Nuclear Astrophysics with Ion Storage Rings

British-German WE-Heraeus-Seminar

29 January - 02 February 2024
at the

Physikzentrum, Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the British-German WE-Heraeus-Seminar:

Our understanding of stellar nucleosynthesis processes is inevitably connected to our knowledge of the properties of exotic nuclei. For instance, the rapid neutron-capture process (r-process), which is believed to be responsible for the production of about one-half of all elements heavier than iron as well as of all thorium and uranium, goes through neutron-rich nuclei far away from the valley of beta-stability. Another example is the rapid proton-capture process (rp-process) powering X-ray bursters, which proceeds along the proton drip line, the imaginary line on the chart of the nuclides beyond which the nuclei are unstable with respect to the emission of a proton. To describe these and other nucleosynthesis processes, various nuclear properties of the exotic nuclei involved are needed.

The advent of radioactive ion beam facilities enabled access to many relevant exotic nuclei. However, a lot of experimental information still remains inaccessible. New experimental developments are required and the ion storage rings provide here new, still unexploited, experimental possibilities. Originally intended for the storage of atoms and nuclei, heavy ion storage rings have also become indispensable tools in the field of nuclear astrophysics. Revolution frequencies of the cooled ions give access to ground state masses and excitation energies of isomeric states. Monitoring particle intensities as a function of storage time gives straightforward access to nuclear half-lives. These data are crucial for astrophysics applications since the nuclear masses and half-lives primarily determine the pathways and the speed of the nucleosynthesis processes on the chart of the nuclides, respectively. Moreover, very recently, storage rings equippedwith thin gas-jet targets have opened doors for in-ring reaction studies that are pivotal for the understanding of the processes that forge the elements in stars and the big bang.

The goal of the seminar is to bring together global experts from experiment and theory in the field working on various storage ring projects for a constructive discussion of the most promising paths to maximize the impact of the available facilities and exploit synergies among the groups. Besides the invited presentations on the status of the leading facilities, the potential of new technological developments will also be discussed. Students and young researchers in the field will have theopportunity to present their ideas in the form of contributed talks and poster presentations.

Introduction

Scientific Organizers:

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Introduction

Venue:	Physikzentrum Hauptstrasse 5 53604 Bad Honnef, Germany Conference Phone +49 2224 9010-120 Phone +49 2224 9010-113 or -114 or -117 Fax +49 2224 9010-130 E-mail gomer@pbh.de Internetwww.pbh.de Taxi Phone +49 2224 2222
Registration:	Marion Reisinger (WE Heraeus Foundation) at the Physikzentrum, reception office Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 28 January 2024

17:00 – 21:00	Registration	
From 18:00	*BUFFET SUPPER and WELCOME*	**Ragandeep Singh Sidhu and Jan Glorius**

Monday, 29 January 2024

08:00 – 08:45	*BREAKFAST*	
08:45 – 09:00		**Welcome Yuri A. Litvinov and Ragandeep Singh Sidhu**
09:00 – 10:00	Michael Wiescher	**The Challenge of Low Temperature Reaction Rates**
10:00 – 11:00	Gabriel Martinez-Pinedo	**Probing heavy element nucleosynthesis through electromagnetic observations**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Jan Glorius	**Proton-Induced Reaction Cross Sections Measured using Stored Heavy Ion Beams**
12:30 – 14:00	*LUNCH*	
14:00 – 15:00	Beatriz Jurado	**Surrogate reactions at heavy-ion storage rings**

Program

Monday, 29 January 2024

15:00 – 16:00	Carlo Bruno	**The CARME@CRYRING project - future scientific aims**
16:00 – 16:30	*COFFEE BREAK & CONFERENCE PHOTO*	
16:30 – 17:00	Oliver Forstner	**Towards the measurement of the astrophysically relevant alpha-capture reaction rate 44Ti(α,p)47V at CRYRING@ESR**
17:00 – 18:30	POSTER FLASHES	
18:30	*DINNER*	

Program

Tuesday, 30 January 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Alexandre Gumberidze	**Atomic physics with highly-charged ions at storage rings**
10:00 – 11:00	René Reifarth	**Nuclear fusion experiments in rings**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:00	Michele Sguazzin	**First NECTAR experiment and future use of solar cells as heavy-ion detectors in storage rings**
12:00-12:30	Camille Berthelot	**Detailed simulations for the next surrogate reaction experiment at the ESR storage ring**
12:30 – 14:00	*LUNCH*	
14:00 – 15:00	Claudia Lederer-Woods (online)	**Neutron Reactions in Stellar Nucleosynthesis**
15:00 – 16:00	Aaron Couture	**First Steps Towards Neutron-Induced Reactions in Inverse Kinematics**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 18:30	POSTER SESSION	
18:30	*DINNER*	

Program

Wednesday, 31 January 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Holger Kreckel	**Molecular Astrophysics at the Cryogenic Storage Ring**
10:00 – 11:00	Sarah Naimi	**Advancing Precision Mass Measurements for Nuclear Astrophysics Experiments at RIKEN with the Rare-RI Ring**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:00	Zhuang Ge	**Mass measurements of N=Z nuclei and the vicinity with Rare-RI Ring in RIKEN for the study rp- and vp processes**
12:00 – 12:30	Andrew Ratkiewicz	**Indirect Constraints of Neutron-Induced Reactions**
12:30 – 14:00	*LUNCH*	
14:00 – 16:30	NucAR Session	
16:30 – 17:00	COFFEE BREAK	
17:00 – 18:00	Meng Wang	**Mass measurements of short-lived nuclides at CSRe**
18:00	*HERAEUS DINNER*	*(social event with cold & warm buffet and complimentary drinks)*

