the context of AGB stars, making it possible to constrain the cross section of the $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$ reaction and influencing the abundances of $^{18}$O, $^{19}$F and $^{15}$N. Finally, in explosive scenarios such as classical novae, the $^{15}\mathrm{N}+\alpha$ elastic scattering is important as it allows us to shed light on the spectroscopy of $^{19}$F mirror nucleus $^{19}$Ne, entering explosive nucleosynthesis through $^{18}\mathrm{F}+p$ capture reactions.

In this work [1], we report on the most extensive measurement and analysis of the $^{15}\mathrm{N}+\alpha$ elastic scattering, making it possible to span $^{19}$F excitation energies over a wide interval, from $\sim 5$ to $\sim 10$ MeV, as well as a broad angular range, to pin down unknown spin parities of observed states. The measurement was carried out through the thick target inverse kinematics method, and the experimental spectra fitted using the R-matrix approach. This analysis allowed us to suggest new spin parity assignments and to identify $^{19}$F states featuring $\alpha-$cluster structures also in the energy regions of astrophysical interest.

[1] M. La Cognata et al., Physical Review C **99**, 034301 (2019).

# Measurement of $^{20}$Ne(d,p)$^{21}$Ne for studies of s-process and neutron poisoning

Joseph Frost-Schenk,[1] A. Laird,[1] R. Longland,[2,3] C. Barton,[1] C. Diget,[1] C. Marshall,[2,3] F. Portillo,[2,3] and K. Setoodehnia[2,3]

[1] *University of York, York, UK*

[2] *Triangle Universities Nuclear Laboratory, NC, USA*

[3] *North Carolina State University, NC, USA*

The s-process in massive stars is an important source of heavy elements at low metallicities. Massive stars with very low metallicity depend largely on rotation induced mixing to produce light nuclei, such as $^{22}$Ne, which is the main source of neutrons for the s-process. Light nuclei are formed in the He burning phase and $^{16}$O is formed through $^{12}$C($\alpha$,$\gamma$). The $^{16}$O absorbs neutrons forming $^{17}$O and therefore competes with heavier s-process elements for available neutrons. The ratio of the subsequent $^{17}$O($\alpha$,$\gamma$) and $^{17}$O($\alpha$,n) dictates to what extent $^{16}$O behaves as a neutron poison, determining how many neutrons are available for the s-process.

States in the region of 7.65-8.00 MeV in $^{21}$Ne correspond to the Gamow window for the $^{17}$O($\alpha$,n)$^{20}$Ne reaction in the temperature range 0.2-0.3 GK. The spin-parity and neutron width of some of the $^{21}$Ne states in the Gamow window are unknown. Some of these states also have significant uncertainty in their energies.

We have conducted a measurement of the $^{20}$Ne(d,p)$^{21}$Ne reaction populating states in the Gamow window using the Triangle Universities Nuclear Laboratory Split-pole Spectrograph. Using this $^{20}$Ne(d,p)$^{21}$Ne reaction we have identified those states with significant neutron widths, hence those most relevant for $^{17}$O($\alpha$,n). Details will be presented on the measurements that were made at 5 angles; preselected using DWBA calculations to maximise the selectivity of spin-parity assignments to $^{21}$Ne states. Furthermore, we have determined the state energies in the astrophysically relevant excitation region and extracted their angular distributions. This work will ultimately lead to further information on $^{21}$Ne states and as such a better understanding of the role $^{16}$O has as a neutron poison for the s-process in massive stars.

# Spectroscopic Study of $^{39}$Ca for Classical Nova Endpoint Nucleosynthesis

J. Liang,[1] A. A. Chen,[1] M. Anger,[2] S. Bishop,[2] T. Faestermann,[2] C. Fry,[3] R. Hertenberger,[4] A. Psaltis,[1] D. Seiler,[4] P. Tiwari,[3] H-F. Wirth,[4] and C. Wrede[3]

[1]*Department of Physics and Astronomy,*
*McMaster University, Hamilton, Ontario L8S 4M1, Canada*

[2]*Department of Physics, Technical University Munich,*
*James-Franck-Str. 1, 685748 Garching, Germany*

[3]*Department of Physics and Astronomy,*
*National Superconducting Cyclotron Laboratory, Michigan State University,*
*640 S. Shaw Ln., East Lansing, MI 48864, USA*

[4]*Faculty of Physics, Ludwig-Maximilians-Universität München,*
*Geschwister-Scholl-Platz 1, 80539 Munich, Germany*

In classical nova nucleosythesis repeated proton capture reactions and beta-decays produce proton-rich isotopes and the endpoint of this nucleosynthesis typically occurs in nuclei close to A $\sim$ 40. There is currently a discrepancy between the observed and predicted isotopic abundances in this mass region. One particular reaction, $^{38}$K(p,$\gamma$)$^{39}$Ca is important in this regard. Nova simulations show that this reaction can alter the isotopic abundances of $^{38}$Ar, $^{39}$K, and $^{40}$Ca significantly when the reaction rate is varied by its maximum uncertainty. Thus, it is important to constrain uncertainties of this reaction rate to accurately predict isotopic abundances.
Although a recent direct measurement has reduced the reaction rate uncertainty, further work is needed to constrain this reaction rate. Specifically, additional measurements to precisely probe the low energy resonances within the Gamow window. To that end, I will present the preliminary results measuring these astrophysically important levels in $^{39}$Ca using the reaction $^{40}$Ca(d,t)$^{39}$Ca. The experiment was carried out at the Maier-Leibnitz-Laboratory (MLL) using the 14 MV MP-Tandem accelerator and Quadrupole 3-Dipole (Q3D) magnetic spectrograph.

# A new measurement of $^{17}$O$(\alpha, n)$ reaction

K. T. Macon,[1,2] A. Boeltzig,[1,2] R.J. deBoer,[1,2] J. Görres,[1,2] Q. Liu,[1,2]
M. Wiescher,[1,2] K. Brandenburg,[3] C.R. Brune,[3] Z. Meisel,[3] S. Burcher,[4]
K.L. Jones,[4] M. Febbraro,[5] R. Toomey,[6] S. Mosby,[7] and K. Smith[7]

[1] *Nuclear Science Laboratory, University of Notre Dame, Notre Dame, Indiana 46556, USA*

[2] *JINA - CEE, Notre Dame, Indiana 46556*

[3] *Edwards Accelerator Laboratory, Ohio University, Athens, Ohio 45701, USA*

[4] *University of Tennessee, Knoxville, TN 37996, USA*

[5] *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*

[6] *Rutgers University, Piscataway, New Jersey 08854, USA*

[7] *Los Alamos National Laboratory*

The weak s-process occurring in the core He-burning and shell C-burning phases of massive stars ($8M_\odot < M < 25M_\odot$) synthesizes a major portion of the elements in the $60 < A < 90$ mass range. The $^{17}$O$(\alpha, n)$ reaction affects the neutron production in the weak s-process by recycling neutrons lost to the most efficient neutron absorber $^{16}$O$(n, \gamma)^{17}$O. An experimental discrepancy was identified in a recent evaluation by P. Mohr in a combined analysis of the current available data and statistical model calculations for this reaction. To resolve this issue, we performed new cross section measurements using the Sta. ANA 5U accelerator at the University of Notre Dame Nuclear Science Laboratory. To determine the $^{17}$O$(\alpha, n_1)$ cross section, angular distributions of secondary gamma rays were measured for $E_\alpha > 1.4$ MeV with the HAGRiD (LaBr3:Ce) array. An array of deuterated liquid scintillator detectors was used to measure the $^{17}$O$(\alpha, n_0)$ cross section from $0.8 < E_\alpha < 1.5$ MeV. Detector response unfolding was used to obtain neutron energy spectra from the observed scintillator light output spectra. This enabled discrimination between neutrons from different final states of $^{20}$Ne and neutrons originating from background reactions. We will present new cross section results from the secondary gamma ray and neutron measurements resolving the data discrepancy, and a multichannel R-Matrix analysis will be used to better constrain the reaction rate.

# First measurement of the $^7$Li$(\gamma, t)^4$He cross section using mono-energetic $\gamma$-ray beams

Catalin Matei,[1] D.L. Balabanski,[1] S. Chesnevskaya,[1] G.L. Guardo,[1] D. Lattuada,[1] Y. Xu,[1] M. Munch,[2] S.D. Pain,[3] K.A. Chipps,[3] H.J. Karwowski,[4] C.Aa. Diget,[5] J. Frost-Schenk,[5] M. La Cognata,[6] R.G. Pizzone,[6] G.G. Rapisarda,[6] C.R. Brune,[7] and K.Y. Chae[8]

[1] *ELI-NP / IFIN-HH, Romania*

[2] *Aarhus University, Denmark*

[3] *Oak Ridge National Laboratory, USA*

[4] *University of North Carolina - Chapel HillL, USA*

[5] *University of York, UK*

[6] *INFN-Laboratori Nazionali del Sud, Italy*

[7] *Ohio University, USA*

[8] *Sungkyunkwan University, Korea*

The $^7$Li$(\gamma, t)^4$He cross section was measured for the first time using mono-energetic $\gamma$-rays with energies between 4.4 and 10 MeV at the High Intensity Gamma-ray Source (HI$\gamma$S) in USA. The reaction is important for the primordial Li-problem and for testing our understanding of the mirror alpha-capture reactions $^3$H$(\alpha, \gamma)^7$Li and $^3$He$(\alpha, \gamma)^7$Be. Most measurements over the last 30 years of the $^3$H$(\alpha, \gamma)^7$Li reaction have explored the energy range below $E_{cm} = 1.2$ MeV but measurements at higher energies could restrict the extrapolation to astrophysically important energies.

The experimental arrangement for measuring the $^7$Li$(\gamma, t)^4$He reaction at HI$\gamma$S included a large-area annular silicon detector array (SIDAR) and several beam characterization instruments. The SIDAR was arranged in a lampshade configuration with twelve YY1 silicon detectors of 300, 500, and 1000 $\mu$m thickness. The results are in disagreement with the previous experimental measurements in the same energy range but the extrapolated S-factor agrees with the adopted value. Details of the experiment at HI$\gamma$S will be presented together with perspectives for future measurements.

# Activation masurement of $\alpha$-induced cross sections for $^{197}$Au

T. Szücs,[1,*] P. Mohr,[1,2] Gy. Gyürky,[1] Z. Halász,[1,3] R. Huszánk,[1]
G. G. Kiss,[1] T. N. Szegedi,[1,3] Zs. Török,[1] and Zs. Fülöp[1]

[1] *Institute for Nuclear Research (MTA Atomki), H-4001 Debrecen, Hungary*

[2] *Diakonie-Klinikum, D-74523 Schwäbisch Hall, Germany*

[3] *University of Debrecen, H-4001 Debrecen, Hungary*

A reliable $\alpha$-nucleus potential is the essential prerequisite for the calculation of ($\gamma$,$\alpha$) reaction rates for heavy neutron-deficient nuclei. This defines the $\gamma$-process path which is responsible for the nucleosynthesis of rare neutron-deficient nuclei, the so-called $p$-nuclei. The $\alpha$-nucleus potential can be derived from the analysis of $\alpha$-elastic scattering and from the cross sections of $\alpha$-induced reactions.

The present experiment on $^{197}$Au extends previous studies towards heavier nuclei where the increasing Coulomb barrier leads to very small cross sections. The new results cover the energy range from about 13.5 to 20 MeV and thus reach the upper end of the Gamow window for stellar temperatures of $T_9 \approx 3$, whereas literature data for $^{197}$Au are available only at higher energies.

A combination of $\gamma$-ray and $X$-ray spectroscopy was used to identify the decays of the residual $^{201}$Tl, $^{200}$Tl, and $^{199}$Tl nuclei from the ($\alpha$,$\gamma$), ($\alpha$,n), and ($\alpha$,2n) reactions which are the dominating reaction channels. At some energies, the $X$-ray activity had to be followed over more than one month to disentangle the contributions of $^{199}$Tl, $^{200}$Tl, and $^{201}$Tl from their different half-lives.

Statistical model calculations were made using the TALYS code. From a strict $\chi^2$-based assessment of the cross sections in the different reaction channels, a set of parameters ($\alpha$-nucleus potential, nucleon-nucleus potential, $\gamma$-ray strength function, and level density) could be identified which provides the best description of the experimental data. The choice of these parameters allows to extrapolate the measured cross sections towards lower energies with significantly reduced uncertainties. A careful discussion of the remaining uncertainties will be provided.

* Present address: Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01328 Dresden, Germany

# On the lifetime of the remnant of GW170817, through the properties of the ejected mass

Antonios Nathanail,[1] Ramandeep Gill,[1,2] and Luciano Rezzolla[1]

[1]*Institut für Theoretische Physik, Max-von-Laue-Strasse 1, D-60438 Frankfurt, Germany*

[2]*Department of Natural Sciences, The Open University of Israel, 1 University Road, POB 808, Raanana, 4353701, Israel*

The main hard pulse of prompt gamma-ray emission in GRB 170817A had a duration of $\sim 0.5\,\mathrm{s}$ and its onset was delayed with respect to the gravitational-wave chirp signal by $t_{\rm del} \approx 1.74\,\mathrm{s}$. Detailed follow-up of the subsequent broadband kilonova emission revealed a two-component ejecta – a lanthanide-poor ejecta with mass $M_{\rm ej,blue} \approx 0.025\,M_\odot$ that powered the early but rapidly fading blue emission and a lanthanide-rich ejecta with mass $M_{\rm ej,red} \approx 0.04\,M_\odot$ that powered the longer lasting redder emission. Both the prompt gamma-ray onset delay and the existence of the blue ejecta with modest electron fraction, $0.2 \lesssim Y_e \lesssim 0.3$, can be explained if the collapse to a black hole was delayed by the formation of a hypermassive neutron star (HMNS). Here, we determine the survival time of the merger remnant by combining two different constraints, namely, the time needed to produce the requisite blue-ejecta mass and that necessary for the relativistic jet to bore its way out of the expanding ejecta. In this way, we determine that the remnant of GW170817 must have collapsed to a black hole after $t_{\rm coll} = 0.98^{+0.31}_{-0.26}\,\mathrm{s}$. We also discuss how future detections and the delays between the gravitational and electromagnetic emissions can be used to constrain the properties of the merged object.

# Precision mass measurements of neutron-rich nuclei for the r-process

D.A. Nesterenko,[1] A. Kankainen,[1] O. Beliuskina,[1] L. Canete,[1] T. Eronen,[1] M. Hukkanen,[1] A. Jokinen,[1] A. de Roubin,[1] M. Vilen,[1] the I201, I215, I220, and I226 experiment collaborations, and the IGISOL group

[1] *University of Jyväskylä, Department of Physics, Finland*

Nuclear masses, giving a direct access to nuclear binding energies, are one of the most sensitive nuclear physics inputs for the calculations of the astrophysical rapid neutron capture process ($r$-process) nucleosynthesis [1]. In this talk, we report on recent precision mass measurements of neutron-rich nuclei performed at the JYFLTRAP double Penning trap mass spectrometer at the IGISOL facility in the JYFL Accelerator Laboratory. Together with the standard Time-of-Flight Ion Cyclotron Resonance (TOF-ICR) technique, the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique is now routinely used at JYFLTRAP [2]. The recent mass measurements have focused on three regions. Firstly, the mass measurements of neutron-rich isotopes of Nd, Pm, Sm, Eu, Gd and Tb have reduced the uncertainties related to the $r$-process calculations for the rare-earth abundance peak [3]. Secondly, the masses of neutron-rich Ag, I and In isotopes have been measured. These nuclei lie close to doubly magic $^{132}$Sn region, which has been shown to have the highest impact on the calculated $r$-process abundances [1]. Thirdly, we have measured masses of neutron-rich Fe, Co, Ni, Cu and Zn isotopes in the vicinity of $^{78}$Ni, which are relevant for the study of core-collapse supernovae. Our measurements significantly reduce the uncertainties of the studied masses, some of which were measured for the first time.

[1] M. Mumpower et al., Prog. Part. Nucl. Phys. **86**, 86 (2016).

[2] D.A. Nesterenko et al., Eur. Phys. J. A **54**, 154 (2018).

[3] M. Vilen et al., Phys. Rev. Lett. **120**, 262701 (2018).

# The creation of the first r-process peak elements, effects of beta decay rates and nuclear masses

Stylianos Nikas,[1,2] G. Martinez-Pinedo,[1,2] and A. Sieverding[1,2]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*

[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany*

The r-process is responsible for the production of about half of the heavy elements observed in the solar abundances. The site of the r-process was unknown until recent observations. The gravitational wave event GW170817, which was identified as a binary Neutron Star Merger (NSM), was followed by the detection of fast fading optical counterpart that is consistent with predictions of a kilonova/macronova, associated with r-process nucleosynthesis. In particular the observation of a bright, fast fading ultra-violet component transitioning to near infared at late times, established the production of heavy element in the aftermath of the neutron star merger.

The complicated atomic structure of lanthanides implies high opacity ejecta which would shift the wavelength of the observed light to the red. The blue color emission of the ejecta at early times indicates the presence of material with low lanthanides abundance and consequently, relatively high electron fractions. We present a study of nucleosynthesis of moderately high $Y_e$ outflows from NSMs and we investigate the astrophysical conditions under which this could be the site for the production of the elements of the r-process abundance pattern for A $<$ 100. The effect of nuclear masses and beta decays on the abundance pattern is explored for a range of conditions consistent with simulations.