Program

Thursday, 01 February 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Iris Dillmann	**The TRIUMF Storage Ring Project**
10:00 – 11:00	Daniel Bemmerer	**Underground nuclear astrophysics**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:00	Eliana Masha	**New direct measurements to constrain Big Bang Nucleosynthesis**
12:00 – 12:30	Konrad Schmidt	**Scientific opportunities of experiments with gas targets**
12:30 – 14:00	*LUNCH*	
14:00 – 15:00	Almudena Arcones	**Nucleosynthesis in core-collapse supernovae and neutron star mergers**
15:00 – 16:00	Manoel Couder	**The St. George and SECAR recoil separators**
16:00 – 16:30	COFFEE BREAK	
16:30 – 17:30	Thomas Davinson	**New charged particle detector systems for storage rings**
17:30 – 18:00	Bogusław Włoch	**Detector developments and technical aspects of the second NECTAR experiment**
18:00 – 18:30	David Leimbach	**Laser spectroscopy of negative ions at DESIREE**
18:30	*DINNER*	

Program

Friday, 02 February 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Zsolt Podolyak	**Isomers in storage rings**
10:00– 11:00	Rudrajyoti Palit	**Reactions involving weakly bound stable isotopes using a hybrid gamma array at PLF and future possibilities**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:00	Timilehin Ogunbeku	**Total Absorption Spectroscopy at the FRIB Decay Station Initiator (FDSi)**
12:00 – 12:30	Heinrich Wilsenach	**Trap System for Measuring Neutron Capture Cross Section of Short-lived Isotopes**
12:30 – 13:00	**Closing and Discussion**	
13:00 – 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Sayed El Moutaouakel Berghout	**Unraveling the Mysteries of Stellar Elemental Production through Nuclear Reactions**
Axel Boeltzig	**Measurements of ^{12,13}C(p,γ) at the Felsenkeller and LUNA Underground Accelerator Laboratories**
Dmytro Dmytriiev	**Position-sensitive Schottky cavity for the heavy-ion storage rings**
Cesar Domingo-Pardo	**Challenges and prospects on neutron-capture cross-section experiments with s-process branching nuclei**
Stephan Fritzsche	**Atomic computations for astrophysical plasma**
Marcel Heine	**Nanoseconds Timing Fusion Reaction Measurements with the STELlar Laboratory**
Lochan Khanal	**Dust properties around asymptotic giant branch stars: iras 20263+4245 under iris, akari and wise survey**
Michael Lestinsky	**Experiments at the Low-Energy Heavy Ion Storage Ring CRYRING@ESR**
Martin Müller	**Activation experiments using decay chains**
Ariel Tarifeno-Saldivia	**Study of decay properties on neutron-rich nuclei around mass A=160 relevant for the formation of the r-process rare-earth peak (REP)**
Laszlo Varga	**Proton capture measurements on stored ions for the γ-process nucleosynthesis**
Giorgio Visentin	**Dielectronic recombination plasma rate coefficients of Na-, Mg- and Al-like iron ions: the role of the 2(s + p) → 4l, nl′ and 3(s + p) → 5l, nl′ resonances**

Posters

Zhongwen Wu	**Nuclear effect on angular and polarization behaviors of characteristic x rays following electron-impact excitation of highly charged ions with non-zero nuclear spin**
Anup Yadav	**Development of new combined jet and extended gas target system for the Felsenkeller underground accelerator laboratory**
Takayuki Yamaguchi	**New physics opportunities at the Rare-RI Ring facility**
Chen Zuyi	**Ground-state mass of ^{22}Al, ^{26}P and^{28}S**

Abstracts of Talks

(in alphabetical order)

Nucleosynthesis in core-collapse supernovae and neutron star mergers

Almudena Arcones[1]

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Our understanding of the origin of heavy elements by the r-process has made great progress in the last years. In addition to the gravitational wave and kilonova observations for GW170817, there have been major advances in hydrodynamic simulations of neutron star mergers and core-collapse supernovae, in the microphysics included in those simulations (neutrinos and high density equation of state (EoS)), in galactic chemical evolution models, in observations of old stars in our galaxy and in dwarf galaxies. This talk will report on recent breakthroughs in understanding the extreme environment in which the formation of the heavy elements occurs, as well as open questions regarding the astrophysics and nuclear physics involved. Observations of old stars and meteorites can strongly constrain the astrophysical site of the r-process, once the nuclear physics uncertainties of extreme neutron-rich nuclei are reduced by experiments and by improved theoretical models.

Underground nuclear astrophysics

Daniel Bemmerer[1]

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

Due to the repulsive Coulomb barrier, nuclear reaction cross sections in the astrophysically relevant energy range are generally very low, in the nanobarn – picobarn range and even below. In order to measure such rare processes, it is necessary to conduct experiments under extremely low-background conditions. One persistent source of background in nuclear cross section measurements are cosmic muon induced effects, part of which evade active veto measures. Therefore, ion accelerators have been placed in underground laboratories, where the muon flux is attenuated by the thick rock overburden. This technique is in some cases complementary to the use of low-energy storage rings for nuclear reaction studies. The use of both techniques on selected cases may help shed light on unknown systematic effects.

The contribution will review the development of underground nuclear astrophysics from the LUNA 50 kV and 400 kV ion accelerators at Gran Sasso, Italy, to the higher-energy underground ion accelerators recently commissioned in the United States, Germany, China, and Italy. Selected science cases include Big Bang nucleosynthesis and stellar hydrogen, helium, and carbon burning. An outlook on future developments will be given.

Detailed simulations for the next surrogate reaction experiment at the ESR storage ring

C. Berthelot[1], B. Jurado[1], J. Pibernat[1], M. Sguazzin[2], B. Wloch[1], J. Glorius[3], M. Grieser[4], Yu. A. Litvinov[3]

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

Neutron-induced reaction cross sections of short-lived nuclei are essential to understand the stellar nucleosynthesis of heavy elements. However, these cross sections are very difficult or impossible to measure due to the difficulty to produce and handle the necessary radioactive targets. The NECTAR (Nuclear rEaCTions At storage Rings) project uses surrogate reactions in inverse kinematics at a heavy-ion storage ring. This allows one to measure the de-excitation probabilities as a function of the excitation energy of the nuclei formed through the surrogate reaction with unrivaled precision and indirectly determine the aforementioned cross sections. An overview of NECTAR, covering its motivation, some selected results from the first experiment, and short- and long-term perspectives, will be presented by Beatriz Jurado.

In this contribution I will show the results of very detailed simulations for the next NECTAR surrogate-reaction experiment, which is scheduled in June 2024 at the ESR. In this experiment, the ^{208}U(d,d') and ^{208}U(d,p) surrogate reactions will be used to form the ^{238}U and ^{239}U compound nuclei, respectively. My simulations show that it will be possible to measure for the first time the fission, γ-ray, neutron and even two-neutron emission probabilities simultaneously.

I will present simulated spectra for the detection of the different reaction residues and discuss the expected detection efficiencies. The efficiencies for the gamma- and neutron-emission channels can reach the outstandingly high value of 100%. In the case of fission, the detection efficiency varies between 60% and 65% and for two neutron emission between 40% and 50%. I will also discuss simulated results for the excitation energy resolution.

The CARME@CRYRING project - future scientific aims

Dr. Carlo G. Bruno
University of Edinburgh UK

Heavy ion storage rings are a novel and revolutionary way to carry out studies of nuclear physics reactions of astrophysical importance. I will focus my talk on the science that can be performed both in the short and longer term with the CARME array [1], located at the world-unique low-energy heavy ion storage ring CRYRING (GSI/FAIR, Germany [2]

CARME was designed and developed primarily for inverse kinematics studies using pure, recirculating radioactive beams impinging on the ultra-pure, thin CRYRING internal target. Some of these beams are not available with these quality and intensities anywhere else in the world, and will allow us to take a step forward in our understanding of a number of explosive stellar sites, such as novae explosions.

In addition, CARME's flexible design will make it possible to exploit stable beams from the CRYRING local ion source to carry out cutting-edge studies of extremely low-energy nuclear reactions of interest in astrophysical sites [3] such as the Big Bang and quiescent burning stars. In particular, ring may allow us to take a step forward in approaching the long-standing puzzle of electron screening in low-energy nuclear reactions, which to this day remains unsolved.

References

[1] C.G. Bruno, et al. Nuc. Inst. Meth. A 1048 (2023) 168007
[2] M. Lestinsky et al., Eur. Phys. J. A 225 (2016) 797
[3] J.J. Marsh, et al.*, in preparation*

The St. George and SECAR Recoil Separators

M. Couder[1,2]

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

The recoil separators St. George and SECAR are specifically designed to study radiative capture reactions of astrophysical interest in inverse kinematics. St. George, at the Nuclear Science Laboratory of the University of Notre Dame, specializes in the study of (alpha,gamma) reactions induced by stable ion beams. While SECAR, at the Facility for Rare Isotope Beams at Michigan State University, is focused on hydrogen and helium radiative capture reactions induced by unstable beams. This talk will discuss the science program of each setup, the technical choices made and the associated challenges. The use of the separator for alternative studies will also be presented.

First Steps Towards Neutron-Induced Reactions in Inverse Kinematics

A. Couture[1]

[1]*Los Alamos National Laboratory, Los Alamos, USA*

The majority of the heavy elements (A>60) found in the universe were made through neutron-induced reactions. Collectively, the *slow* (*s*-), *rapid* (r-), and intermediate (i-) neutron capture processes have been used to describe the origins of these heavy elements. The possible astrophysical sites span low-mass asympototic branch (AGB) stars through neutron star mergers. This covers a wide range of neutron densities, temperatures, and time scales. All of these require nuclear physics input including nuclear masses, beta-decay lifetimes, and reaction cross sections, most for unstable isotopes.

Experimental determination of nuclear masses and decay properties has seen an explosion of capability brought about by the growth of radioactive ion beam facilities. Such a revolution has not, to date, occurred with neutron-induced reactions *because there is no neutron target*. This landscape has changed with the idea of coupling an ion storage ring to a neutron spallation target first suggested by Reifarth *et al.* [1].

The Los Alamos Neutron Science Center (LANSCE) has the requisite high-intensity, high-energy proton accelerator and spallation physics expertise for such a neutron target facility. A new project has been undertaken to perform the first neutron capture measurement in inverse kinematics to test the feasibility of a true neutron target to be coupled to an ion storage ring. In this seminar, I will discuss the opportunities presented by a neutron target facility and the near-term experimental program at Los Alamos with the Neutron Target Demonstrator experiment.

References

[1] R. Reifarth, K. Göbel, T. Heftrich, M. Weigand, B. Jurado, F. Käppeler, and Y. Litvionov Phys. Rev. Accel. Beams **20**, 044701 (2017).

New charged particle detector systems for storage rings

<u>T.Davinson</u>[1] *et al.*

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

The combination of the ESR and CRYRING storage rings at GSI provides a unique opportunity to study nuclear reactions with radioactive beams. We discuss the experimental methodology, the development of XHV-compatible double-sided silicon strip detectors and the design and implementation of an in-ring spectrometer to study nuclear reactions of astrophysical interest in inverse kinematics with high energy resolution.

The TRIUMF Storage Ring Project

Iris Dillmann[1,2], Rick Baartman[1,2], Alan Chen[3], Barry Davids[1,4], Falk Herwig[2], Tobias Junginger[2,1], Dobrin Kaltchev[1], Oliver Kester[1,2], Annika Lennarz[1,5], Thomas Planche[1,2], Chris Ruiz[1,2], Nicole Vassh[1]

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[3] McMaster University, Hamilton ON, Canada,
[4]Simon Fraser University, Burnaby BC, Canada,
[5] McGill University, Montreal QC, Canada

Heavy-ion storage rings connected to radioactive beam facilities offer a unique environment for nuclear physics experiments. However, so far they have been only coupled to in-flight fragmentation facilities, for example the ESR and the CRYRING at GSI Darmstadt/ Germany, the CSR at HIRF in Lanzhou/ China, and the Rare RI Ring at RIKEN Nishina Center in Japan.