# Observational signatures of magneto-rotational supernovae associated with r-process jets

Nobuya Nishimura,[1] Jin Matsumoto,[2] Hidetomo Sawai,[3] and Tomoya Takiwaki[4]

[1] *YITP, Kyoto University, Kyoto 606-8502, Japan*

[2] *Department of Applied Physics, Fukuoka University, Fukuoka 814-0180, Japan*

[3] *Research Organization for Information Science & Technology, Kobe 650-0047, Japan*

[4] *National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*

Magnetically-driven supernovae of massive stars have been expected as a viable astrophysical site of heavy-elements, including r-process nuclei, as well as the central engine of gamma-ray bursts, magnetar formation, and other peculiar supernovae (e.g., superluminous supernovae). However, there has not been direct observation and detailed nucleosynthetic properties of this type of supernovae are still unclear.

In this talk, I show recent results of nucleosynthesis for magneto-rotational supernovae associated with jet-like explosions producing r-process nuclei. Using the simplified models for the r-process-rich inner ejecta based on our previous studies [1, 2], we extended propagation of the shock wave to the stellar surface and calculated complete sets of nucleosynthesis yields from lighter elements to r-process nuclei. We discuss the possibilities of observational constraints on the nucleosynthesis properties of magnetically-driven supernovae, e.g., chemical evolution of galaxies and the ejection process of radioactive nuclei.

---

[1] N. Nishimura, T. Takiwaki, and F.-K. Thielemann, The Astrophysical Journal **810**, 109 (2015).

[2] N. Nishimura, H. Sawai, T. Takiwaki et al., The Astrophysical Journal Letters **836**, L21 (2017).

# Isotopic Abundances in Presolar SiC Grains accounted by s-Processing from MHD-induced Mixing in low mass AGB stars

Sara Palmerini,[1,2] Maurizio Busso,[1,2] and Diego Vescovi[3,2]

[1]*Dipartimento di Fisica e Geologia Università degli Studi di Perugia, Italy*

[2]*I.N.F.N. sezione di Perugia, Italy*

[3]*Gran Sasso Science Institute, L'Aquila, Italy*

In the past years the observational evidence that s-process elements from Sr to Pb are produced by stars ascending the so-called Asymptotic Giant Branch (or AGB) could not be explained by self-consistent models, forcing researchers to extensive parameterizations. The crucial point is to understand how protons can be injected from the envelope into the He-rich layers, yielding the formation of $^{13}$C and then the activation of the $^{13}C(\alpha,n)^{16}O$ reaction. Only recently, attempts to solve this problem started to consider quantitatively physically-based mixing mechanisms. Among them, MHD processes in the plasma were suggested to yield mass transport through magnetic buoyancy. In this framework, we compare results of nucleosynthesis models for low mass AGB stars ($M \leq 3M_{\odot}$), developed from the MHD scenario, with the record of isotopic abundance ratios of s-elements in presolar SiC grains, which were shown to offer precise constraints on the $^{13}$C reservoir. We find that n-captures driven by magnetically-induced mixing can well account for the SiC data and that this is due to the fact that our $^{13}$C distribution fullfils the above constraints rather accurately. We show comparisons between model predictions and measurements for isotopes of Sr, Zr, Ba, Mo and Ru as representative examples of light and heavy s-elements.

# Nucleosynthesis of "light" heavy nuclei in neutrino-drive winds. Role of ($\alpha$,$n$) reaction rates.

J. Pereira,[1,2] A. Arcones,[3,4] J. Bliss,[3,4] and F. Montes[1,2]

[1]*National Superconducting Cyclotron Laboratory, MSU, East Lansing, MI 48824, USA*

[2]*Joint Institute for Nuclear Astrophysics, http://www.jinaweb.org*

[3]*Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, D-64291, Germany*

[4]*GSI Helmholtzzentrum für Schwerionenforschung,*

*GmbH, Plankstr. 1, Darmstadt, D-64291, Germany*

The observation of a kilonova (AT 2017gfo) associated with the gravitational-wave source GW170817 in the summer of 2017 provided direct evidence that heavy nuclei are synthetized in binary neutron-star mergers. Whereas this site is likely the host for the main r process, responsible for the robustness of the abundance pattern in the region past Z=56, other astrophysical sources might contribute to the production of lighter heavy elements around the so-called 1st peak (e.g. Sr, Y, Zr).

Neutrino-driven winds following core-collapse supernovae explosions have been proposed as a possible scenario where the synthesis of the so-called light heavy nuclei (between Fe and Ag) might occur. Steady-state model calculations, combined with nucleosynthesis reaction networks indicate a substantial sensitivity of the element abundances to ($\alpha$,$n$) reaction rates and the astrophysical conditions (e.g. alpha-to-seed and neutron-to-seed ratios). In this presentation, I will summarize the most relevant aspects of our study, emphasizing the ($\alpha$,$n$) nuclear reactions that have the most impact in the resulting abundances. Preliminary experimental results on some of these reactions will be briefly discussed.

# The Study of the $^{6}$Li(p,$\gamma$)$^{7}$Be Reaction at LUNA

Denise Piatti for LUNA Collaboration[1]

[1] *INFN of Padua, via Marzolo 8 35131 Padova, Italy*

The $^{6}$Li(p, $\gamma$)$^{7}$Be reaction is involved in several astrophysical scenarios such as the Big Bang Nucleosynthesis and $^{6}$Li destruction in pre-main and in main sequence stars.

A recent direct measurement of the $^{6}$Li(p, $\gamma$)$^{7}$Be cross section found a resonance-like structure at $E_{c.m.} = 195$ keV, corresponding to a $E_x \sim 5800$ keV excited state in $^{7}$Be [1]. This result has not been confirmed neither by other direct measurements nor by theoretical calculations [2, 3]

In order to clarify the existence of this resonance a new experiment was performed at the Laboratory for Underground Nuclear Astrophysics (LUNA), located under 1400 m of dolomite rocks of Gran Sasso. Thanks to the extremely low background environment the $^{6}$Li(p, $\gamma$)$^{7}$Be cross section can be measured down to low energies with unprecedented sensitivity.

The high intensity proton beam from the LUNA400kV accelerator was delivered to $^{6}$Li evaporated targets of different composition and thickness. To detect the gamma rays from the $^{6}$Li(p, $\gamma$)$^{7}$Be a HPGe detector was mounted in close geometry. In order to have a simultaneous detection of charged particles from the $^{6}$Li(p, $\alpha$)$^{3}$He channel a silicon detector was also used. Two independent Ion Beam Analysis techniques: Nuclear Reaction Analysis and Elastic Recoil Detection Analysis were performed at the Helmholtz Zentrum Dresden Rossendorf in Dresden to characterize the targets. The talk will provide a detailed description of the experimental setup. In addition preliminary results will be reported.

[1] J.J. He, et al., Phys. Lett. B **725**, 287-291 (2013).

[2] R.M. Prior, et al., Phys. Rev. C **70**, **70** 055801 (2004).

[3] F.C. Barker, Aust. J. Phys. **33**, 159 (1980).

# The $^7$Be$(\alpha,\gamma)^{11}$C with DRAGON for $\nu p$–process nucleosynthesis

A. Psaltis,[1] A. A. Chen,[1] D. S. Connolly,[2] B. Davids,[2] G. Gilardy,[3,4] R. Giri,[5] U. Greife,[6] W. Huang,[2,7] D. A. Hutcheon,[2] J. Karpesky,[6] A. Lennarz,[2] J. Liang,[1] M. Lovely,[6] S. N. Paneru,[5] C. Ruiz,[2] G. Tenkila,[8] and M. Williams[2]

[1] *McMaster University*
[2] *TRIUMF*
[3] *Joint Insitute for Nuclear Astrophysics, University of Notre Dame*
[4] *Université de Bordeaux*
[5] *Ohio University*
[6] *Colorado School of Mines*
[7] *University of Northern British Columbia*
[8] *University of British Columbia*

The production of the p–nuclei is one of the unsolved puzzles in nuclear astrophysics. A possible mechanism is the nucleosynthesis in the neutrino–driven winds of core–collapse supernovae ($\nu p$–process), but it carries uncertainties, mostly in the supernova dynamics and the nuclear physics input [1, 2]. The *pp*-chain breakout reaction $^7$Be$(\alpha,\gamma)^{11}$C, which occurs prior the supernova explosion, was identified as an important link which can influence the nuclear flow of the $\nu p$–process [2]. Nevertheless, its reaction rate is poorly known over the relevant energy range (T= 1.5-3 GK). To improve the $^7$Be$(\alpha,\gamma)^{11}$C rate for $\nu p$–process nucleosynthesis temperatures, the first direct measurement of resonances with unknown strength was recently performed at TRIUMF. A radioactive $^7$Be beam ($t_{1/2}$ = 53.24 d) beam and the DRAGON recoil separator were used [3]. The experimental details and preliminary results for the resonance strengths will be discussed.

[1] C. Fröhlich *et al.*, Phys. Rv. Lett. **96**, 142502 (2006).
[2] S. Wanajo, H.–T. Janka and S. Kubono, ApJ **729**, 46 (2011).
[3] D. A. Hutcheon *et al.*, Nucl. Instrum. Methods Phys. Res A, **498**, 190 (2003).

# On the chemical enrichment of dwarf spheroidal galaxies

Moritz Reichert⋆,[1] Camilla J. Hansen,[2] Martin Obergaulinger,[1,3] and Almudena Arcones[1,4]

[1] *Institut für Kernphysik, TU-Darmstadt*

[2] *Max-Plank Institute for Astrophysics, Heidelberg*

[3] *Departament d'Astonomia i Astrofísca, Universitat de València*

[4] *GSI Helmholtzzentrum, Darmstadt*

Dwarf galaxies can provide unique hints to understand the origin of r-process elements. Even if neutron star merger (NSM) have been confirmed as an r-process site, magneto-rotational-driven supernovae (MR SN) could also contribute to the production of heavy elements. Moreover, they could help explaining several observations that are difficult to reconcile with NSM alone. Our aim is to distinguish peculiar abundance trends that serve as a fingerprints of early r-process nucleosynthesis in NSM or possibly MR SN. Observational data from different studies could hide a possible trend within the elements due to different techniques when deriving stellar parameters. Therefore, we consistently determine the stellar parameters and abundances of Mg, Sc, Cr, Ni, Sr, Y, Ba and Eu of $\sim$ 400 stars contained in 12 different dwarf galaxies. Since these elements form within different production sites, we can reveal commonalities and unique chemical enrichments across different dwarf galaxies.

⋆ Supported by SFB 1245 and ERC Starting Grant EUROPIUM-677912

# CASPAR and DIANA: Recent and Future Underground Nuclear Astrophysics Results

Daniel Robertson,[1] Axel Boeltzig,[1] Tyler Borgwardt,[2] Manoel Couder,[1] Bryce Frentz,[1] Joachim Göerres,[1] August Gula,[1] Mark Hanhardt,[2] Thomas Kadlecek,[2] Chamaka Senarath,[2] Frank Strieder,[2] and Michael Wiescher[1]

[1] *Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, IN, 46556, United States*

[2] *Department of Physics, South Dakota School of Mines & Technology, Rapid City, SD, 57701, USA*

The broad field of Nuclear Astrophysics considers a wide range of stellar burning processes and nuclear interactions all feeding into the chemical evolution of our Universe. In order to probe such a diverse range of nuclear processes, a complementary set of experimental and theoretical tools must be developed. The profound difficulty in measuring low-energy reactions in the stellar burning regime highlights the need for the development of such techniques. Ongoing advancements consider higher intensity accelerators, more robust and isotopically enriched target material and lower background interference, to name a few. Underground Nuclear Astrophysics facilities such as CASPAR, utilize natural background suppression to extend current experimental data to the lower energies required. New facilities around the world are coming on-line with a view to capitalizing on underground cosmic-ray suppression, each offering unique techniques and capabilities. This talk will highlight recent and future CASPAR campaigns incorporting above and below ground measurements of reactions including $^{14}$N(p,$\gamma$), $^{11}$B($\alpha$,n), $^{22}$Ne($\alpha$,n) and $^{22}$Ne($\alpha$,$\gamma$).

# Electron-capture induced thermonuclear supernovae: explosion and nucleosynthesis

Friedrich K. Röpke,[1] Samuel Jones,[2] and Sebastian Ohlmann[3]

[1]*Institut für Theoretische Astrophysik,*
*Zentrum für Astronomie der Universität Heidelberg*
*and Heidelberg Institute for Theoretical Studies*

[2]*Los Alamos National Laboratory*

[3]*Max Planck Computing and Data Facility, Garching*

Electron capture reactions may lead to a gravitational collapse of a massive oxygen-neon white dwarf. At the same time, they initiate thermonuclear burning that can counteract this effect. Therefore, the fate of the star – a core-collapse supernova producing a neutron star or a thermonuclear explosion – is uncertain. We present three-dimensional hydrodynamic simulations of the propagation of thermonuclear flames in oxygen-neon white dwarfs aiming to answer this question. Predictions for nucleosynthesis yields from the expected events that can help to constrain the scenarios.

# Impact of the equation of state in core-collapse supernovae

Sabrina Schäfer,[1,2] Hannah Yasin,[1] Almudena Arcones,[1,3] and Achim Schwenk[1,2,4]

[1] *Institut für Kernphysik, Technische Universität Darmstadt*

[2] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

[3] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

[4] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

Neutron stars originate in core-collapse supernovae, which are one of the most energetic events in the universe. In core-collapse supernova simulations, the equation of state is a key ingredient. However, matter at high densities is only poorly constrained and the nuclear equation of state is still not fully understood. Equations of state that are available for supernova simulations differ considerably in their underlying theory as well as nuclear physics input. We investigate the impact of different nuclear matter properties on the equation of state in core-collapse supernovae. To this end, we introduce a range of equations of state based on the Lattimer and Swesty equation of state that vary the nucleon effective mass, incompressibility, symmetry energy, and nuclear saturation point. Larger effective masses lead to lower pressures at nuclear densities and a lower thermal index. This has an important impact on the proto-neutron star contraction and shock evolution.

*This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Projektnummer 279384907 - SFB 1245 and the European Research Council Grant No. 677912 EUROPIUM.

# Measurement of radiative $\alpha$-capture cross sections on $^{98}$Ru and $^{144}$Sm for $\gamma$-process nucleosynthesis

Philipp Scholz,[1] Felix Heim,[1] Marvin Körschgen,[1] Martin Müller,[1] and Andreas Zilges[1]

[1] *University of Cologne, Institute for Nuclear Physics, Cologne, Germany*

Since $p$ isotopes cannot be produced in neutron-capture reaction networks, a production mechanism via photodisintegration reactions was proposed - the $\gamma$ process. The specific path of this reaction network, however, depends strongly on the statistical averaged ratios for proton-, neutron-, and $\alpha$ decay widths. It was shown in the past, that especially the uncertainties in the $\alpha$ decay widths might have a huge impact on the isotopic abundance of the $\gamma$-process ashes. Besides systematic studies of the $\alpha$+nucleus optical-model potential, direct measurements of ($\alpha$,$\gamma$) reaction are needed to reduce the unpredictability of $(\gamma, \alpha)$ reaction rates.

In this talk, we will present preliminary results from direct measurements of the $^{98}$Ru($\alpha$,$\gamma$) and $^{144}$Sm($\alpha$,$\gamma$) cross sections via in-beam measurements at the University of Cologne and the Ruhr-Universität Bochum and activation experiments at the Physikalisch Technische Bundesanstalt in Braunschweig and the Technische Universität Dresden. The in-beam experiment might help to improve our understanding of the $\gamma$-process contribution to the $p$ nuclei in the $A \sim 100$ mass region, while the activation experiment is important for the dertermination of the initial isotopic abundance ratio of the $^{146}$Sm/$^{144}$Sm chronometer. Details on the different experimental techniques as well as the various setups in Cologne, Bochum, Braunschweig, and Dresden will be presented.

This work has been supported by the Deutsche Forschungsgemeinschaft under the contract DFG(ZI 510/8-1).

# First results from HECTOR: High EffiCiency TOtal absorption spectrometeR for p-process nucleosynthesis studies

A. Simon,[1,*] R. Kelmar,[1] O. Olivas-Gomez,[1] P. Millican,[1] E. Churchman,[1] C. S. Reingold,[1] S. Kelly,[1] S. L. Henderson,[1] A. Spyrou,[2] F. Naqvi,[1] A. Dombos,[1] A. Palmisano,[2] M. K. Smith,[1] D. Robertson,[2] E. Stech,[1] W. P. Tan,[1] T. Anderson,[1] A. M. Clark,[1] S. L. Henderson,[1] C. Seymour,[1] M. A. Skulski,[1] S.Y. Strauss,[1] and B. Vande Kolk[1]

[1]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, IN 46556-5670, USA*

[2]*NSCL, Michigan State University, East Lansing, MI 48824, USA*

The p-process is a nucleosynthesis scenario that occurs during an explosion of a supernova and produces the proton-rich isotopes of elements between Se and Hg. The p-process involves series of ($\gamma$,n), ($\gamma$,p) and ($\gamma$,$\alpha$) reactions on pre-existing s-process seed nuclei. The reactions relevant for the p-process can be studied in the laboratory via the inverse ones: the capture of protons or $\alpha$-particles. For these measurements, the High EffiCiency TOtal Absorption SpectrometeR (HECTOR) was developed at the University of Notre Dame.

HECTOR is a NaI(Tl) summing detector comprised of 16 separate NaI(Tl) crystals, each read by 2 photomultipliers. The array is designed for precision cross section measurements for (p,$\gamma$) and ($\alpha$,$\gamma$) reactions across the p-process Gamow window. The summing efficiency is a function of the total $\gamma$-ray energy and the average $\gamma$-ray multiplicity: for the $^{60}$Co, source it is 52.7 (2.0)% and for typical cross section measurements it ranges between 20-30%. The first measurements of the p- and $\alpha$-capture reactions on Pd and Cd proton-rich isotopes will be presented in this talk. The results will be compared to the cross sections obtained with other techniques, when available, and to the Hauser-Feshbach model calculations using the Talys code.

This work is supported by the NSF under grants number: PHY-1614442 (Simon), PHY-1713857 (NSL), PHY-1430152 (JINA-CEE).

* anna.simon@nd.edu

# Forbidden $^{20}$Ne $\rightarrow$ $^{20}$F electron capture in intermediate-mass stars

Dag F. Strömberg,[1,2] Gabriel Martínez-Pinedo,[1,2] Samuel Jones,[3,4] Oliver S. Kirsebom,[5] and Frédéric Nowacki[6]

[1] *Institut für Kernphysik, TU Darmstadt, Germany*

[2] *GSI Helmholtzzentrum für Schwerionenforschung, Germany*

[3] *Heidelberger Institut für Theoretische Studien, Germany*

[4] *X Computational Physics Division, LANL, USA*

[5] *Department of Physics and Astronomy, Aarhus University, Denmark*

[6] *Université de Strasbourg, CNRS, IPHC UMR 7178, France*

The range 7 to 11 solar masses bridge the gap between massive stars (which explode as core-collapse supernovae) and light stars (which end as CO white dwarfs). These intermediate-mass stars form degenerate ONe cores following carbon burning. In some cases the cores grow dense enough to trigger electron capture on various nuclei. Most notably, the double electron capture $^{20}$Ne $\rightarrow$ $^{20}$F $\rightarrow$ $^{20}$O releases enough heat to trigger runaway oxygen burning.

We show that the electron capture on $^{20}$Ne is triggered by the second-forbidden non-unique transition between the ground states of $^{20}$Ne and $^{20}$F. This transition has recently been measured and found to have a significant strength. Stellar models that take this measurement into account ignite oxygen off-centre and at lower densities compared with those without the forbidden transition. This increases the likelihood of a thermonuclear explosion with an ONeFe remnant as opposed to a collapse to a neutron star.

This work is supported by the Deutsche Forschungsgemeinschaft through the contract SFB 1245 and the EU COST Action CA16117.

# Study of the alpha-nucleus optical potentials used in the weak r-process nucleosynthesis models by the measurement of the $^{96}$Zr($\alpha$,n)$^{99}$Mo and $^{100}$Mo($\alpha$,n)$^{103}$Ru reaction cross sections

T.N. Szegedi,[1] G.G. Kiss,[1] and Gy. Gyürky[1]

[1] *Institue for Nuclear Research (ATOMKI), Debrecen, POB.51, 4001, Hungary*

In neutrino-driven winds above a nascent neutron star or after the merging of two neutron stars, light r-process elements may be formed at high temperatures in a very short time scale of the order of milliseconds. It was shown by sensitivity studies that this — so-called — weak r-process nucleosynthesis runs close to the valley of stability and stable isotopes between $^{56}$Fe and $^{109}$Ag can be synthesized via ($\alpha$,n) and ($\alpha$,xn) reactions [1–4].

The modelling of the weak r-process requires a large nuclear reaction network calculation, consisting of a few thousand reactions, in which the cross sections of the alpha-induced reactions are taken from the Hauser-Feshbach model using global alpha-nucleus optical model potentials (OMP). However, the use of different OMPs in the calculations can cause up to an order of magnitude discrepancy between the predicted cross sections [3, 4]. There is a lack of precise ($\alpha$,n) data in the $50 \leq A \leq 100$ mass region, therefore, to improve the reliability of the statistical model calculations, alpha-induced cross section measurements were carried out on two neutron-rich stable isotopes — $^{96}$Zr and $^{100}$Mo — at Atomki using the activation method. The experimental data as well as the comparison with cross section predictions calculated with OMPs used in the weak r-process network will be presented.

[1] Y. -Z. Qian and G. J. Wasserburg, Phys. Rep. **442**, 237 (2007).

[2] A. Arcones and F. Montes, Astrophys. J. **731**, 5 (2011).

[3] J. Bliss *et al.*, J. Phys. G: Nucl. Part. Phys. **44**, 054003 (2017).

[4] F. Pereira and F. Montes, , Phys. Rev. C **93**, 034611 (2016).

# NuGrid stellar data set: updated $s$-process nucleosynthesis

Ashley Tattersall,[1,2] U. Battino,[1,2] C. Lederer-Woods,[1,2] J. W. den Hartogh,[3,2]
P. Denisenkov,[4,5,2] F. Herwig,[4,5,2] R. Hirschi,[6,7,2] M. Pignatari,[8,3,5,2] and R. Trappitsch[9,2]

[1] *School of Physics and Astronomy, University of Edinburgh, UK*

[2] *The NuGrid collaboration, http://www.nugridstars.org*

[3] *Konkoly Observatory, Budapest, Hungary*

[4] *Department of Physics & Astronomy, University of Victoria, Canada*

[5] *Joint Institute for Nuclear Astrophysics, USA.*

[6] *Keele University, keele, ST5 5BG, UK*

[7] *Kavli IPMU (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

[8] *E.A. Milne Centre for Astrophysics, University of Hull, UK*

[9] *Nuclear and Chemical Sciences Division, LLNL, Livermore, CA 94551*

The abundances of the heavy elements beyond iron that we observe today in the solar system are mainly the result of the two nucleosynthesis processes: the slow neutron capture ($s$-) process and the rapid neutron capture ($r$-) process. Low-mass Asymptotic Giant Branch (AGB) ($2 < M/M_{\odot} < 3$) and massive ($M/M_{\odot} > 10$) stars have been identified as the sites of the $s$-process. We provide a new set of low-mass AGB models with initial masses $M/M_{\odot}$ = 2,3 and Z = 0.01, 0.02 and 0.03. Internal gravity wave mixing is the physics mechanism responsible for the formation of a $^{13}$C-pocket on average three times larger than our previous data set. Consequently the $s$-process production is significantly enhanced. Abundances are compared to other stellar datasets available in the literature and to a wide range of observations, including carbon-stars, barium stars, post-AGB stars, and pre-solar grains. The full nucleosynthesis was calculated in post-processing using the NuGrid mppnp code.

Oral contribution

# r-Process Sites and their Imprint in Galactic Chemical Evolution

Friedrich-Karl Thielemann[1,2]

[1] *University of Basel*

[2] *GSI Darmstadt*

From low metallicity stars and the presence of radioactive isotopes in deep-sea sediments we know that the main r-process, producing the heaviest elements, is a rare event. The question remains whether neutron star mergers, via GW170817 the only proven r-process site, are the only contributors. Early galactic evolution as well as variations in nucleosynthesis signatures, e.g. actinide boost stars, might indicate the need for other sites. We discuss and present the possible options.

# Modelling the formation of the $^{13}$C neutron source in AGB stars

Diego Vescovi[1,2,3] and Sergio Cristallo[3,2]

[1] *Gran Sasso Science Institute, Viale Francesco Crispi, 7, 67100, L'Aquila, Italy*

[2] *INFN, Section of Perugia, Via A. Pascoli snc, 06123, Perugia, Italy*

[3] *INAF, Observatory of Abruzzo, Via Mentore Maggini snc, 64100, Teramo, Italy*

Half of the elements heavier than iron are produced during the asymptotic giant branch (AGB) phase of low-mass stars through a series of slow neutron captures and $\beta$-decays. During this phenomenon, called $s$-process, Free neutrons are relased by the $^{13}$C($\alpha$, n)$^{16}$O reaction, which works at about 100 MK in radiative conditions. Currently, a major source of uncertainty in AGB models is the partial-mixing process of hydrogen, required for the formation of the so-called $^{13}$C pocket. Among the attempts to derive a self-consistent treatment of this physical process, there are 2D and 3D simulations of magnetic buoyancy [1]. The strong magnetic fields ($10^4$-$10^6$ G) requested by this formulation have been shown by the KEPLER mission to be typical of low mass stars [2]. The$^{13}$C pocket resulting from mixing induced by magnetic buoyancy extends over a region larger than those so far assumed, showing an almost flat $^{13}$C distribution and a negligible amount of $^{14}$N. Recently, it has been proved to be a good candidate to match the records of isotopic abundance ratios of $s$-elements in presolar SiC grains [3, 4]. However, up to date such a magnetic mixing has been applied in post-process calculations only [5], being never implemented in an stellar evolutionary code. Here we present new stellar models, performed with the 1-d hydrostatic FUNS evolutionary code [6], which include magnetic buoyancy. We comment the resulting $s$-process distributions and show preliminary comparisons to spectroscopic observations and pre-solar grains measurements.

---

[1] Nucci, M. C. and Busso, M., Astrophys. J. **787**, 141 (2014).

[2] Fuller, J., Cantiello, M., Stello, D. et al., Science **350**, 423-426 (2015).

[3] Palmerini, S., Trippella, O., Busso, M., Vescovi, D., et al., GCA **221**, 21-36 (2018).

# Neutron Capture Cross Section of $^{10}$Be

Meiko Volknandt,[1] Klaus Eberhardt,[2] Anne Endres,[1] Philipp Erbacher,[1] Matthias Fix,[1] Kathrin Göbel,[1] Tanja Heftrich,[1] Stefan Heinitz,[3] Enno Hrivula,[1] Arnd Junghans,[4] Franz Käppeler,[5] Christoph Langer,[1] Alberto Mengoni,[6] René Reifarth,[1] Stefan Schmidt,[1] Dorothea Schumann,[3] Benedikt Thomas,[1] Daniel Veltum,[1] Mario Weigand,[1] Norbert Wiehl,[2] and Clemens Wolf[1]

[1] *Goethe University Frankfurt, Germany*

[2] *University of Mainz, Germany*

[3] *Paul-Scherer-Insitut Villingen, Switzerland*

[4] *Helmholtz-Zentrum Dresden-Rossendorf, Germany*

[5] *KIT, Germany*

[6] *CERN, Switzerland*

The pattern of the solar abundances of nuclides features a conspicuous minimum in the region of the light elements Li, Be, and B. The main origin of these scarce elements are thought to be spallations of C, N and O in the interstellar and circumstellar matter by cosmic gamma rays. It is referred to as interstellar nucleosynthesis. However, it is essential for the understanding of how the big bang nucleosynthesis and nuclear reactions in stars contributed to the observed abundances, to determine the involved capture reaction cross sections in this mass area. One of those, which has not been measured so far, is the $^{10}$Be(n,$\gamma$) cross section.

The $^{10}$BeO sample with 6.6 $10^{19}$ $^{10}$Be atoms has been produced at PSI. The sample was irradiated in a cyclic activation at the TRIGA reactor in Mainz. The characteristic $\gamma$-rays following the decay of $^{11}$Be were measured using $LaBr_3$ scintillation detectors. The measurements were performed with and without cadmium wrapping to disentangle the thermal and epithermal components of the neutron flux.

An experiment to determine this cross section in the keV-regime is planned for this year at the Van de Graaff accelerator at the Goethe University Frankfurt. The $^{7}$Li(p,n) reaction at 1912 keV provides a neutron spectrum corresponding to a stellar environment with $kT = 25$ keV.

# First direct measurement of $^{56}$Ni($\alpha$,p)$^{59}$Cu to constrain X-Ray burst models

Louis Wagner[1] and the JENSA Collaboration[2]

[1] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA*

[2] *http://www.jensajet.org/collaboration/authors*

For a deeper understanding what drives nucleosynthesis in extreme astrophysical scenarios like X-Ray bursts, a variety of reaction rates of proton and alpha capture reactions with unstable isotopes have to be known. To a large extend they rely only on theoretical models with large uncertainties. Radioactive ion beam accelerators like at the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) provide great opportunities to study these reactions experimentally. The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas target system was constructed to take advantage of these low intensity beams at the National Superconducting Cyclotron Laboratory (NSCL) at MSU for direct measurements of capture and transfer reactions.

Sensitivity studies of Type I X-Ray burst models show that the reaction $^{59}$Cu(p,$\alpha$)$^{56}$Ni competes with the rp-process and has one of the greatest impacts on the burst light curve. The cross section of the reaction can be constraint by the time-inverse reaction $^{56}$Ni($\alpha$,p)$^{59}$Cu, because it is predicted that only the ground state is populated at astrophysical energies. The contribution presents preliminary results of the recent alpha capture experiment on $^{56}$Ni with JENSA that can constrain the uncertainty of nuclear physics input of X-Ray burst models. As an outlook the JENSA hydrogen operation upgrade for day-one experiments once FRIB is running will be discussed.

I acknowledge support from NSF grants PHY-1430152 (JINA Center for the Evolution of the Elements) and PHY-1565546 (NSCL).

# Sandblasting The R-process:Spallation Of R-process Nuclei Ejected From A NSNS Event

Xilu Wang,[1] Brian Fields,[2] Matthew Mumpower,[3]
Trevor Sprouse,[1] Rebecca Surman,[1] and Nicole Vassh[1]

[1] *University of Notre Dame, Notre Dame, IN 46556, United States*

[2] *University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States*

[3] *Los Alamos National Lab, Los Alamos, NM 87544, United States*

Neutron star mergers are r-process nucleosynthesis sites, which eject materials at high velocity ranging from 0.1c to 0.3c for different regions. Thus the r-process nuclei ejected from a neutron star merger event are sufficiently energetic to have spallation nuclear reactions with the interstellar medium particles. The spallation reactions tend to shift the r-process abundance patterns towards the solar data, and smooth the abundance shapes. The spallation effects depend on both the initial r-process nuclei conditions, which is determined by the astrophysical trajectories and nuclear data adopted for the r-process nucleosynthesis, and the propagation with various ejecta velocities and spallation cross-sections.

# Neutron sources for the i-process

Michael Wiescher[1]

[1] *University of Notre Dame, IN, USA*

The neutron source for the i-process is by definition the $^{13}$C($\alpha$,n) reaction. Yet, that should not exclude other alpha induced nuclear reactions that could contribute to the neutron flux in dynamic helium rich environments. A number of recent experimental studies and considerations will be presented discussing the $^{13}$C($\alpha$,n) and the possible contributions of other ($\alpha$,n) reactions on light nuclei.

# Long-time simulations of core-collapse supernovae

Hannah Yasin,[1] Maximilian Witt,[1] Carlos Mattes,[1] Moritz Reichert,[1]
Almudena Arcones,[1,2] Martin Obergaulinger,[1] and Sean Couch[3]

[1]*Institut für Kernphysik, Technische Universität Darmstadt*

[2]*GSI Helmholtzzentrum für Schwerionenforschung*

[3]*Department of Physics and Astronomy, Michigan State University*

Core-collapse supernovae (CCSN) are one of the most energetic events in the universe. They provide conditions extreme enough to produce elements up to silver, and maybe heavier. Numerical simulations of these events are essential to understand the conditions that are relevant for nucleosynthesis, where especially the late-time evolution of the explosion (up to several seconds after bounce) plays an important role.

We perform a systematic study of the impact of neutrinos and rotation on the long-time CCSN evolution, following the shock expansion up to five seconds after bounce. Our results indicate that rotation impacts mass accretion rates and reduces neutrino luminosities, as suggested in previous studies. This has an important impact on the ejected matter and its nucleosynthesis. Moreover, our broad study based on over 20 two-dimensional simulations, provides unique new information of supernova nucleosynthesis and uncertainties.

Supported by the Deutsche Forschungsgemeinschaft through SFB 1245 (Projektnummer 279384907) and the European Research Council Grant No. 677912 EUROPIUM.

# From the crust to the core of Neutron stars with Quark-meson coupling model

Sofija Antic,[1] Jirina R. Stone,[2,3] and Anthony W. Thomas[1]

[1] *CSSM, Department of Physics, University of Adelaide SA 5005 Australia*

[2] *Department of Physics (Astro), University of Oxford, OX1 3RH United Kingdom*

[3] *Department of Physics and Astronomy, University of Tennessee, TN 37996 USA*

The Neutron star physics has been going through some remarkable progress in the recent years, with much more yet to come through the novel observations and data on these natural 'laboratories' of cold dense matter. To describe them, we are introducing the quark-meson coupling (QMC) model [1] where nuclear medium effects are treated through modification of the internal structure of the nucleon. Within this novel approach the QMC EDF depends on a single set of only four adjustable parameters, which have clear physical basis, and give results of similar quality as the (non)relativistic MF models or EDF approaches. The model was already successfully applied to the ground state calculations of finite nuclei [2] and to predict the cold non-rotating neutron stars properties [3].

The latest advances of QMC model will be presented when applied to the NS physics, starting from the nuclei sequence calculation for NS outer crust, elaborating on the challenges to describe the inner crust and going up to the high densities in the cores of todays heaviest known neutron stars, exploring the insights for the QMC model coming from GW measurements [4].

---

[1] P.A.M. Guichon, J.R. Stone, A.W. Thomas, Prog. Part. Nucl. Phys. **100**, 262-297 (2018).

[2] J.R. Stone, P.A.M. Guichon, P.G. Reinhard, A.W. Thomas, Phys. Rev. Lett. **116**, no. 9 (2016).

[3] J.R. Stone, P.A.M. Guichon, H.H. Matevosyan, A.W. Thomas, Nucl. Phys. A **792**, 341 (2007).

[4] T. Motta, A.M. Kalaitzis, S. Antić, P.A.M Guichon, J.R. Stone, A.W. Thomas, arXiv:1904.03794 (2019).