Neutron capture reactions play a crucial role for the understanding of the synthesis of elements heavier than iron in stars and stellar explosions via the slow (s), intermediate (i), and rapid (r) neutron capture processes. Whereas most of the s-process neutron captures occur on stable or long-lived nuclei along the line of stability and have been experimentally constrained in the past decades, measuring directly the neutron capture cross sections of short-lived nuclides ($T_{1/2}$ << 1 y) has been so far out of reach and lead to large deviations between various Hauser-Feshbach predictions for very neutron-rich nuclei.

Recently, methods to couple neutron-producing "facilities" to a storage ring were outlined [1,2]. Our storage ring project at TRIUMF [3] proposes to use a compact neutron source coupled to a low-energy storage ring (E= 0.1-2 MeV/u) and the existing ISAC radioactive beam facility.

The TRISR project and its work packages are presented, and possible astrophysical neutron capture measurements are discussed. If the design study is successful, a world-wide unique pioneering facility could be built within the next 10 years.

References

[1] R. Reifarth and Y. Litvinov, Phys. Rev. ST Accel. Beams 17 (2014) 014701.
[2] R. Reifarth et al., Phys. Rev. Accel. Beams 20 (2017) 044701.
[3] I. Dillmann et al., Eur. Phys. J. A59 (2023) 105.

Towards the measurement of the astrophysically relevant alpha-capture reaction rate $^{44}Ti(\alpha,p)^{47}V$ at CRYRING@ESR

O. Forstner[1,2] **and Ti-44@CARME Collaboration**

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[2] Helmholtz Institute Jena, Jena, Germany
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The long-lived radionuclide ^{44}Ti ($t_{1/2}$=60 a) is a perfect tool to study nucleosynthesis in a core-collapse supernova. The low-energetic gamma photons (68 and 78 keV) of the decay to ^{44}Sc are directly observable by satellite-based gamma ray observatories. This allows to estimate the amount of ^{44}Ti produced during a supernova and subsequently test supernova models. However, this requires a precise knowledge of the nuclear reactions responsible for the production and consumption of ^{44}Ti. The dominant consumption reaction is $^{44}Ti(\alpha,p)^{47}V$. This rate of this reaction has up to now only been measured at energies above the Gamow window and one measurement at ISOLDE at CERN [1] in the Gamow window is still under debate. Therefore, a precise determination of the reaction rate is highly demanded. CRYRING@ESR in combination with the gas-jet target and the CARME detector array is perfectly suited to study this reaction [2]. The energy range of CRYRING overlaps with the Gamow window for this reaction at core-collapse supernovae. The experiment was already proposed at the 2020 G-PAC and was granted beam-time. However, due to massive impact by the Covid-19 pandemic situation the required installations where not ready. It was again submitted to the 2022 G-PAC as LOI and was positively evaluated. The CARME detector and the gas-jet target were successfully commissioned in 2022, which opens the way to perform this important experiment.

References

[1] V. Margerin et al., Phys. Lett. B **731**, 358 (2014)
[2] O. Forstner et al., X-Ray Spectrom. **49**, 129-432 (2020)

Mass measurements of N=Z nuclei and the vicinity with the Rare-RI Ring at RIKEN

Z. Ge[1], T. Uesaka[2]

on behalf of the IGISOL collaboration and Rare-RI Ring collaboration

[1]*University of Jyväskylä, Jyväskylä, Finland*
[2]*RIKEN Nishina center, Wako, Japan*

Nuclear masses have the most decisive influence on the modelling of the astrophysics rp-process and the νp-process. They determine the position of the proton drip line, the separation energies (i.e., the Q values of neutron or proton captures), and the Q values for beta/alpha decay and nuclear reactions. The masses of the neutron-deficient heavy N=Z nuclei and the vicinity (including ^{100}Sn) close to the proton dripline are important inputs for the rp-process and vp-process as well as nuclear structure studies. To reach this region and to have an effective use of the precious beam time, two complementary time-of-flight mass measurement techniques including the isochronous mass spectrometry (IMS), Rare-RI Ring, to get access to the heaviest N=Z nuclei (A=78-100) and the vicinity close to the astrophysical rp-process and the vp-process paths will be used at RIBF. The proposed experiment to measure this region was approved at RIBF in RIKEN. The nuclei will be produced via the fragmentation of a ^{124}Xe beam (345 MeV/nucleon) with an intensity of 140 pnA (~8.7×10^{11} pps) or higher bombarding on a ^{9}Be target. In this contribution, we will report on the new techniques and progresses for mass measurements of N=Z nuclei and the vicinity near the proton dripline with the Rare-RI Ring in RIKEN.

References

[1] A. Ozawa et al., Prog. Theo. Exp. Phys. **2012**, 03C009 (2012).
[2] Z. Ge, T. Uesaka, S. Naimi et al., Hyperfine Interact **240**: 92 (2019)

Proton-Induced Reaction Cross Sections Measured using Stored Heavy Ion Beams

J. Glorius[1]

[1]*GSI Helmholtzzentrum, Darmstadt, Germany*

To understand and model element synthesis and energy budget in stars a large number of nuclear reaction cross sections must be known. For explosive stellar scenarios, like supernovae or x-ray bursters, this heavily involves nuclei beyond stability. However, due to the challenges inherent to related experiments, the lack of available experimental data in this domain is severe.

A new method for measuring cross sections of proton-induced reactions has been developed using cooled and decelerated beams at the ESR heavy ion storage ring at GSI. It enables studies of (p,γ) and (p,n) reactions on radioactive ions inside or close to the astrophysical Gamow window, which can deliver the necessary constraints for nuclear theory and astrophysics.

Most recently, the technique was upgraded, enabling the first successful application to a radioactive beam produced in the Fragment Separator. This talk will give an overview of past and recent developments and results, as well as an outlook on future experiments and physics cases.

Atomic physics with highly-charged ions at storage rings

A. Gumberidze

[1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

In the contribution, I will present a brief overview of the atomic physics research at ESR, CRYRING@ESR and HITRAP facilities. Selected results from some of the recent beam times conducted within the FAIR Phase-0 program will be shown as well. A short outlook for the mid-term as well as long-term future for the atomic physics experiments at GSI will also be presented.