# $^{80}$Se(n,$\gamma$) cross-section measurement at n_TOF (CERN)

V. Babiano-Suarez,[1] C. Domingo-Pardo,[1] L. Caballero,[1] I. Ladarescu,[1] J.L. Tain,[1] F. Calviño,[2] A. Casanovas,[2] A. Segarra,[2] A. Tarifeño Saldivia,[2] C. Guerrero,[3] , J. Lerendegui-Marco,[3] M.A. Millan-Callado,[3] J.M. Quesada,[3] M.T. Rodríguez-González,[3] S. Heinitz,[4] E.A. Mauregui,[4] R. Dressler,[4] N. Kivel,[4] D. Schumann,[4] U. Köster[5],[5] and The CERN n_TOF Collaboration

[1]*IFIC (CSIC-University of Valencia), Spain*

[2]*UPC-Barcelona, Spain*

[3]*University of Seville, Spain*

[4]*Paul Scherrer Institut (PSI), Villigen, Switzerland*

[5]*Institut Laue-Langevin (ILL), Grenoble, France*

We have measured the $^{80}$Se(n,$\gamma$) cross section with high accuracy and high resolution at CERN n_TOF over the full energy range of astrophysical interest. These data are needed for a consistent interpretation of the temperature-sensitive s-process branching at $^{79}$Se. The latter represents a key branching point in the nucleosynthesis of heavy elements during core He-burning and shell C-burning in massive stars. In particular, the $^{80}$Se cross section affects the stellar yield of the "cold" s-only branching product in this region, namely $^{82}$Kr. There exists only one previous TOF measurement on $^{80}$Se, which however suffers of low resolution and insufficient completeness. New preliminary cross-section results will be presented together with a discussion of their possible astrophysical impact.

# Investigation of the $^{7}$Li(p,n) neutron fields at high energies

Benjamin Brückner,[1] P. Erbacher,[1] K. Göbel,[1] T. Heftrich,[1] K. Khasawneh,[1] D. Kurtulgil,[1] C. Langer,[1] R. Nolte,[2] M. Reich,[1] R. Reifarth,[1] M. Weigand,[1] M. Wiescher,[3] and M. Volknandt[1]

[1] *Goethe University, Frankfurt am Main, Germany*

[2] *Physikalisch Technische Bundesanstalt, Braunschweig, Germany*

[3] *University of Notre Dame, Notre Dame, USA*

The neutron activation method has been proven to be a well-suited tool for the investigation of neutron capture cross sections relevant for the main s-process component. Neutrons can be produced via $^{7}$Li(p,n) reaction facilitating Van de Graaf accelerators and metallic lithium targets. This can produce a Maxwellian spectrum of neutrons corresponding to a temperature of $k_B T = 25\,\mathrm{keV}$, mimicking the s-process scenario in low-mass asymptotic giant branch (AGB) stars. The weak s-process however takes place in massive stars at temperatures between 25 and 90 keV. Until now the recreation of quasi-stellar neutron spectra with higher energies via the $^{7}$Li(p,n) reaction were unsuccessful. Simulations using the PINO[1] code however suggested that a Maxwellian spectrum corresponding to $k_B T = 90\,\mathrm{keV}$ can be resembled by a linear combination of various different neutron spectra. The resulting spectrum averaged cross sections can then be combined to a 90 keV Maxwellian Averaged Cross Section (MACS). In order to validate the PINO code at these higher energies, measurements were carried out at the PTB Ion Accelerator Facility (PIAF) in Braunschweig. The neutron fields could be measured using a pulsed proton beam and three $^{6}$Li-glass scintillation detectors which were mounted at different angles. The neutron energy was determined by time-of-flight (TOF).

---

[1] R. Reifarth et. al., Nuclear Instruments and Methods in Physics Research A **608**, 139 (2009).

# N-BODY CODE IMPLEMENTATION OF LARGE SCALE GRAVITATIONAL POTENTIAL SCREENING

Alvina Burgazli,[1] Maxim Eingorn,[2] and Alexander Zhuk[3]

[1]*Astronomical Observatory, Odesa National University, Dvoryanskaya st.2, Odesa 65082, Ukraine*

[2]*Department of Mathematics and Physics, North Carolina Central University, Fayetteville st. 1801, Durham, North Carolina 27707, U.S.A.*

[3]*Department of Physics, Istanbul Technical University, Maslak 34469 Istanbul, Turkey*

There was considered the Universe filled with cold dark matter in the form of discrete inhomogeneities (e.g., galaxies) and dark energy in the form of arbitrary continuous perfect fluids. The background space-time geometry is defined by the Friedmann metric. It was developed the first-order scalar and vector cosmological perturbation theory in the weak gravitational field. Such approach works at all cosmological scales and incorporates linear and nonlinear effects with respect to energy density fluctuations. The gravitational potentials produced by matter fluctuations are characterized by a finite time-dependent Yukawa interaction range being the same for each individual contribution and which is of the order of 3700 Mpc at the present time. Therefore, the gravitational potential of the n-th fluctuation is exponentially suppressed at such scales. This suppression is called the cosmological screening. At smaller scales the Newtonian expression for the gravitational potential was reproduced.. The gravitational potential screening at large scales was implemented in an N-body code by adding the cosmological screening for taking into account Yukawa suppression on a large scale by the dynamic evolution of density perturbations.

# The Early Generations of Rotating Massive Stars and the Abundances of Extremely Metal-Poor Stars

Arthur Choplin[1]

[1]*Department of Physics, Faculty of Science and Engineering, Konan University, 8-9-1 Okamoto, Kobe, Hyogo 658-8501*

The study of the long-dead early generations of massive stars is crucial in order to obtain a complete picture of the chemical evolution of the Universe. The nature of these stars can be inferred indirectly by investigating the origin of low-mass metal-poor stars observed in our neighborhood, some of which are almost as old as the Universe. The material forming these low-mass metal-poor stars is generally thought to have been inherited from the ejecta of one or very few previous massive stars. I will show how the physics - especially rotation and nucleosynthetic processes - of the early generations of massive stars may be constrained by combining stellar evolution models including s-process and rotation with observations of metal-poor stars. A new abundance fitting analysis of about 200 extremely metal-poor stars will be discussed. From this study can be derived the characteristics of the best massive star progenitors, in particular their velocity distribution.

# Measurement of the $^{14}N(\alpha,\gamma)^{18}F$ Reaction with the St. George Recoil Separator

M. Couder,[1] C. Seymour,[1] G. P. A. Berg,[1] A. C. Dombos,[1] G. Gilardy,[1] J. Hinnefeld,[2] P. Huestis,[1] L. Morales,[1] S. Moylan,[1] D. Robertson,[1] M. Skulski,[1] and M. Wiescher[1]

[1]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, IN 46556, United States*

[2]*Department of Physics, Indiana University South Bend, South Bend, IN 46634, United States*

The study of low energy radiative capture reactions is of prime interest for many nuclear astrophysics scenarios. St. George, a recoil separator dedicated to the study of $(\alpha,\gamma)$ reactions, has been built and commissioned. We will discuss the recent measurement of well-known resonances in the $^{14}N(\alpha,\gamma)^{18}F$ reaction. This study finalizes the commissioning phase of St. George. The results obtained and future measurements will be presented.

# On Barium stars and the s-process in AGB stars

Borbála Cseh,[1] Maria Lugaro,[1] Valentina D'Orazi,[2] Denise B. de Castro,[3] Claudio B. Pereira,[4] Amanda I. Karakas,[5] László Molnár,[1] Emese Plachy,[1] and Róbert Szabó[1]

[1]*Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1121 Budapest, Hungary*

[2]*INAF Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy*

[3]*Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences, 00-716 Warsaw, Poland*

[4]*Observatorio Nacional, Rua General Jos Cristino, 77 Sao Cristovao, Rio de Janeiro, Brazil*

[5]*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, VIC 3800, Australia*

Barium stars belong to a binary system where the companion star has evolved through the AGB phase and transferred elements heavier than Fe produced by the slow neutron-capture process onto the secondary star, which is now observed. A new large set of homogeneous high resolution spectra of Ba stars makes it now possible to meaningfully compare the observational data with different AGB models and with other observations (e.g., post-AGB stars or stardust grains). The Ba star data shows an incontestable increase of the hs-type/ls-type element ratio (for example, [Ce/Y]) with decreasing the metallicity. The trend in the Ba star observations is predicted by non-rotating AGB models where $^{13}$C is the main neutron source. Observations of the cores of red giant stars and of white dwarfs (the ancestors and the progeny of AGB stars, respectively) inferred via asteroseismology from Kepler observations show low core rotational velocities, which is in agreement with the results from the Ba star data and may derive from coupling between the core and the envelope.

# Electron screening effect

A. Cvetinović,[1] M. Lipoglavšek,[1] and I. Tišma[1]

[1] *Jožef Stefan Institute, Slovenia*

In nuclear reactions induced by low-energy charged particles, atomic electrons can participate in the process by screening the nuclear charge and so, effectively reduce the repulsive Coulomb barrier. Consequently, the measured cross section is enhanced by an effect called electron screening. In numerous experiments, different research groups obtained extremely high values of electron screening, that are in several cases (depending on target-nuclei environment) more than an order of magnitude above the prediction based on available theoretical model in adiabatic limit.

Trying to understand this process, the effect of electron screening has been investigated by our group for already several years. We measured the highest value of electron screening in a graphite target. The measured value is about a factor of 50 above the adiabatic limit prediction and much higher than any potential measured so far. Further, our results pointed out that the $Z$ dependence of the screening is even higher than $Z^2$ instead of expected linear dependence. This rules out the theory based on static electron densities. In order to explain our data, we proposed a new model assuming that an electron is caught in the attractive potential of the two approaching nuclei, similar to the potential of the hydrogen molecular ion. Most recently, we observed a new type of nuclear reaction supporting our model of electron screening process. Namely, we studied the proton induced nuclear fusion reaction on deuterium implanted in a graphite target, which normally produces a 3He nucleus and a $\gamma$-ray, but sometimes an electron can be emitted instead of a $\gamma$-ray. Up to now we observed such electrons only in a graphite target, but in order to confirm our findings under different experimental conditions, we plan to study this process with deuterium implanted in a titanium target. However, in order to keep the experiment under known conditions, we first have to understand electron screening in titanium. For this purpose we measured the $^{11}$B(d,p)$^{12}$B, $^{16}$O(d,p)$^{17}$O and $^{19}$F(d,p)$^{20}$F reactions in inverse kinematics. Our latest results will be presented.

# The Lane Emden physical model with fractional calculus approach

Zoubir Dahmani[1] and Yasmine Bahous[2]

[1]*Laboratory LPAM, Faculty os SEI, University of Mostaganem*

[2]*Department of MI, University of Mostaganem*

In this presentation, we are concerned with a generalized Lane Emden problem of factional order type. We begin by proving some existence results. Then, based on some new fractional concepts, we study the stability of solutions for the problem. Some applications are discussed.

# Nucleosynthesis in advective accretion disc and outflow: possible explanation for overabundances in winds from X-ray binaries

Sudeb Ranjan Datta[1] and Banibrata Mukhopadhyay[1]

[1]*Indian Institute of Science, Bangalore, India*

Multiple spectroscopic lines of different elements observed in winds from X-ray binaries (XRBs), based on one zone model, indicate super-solar abundance of elements, e.g. Mg, Si, S, Ar, Ca, Cr, Mn, Co. The one zone model considers similar hydrodynamics of underlying winds. In order to find a possible origin of these overabundances, we explore nucleosynthesis in advective, geometrically thick, sub-Keplerian, accretion disc in XRBs and active galactic nuclei (AGNs), and further in outflows launched from the disc. Based on flow hydrodynamics and solving nuclear network code therein by semi-implicit Euler method, we obtain abundance evolution of the elements. Although the density is very low, due to very high temperature of advective disc than Keplerian Shakura-Sunyaev disc (SSD), it is quite evident that significant nucleosynthesis occurs in the former. As the temperature at the base of the outflow is constrained by the temperature of disc, nucleosynthesis also occurs in the outflow contingent upon its launching temperature. Till now, the outer region of XRB and AGN discs is understood to be colder SSD and inner region to be advective disc, together forming a disc-wind system. Hence, newly evolved abundances after processing through outflow can change the abundances of different elements present in the environment of the whole disc-wind system. We find 2-6 times overabundant Mg, Si, Ar, Cr with respect to the respective solar abundances, which is consistent observationally. Thus for most XRBs, when only iron lines are present, inclusion of these evolved abundances is expected to change the observational analysis drastically.

---

[1] S.R. Datta & B. Mukhopadhyay, MNRAS **486**, 1641-1651 (2019).

# MNT reactions at ion catcher facilities - a new way to produce and study heavy neutron-rich nuclei

T. Dickel,[1,2] A. Kankainen,[3] D. Amanbayev,[1] O. Beliuskina,[3] P. Constantin,[4] H. Geissel,[1,2] L. Gröf,[1] C. Hornung,[1] A. Karpov,[5] I. Mardor,[6] G. Münzenberg,[2] D. Nichita,[4] I. Pohjalainen,[3] S. Purushothaman,[2] W. R. Plaß,[1,2] M. Reponen,[3] A. Rotaru,[4] C. Scheidenberger,[1,2] A. Spataru,[2,4] J. S. Winfield,[2] A. Zadvornaya,[3] and the Super-FRS Experiment and IGISOL Collaborations

[1] *Justus Liebig University, Giessen, Germany*

[2] *GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany*

[3] *University of Jyväskylä, Finland*

[4] *IFIN-HH/ELI-NP, Magurele - Bucharest, Romania*

[5] *JINR, Dubna, Russia*

[6] *SOREQ, Yavne, Israel*

Heavy neutron-rich nuclei play a key role in the formation of the third abundance peak in the astrophysical rapid neutron capture process. Producing very neutron-rich isotopes that are heavier than fission fragments is a big experimental challenge, because the conventional methods (fragmentation, spallation and fusion) preferably produce neutron-deficient nuclei. Multi-nucleon transfer reactions (MNT), with energies above the Coulomb barrier, between medium-heavy to heavy beams and heavy targets have been suggested and investigated as a possible alternative method. The nuclides produced in MNT reactions can be thermalized in gas-filled stopping cells and delivered as cooled high quality beams to decay, laser and mass spectrometry experiments. In this way their ground and isomeric state properties can be studied in high precision measurements. The method has been pioneered at the KISS experiment at RIKEN, Japan. In experiments at IGISOL, Finland and the FRS Ion Catcher, Germany, we will perform broadband measurements of the reaction products, with the aim to improve the understanding of the reaction mechanism and determining the properties of the ground and isomeric states of the produced nuclides. First results and plans for approved experiments will be presented.

# The Stellar $^{72}\mathrm{Ge}(n,\gamma)$ Cross Section for weak s-process: A First Measurement at n_TOF

Mirco Dietz,[1] C. Lederer-Woods,[1] and the n_TOF Collaboration[2]

[1] *School of Physics and Astronomy, University of Edinburgh, United Kingdom*

[2] *European Organization for Nuclear Research (CERN), Switzerland*

The slow neutron capture process (s-process) is responsible for producing about half of the elemental abundances heavier than iron in the universe. Neutron capture cross sections on stable isotopes are a key nuclear physics input for s-process studies. The $^{72}\mathrm{Ge}(n,\gamma)$ Maxwellian Averaged Cross Section (MACS) has an important influence on production of isotopes between Ge and Zr in the weak s-process in massive stars [1] and so far only theoretical estimations are available [2].

An experiment was carried out at the neutron time-of-flight facility n_TOF [3] at CERN to measure the $^{72}\mathrm{Ge}(n,\gamma)$ reaction for the first time at stellar neutron energies. At n_TOF, the neutron beam has a large energy range (few meV to several GeV). The capture measurement was performed using an enriched $^{72}\mathrm{GeO_2}$ sample at a flight path length of 184 m, which provided high neutron energy resolution. The prompt gamma rays produced after neutron capture were detected with a set of liquid scintillation detectors ($C_6D_6$). The neutron capture yield is derived from the counting spectra taking into account the neutron flux and the gamma-ray detection efficiency using the Pulse Height Weighting Technique [4].

Over 70 new neutron resonances were identified, providing an improved resolved reaction cross section to calculate MACSs. I will present the experiment, data analysis and first results for MACSs, including their impact on stellar nucleosynthesis.

[1] M. Pignatari *et al.*, The Astroph. J. **33**, 1557-1577 (2010).

[2] I. Dillmann et al., Nuclear Data Sheets **120**, 171-174 (2014); (http://www.kadonis.org).

[3] C. Guerrero *et al.*, Eur. Phys. J. A **49**, 27 (2013).

[4] U. Abbondanno *et al.*, Nucl. Instr. Meth. Phys. Res. A **521**, 454-467 (2004).