References

[1] M. Lestinsky et al, Eur. Phys. J. Special Topics **225**, 797-882 (2016)
[2] B. Zhu et al, Phys. Rev. A **105,** 052804 (2022)
[3] M. Lestinsky et al, Atoms **10** 141 (2022)

Surrogate reactions at heavy-ion storage rings

B. Jurado[1,] M. Sguazzin[1], M. Grieser[2], J. Pibernat[1], J. A. Swartz[1],
J. Glorius[3], Y. Litvinov[3], *C. Berthelot[1], W. Wloch[1] et al.*

[1]LP2I, Bordeaux, France
[2] MPIK, Heidelberg, Germany
[3] GSI, Darmstadt, Germany

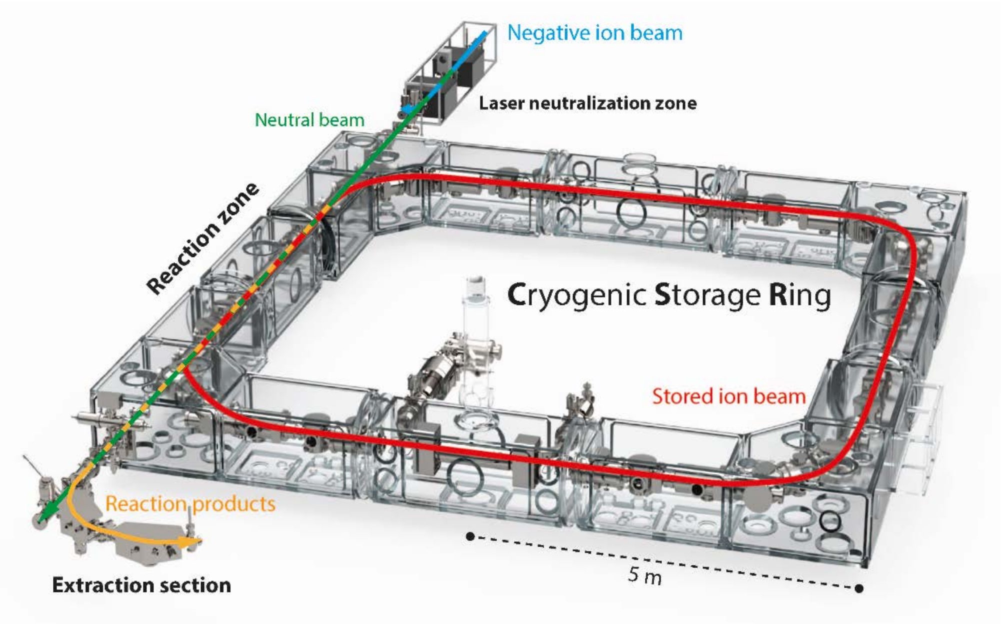
Obtaining reliable cross sections for neutron-induced reactions on unstable nuclei nuclei is crucial to our understanding of the stellar nucleosynthesis of heavy elements. However, the measurement of these cross sections is very complicated, or even impossible, due to the radioactivity of the targets involved. Our aim is to circumvent this problem by using the surrogate-reaction method in inverse kinematics at heavy-ion storage rings, which offer unique and largely unexplored possibilities for the study of nuclear reactions. In this talk, we will present the technical developments and the methodology, which we are developing to perform high-precision surrogate-reaction experiments at the Experimental Storage Ring (ESR) of the GSI/FAIR facility. In particular, we will present the results of the first experiment, which we successfully conducted at the ESR, and briefly describe the perspectives for future measurements.

Molecular Astrophysics at the Cryogenic Storage Ring

Holger Kreckel for the CSR team

Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

The Cryogenic Storage Ring (CSR) at the Max Planck Institute for Nuclear Physics in Heidelberg is the largest electrostatic storage ring project in the world [1]. The CSR combines electrostatic ion optics with extreme vacuum and cryogenic temperatures. Small infrared-active molecular ions (like, e.g., CH^+, HeH^+ and OH^+) will cool to their lowest rotational quantum states by spontaneous emission of radiation within a few minutes of storage inside the CSR [2,3,4,5].



Equipped with an ion-neutral collision setup and a low-energy electron cooler, the CSR offers unique possibilities for astrochemical experiments under true interstellar conditions. We will present an overview of the capabilities of the CSR, along with experimental results on collision experiments between cold molecular ions and free electrons, photons, and neutral atoms, yielding state-selective rate coefficients for astrophysically important processes.

References

[1] Von Hahn et al, Rev. Sci. Instrum. 87, 063115 (2016)
[2] O’Connor et al, Phys. Rev. Lett 117, 113002 (2016)
[3] Meyer et al, Phys. Rev. Lett 119, 02320 (2017)
[4] Novotny et al., Science 365, 676 (2019)
[5] Kalosi et al, Phys. Rev. Lett. 128, 183402 (2022)

Neutron Reactions in Stellar Nucleosynthesis

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Neutron induced reactions play a key role in stellar nucleosynthesis processes, and reaction cross sections are an important input to predict abundances produced. There is a wealth of experimental data of stellar neutron cross sections on stable isotopes. However reactions on unstable nuclei, relevant for stellar environments with high neutron densities, are challenging to measure due to both reaction partners being unstable. I will present an overview of recent experimental progress on neutron induced reaction measurements and future possibilities.

Laser spectroscopy of negative ions at DESIREE

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In multi-electron systems such as atoms and molecules, the electron-electron interaction poses a major challenge for the accurate theoretical description of atomic structure and dynamics, requiring sophisticated numerical approaches. These theoretical models are then also used to provide required information for experimental analysis such as for nuclear square charge radii determinations from isotope shift measurements [1].

Negative ions can serve as excellent probes for these tests, in addition to a variety of applications in other fields [2-4]: since the Coulomb potential of the nucleus is almost entirely screened, the binding of the additional electron in a negative ion is primarily due to the many body interactions between electrons. Consequently, negative ions are sensitive probes of these effects.

However, due to the weak binding potential, the energy gained by attaching an electron to a neutral atom, referred to as electron affinity (EA), is typically only in the order of one eV. For the same reason, negative ions typically lack bound excited states with opposite parity, noticeable exceptions being lanthanum, cerium, osmium, thorium and uranium [5-9]. Consequently, the EA is the only parameter which can be probed with high precision, typically via laser photodetachment threshold spectroscopy (LPTS).

Transitions due to magnetic dipole (M1) and electric quadrupole interactions (E2) can occur between fine structure and hyperfine structure levels respectively, but are weak and typical possess lifetimes of the order of several seconds, requiring storage rings such as DESIREE in Stockholm, Sweden [5], where these anions can be stored for several lifetimes. In addition, storing the ions for an extended period enables the relaxation and “clean-out” of excited states, giving the opportunity to perform high precision photodetachment measurements of EAs, such as recently demonstrated by Kristianssen *et al.* for the oxygen anion [6].

Here, we will present recent results from measurements of the anions of Si, Th and Sn at DESIREE.

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Probing heavy element nucleosynthesis through electromagnetic observations

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Half of the elements heavier than iron are produced by a sequence of neutron captures, beta-decays and fission known as r-process. It requires an astrophysical site that ejects material with extreme neutron rich conditions. Once the r-process ends, the radioactive decay of the freshly synthesized material is able to power an electromagnetic transient with a typical intrinsic luminosity. Such kilonova was observed for the first time following the gravitational signal GW170817 originating from a merger of two neutron stars. This observation answered a long lasting question in nuclear astrophysics related to the astrophysical site of the r process. In this talk, I will summarize our current understanding of r process nucleosynthesis. I will also illustrate the unique opportunities offered by kilonova observations to learn about the in-situ operation of the r-process and the properties of matter at extreme conditions. Achieving these objectives, requires to address fundamental challenges in astrophysical modeling, the physics of neutron-rich nuclei and high density matter, and the atomic opacities of r-process elements required for kilonova radiative transfer models. Finally, I will introduce a new nucleosynthesis process, the νr-process, that operates in ejecta subject to very strong neutrino fluxes producing p-nuclei starting from neutron-rich nuclei. It may solve a long standing problem related to the production of ^{92}Mo and the presence of long-lived ^{92}Nb in the early solar system.

New direct measurements to constrain Big Bang Nucleosynthesis

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Big Bang nucleosynthesis (BBN) is a fundamental process that takes place shortly after the birth of the universe. It is responsible for the production of light elements such as H, He, and Li and serves as a powerful tool for understanding the early universe, its composition, and the physical processes that governed its evolution. The ^{2}H(p,γ)^{3}He reaction is one of the deuterium destruction channels during Big Bang Nucleosynthesis and affects the primordial deuterium abundance. This abundance, in turn, may probe fundamental cosmological parameters such as the baryon-to-photon ratio (η) and the number of neutrino species (N_{ν}).

The ^{2}H(p,γ)^{3}He reaction has been measured in the BBN energy range with very high precision by the LUNA collaboration [1]. New experimental data above the BBN energy range have been reported by Turkat et al. [2] using solid deuterium targets. To constrain the tension between these two data-set, the talk will show data from a new experimental campaign on ^{2}H(p,γ)^{3}He reaction in a wide energy range at the underground laboratory Felsenkeller in Dresden, Germany.

The talk will also address the need for new high-precision measurements of the ^{2}H(^{2}H,n)^{3}He and ^{2}H(^{2}H,p)^{3}H reactions in the BBN energy range, which may be done in the future at CRYRING at GSI/FAIR.

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Advancing Precision Mass Measurements for Nuclear Astrophysics Experiments at RIKEN with the Rare-RI Ring

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Situated at the RI Beam Factory within RIKEN, the Rare-RI Ring marks a significant advancement in the field of Isochronous Mass Spectrometry. It is specifically tailored to address the demanding requirements of precise mass measurements for rare isotopes, which often have limited production yields and very short half-lives. Distinguished as a storage ring akin to a cyclotron, the Rare-RI Ring offers a unique feature, allowing it to selectively accept pre-identified rare isotopes on an individual event basis. This ensures that background-free accurate mass measurements can be achieved for the scarcest isotopes across a wide range of momentum values.

This innovative operational mode has effectively overcome the challenge of achieving mass measurements at the parts-per-million (ppm) level for exceedingly rare isotopes. A recent milestone in determining the new mass of a palladium isotope, located 15 neutrons away from stability, has unveiled the impact of precise mass measurements on the modeling of the r-process abundance.

In this presentation, I will highlight the technological achievements and delve into the upcoming extensive scientific program planned for the Rare-RI Ring.

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Total Absorption Spectroscopy at the FRIB Decay Station Initiator (FDSi)

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Ground state to ground state beta-decay transition strengths are sensitive probes for understanding the phenomenon of Urca cooling in neutron star crusts. The strength of the electron capture and beta decay ^{55}Ca-^{55}Sc cycle has been predicted to significantly influence the thermal structure of accreting neutron stars that exhibit superbursts. No previous measurements of this transition exist due to the difficulties in producing such neutron-rich nuclei in sufficient quantities. Total Absorption Spectroscopy has emerged as an indispensable tool for constraining uncertainties in transition strength measurements due to the use of high-efficiency detectors such as the Modular Total Absorption Spectrometer (MTAS).

During the second-ever FRIB experiment, neutron-rich nuclei in the region of ^{54}Ca were produced and delivered to the FDSi as a “cocktail” secondary beam. I will present a general overview of the second FDSi experiment, and preliminary results relevant to the nuclear astrophysics questions sought to be addressed by this experiment.

Reactions involving weakly bound stable isotopes using a hybrid gamma array at PLF and future possibilities

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An overview of the BARC-TIFR Pelletron Linac Facility (PLF) at TIFR, Mumbai, and the experimental programmes will be presented. The availability of weakly bound stable nuclei such as 6,7Li and 9Be at PLF provides opportunities to study various nuclear structure phenomena and elucidate new aspects of reaction dynamics. Recently, several experiments have been conducted using a hybrid array of clover HPGe and $LaBr_3$(Ce) detectors coupled to the charged particle detectors at PLF to study the reaction mechanisms and various nuclear structure phenomena [1,2,3]. Some of the results from these experiments will be presented. We will also discuss the plan for future research facilities in India for low-energy nuclear physics and nuclear astrophysics.