# Position-sensitive resonant Schottky cavity

D.Dmytriiev,[1,2] M.S.Sanjari,[1] and Yu. A. Litvinov[1,2]

[1] *GSI Helmholtzzentrum fr Schwerionenforschung, 64291 Darmstadt, Germany*

[2] *Universitt Heidelberg, Germany*

Studying the rapid neutron capture process (r-process) in stellar environments, that leads to the creation of elements heavier than 56-Fe, remains one of the fundamental questions of modern physics and therefore an active field of research within nuclear astrophysics. Apart from other key measurables like neutron capture cross section and decay lifetimes, nuclear masses are of outmost importance for pinpointing the r-process using theoretical and experimental approaches. Exotic nuclides which participate in the r-process due to their low production yield and short half-life can be efficiently investigated in storage rings. In such facilities non-destructive methods of particle detection are often used for in-flight measurements based on frequency analysis. Apart from their applications in the measurements of beam parameters, they can be used in non-destructive in-ring decay studies of radioactive ion beams. Due to the low signal level the detectors should be very sensitive and fast because of short lifetime of the particles. Resonant Schottky cavity pickups fulfill such requirements. In addition, position sensitive Schottky pick-up cavities can enhance precision in the isochronous mass measurement technique. The goal of this work is to design such a position sensitive resonant Schottky cavity pickup based on theoretical calculations and simulations. Keywords: storage rings, Shottky detector, ion beam measurement

# The cosmic journey of iridium

Thorsten Döhring[1]

[1] *TH Aschaffenburg - University of Applied Sciences, Aschaffenburg, Germany*

Iridium is an extraordinary material with very special qualities. Therefore this noble metal is the material of choice for many technical applications on Earth. Within this conference contribution the life cycle of iridium is presented. All iridium atoms in the universe are initially born via the r-process in extreme cosmic events; thereby the majority of iridium is produced in the collision of two neutron stars [1]. On Earth iridium is quite rare, only about 0.4 ppm of Earths crust is made from this material. However, geologically there is a remarkable iridium anomaly found in the Cretaceous-Tertiary boundary layer, where the amount of iridium increases by a few orders of magnitude. The common hypothesis to explain this strange anomaly is the impact of a heavy meteoroid in the Gulf of Mexico about 65 million years ago [2]. This catastrophic event distributes the higher iridium content of the impactor allover Earths surface and probably caused the extinction of the dinosaur. Today about ten tons of iridium per year are used for technical applications worldwide. Here especially the space applications of iridium are of interest. At Aschaffenburg University iridium coatings are developed as reflection layers for space based X-ray telescopes [3]. Via such iridium coated mirrors the X-ray pattern of the merger of two neutron stars could be observed, where fresh iridium atoms are born. Iridium has been also used as cover material for the thermonuclear batteries of the Voyager space probes - which are just leaving our solar system [4]. So the cosmic journey of iridium is really a fascinating round trip from stars to Earth and into space again.

---

[1] A. Frebel and T. C. Beers, Physics Today **71(1)**, 16 (2018).

[2] C. Koeberl and K. G. MacLeod, Catastrophic Events and Mass Extinctions (2002).

[3] T. Döhring et al., Proceedings of SPIE **10235**, 1023504 (2017).

[4] W. R. Kanne, Welding Journal **62**, 17 (1983).

# The Preliminary Atmospheric Parameters of HD 154713 and HD 137928

Aslı Elmaslı,[1] Şeyma Çalışkan,[1] and Kübraözge Ünal[1]

[1] *Ankara University, Turkey*

We determined the preliminary atmospheric parameters of the two A-type stars HD 154713 and HD 137928. These stars high resolution echelle spectra, covering a wavelength range of 3500-7900 $\mathring{A}$, were obtained from the Coude echelle spectrograph attached to the 1.5m telescope at the TÜBITAK National Observatory on the $24^{th}$ of April 2018. We calculated the effective temperature and surface gravity of both stars by making use of photometric calibrations applied to Strömgren colors. The model atmospheres were generated by using the ATLAS9 code in Local Thermodynamic Equilibrium. The synthetic spectra produced from SYNTHE were used to fit on the observed H beta profiles to compare its compatibility. The iron lines equivalent widths were measured from each observed stellar spectra to derive their metallicities and microturbulences.

# Study of the $^{2}$H(p,$\gamma$)$^{3}$He cross section at $E_\mathrm{p} = 400\,\mathrm{keV}$ - $800\,\mathrm{keV}$

Sebastian Hammer,[1,2] Eliana Masha,[3] S. Akhmadaliev,[2] D. Bemmerer,[2] F. Cavanna,[4] P. Corvisiero,[4] R. Depalo,[5] F. Ferraro,[4] M. Grieger,[2] A. Guglielmetti,[3] C. Gustavino,[6] T. Hensel,[2] J. Julin,[2] M. Koppitz,[1,2] F. Ludwig,[2] L. Marcucci,[7] V. Mossa,[8] F. Munnik,[2] R. Schwengner,[2] K. Stöckel,[2] T. Szücs,[2] S. Turkat,[1] L. Wagner,[2] and K. Zuber[1]

[1] *Technische Universität Dresden, Germany*

[2] *Helmholtz - Zentrum Dresden - Rossendorf, Germany*

[3] *INFN Sezione di Milano and Università degli Studi di Milano, Italy*

[4] *INFN Sezione di Genova and Università degli Studi di Genova, Italy*

[5] *INFN Sezione di Padova and Università degli Studi di Padova, Italy*

[6] *INFN Sezione di Roma, Italy*

[7] *INFN Sezione di Pisa and Università degli Studi di Pisa, Italy*

[8] *INFN Sezione di Bari and Università degli Studi di Bari, Italy*

The production of deuterium marks a crucial step for the nucleosynthesis of light elements during the Big Bang Nucleosynthesis (BBN). The precision on the deuterium abundance is currently limited by the uncertainty of its destruction via the $^{2}$H(p,$\gamma$)$^{3}$He - reaction . Furthermore, in the considered energy range there is only one experimental data set available , which was conducted in 1962.

The present work reports on a recently performed experimental study on the $^{2}$H(p,$\gamma$)$^{3}$He cross section at energies of $E_\mathrm{p} = 400$ - $800\,\mathrm{keV}$. This range snuggles into the energy window which is most important for the BBN. For this purpose, a proton beam was provided by the 3 MV Tandetron accelerator at the Helmholtz - Zentrum Dresden - Rossendorf in January 2018, where a solid target experiment with deuterated titanium samples was performed. The emitted $\gamma$ - rays were detected by two high - purity germanium detectors. The amount of target atoms was determined in situ by the Nuclear Reaction Analysis using the $^{2}$H($^{3}$He,p)$^{4}$He - reaction and the Elastic Recoil Detection Analysis.

# Partial cross sections of $^{181}$Ta(n,$\gamma$) using BEGe detectors

Tanja Heftrich,[1] Benjamin Brückner,[1] Asmaa El Mard,[1] Kathrin Göbel,[1] Deniz Kurtulgil,[1] Timotheus Kisselbach,[1] Christoph Langer,[1] René Reifarth,[1] Silas Sheriff,[1] Meiko Volknandt,[1] and Mario Weigand[1]

[1] *Goethe Universität Frankfurt, Frankfurt*

Heavy nuclei are mainly synthesised by a sequence of neutron captures and beta decays - the s-process. The corresponding neutron energies in the different astrophysical sites range from 1 keV to 1 MeV. By using the activation technique, neutron capture reactions of small samples can be studied. A sample is irradiated by quasi stellar neutrons in order to produce radioactive isotopes. The decay of the radioactive nuclei can be detected by their characteristic gamma rays. For this purpose, sensitive experimental equipment is needed.

A $4\pi$-setup consising of two Broad Energy Germanium Detectors (BEGe) was recently built at the Goethe Universitty Frankfurt. It will used to detect gamma rays emitted by the radioactive sample with high efficiency over a broad energy range. The observation of the time-dependence of the freshly produced activity allows the additional disentanglement of the partial cross sections populating isomeric states or the ground state. The partial cross sections have so far nor been resolved in the keV-regime for this isotope. A corresponding activation measurement of the neutron capture on $^{181}$Ta(n,$\gamma$) was performed.

# Investigation of the Coulomb dissociation of $^{15}$C at SAMURAI

D. Hegedus,[1] Y. Kondo,[2] T. Nakamura,[2] A. Horvath,[1] R. Tanaka,[2] T. Aumann,[3] F. Delaunay,[4] N. Fukuda,[2] J. Gibelin,[4] J. Hwang,[5] N. Inabe,[2] T. Isobe,[2] S. Kim,[5] N. Kobayashi,[2] T. Kobayashi,[6] T. Kubo,[2] K. Kusaka,[2] F. M. Marques,[4] Y. Matsuda,[7] R. Minakata,[7] T. Motobayashi,[2] T. Murakami,[7] S. Nishi,[2] S. Ogoshi,[2] J. Onishi,[2] N. A. Orr,[4] H. Otsu,[2] T. Sako,[2] H. Sato,[2] Y. Sato,[5] K. Sekiguchi,[6] Y. Shimizu,[2] H. Suzuki,[2] K. Takahashi,[6] H. Takeda,[2] S. Takeuchi,[2] T. Teranishi,[8] Y. Togano,[9] and K. Yoneda[2]

[1]*Eotvos Lorand University, Budapest*

[2]*Tokyo Institute of Technology, RIKEN Nishina Center*

[3]*TU, Darmstadt*

[4]*LPC-ENSICAEN*

[5]*Seoul National University*

[6]*Tohoku University*

[7]*Kyoto University*

[8]*Kyushu University*

[9]*EMMI, GSI*

We investigated the 15C(gamma,n)14C breakup reaction at 240 MeV/nucleon bombarding energy at RIKEN using the SAMURAI spectrometer and detection setup. Our aim is to examine the kinetic properties of the Coulomb dissociation of the 15C. In the analysis we are using several method to make conclusion for the inverse reaction of the electromagnetic part of the breakup that is the neutron capture of the 14C which has astrophysical importance. Our particular interest is to gain insight into the details of the breakup reaction with the measurement of the impact parameter dependence of the process. It is available since the very good angular resolution of the beam tracking drift chambers used in the setup. We present the experimental results of the excitation energy spectrum for different impact parameter intervals between 12 fm, 18 fm, 28 fm and 80 fm.

# Actinide-Rich or Actinide-Poor, Same $r$-Process Progenitor

Erika M. Holmbeck,[1,2] Anna Frebel,[3,2] G. C. McLaughlin,[4,2] Matthew R. Mumpower,[5,6,2] Trevor M. Sprouse,[1] and Rebecca Surman[1,2]

[1]*Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA*

[2]*JINA Center for the Evolution of the Elements, USA*

[3]*Department of Physics and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[4]*Department of Physics, North Carolina State University, Raleigh, NC 27695, USA*

[5]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, 87545, USA*

[6]*Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM, 87545, USA*

The astrophysical production site of the heaviest elements in the universe remains a mystery. Incorporating heavy element signatures of metal-poor, $r$-process enhanced stars into theoretical studies of $r$-process production can offer crucial constraints on the origin of heavy elements. We apply the "Actinide-Dilution with Matching" model to a variety of stellar groups ranging from actinide-deficient to actinide-enhanced to empirically characterize $r$-process ejecta mass as a function of electron fraction ($Y_e$). We find that actinide-boost stars do not indicate the need for a unique and separate $r$-process progenitor. Rather, small variations of neutron richness within the same type of $r$-process event can account for all observed levels of actinide enhancements. The very low-$Y_e$, fission-cycling ejecta of an $r$-process event need only constitute 10–30% of the total ejecta mass to accommodate most actinide abundances of metal-poor stars. We find that our empirical $Y_e$ distributions of ejecta are similar to those inferred from studies of GW170817 mass ejecta ratios, which is consistent with neutron-star mergers being a source of the heavy elements in metal-poor, $r$-process enhanced stars.

# The first experimental determination of the second-forbidden transition between the ground states of $^{20}$F and $^{20}$Ne

Marjut Hukkanen,[1,2] O. S. Kirsebom,[3] and I230 collaboration

[1]*Department of Physics, University of Jyväskylä, Finland*

[2]*Centre d'Etudes Nucléaires de Bordeaux Gradignan, Université de Bordeaux, France*

[3]*Department of Physics and Astronomy, Aarhus University, Denmark*

The final evolution of 8 - 10 $M_\odot$ stars depends sensitively on the electron capture rates in the ONe core. In particular, electron captures on $^{20}$Ne, dominated by the second-forbidden, non-unique transition to the ground state of $^{20}$F, have been shown to play a key role [1, 2]. The strength of the transition can be determined from the branching ratio of its inverse transition, the ground state to ground state $\beta$-decay of $^{20}$F. We have determined this rare second-forbidden, non-unique transition for the first time at the IGISOL-4 facility in the JYFL Accelerator Laboratory.

$^{20}$F was produced via $^{19}$F$(d,p)^{20}$F reactions using a 6 MeV deuteron beam on a $BaF_2$ target. The produced $^{20}F^+$ ions were implanted on a thin carbon foil at the experimental setup which consisted of a refurbished Siegbahn-Slätis type intermediate-image magnetic spectrometer, and a plastic scintillator for detecting the $\beta$ particles for the branching ratio determination. The detector was divided into three parts: two inner detectors in a $\Delta$E-E configuration surrounded by an outer detector for vetoing cosmic rays. The plastic scintillator was protected by a positron shield, and a $LaBr_3$ detector was used for measuring the 1.6 MeV $\gamma$-rays from the $^{20}$F $\beta$-decay to the first excited state in $^{20}$Ne. The deduced branching ratio of the second-forbidden transition was $0.99(25) \cdot 10^{-5}$ leading to $\log ft = 10.51(11)$. This is the strongest measured second-forbidden, non-unique transition so far. The impact on related stellar evolution models will be presented in another contribution in this conference.

---

[1] G. Martinez-Pinedo *et al.*, Phys. Rev. C **89**, 045806 (2014).

[2] J. Schwab *et al.*, MNRAS **453**, 1910-1927 (2015).

# Influence of astrophysical and nuclear physics uncertainties on the nucleosynthesis in core-collapse supernova neutrino-driven winds

Maximilian Jacobi,[1] Julia Bliss,[1] and Almudena Arcones[1,2]

[1] *Institut für Kernphysik, TU Darmstadt, Germany*

[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*

Neutrino-driven winds emerging after a successful core-collapse supernovae can produce the lighter heavy elements between Fe and Ag depending on the properties of the ejecta. However, despite the fast progress in supernovae simulations in the last decades, there are still large uncertainties in the astrophysical conditions. We rely on a steady-state neutrino-driven wind model to systematically study the influence of astrophysical uncertainties on the nucleosynthesis evolution in neutrino-driven ejecta. Furthermore, uncertainties in the nuclear physic input to the nucleosynthesis calculation have an impact the abundance patterns. In order to identify key reactions, we perform sensitivity studies based on a Monte Carlo approach for a variety of astrophysical conditions in neutron- and proton-rich ejecta.

Supported by the European Research Council Grant No. 677912 EUROPIUM and the Deutsche Forschungsgemeinschaft through SFB 1245 (Projektnummer 279384907).

preprintAbstract for the Nuclear Physics in Astrophysics IX conference"

# Nucleosynthetic contribution of stable and radio - active elements from various sources for Chemical Evolution of Galaxy

Tejpreet Kaur (tejpreet@pu.ac.in)[1] and Sandeep Sahijpal (sandeep@pu.ac.in)[1]

[1]*Department of Physics, Panjab University, Chandigarh, India 160014.*

According to present day understanding, Big Bang resulted in the formation of universe at immensely high temperature. As the universe cooled down, primordial nucleosynthesis resulted in the formation of mainly Hydrogen($^1$H)($\sim$76%), Helium($^4$He)($\sim$24%) with small fraction of $^2$H , $^3$He, $^6$Li and $^7$Li [1]. All other heavier elements were formed by stars of different masses and ages at various evolutionary stages of their life inside the galaxies. From observational data and theoretical modelling, we know that at the time of the formation of the Solar system the metallicity of ISM gas was around $\sim$ 0.0143 [2]. We have performed the galactic chemical evolution (GCE) simulations for Milky way galaxy using Monte Carlo technique to predict various galactic observables such as Star Formatio Rate (SFR), Supernova rates (SN Ia, SN Ib/c & II ), total surface mass density of gas and stars, temporal evolution of Z and [Fe/H] and abundance gradients of elements C, N, O, Mg, Si, Ca, Ti, Fe and Zn [3]. These models have been developed for two and three infall accretion episodes for the gradual accretion of gas onto the galaxy to form Halo, Thick disc and Thin disc. The effect of radial gas inflows and mixing on abundance gradients is also explored in these models.

The abundance trends for short lived radio nuclides (SLRs) ($\tau$<10 Myr) $^{26}$Al, $^{36}$Cl, $^{41}$Ca, $^{53}$Mn and $^{60}$Fe are also deduced for the galaxy [4]. In the simulations, various formation scenario for solar system are explained by forming stellar clusters in the Solar neighbourhood around $\sim$ 9 Gyr. We have obtained the canonical abundance values of SLRs in the early solar system which mainly came from the massive stars in the clusters. These values are compared with the observational values obtained from the meteoritic samples [6] and gamma ray flux [5].

[1] Pagel, B. E. J., Nucleosynthesis and Chemical Evolution of Galaxies, Cambridge, UK: Cambridge University Press. 392 (1997).
[2] Asplund, M., Grevesse, N, Sauval, A. J. and Scott, P., ARA&A **47**, 481 (2009).
[3] Sahijpal, S. and Kaur, T. , MNRAS **481**, 5350 (2018).
[4] Kaur, T. and Sahijpal, S., Lunar and Planetary Science Conference **50**, 1932 (2019).
[5] Diehl, R. et al., Nature **439**, 45 (2006).
[6] Huss, G. R., Meyer, B. S., Srinivasan, G., Goswami, J. N. and Sahijpal, S., GCA **73**, 4922 (2009).

# Several BBN Constraints on Beyond Standard Model Physics

Daniela Kirilova 1,[1] Emanuil Chizhov-b,[2] and Vassillen Chizhov-c[3]

[1]*Institute of Astronomy and NAO, Bulgarian Academy of Sciences 1, Sofia, Bulgaria 1*

[2]*Physical Department, Sofia University2, Sofia, Bulgaria 2*

[3]*Saarland University 3, Saarbrucken, Germany 3*

We present several Big Bang Nucleosynthesis constraints on nonequilibrium processes in the Early Universe, representing Beyond Standard Model Physics, including neutrino oscillations, processes with considerable lepton asymmetry, with sterile neutrinos, additional interactions, etc.