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Isomers in storage rings

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The nuclear data needed for the abundance calculations are mainly masses (used to calculate Q values and, crucially, reaction cross sections) and lifetimes. Properties of long lived isomers are included as separate nuclides in the network calculations, while those of other excited states are not used. The effect on nucleosynthesis of isomeric states depends on their lifetimes and the properties of the environment. At low temperature the ground state and isomer can be treated as completely different species, while at very high temperature as completely thermalised. Between these extremes, the effective lifetime of a nuclear species is temperature dependent [1,2,3].

Storage rings are sensitive to long-lived isomeric sates, providing information on their excitation energies, lifetimes and decay modes. The Experimental Storage Ring at GSI was used to identify a number of isomeric states in the deformed neutron-rich mass A~180 region [4]. The decay schemes of some of them were elucidated in dedicated experiments following population in multi-nucleon transfer reactions (e.g. [5]). Previous experiments as well as opportunities for future studies with storage rings will be discussed.

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Indirect Constraints of Neutron-Induced Reactions. **Andrew Ratkiewicz**[1]

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Neutron-induced reactions on unstable nuclei are of interest to many areas of basic science (such as nuclear astrophysics) and applications. However, these reactions are often difficult or impossible to directly measure due to the radioactive nature of the target. As a result, several indirect techniques have been developed to provide constraints on these reactions. One such technique is the Surrogate Reaction Method, which can constrain a wide variety of the observables associated with neutron-induced reactions as well as some of the properties of unstable nuclei. I will describe this technique, how it has been traditionally exercised, and discuss exciting new developments which will enable it to be deployed to constrain reactions on and the properties of even more exotic nuclei.

Nuclear fusion experiments in rings

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Most of the time, stars gain their energy from fusion of the very light left-overs of the Big Bang into heavier elements over long periods of time. The observation of radioactive isotopes in different regions of the Universe is an indicator of this ongoing nucleosynthesis. In addition, short-lived nuclei are often intermediate steps during the nucleosynthesis in stars. A quantitative analysis of these relations requires a precise knowledge of reaction cross sections involving unstable nuclei. The corresponding measurements are very demanding and the applied techniques therefore manifold.

Ion storage rings offer unprecedented possibilities to investigate nuclear fusion reactions of radioactive isotopes of astrophysical importance in inverse kinematics. During the last years, a series of pioneering proton-fusion experiments proofed the feasibility of this concept at the Experimental Storage Ring (ESR) at GSI. The Los Alamos National Laboratory has funded a Neutron Target Demonstrator (NTD) project, which eventually aims at combining a spallation neutron source with an ion storage ring to investigate neutron-fusion reactions. I will present a short overview of recent achievements in the area of fusion reactions at rings, provide the astrophysical background and discuss further needs and ideas for possible future setups.

Scientific opportunities of experiments with gas targets

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Future nuclear astrophysics experiments need next-generation gas target setups to handle the demands of various experimental setups. New gas targets are deployed along storage rings, in front of recoil separators, and everywhere else where chemically clean targets are required to minimize beam induced background. For the underground accelerator laboratory Felsenkeller in Dresden, Germany, a new state-of-the-art gas target setup is under commissioning. It is unique in combining a highly localized gas jet with an extended, static gas target. The talk will present gas-target utilizing experiments that are complementary to proposed experiments with CRYRING at GSI/FAIR, Germany.

First NECTAR experiment and future use of solar cells as heavy-ion detectors in storage rings

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Neutron-induced reaction cross sections of unstable nuclei are essential for understanding the synthesis of heavy elements in stars and for applications in nuclear technology. However, their direct measurement is very complicated due to the radioactivity of the targets involved. In the frame of the NECTAR (Nuclear rEaCTions At storage Rings) project, we propose to circumvent this problem by combining the surrogate reaction method in inverse kinematics with the unique possibilities of storage rings. Thanks to this new technique it is possible to measure the probabilities for competing decay channels (gamma-emission, one and two neutron emission and fission) of radioactive nuclei as a function of the compound-nucleus excitation energy. These probabilities are then used to constrain fundamental quantities that describe the de-excitation of the compound nucleus such as level densities, gamma-ray strength functions and fission barriers, significantly improving the predictions of the neutron-induced reaction cross sections of interest. In June 2022 we performed the first successful surrogate reaction experiment at the Experimental Storage Ring (ESR). I will present the details of the used experimental set-up, the data analysis and some results of our first experiment. In the second part of my talk I will present our studies on solar cells, which appear as a very interesting alternative to Si detectors for the detection of heavy-ions at storage rings.

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Mass measurements of short-lived nuclides at CSRe-Lanzhou

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Accurate nuclear masses not only provide indispensable information on nuclear structure, but also deliver important input data for applications in nuclear astrophysics. The challenge today is to obtain accurate masses of nuclei located far away from the valley of stability. Recently, we have developed a brand new technique, the Br-defined isochronous mass spectrometry (IMS), at the cooler storage ring CSRe in Lanzhou [1,2]. Using the simultaneously determined revolution times and velocities of the stored ions, the relation between ions' magnetic rigidities and orbit lengths is established, allowing to determine the magnetic rigidity of any stored ion according to its orbit length. Consequently, m/q values of the unknown-mass nuclides are determined. High mass resolving power has been achieved covering a large m/q-range over the full Br-acceptance of the storage ring, starting a new era of the IMS. By using the Br-defined IMS, the masses of 70Kr, 66Se, 64As, 62Ge were measured for the first time and the mass precision was improved for some other nuclides. The new mass results were used to study relevant problems in nuclear structure and astrophysics [3,4].

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The Challenge of low Temperature Reaction Rates

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Nuclear reactions in stars drive stellar evolution and provide the seed material for subsequent stellar explosion events. Because of the temperature and density conditions in stars, the reaction rate is determined by the low energy cross section, which in most cases is unknown and relies on theoretical extrapolation techniques. This requires a detailed knowledge of the threshold effects that determine the cross sections. This talk presents a summary of the most important low energy reactions and the uncertainties presently associated with their cross section determination.