# Analysis of Deuterium-Tritium Fusion Reaction by PT-Supersymmetric Square Well

Taha Koohrokhi[1]

[1]*Department of Physics, Faculty of Sciences, Golestan University, Gorgan, Iran*

The quantum tunneling probability, fusion cross section, astrophysical S-factor, nuclear phase shifts and thermonuclear reaction rate for $\mathrm{T(d,n)^4He}$ reaction have analyzed by PT-supersymmetric quantum mechanics. An unbroken PT-symmetry complex square well is derived by unbroken supersymmetric quantum mechanics. In a while, scattering and absorption of particles are described by real and imaginary parts of the potential, respectively, the PT-symmetry guarantees that the nuclear well has real energy spectrum.

# Mass measurements of neutron-rich In isotopes in the A≈130 region across the N=82 neutron shell at TITAN, TRIUMF

G. Kripkó-Koncz,[1] J. Bergmann,[1] T. Dickel,[1,2] K. Dietrich,[3] J. Dilling,[3,4] D. Fusco,[3] C. Izzo,[3] A. Jacobs,[3,4] B. Kootte,[3,5] A.A. Kwiatkowski,[3] Y. Lan,[3,4] D. Lascar,[3,6] K.G. Leach,[7] E. Leistenschneider,[3,4] M. Lykiardopoulou,[3,4] I. Mukul,[3] S.F. Paul,[3,8] W.R. Plaß,[1,2] M.P. Reiter,[1,3] C. Scheidenberger,[1,2] J.L. Tracy, Jr.,[3] and the TITAN collaboration

[1] *Justus-Liebig-Universität Gießen, Gießen, Germany*

[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*

[3] *TRIUMF, Vancouver, BC, Canada*

[4] *University of British Columbia, Vancouver, BC, Canada*

[5] *University of Manitoba, Winnipeg, MB, Canada*

[6] *Northwestern University, Evaston, IL, USA*

[7] *Colorado School of Mines, Golden, Colorado, USA*

[8] *Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

The atomic masses of exotic nuclei provide key information for the understanding of nuclear structure and astrophysics. Exotic nuclei can be produced with very high rates at the ISOL facility ISAC at TRIUMF (Vancouver, Canada). TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) is a multiple ion-trap system for high-precision mass measurements and in-trap decay spectroscopy. A multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) has been installed and integrated into the TITAN experiment. It is based on an established concept tested at the FRS Ion Catcher at GSI. It is well suited to perform high precision mass measurements, particularly for short-lived isotopes produced at low rate. Furthermore, the ion of interest can be separated from isobaric contaminations with mass-selective re-trapping prior to the mass measurement itself, thus improving the background handling capabilities of the MR-TOF-MS. Such improved capabilities of TITAN have been used to measure the masses of neutron-rich indium isotopes. The new mass values will reduce the nuclear uncertainties associated with the production of A≈130 isotopes in the r-process.

# Measurement of $^{69,71}$Ga(n,$\gamma$) at astrophysical energies using the neutron time of flight facility n_TOF at CERN

D. Kurtulgil,[1] K. Göbel,[1] S. Fiebiger,[1] F. Käppeler,[2] C. Lederer-Woods,[3]
S.-J. Lonsdale,[3] R. Reifarth,[1] M. Weigand,[1] and P. Woods[3]
(for the n_TOF collaboration)

[1] *Goethe University Frankfurt, Frankfurt, Germany*
[2] *Karlsruhe Institute of Technology, Karlsruhe, Germany*
[3] *University of Edinburgh, Edinburgh, United Kingdom*

The origin of most elements heavier than iron in stellar nucleosynthesis can be explained by slow and rapid neutron capture reactions. In order to reproduce the observed isotopic abundances in nucleosynthesis simulations, an exact knowledge of the involved reaction rates at astrophysical energies is necessary. The stable isotopes $^{69}$Ga and $^{71}$Ga play an important role in the weak s-process, but experimental data for the corresponding neutron capture reactions are scarce.

We measured the neutron capture cross-section of isotopically enriched $^{69}$Ga and $^{71}$Ga samples at the n_TOF experiment's EAR1 beamline at CERN, Geneva. The time of flight technique with a flight path of about 200 m enabled us to cover a neutron energy range from eV to several hundred keV with a very good resolution.

# Towards a study of the holy grail reaction $^{12}$C$(\alpha,\gamma)^{16}$O at Felsenkeller

Felix Ludwig,[1,2] Steffen Turkat,[2] Daniel Bemmerer,[1] and Kai Zuber[2]

[1] *Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany*

[2] *Technische Universität Dresden, 01069 Dresden, Germany*

The reaction $^{12}$C$(\alpha,\gamma)^{16}$O is of paramount importance for the nucleosynthesis of heavier elements in stars. It takes place during helium burning and determines the abundance of $^{12}$C and $^{16}$O.

Due to the low cross section of the reaction underground experiments are needed to measure this reaction at astrophysically relevant energies. A setup for a study of this reaction with a $^{12}$C beam on implanted $^{4}$He targets has recently been completed at the new Felsenkeller underground laboratory.

This contribution will report on Monte Carlo simulations of the setup and first $^{12}$C beam tests underground.

# New Methods in Theoretical Astrophysics

Igor Makarov[1]

[1] *Haifa, Israel*

We discovered the following: (1) there are only two fundamental particles virtual electron (electrino) and virtual positron (positrino) their interaction gives birth to virtual positronium characterized by energy virtual positroniums exchange photons and acquire states, called complex positroniums or composiums (2) there exists ether, the primary physical medium, consisting of composiums (3) in ether there takes place spontaneous generation of mesons and neutrons cosmic rays and microwave background are proper radiations of ether experimental data on cosmic rays enabled us to evaluate correlation function of ether and dimensions of some particles mean radius of real electron proved to be about 0.01 fm (4) in respect to ether excitation, neutron is linear system with continuously distributed parameters consistent spatially with ether (5) H-atom is linear system with lumped parameters its structural function is consistnt in time with ether H-atom consists of three quarks described by real symmetric matrices agents of their processes correspond to so called gluons (6) essence of nuclear interaction is conservation of energy by alternate transformation of electric energy to magnetic one and vice versa, atom of deuterium (D-atom) being its fundamental case (7) excited by photons, atoms and neutrons respond with neutrinos (8) nuclear structure evolves by shells, D-atom being its basic element there are seven shells: He-shell (2-shell), octahedral shell (8-shell), icosahedral shell (18-shell), double-icosahedral shell (36-shell) and three inverse shells of 18, 8 and 2 D-atoms additional neutrons perform inter-shell interaction electron shells are integral components of nuclear structure (9) every nuclear shell can be modeled by electric LCR-network, so that whole atom can be represented by matrix of impedances atom with atomic number m consists of m D-atoms, is represented by network with m degrees of freedom and, when excited, emits m-neutrinos (10) stellar medium simulates conditions of ether, so that atoms produced in it become different models of ether, achieving their perfection in U-atom its structure being actually realization and exposition of implicit structure of H-atom.

# Recent Results From the TUNL Split-pole Spectrograph

Caleb Marshall,[1] Richard Longland,[1] Federico Portillo,[1] and Kiana Setoodehnia[2]

[1]*North Carolina State University, Raleigh, NC*

[2]*European X-ray Free Electron Laser GmbH, Schenefeld, Germany*

Energy in stars is generated by charged particle nuclear reactions occurring below the coulomb barrier. Our understanding of stellar evolution and nucleosynthesis is therefore closely linked to our knowledge of nuclear reaction cross sections. However, directly measuring these reactions at stellar energies in the lab can be impractical or impossible, in which case novel techniques such as transfer reactions must be used to constrain the cross sections. The high-resolution Enge Split-pole spectrograph at the Triangle Universities Nuclear Laboratory (TUNL) is devoted towards performing these types of indirect measurements for astrophysics. Over the last few years the spectrograph was fully rebuilt, upgraded, and tested, and is now under active use. We will report on the capabilities of the facility and highlight some of the first experimental results, which have helped us measure key reactions important to understanding nucleosynthesis in classical novae and abundance anomalies in globular clusters.

# Level structure study of $^{27}$Si relevant to the $^{26}$Al(p,$\gamma$)$^{27}$Si reaction

Hanane Mebrek,[1] Mouna Bouhelal,[2] and Derradji Bahloul[1]

[1]*PRIMALAB Laboratory; Departement of Physics, University of Batna 1, Avenue Boukhloufa M El Hadi, 05000 Batna, Algeria*

[2]*Laboratoire de Physique Appliquée et Théorique, Larbi Tebessi University, Tébessa 12022, Algeria*

The major challenge in nuclear astrophysics is to find ways to determine reaction rates at excitation energies relevant for burning in the stellar environment. These rates depend upon the spectroscopic properties of states in the produced nucleus. The most studied reactions are radiative proton-capture, (p,$\gamma$) reaction.

We are interested to the study of $^{26}$Al(p,$\gamma$)$^{27}$Si. The J$^{\pi}$ assignments of states in $^{27}$Si above the proton threshold energy ($S_p$=7463 keV) over $E_x$=7,0-8,1 MeV [1] play a crucial role in the calculation of the reaction rate .

We calculated, using the PSDPF interaction [2], the spectroscopic properties of levels in $^{27}$Si. The $^{26}$Al(p,$\gamma$) reaction rate and spectroscopic factors were also calculated. A detailed discussion of the comparison of our results to experimental available data will be presented.

[1] A. Parikh, et al., Phys. Rev. C **84**, 065808 (2011).

[2] M. Bouhelal, et al., Nucl. Phys. A **864**, 113 (2011).

# Big Bang nucleosynthesis simulations for $^{2}$H abundance predictions

Conrad Möckel[1]

[1] *HZDR,TU Dresden*

Big Bang nucleosynthesis (BBN) addresses the light isotope production in the first few minutes of the universe by numerically solving the differential equations introduced by the reaction network, in the setting of general relativity. Thereby it is an excellent method of probing our understanding of the physics of the early universe. With recent observations made by R. Cooke et al. (2016) and the Planck mission (2018) concerning the primordial deuterium abundance and baryon to photon density today, respectively, BBN has entered the high precision era. However, some tension between prediction and measurement is present.
In this poster it is studied whether or not concordance can be achieved by varying certain input parameters (e.g. $N_{\mathrm{eff}}$, $G_{\mathrm{N}}$, $\omega_{\mathrm{b}}$) and thermonuclear reaction rates using the PRIMAT code by C. Pitrou et al. (2018).

# A BGO set-up for the direct measurement of the $^{2}$H(p, $\gamma$)$^{3}$He fusion cross section at LUNA

Viviana Mossa[a] on behalf of the LUNA collaboration[1]

[1] *INFN, Istituto Nazionale di Fisica Nucleare, sezione di Bari, 70125 Bari, Italy*

Deuterium is the first nucleus produced in the Universe, whose accumulation marks the beginning of the so called Big Bang Nucleosynthesis (BBN). Its primordial abundance depends on the cross sections of relevant nuclear reactions involved in the deuterium construction and destruction during the BBN. Presently the main obstacle to an accurate theoretical deuterium abundance evaluation is due to the poor knowledge of the $^{2}$H(p, $\gamma$)$^{3}$He cross section at BBN energies ($30 < E_{cm}[keV] < 300$) [1].

In this poster a new experimental approach to accurately measure the reaction cross section is described. The measurement is based on the LUNA accelerator, located at the underground INFN Gran Sasso laboratory, and a windowless gas target of $^{2}H$. The experiment consists of two main phases characterized by two different setups. The former is based on a close $4\pi$ BGO detector, whose high efficiency (about 60% in the energy range of interest) provides measurements down to very low energies [2]. The latter, instead, covers the medium-high energies ($70 < E_{cm}[keV] < 260$) using a High Purity Germanium detector (HPGe), whose high resolution allows the differential cross section of the reaction to be evaluated by using the peak shape analysis.

In this poster the characterization of the first phase (the BGO phase) set-up, the background conditions, the potential sources of uncertainty and the preliminary results will be discussed.

---

[1] E. Di Valentino et al., Phys. Leyy. D **90**, 023543 (2014).

[2] V. Mossa, Study of the $^{2}H(p,\gamma)^{3}He$ reaction in the Big Bang Nucleosynthesis energy range Universitá degli Studi di Bari, PhD Thesis, (2018).

# Astrophysical production of $^{146}$Sm in nuclear p-processes

Cristiana Oprea,[1] Alexandru Mihul,[2] Alexandru Ioan Oprea,[1] Sorin Zgura,[3] Mihai Potlog,[3] and Alina Neagu[3]

[1]*Joint Institute for Nuclear Researches (JINR)*
*Frank Laboratory of Neutron Physics (FLNP)*
*141980 Dubna Moscow Region Russian Federation*

[2]*European Organization for Nuclear Research (CERN), CMS*
*CH-1211 Genve 23, Switzerland*

[3]*Institute for Space Sciences (ISS)*
*RO-077125 Bucharest Magurele, Romania*

The large time of life of $^{146}$Sm suggests the possibility to use this p-nuclide as astrophysical chronometer to study the geochemical galactic evolution. Due to the high temperature and large densities of gamma quanta, neutrons and protons in stellar environment $^{146}$Sm nucleus can be obtained in ($\gamma$,n), (n,2n), (p,2n) processes on $^{147}$Sm. The knowledge of corresponding cross sections of gamma rays, neutrons and protons induced processes is of a great importance for the explanation of ($^{146}$Sm/$^{144}$Sm) ratio uncertainties observed on the Earth, meteorites, Moon and other celestial bodies.

Cross sections of ($\gamma$,n), (n,2n), (p,2n) processes induced by fast gamma rays, neutrons and protons on $^{147}$Sm from threshold up to 25 MeV were evaluated and predicted in the frame of Hauser-Feshbach statistical model by using Talys software and own computer programs. For each nuclear reaction contribution of direct, compound and pre-equilibrium mechanisms were determined. For ($\gamma$,xn) reaction, transition multiplicity function is used in the analysis of theory and measurements results. Theoretical evaluations are compared with existing experimental data for other nuclear processes as well. Parameters of optical potential in the incident and emergent channels and of nuclear densities were extracted. Calculated cross sections together with corresponding nuclear data were used in the evaluation of astrophysical rates and of elemental abundances from nuclear networks.

# Direct measurement of the $^{19}$F(p,$\alpha$)$^{16}$O reaction using the LHASA detector array

T. Petruse,[1] G. L. Guardo,[1] M. La Cognata,[2] D. Lattuada,[1] C. Spitaleri,[2] D. Balabanski,[1] E. Aciksoz,[1] L. Acosta,[3] L. Capponi,[1] D. Carbone,[2] S. Cherubini,[2] D. Choudhury,[1] G. D'Agata,[4] A. Di Pietro,[2] P. Figuera,[2] M. Gulino,[2] A. I. Kilik,[4] M. La Commara,[5] L. Lamia,[2] C. Matei,[1] S. Palmerini,[6] R. G. Pizzone,[2] S. Romano,[2] P.-A. Soderstrom,[1] R. Sparta,[2] A. Tumino,[2] and S. Vinales Onses[7]

[1]*Extreme Light Infrastructure - Nuclear Physics / IFIN-HH, Magurele, Romania*

[2]*Laboratori Nazionali del Sud - INFN, Catania, Italy*

[3]*National Autonomous University of Mexico, Mxico D.F., Mxico*

[4]*Nuclear Physics Institute of ASCR, Rez, Czech Republic*

[5]*Universita di Napoli Federico II, Napoli, Italy*

[6]*INFN - Sezione di Perugia, Perugia, Italy*

[7]*Consejo Superior de Investigaciones Cientficas, Madrid, Spain*

The cosmic origin of fluorine is highly uncertain. Its production and destruction is strictly connected to the physical conditions in stars, and because of this, the fluorine abundance will place a severe constraint on stellar evolution models. The main fluorine destruction channel in the H-rich layer of an Asymptotic Giant Branch (AGB) star is the $^{19}$F(p,$\alpha$)$^{16}$O reaction. At present time, theoretical models predict larger fluorine abundances than observed in AGB stars. This discrepancy requires a revision of the nuclear reaction rates involved in the production and destruction of fluorine. In 2015, new measurements of the $^{19}$F(p,$\alpha$)$^{16}$O reaction at deep sub-Coulomb energies were performed by Lombardo et. al. Unfortunately, those data are larger by a factor of 1.4 with respect the previous data reported in the NACRE compilation in the energy region 0.6-0.8 MeV. Using the Large High Resolution Array of Silicons for Astrophysics (LHASA), we performed a new direct measurement of the $^{19}$F(p,$\alpha$)$^{16}$O. The goal of this experiment is to reduce the uncertainties in the nuclear reaction rate of the $^{19}$F(p,$\alpha$)$^{16}$O reaction. Experimental details, calibration procedure, angular distributions and some preliminary results will be presented.

# Cross section measurement of the reaction $^{96}$Ru(p,$\gamma$) via the activation method

Markus Reich,[1] Jan Glorius,[2] Joachim Goerres,[3] Yuri Litvinov,[2] Rene Reifarth,[1] Edward Stech,[3] Meiko Volknandt,[1] and Michael Wiescher[3]

[1] *Goethe-Universitaet Frankfurt, Max-von-Laue Strae 1, 60438 Frankfurt, Germany*

[2] *GSI Helmholtzzentrum fuer Schwerionenforschung GmbH, Darmstadt, 64291, Germany*

[3] *University of Notre Dame, Notre Dame, Indiana 46556, USA*

96Ru is one of about 35 neutron deficient nuclides, that can not be produces in neutron capture processes like the s(low)- or the r(apid)-process. In two different experiments the reaction cross section of $^{96}$Ru(p,$\gamma$)$^{97}$Rh has been measured with two different methods. Bork et al. (1998) performed an experiment by means of the activation method at proton energies between 2-3 MeV. In 2015, Bo Mei et al. measured the cross section of the same reaction in inverse kinematics at the ion storage ring ESR at GSI (Helmholtzzentrum fr Schwerionenforschung, Darmstadt, Germany) at proton energies from 9 to 11 MeV. The luminosity was determined with two different methods, both based on electron capture events which occur in the H2 gas. As part of this work, the $^{96}$Ru(p,$\gamma$)$^{97}$Rh cross section has been measured at 3.2MeV to compare with a previous activation experiment as well as between 9 and 11MeV, again in an activation experiment. The experimental setup and preliminary results of this experiment are presented.

# Study of the $^{3}$He($\alpha$,$\gamma$)$^{7}$Be reaction at Dresden Felsenkeller

Konrad Schmidt,[1] Steffen Turkat,[1] Daniel Bemmerer,[2] Marcel Grieger,[1,2] Sebastian Hammer,[1,2] Thomas Hensel,[1,2] Felix Ludwig,[1,2] Simon Rümmler,[1,2] Ronald Schwengner,[2] Klaus Stöckel,[1,2] Tamás Szücs,[2] and Kai Zuber[1]

[1] *Technische Universität Dresden, Germany*

[2] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany*

A key reaction in both Big-Bang nucleosynthesis (BBN) and p-p-chain hydrogen burning is the $^{3}$He($\alpha$,$\gamma$)$^{7}$Be reaction. The aim of the present study is a comprehensive data set covering the entire BBN range. In a first campaign, $\gamma$-ray angular distributions have been measured at the 3 MV Tandetron accelerator of Helmholtz-Zentrum Dresden-Rossendorf (HZDR) with implanted $^{3}$He targets. Activated samples of $^{7}$Be ($\approx$ 53 d half-life) have been counted at the shallow-underground laboratory Dresden Felsenkeller using a new 150% HPGe detector shielded from cosmic rays by ultra-low background copper and lead, active plastic scintillation veto detectors and 140 m water equivalent of rock. A second campaign is planned underground at the new 5 MV Pelletron accelerator Dresden Felsenkeller with a currently designed gas target that can be operated as an extended gas chamber or as a gas jet. Preliminary results of the angular distribution and activation data from the first campaign will be presented as well as the latest status of the Felsenkeller gas-target setup.

# The $^{22}$Ne$(p,\gamma)^{23}$Na reaction from 800 to 1900 keV

Franziska Schoger,[1,2] Daniel Bemmerer,[2] and Rosanna Depalo[3,4]

[1] *Technische Universität Dresden, 01062 Dresden, Germany*

[2] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01328 Dresden, Germany*

[3] *Istituto Nazionale di Fisica Nucleare,*

*Sezione di Padova, 35131 Padova, Italy*

[4] *Dipartimento di Fisica e Astronomia,*

*Università degli Studi di Padova, 35131 Padova, Italy*

The NeNa cycle affects the synthesis of elements with $A = 20 - 25$ in asymptotic giant branch stars, classical novae and type Ia supernovae. The $^{22}$Ne$(p,\gamma)^{23}$Na reaction is a part of that cycle. Its thermonuclear reaction rate is dominated by many resonances. Recently, the LUNA collaboration reported new data on a number of resonances between $E_{\mathrm{p}} = 71 - 400$ keV [1–3].

At the Rossendorf 3 MV Tandetron, five resonances at 436, 479, 639, 661 and 1279 keV were studied [4].

The present poster reports on the study of six additional resonances at $E_{\mathrm{p}}$ =851, 948, 1502, 1592, 1720 and 1834 keV. The targets were produced at the 200 keV high-current implanter at Legnaro National Laboratories (Italy). In the experiment, two high purity germanium detectors were used. For the analysis the by now well known 1279 keV resonance was used as reference.

[1] Ferraro, F. et al., Phys. Rev. Lett. **121**, 172701 (2018).

[2] Cavanna, F. et al., Phys. Rev. Lett. **115**, 252501 (2015).

[3] Bemmerer, D. et al., EPL **122**, 52001 (2018).

[4] Depalo, R. et al., Phys. Rev. C **92**, 045807 (2015).

# Overview of the HVE Singletron accelerators developed for Nuclear Astrophysics

A. Sen,[1] G. Domínguez-Cañizares,[1] A. Shornikov,[1] N.C. Podaru,[1] and D.J.W. Mous[1]

[1] *High Voltage Engineering Europa BV,*
*P.O. Box 99, 3800AB, Amersfoort, The Netherlands*

HVE has designed and built a dedicated 3.5 MV single ended DC accelerator to satisfy the stringent demands of the LUNA-MV project (INFN-LNGS L'Aquila, Italy) for astrophysics research, with high energy stability, low terminal voltage ripple and high beam currents for light ions. The system has incorporated a 10 GHz, all permanent magnet ECR ion source in its high voltage terminal.
Factory test results demonstrated ion beam currents of $H^+$ (~1 mA), $^4He^+$ (~1 mA), $^{12}C^+$ (150 $\mu$A) and $^{12}C^{2+}$ (100 $\mu$A) at target in the terminal voltage range of 0.5-3.5 MV. Beam energy stability and ripple are in the order of $10^{-5}$ and energy reproducibility is $10^{-4}$. Beam current stability is $\approx 5\%$ over 24 hours without feedback, but typically $< 1\%$ per hour using a feedback system.

Different specifications are required by another project at TUNL, Duke University, Durham USA, where a replacement for the JN1000 Van de Graaff accelerator system is foreseen. A 2 MV version of the Singletron range providing beam currents in excess of 2 mA for H and He, and featuring 2 ns pulsing capability is being designed for this project. This system is equipped with a new 5.8 GHz, all permanent magnet, ECR source and a chopper-buncher in the high voltage terminal, capable of nanosecond pulsing for H, He and D.
In this contribution, we will discuss the design features of both accelerators, specifically ion optical properties. Results on the performance tests of the LUNA-MV system will be given.

# $TeV$ -Scale Resonant Leptogenesis with New Scaling Ansatz on Neutrino Dirac Mass Matrix from A4 Flavor Symmetry

H .Benaoum[1] and S. Shaglel[1]

[1] *University of Sharjah, UAE*

We propose a new scaling ansatz in the neutrino Dirac mass matrix to explain the low energy neutrino oscillations data, baryon number asymmetry and neutrinoless double beta decay. In this work, a full reconstruction of the neutrino Dirac mass matrix has been realized from the low energy neutrino oscillations data based on type-I seesaw mechanism. A concrete model based on A4 flavor symmetry has been considered to generate such a neutrino Dirac mass matrix and imposes a relation between the two scaling factors. In this model, the right-handed Heavy Majorana neutrino masses are quasi-degenerate at TeV mass scales. Extensive numerical analysis studies have been carried out to constrain the parameter space of the model from the low energy neutrino oscillations data. It has been found that the parameter space of the Dirac mass matrix elements lies near or below the MeV region and the scaling factor k1 has to be less than 10. Furthermore, we have examined the possibility for simultaneous explanation of both neutrino oscillations data and the observed baryon number asymmetry in the Universe. Such an analysis gives further restrictions on the parameter space of the model, thereby explaining the correct neutrino data as well as the baryon number asymmetry via a resonant leptogenesis scenario. Finally, we show that the allowed space for the effective Majorana neutrino mass mee is also constrained in order to account for the observed baryon asymmetry.

# A study of nuclear reaction mechanics at low energies

Manoj Kumar Sharma[1]

[1] *Department of Physics, Shri Varshney College, Aligarh, INDIA*

The study of pre-compound emission in $\alpha$-induced reactions, particularly at the low incident energies, is of considerable interest as the pre-compound emission is more likely to occur at higher energies. With a view to study the competition between the compound and the pre-compound emission processes in $\alpha$-induced reactions at different energies and with different targets, a systematics for neutron emission channels in targets $^{51}$V, $^{55}$Mn, $^{93}$Nb, $^{121,123}$Sb and $^{141}$Pr at energy ranging from astrophysical interest to well above it, has been developed.

The off-line $\gamma$-ray-spectrometry based activation technique has been adopted to measure the excitation functions. The experimental excitation functions have been analysed within the framework of the compound nucleus mechanism based on the Weisskopf-Ewing model and the pre-compound emission calculations based on the geometry dependent hybrid model. The analysis of the data shows that experimental excitation functions could be reproduced only when the pre-compound emission, simulated theoretically, is taken into account.

The strength of pre-compound emission process for each system has been obtained by deducing the pre-compound fraction. Analysis of data indicates that in $\alpha$-induced reactions, the pre-compound emission process plays an important role, particularly at the low incident energies, where the pure compound nucleus process is likely to dominate.

[1] M. K. Sharma, Phys. ReV. C **99**, 014608 (2019).

# Machine learning for energy surfaces for neutron star inner crusts

Matthew Shelley[1] and Alessandro Pastore[1]

[1] *University of York, United Kingdom*

The neutron star equation of state (EoS) plays a crucial role in determining static and dynamic properties of neutron stars. The latter has recently received significant attention due to the multi-messenger detection of a neutron star merger [1].

An important component of the EoS is its low-density crust. In this, we expect finite nuclei, embedded in an electron gas (the outer crust), or in electron and neutron gases (the inner crust). Determining the proton numbers of the nuclei at different inner crust densities is a longstanding problem in nuclear physics [2], partly because of the computational burden of the calculations. The energy minimizations performed across the density range of the inner crust require significant computational time.

Gaussian Process Emulation (GPE) is a regression method from machine learning, with a wide range of applications in nuclear physics, and in many other scientific domains. We have already successfully applied GPE to an inner crust energy minimization [3, 4], done with nuclear energy density functional calculations. I will present an iterative version of GPE, building on previous work [3–5]. We use here semi-classical calculations with the Thomas-Fermi approximation, including pairing effects at the BCS level. With iterative GPE, we can dramatically reduce the number of calculations needed to determine the composition of the inner crust. This will enable us to expand our investigations into the structure, by including temperature effects and by using fully microscopic calculations.

---

[1] B. P. Abbott, et al., Phys. Rev. Lett. **119**, 161101 (2017).

[2] J. W. Negele, D. Vautherin, et al., Nucl. Phys. A **207**, 298 (1973).

[3] A. Pastore, M. Shelley, C. A. Diget, PoS (INPC2016) p 145 (2016).

[4] A. Pastore, M. Shelley, S. Baroni, C. A. Diget, J. Phys. G: Nucl. Part. Phys. **44**, 094003 (2017).

[5] M. Shelley, P. Becker, A. Gration, A. Pastore, arXiv:1811.09130 (2018).

# Mass measurement of neutron-rich nuclei using Experimental Storage Ring (ESR)

Ragandeep S. Sidhu,[1] R. J. Chen,[1] Yu. A. Litvinov,[1] and for the FRS-ESR collaboration

[1] *GSI Helmholtzzentrum fuer Schwerionenforschung, 64291, Darmstadt, Germany.*

Precision mass and half-lifetime measurements of exotic nuclei have always been crucial for understanding nuclear structure properties of bound nuclei. Storage ring mass spectrometry [1, 2] is one of the direct methods by means of which the masses and half-lifetimes of very exotic nuclei can be measured. The combination of FRagment Separator (FRS) and Experimental Storage Ring (ESR) at GSI Helmholtz Centre for Heavy Ion Physics, Darmstadt has been employed for past few decades for the purpose of mass measurements of exotic nuclei on both, neutron-rich and neutron-deficient sides of the nuclear chart.

With the motivation for the better understanding of the properties of short-lived exotic nuclei, an Isochronous Mass Spectrometry (IMS) experiment was performed using a 410-415 MeV/u $^{238}U$ projectile beam at GSI, Darmstadt by M. Matos et al. [3] in 2002. Many neutron rich nuclides were produced via abrasion-fission of the projectile beam with isochronous settings on $^{130,133,135}Sn^{50+}$ isotopes. However, except for the PhD thesis [3], the results of the experiment remained unpublished. We reanalyse the data by using improved analysis procedures developed at Institute of Modern Physics (IMP), Lanzhou. In this poster, we discuss some new and improved results from the revised data analysis of the above mentioned experiment.

[1] B. Franzke et al., Mass Spectrom. Rev. **27**, 428 (2008).

[2] Yu. A. Litvinov et al., Nucl. Phys. A **756**, 3 (2005).

[3] M. Matos, New mass measurements of short-lived neutron rich $^{238}U$ fission fragments at the FRS-ESR facilities. Ph. D. Thesis, Justus Liebig University Giessen, 2004.

# Cross sections of the $^{113}$In$(\gamma, n)^{112m,g}$In reaction for the $\gamma$-process

Yevgen Skakun,[1] Igor Semisalov,[1] Anastasiia Chekhovska,[1,2] and Valentin Kasilov[1]

[1]*Institute of High Energy Physics and Nuclear Physics, NSC KIPT, Kharkiv, Ukraine*

[2]*V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*

The vast majority of naturally abundant isotopes of trans-iron chemical elements were synthesized in the stellar scenarios of slow (s) and rapid (r) neutron capture of nuclear reactions. However there is a group of about 35 so-called p-nuclei which could not be made in these processes because of the relation of their masses with the masses of nuclei of neighboring isobars. The indium-113 ($^{113}$In) isotope is included in this group although could be additionally formed in the r-process in small amounts. To understand the stellar nucleosynthesis of the p-nuclei there is need to know a large set of certain nuclear data among which the very important ones are proton and photon induced nuclear reaction cross sections. In this work using the electron linear accelerator (LINAC-30) of the NSC KIPT (Kharkiv) and off-line high resolution gamma-ray spectrometry the photoactivation yields of the $^{113}$In$(\gamma, n)^{112m,g}$In photonuclear reaction producing the isomeric and ground states of the residual ($T^m_{1/2} = 20.56m$, $J^\pi_m = 4^+$, $T^g_{1/2} = 14.97m$, $J^\pi_g = 1^+$) were measured in the bremsstrahlung end-point energy range from the threshold (9.44 MeV) to 14 MeV–the relevant one for the $\gamma$-scenario modeling. The individual yields for each member of the $^{112m,g}$In isomeric pair production were defined from the intensities of the following $\gamma$-rays. The method of approximation of the experimental yield of a photonuclear reaction by a parametric function connecting it with the cross section was used to determine the latter. Analyzing the decay curve of the genetically coupled $^{112m,g}$In isomeric pair we were able both to determine new values of the branching coefficients of the $\gamma$-rays following the $^{112g}$In nuclide decay which turned out to be different from the currently accepted ones and to derive the correct values of the experimental reaction yields. The experimental data are compared with the predictions of the Hauser-Feshbach statistical theory of nuclear reactions implemented by computer codes NON-SMOKER and TALYS varying the models of nuclear level density and radiation strength function.

# Indirect study of the $^3He(n,p)^3H$ reaction at cosmological energies

C. Spampinato,[1,2,3] R.G. Pizzone,[1] R. Spartà,[1,2] M. Couder,[4] Wanpeng Tan,[4] L. Boccioli,[5] V.Burjan,[6] K.Y. Chae,[7] G. D'Agata,[6] G.L. Guardo,[1] M. La Cognata,[1] L. Lamia,[1,2] D. Lattuada,[1] J.Mrazek,[6] S. Palmerini,[5] S. Romano,[1,2] C. Spitaleri,[1,2] A. Tumino,[1,8] and M. Wiescher[4]

[1]*INFN Laboratori Nazionali del Sud, Catania Italy*

[2]*Dipartimento di Fisica e Astronomia, Università di Catania, Catania*

[3]*CSFNSM, Catania*

[4]*Physics and Astronomy Department, Notre Dame University, USA*

[5]*INFN and University of Perugia, Italy*

[6]*Cyclotron Institute, Academy of Science of the Czech Rep., Rez, Czech Rep.*

[7]*Sungkyunkwan University (SKKU)*

[8]*Kore University, Enna, Italy*

One of the cornerstones of the Big Bang cosmological model is the Big Bang nucleosynthesis (BBN). A series of 12 reactions converts the initial protons and neutrons into helium isotopes and a very small, although very important amount of $^7Li$. In this network of reactions, the $^3He(n,p)^3H$ has an important role which impacts the final $^7Li$ abundance. The Trojan Horse Method (THM) has been applied to the $^3He(d,pt)H$ reaction in order to extract the astrophysical $S(E)$-factor in the Gamow energy range. The experiment was performed thanks to Notre Dame Tandem of the Physics and Astronomy Department of the N.D. University (USA). In this poster the experimental setup will be described together with the first preliminary result.

# Gamma, neutron and muon background in the new Felsenkeller underground accelerator laboratory

Tamás Szücs,[1] Daniel Bemmerer,[1] Marcel Grieger,[1,2]
Thomas Hensel,[1,2] Felix Ludwig,[1,2] and Kai Zuber[2]

[1] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01328 Dresden, Germany*

[2] *Technische University Dresden, 01062 Dresden, Germany*

Astrophysically relevant nuclear reactions between charged particles usually occurring in stars at deep sub-Coulomb energies. A direct experimental study of such reactions in the laboratory requires high luminosity coupled with low background in the detectors to compensate for the tiny reaction yield to be measured.

The new Felsenkeller underground accelerator laboratory is equipped with a high current particle accelerator and has very low background.

This contribution will report about the experimental study of the muon flux and angular distribution of the muons in the new laboratory, which is required to optimize the veto detector arrangements. In addition, the measured neutron flux and energy spectrum at Felsenkeller will be reported. Finally, the actual $\gamma$ background in muon vetoed HPGe detectors will be presented. The measured background and known ion beam current will allow the study many astrophysically relevant reactions direct in their stellar energy range.

# Status report of the TRIGA-TRAP experiment

Jacques. J. W. van de Laar,[1,2] K. Blaum,[3] M. Block,[1,2,4] S. Chenmarev,[1,2,5] Ch. E. Düllmann,[1,2,4] S. Lohse,[1,2] Sz. Nagy,[3] and F. Schneider[1,2]

[1]*Institut für Kernchemie, Johannes Gutenberg-Universität Mainz, DE*

[2]*Helmholtz Institut Mainz, DE*

[3]*Max-Planck-Institut für Kernphysik, Heidelberg, DE*

[4]*GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, DE*

[5]*Petersburg Nuclear Physics Institute, Gatchina, RU*

(Dated: July 29, 2019)

Superheavy elements exist exclusively because of quantum-mechanical shell effects. With increasing proton number the Coulomb repulsion increases rapidly and these shell effects gain in importance for heavy nuclei, as they can increase the nuclear lifetimes by many orders of magnitude. The effect is most pronounced in the vicinity of shell closures. One of the relevant shell closures was identified at $N = 152$. Signatures for shell closures include a sudden drop in the two-neutron separation energy $S_{2n}$. This can experimentally be determined by high-precision measurements of the masses of nuclides in the vicinity of the shell closure. The TRIGA-TRAP experiment is a double Penning-trap mass spectrometer used to perform high-precision mass measurements of long-lived transuranium isotopes and short-lived fission-products at the research reactor TRIGA Mainz. It thus ideally complements the on-line capabilities of the SHIPTRAP setup at GSI Darmstadt. Prompted by a recent recharge of the TRIGA-TRAP superconducting magnet, the experimental setup was upgraded and recommissioned. Currently, measurements to investigate systematic effects are ongoing. A measurement campaign of several transuranium isotopes is planned for the next months. The status, latest results, and an outlook for the TRIGA-TRAP facility will be presented.

# Towards background-free studies of capture reactions in a heavy-ion storage ring

László Varga,[1] K. Blaum,[2] T. Davinson,[3] J. Glorius,[1] B. Jurado,[4] C. Langer,[5] C. Lederer-Woods,[3] Yu. A. Litvinov,[1] R. Reifarth,[5] Z. Slavkovská,[5] T. Stöhlker,[1,6] P. J. Woods,[3] and Y. M. Xing[1]

[1] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, 64291, Germany*

[2] *Max-Planck-Institut für Kernphysik, Heidelberg, 69117, Germany*

[3] *School of Physics & Astronomy, University of Edinburgh, Edinburgh, EH9 3FD, UK*

[4] *Centre d'Etudes Nucléaires de Bordeaux Gradignan (CENBG), F-33175 Gradignan, France*

[5] *Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, 60438, Frankfurt am Main, Germany*

[6] *GSI, Branch Office Helmholtz Institute Jena, 07743 Jena, Germany*

Stored and cooled highly-charged ions offer unprecedented capabilities for precision studies in the realm of atomic-, nuclear-structure and astrophysics [1]. After the successful investigation of the cross section of the $^{96}$Ru$(p,\gamma)^{97}$Rh reaction in 2009 [2], the first measurement of the $^{124}$Xe$(p,\gamma)^{125}$Cs reaction cross section has been performed with decelerated fully-ionized $^{124}$Xe ions in 2016 at the Experimental Storage Ring (ESR) of GSI [3]. Using a Double Sided Silicon Strip Detector, introduced directly into the ultra-high vacuum environment of the storage ring, the cross sections were measured at 5 different energies between 5.5 AMeV and 8 AMeV. Elastic scattering on the $H_2$ gas jet target is the major source of background. Monte Carlo simulations show that an additional slit system in the ESR in combination with the energy information of the Si detector will make background free measurements of the proton-capture products possible. It will tremendously increase the sensitivity of the method.

[1] Bosch, Fritz and others, Prog. Part. Nucl. Phys. **73**, 84-140 (2013).

[2] Mei, Bo and others, Phys. Rev. **C92**, 035803 (2015).

[3] Glorius, J. and others, Phys. Rev. Lett. **122**, 092701 (2019).

# The measurement of p-nuclei alpha decay

Heinrich Wilsenach,[1] Yordan Georgiev,[2] Réne Heller,[3] Ulli Koester,[4] Volker Neu,[5] Philipp Scholz,[6] Tommy Schönherr,[2] and Kai Zuber[1]

[1]*IKTP TU-Dresden, Dresden, Germany*

[2]*Transport Phenomena in Nanostructures, Dresden-Rossendorf, Germany*

[3]*Institute of Ion Beam Physics and Materials Research, Dresden-Rossendorf, Germany*

[4]*Institut Laue-Langevin, Grenoble, Isere, France*

[5]*Institute for Metallic Materials, Dresden, Germany*

[6]*Institute for Nuclear Physics, University of Cologne, Köln, North Rhine-Westphalia, Germany*

For heavy proton rich nuclei created in the p-process often only the alpha decay channel is energetically allowed. These nuclei are long living with half-lives up to billions of years. Due to the wide range of half-lives these p-nuclei play a vital role in Geo- and Cosmo-chronometry. One of the crucial requirements of this technique is a high precision of the half-lives. Measuring this quantity is challenging as the material usually has a very low natural abundance. This means that the isotopes of interest will have to be made accurately in a quantity to enable a sufficiently detectable signal.

Alpha decay also plays a role in activation experiments where the product decays through the emission of an alpha particle. One such experiment is the investigation on the $^{144}$Sm($\alpha$,$\gamma$)$^{148}$Gd cross-section, which can be measured due to the alpha decay of $^{148}$Gd. This cross-section is important for p-process nucleosynthesis.

To overcome this challenge an ultra-low background alpha chamber was designed and constructed at IKTP TU-Dresden. The gas filled ionisation chamber was chosen for this task as it has a remarkably high efficiency $(98.6 \pm 2.2)\%$. The chamber was specially designed and built to measure low signal rates and has a background in the region of interest (1 MeV to 4 MeV) of around 0.27 counts per day per MeV.

The presentation will discuss samples made at the ISOLDE facility at CERN, as well as the alpha counting method used to determine the $^{144}$Sm($\alpha$,$\gamma$)$^{148}$Gd cross-section.

# A method for reaction luminosity determination in a storage ring

Y.M. Xing,[1] T. Davinson,[2] J. Glorius,[1] B. Jurado,[3] C. Langer,[4] C. Lederer-Woods,[5] Yu. A. Litvinov,[1] R. Reifarth,[4] Z. Slavkovská,[4] T. Stöhlker,[6] L. Varga,[1] and P. J. Woods[2]

[1]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, 64291, Germany*

[2]*School of Physics & Astronomy, University of Edinburgh, Edinburgh, EH9 3FD, UK*

[3]*Centre d'Etudes Nucléaires de Bordeaux Gradignan (CENBG), CS 10120, F-33175 GRADIGNAN Cedex, France*

[4]*Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, 60438, Frankfurt am Main, Germany*

[5]*School of Physics & Astronomy, University of Edinburgh, Edinburgh, EH93FD, UK*

[6]*Max-Planck-Institut für Kernphysik, Heidelberg, 69117, Germany*

Reactions induced by charged-particles play an important role in the research of explosive scenarios in astrophysics. The energy range for the Gamow window of these reactions under astrophysical conditions is around only a few MeV or less. For such low-energy reaction cross-section measurements performed at a storage ring, background due to Rutherford scattering is typically an obstacle. However, the known distribution of this fundamental scattering process can be employed for *in situ* determination of reaction luminosity, which enters directly into the cross-section calculation and is a crucial parameter in the experiments.

We propose a method to simulate the realistic scattering distribution for a specific detector geometry. By comparing the simulation and experiment, the luminosity can accurately be extracted. This method provides a reliable way to measure the luminosity. It is especially useful if the luminosity determination through other methods is complicated or impossible.

# Direct mass measurement for $^{103}$Sn and its impact on $rp$-process endpoint SnSbTe cycle

Xing XU[1,2] and on behalf of HIRFL-CSR mass measurment collaboration

[1]*School of Science, Xi'an Jiaotong University, 710049 Xi'an, China*

[2]*Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China*

The nuclide $^{103}$Sn was produced by projectile fragmentation of $^{112}$Sn at a energy of 400 MeV/u, and its mass was directly measured by a storage-ring based isochronous mass spectrometry at HIRFL-CSR facility in Lanzhou, China. The new mass value deviated the literature one, which was indirectly determined from $\beta$-decay spectrum of $^{103}$In, by about $2.5\sigma$, and the mass precision was improved by a factor of two.

Since the decay energies of proton or $\alpha$ particle were precisely measured in the decay chain of $^{112}$Cs$(p)^{111}$Xe$(\alpha)^{107}$Te$(\alpha)^{103}$Sn, masses of other three nuclides will also shift following the change of $^{103}$Sn mass. The mass surfure of the four isotopic chain seem to be more smooth according to the systematic behavior of two-neutron separation energies.

Astrophysical network calculations indicate that the $rp$ process in x-ray bursts ends at a SnSbTe cycle and cannot proceed past tellurium isotopes due to the low $\alpha$ separation energies of neutron-deficient tellurium isotopes. The main reaction flow of this cycle is $^{103}$Sn$(\beta+)^{103}$In$(p,\gamma)^{104}$Sn$(\beta+)^{104}$In$(p,\gamma)^{105}$Sn$(p,\gamma)^{106}$Sb$(p,\gamma)^{107}$Te$(\gamma,\alpha)^{103}$Sn. The change of $^{107}$Te mass will influence on the competition between $^{106}$Sb$(p,\gamma)^{107}$Te and 106Sb ($\beta+$) 106Sn, and thus determine the amount of the SnSbTe cycle. However, since the reaction rate of $^{106}$Sb$(p,\gamma)^{107}$Te is about 3 orders of magnitude stronger than that of $^{106}$Sb$(p,\gamma)^{107}$Te. Our new mass will not change amount of the SnSbTe cycle too much.

# Multiple fragmentation of relativistic nuclei in nuclear track emulsion

A.A. Zaitsev[1] and P.I. Zarubin[1]

[1] *Joint Institute for Nuclear Research (JINR), Dubna, Russia*

The phenomenon of dissociation of relativistic nuclei observed with a unique completeness in the nuclear track emulsion (NTE) makes it possible to study ensembles of nucleons and lightest nuclei of interest to nuclear physics and nuclear astrophysics [1]. The advantages of the NTE technique include a record resolution in determining emission angles and the possibility of identifying the relativistic fragments He and H. Individual features of the nuclei under study are manifested in probabilities of dissociation channels. In such an approach the cluster structure of the light stable and radioactive isotopes was systematically examined in the framework of the BECQUEREL experiment [2] at the JINR Nuclotron. Recently, among the unstable $^{8}$Be and $^{9}$B nuclei were identified projectile fragments in the dissociation of $^{9}$Be, $^{10}$B, $^{10}$C, $^{11}$C by the invariant mass of relativistic He and H pairs and triples, and the Hoyles state in the $^{12}$C case [3, 4]. At the upcoming stage the BECQUEREL experiment will be aimed at properties of the baryonic matter arising in dissociation of heavy nuclei by simultaneous determination of yields of relativistic H and He isotopes and neutrons. NTE layers long-wise exposed to beams of the NICA Collider will serve as the research material allowing investigating light nuclear ensembles of unprecedented multiplicity and diversity.

---

[1] P.I. Zarubin, Lect. Notes in Physics, Clusters in Nuclei **875**(3), 51 (2014).

[2] The BECQUEREL Project http://becquerel.jinr.ru/movies/movies.html.

[3] D.A. Artemenkov *et. al.*, Phys. Part. Nucl. **48**, 147 (2017).

[4] D.A. Artemenkov *et. al.*, Rad. Meas. **119**, 119-203 (2018).

# NEW STUDY OF THE ASTROPHYSICAL REACTION 12C(alpha,gamma)16O

Mohammed Akram ZERMANE[1] and Nadia OULEBSIR[2]

[1]*laboratoire de Physique Thorique de l'Universite A.Mira de Bejaia, Algerie*

[2]*laboratoire de Physique Thorique de l'Universite A.Mira de Bejaia, Algerie*

12C(alpha, gamma)16O capture reaction is considered to be the most important thermonuclear reaction in non-explosive astrophysical sites and its reaction rate is an important nuclear parameter in many stellar evolution models. This reaction was investigated through the direct -transfer reaction (7Li, t) at 28 and 34 MeV incident energies. After the determination of the reduced -widths of the subthreshold 2+ and 1 states of 16 O from the DWBA analysis and the E2 and E1 S-factor from 0.01MeV to 4.2MeV in the center-of-mass energy and also the numerical determination of the reaction rate of this reaction at r=6.5 fm and at a different stellar temperature (0.06 Gk-2 GK), we will determine a new reaction rate of this reaction at r=7.7 fm.

# Neutron and Proton Captures on $^{16}$O

Shisheng Zhang[1] and Meng He[1]

[11] *School of Physics, Beihang University, Beijing 100191, China*

We revisit neutron and proton captures on $^{16}$O from astrophysics interest. Structure information is extracted from RMF+ACCC+BCS approach by NL1, NL2, NL3, NLSH and TM1 interactions, in which bound states, resonant states and pairing can be treated in a self-consistent microscopic way. Meanwhile, new Woods-Saxon potentials are proposed to reproduce the experimental one-nucleon separation energies and charge radii. With those structure information, reaction rates are calculated and compared with available JINA database. Single-particle resonance contributions are quantitatively considered and their roles in reaction rates are shown.

# Dualities and pion condensation in dense hadron/quark matter

Roman Zhokhov[1]

[1] *IHEP, Protvino, Russia*

In this talk the phase structure of the dense quark matter has been investigated in the presence of baryon $\mu_B$, isospin $\mu_I$, chiral $\mu_5$ and chiral isospin $\mu_{I5}$ chemical potentials in the framework of Nambu–Jona-Lasinio model. It has been shown that in the large-Nc limit (Nc is the number of colors of quarks) there exist duality correspondences (symmetries) at the phase portrait, which are the symmetries of the thermodynamic potential and the phase structure itself. The first one is a duality (symmetry) between the chiral symmetry breaking and the charged pion condensation phenomena. And there are two other dualities that hold only for chiral symmetry breaking and charged pion condensation phenomena separately. For example, we have shown that charged pion condensation does not feel the difference between chiral and isospin imbalances of the medium. The duality between the chiral symmetry breaking and the charged pion condensation phases has been established for the first time in low-dimensional toy model for QCD, then it has been checked to take place in a more realistic effective model for QCD. They were shown to exist in the matter with chiral imbalance that can be produced in compact stars or heavy ion collisions. One of the key conclusions of these studies is the fact that chiral imbalance generates charged pion condensation in dense baryonic/quark matter.

It is known that chiral imbalance can occur in high energy experiments of the collision of heavy ions, due to temperature and sphaleron transitions. Our studies show that different types of chiral imbalance can occur in the cores of neutron stars or in heavy ion experiments, where large baryon densities can be reached, due to another phenomena - the so-called chiral separation and chiral vortical effects.

# Equation of state effects in core-collapse supernovae

Sabrina Schäfer,[1,2] Hannah Yasin,[1] Almudena Arcones,[1,3] and Achim Schwenk[1,2,4]

[1] *Institut für Kernphysik, Technische Universität Darmstadt*

[2] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

[3] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

[4] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

We investigate the impact of different properties of the nuclear equation of state in core-collapse supernovae, with a focus on the proto-neutron-star contraction and its impact on the shock evolution. To this end, we introduce a range of equations of state that vary the nucleon effective mass, incompressibility, symmetry energy, and nuclear saturation point. This allows us to point to the different effects in changing these properties from the Lattimer and Swesty to the Shen *et al.* equations of state, the two most commonly used equations of state in simulations. In particular, we trace the contraction behavior to the effective mass, which determines the thermal nucleonic contributions to the equation of state. Larger effective masses lead to lower pressures at nuclear densities and a lower thermal index. This results in a more rapid contraction of the proto-neutron star and consequently higher neutrino energies, which aids the shock evolution to a faster explosion.

*This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Projektnummer 279384907 - SFB 1245 and the European Research Council Grant No. 677912 EUROPIUM.

# Nucleosynthesis in Type Ia Supernovae

Florian Lach[1] and Friedrich K. Röpke[1]

[1]*Institut für Theoretische Astrophysik,*

*Zentrum für Astronomie der Universität Heidelberg*

*and Heidelberg Institute for Theoretical Studies*

In addition to various sources such as winds from massive stars the Universe is enriched with metals via supernova explosions. Yields from simulations of these events can then be used as an input for galactic chemical evolution calculations. In turn, the outcome of galactic chemical evolution simulations and observations of abundances can also be used to constrain the source of a particular element to a certain explosion scenario. To provide the necessary yields for these studies, detailed numerical simulations of supernova explosions including studies of their nucleosynthesis results have to be carried out.

We therefore present the nucleosynthesis yields of a variety of Type Ia supernova explosion models taken from the *HESMA* [1] archive. Our analysis contains pure deflagrations of Chandrasekhar mass white dwarfs (WDs), pure detonations of sub-Chandrasekhar mass WDs, the violent merger of two WDs and double detonations models including the detonation of a helium shell of top of the WD. We put special emphasis on the nucleosynthetic yields from the $\alpha$-rich freezeout and the normal freezeout regime. The identification of particular elements characteristic for one those burning regimes in combination with predictions from galactic chemical evolution can then put constraints on the progenitor as well as the actual explosion mechanism of Type Ia supernovae.

[1] Kromer, M and Ohlmann, S and Röpke, FK, Simulating the observed diversity of Type Ia supernovae, (2017).