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

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One of the current limitations of predicting the nuclear astrophysics r-process abundance is the need for experimental data of neutron-capture cross-sections of radioactive neutron-rich isotopes. These cross-sections are also invaluable for nuclear reactions and nuclear structure in general. Their measurement is currently considered very challenging due to the instability of the targets and projectile.

To overcome this limitation, we plan to stop and thermalise fission fragments in a cryogenic stopping cell. These fragments will then form a cooled low-energy beam, which will be transported into an RF trap system (coined 'NG-Trap' [1]). An intense neutron beam will consequently irradiate this trapped 'cloud target'. The reacted ions will be mass-selected, identified and counted using a multiple-reflection time-of-flight mass-spectrometer (MR-TOF-MS), thus extracting (n,γ) cross-sections.

The talk will discuss the current status of a triple-RFQ system [2] operating at Tel-Aviv University and present a measured trap capacity of more than 10^{10} ions. The system is the first step in designing the final NG-Trap system to be installed at the Soreq Applied Research Accelerator Facility (SARAF) [3], currently under construction in Yavne, Israel.

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Detector developments and technical aspects of the second NECTAR experiment

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To fully understand the phenomena leading to the creation of heavy elements in stars, knowledge of the neutron induced cross-sections is essential [1]. In the case of the rapid neutron capture (r-process), the direct measurement of these cross sections is often impossible due to the short lifetimes of the nuclei of interest and their high radioactivity. A well-known approach to overcome these difficulties is the use of surrogate reactions, where the compound nucleus formed in the neutron-induced reaction is produced through an alternative, experimentally accessible reaction and the probabilities for the different decay modes are measured [2]. However, when used in direct kinematics, this approach also has its drawbacks, including significant background or difficulties in detecting low-energy neutrons. To address these challenges, we proposed the NECTAR project [3], in which we intend to measure decay probabilities in inverse kinematics using a heavy-ion storage ring. One of its major advantages lies in the direct detection capability of heavy nuclei produced after the de-excitation of the compound nucleus, which would normally be stopped in a target. Following a successful experiment at the ESR storage ring in June 2022, during which, among other achievements, the neutron-emission probability of Pb-208 was measured for the first time, preparations are being made for another experimental campaign at the ESR, this time with a U-238 beam.

This contribution focuses more on the instrumentation aspects of our next experiment, presenting the detection and acquisition systems, with a particular emphasis on our new fission detectors, one of which is based on the innovative technology of solar cells.

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Abstracts of Posters

(in alphabetical order)

Title: **Unraveling the Mysteries of Stellar Elemental Production through Nuclear Reactions**

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The quest to comprehend the intricate interplay of nuclear reactions within the heart of stars stands as a fundamental pursuit in unlocking the secrets of stellar evolution and nucleosynthesis. This research endeavors to probe the mechanisms governing nuclear reactions occurring within the cores of massive stars. Employing sophisticated computational simulations, this study aims to elucidate the profound impact of diverse reaction pathways on the genesis of heavy elements within stellar environments.

The pivotal significance of specific nuclear reactions in shaping the observed elemental abundances across a spectrum of stellar populations is a focal point of this investigation. Through the integration of empirical observations and theoretical modeling, this research aspires to furnish invaluable insights into the intricate tapestry of nuclear astrophysics.

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Measurements of ^{12,13}C(p,γ) at the Felsenkeller and LUNA Underground Accelerator Laboratories

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The radiative capture reactions ^{12}C(p,γ)^{13}N and ^{13}C(p,γ)^{14}N are part of the CNO-cycle. Coordinated experiments at the LUNA-400 kV accelerator at LNGS (Italy) and at the 5 MV accelerator of the HZDR Felsenkeller laboratory (Germany) aimed at direct cross section measurements of both reactions at astrophysical energies. Utilizing low-background setups underground and the complementary capabilities of the two laboratories, the campaigns targeted overlapping energy ranges to obtain comprehensive data sets for the two reactions. In this poster I will present the experiments at both laboratories, the status of their analysis and the recently published [1,2] first results.

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Position-sensitive Schottky cavity for the heavy-ion storage rings

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Studying the rapid neutron capture process (r-process) in stellar environments, that leads to the creation of elements heavier than 56Fe, remains one of the fundamental questions of modern physics and therefore an active field of research within nuclear astrophysics [1]. 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 [2], [3]. In such facilities non-destructive methods of particle detection are often used for in-flight measurements based on frequency analysis [4]. 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 [5]. 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. 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. A brief description of the detector system from elliptical and cylindrical cavities is also described in this work.

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Challenges and prospects on neutron-capture cross-section experiments with s-process branching nuclei

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The recent upgrade of the CERN n_TOF neutron-spallation target has resulted in improved experimental conditions regarding neutron-energy resolution and background level [1]. A concomitant effort has been also made in terms of detection systems, thereby remarkably improving some limitations of previous set-ups [2,3]. These upgrades, together with a major effort on sample production at PSI-Switzerland and ILL-France, have enabled the first direct neutron-capture cross section measurements on the radioactive isotopes ^{79}Se [4] and ^{94}Nb [5]. On one hand, the beta-decay of ^{79}Se shows a prominent thermal dependency, which can be exploited to benchmark the thermal conditions in stellar models. On the other hand, the interplay between beta-decay and neutron-capture at ^{94}Nb in AGB stars may influence the production of ^{94}Mo, whose isotopic abundance in presolar SiC grains is yet an important topic of debate. However, such radioactive samples are very difficult and expensive to produce in sufficient amounts and with the required enrichments for this type of experiment. Furthermore, direct measurements on highly-radioactive samples utilizing state-of-the-art TOF methods allow one to cover only the low energy part of the stellar spectrum, requiring theory and models for the extrapolation into the relevant 30keV-90keV thermal energy range [4]. Clearly, new developments and techniques are needed to advance further in this field. In this respect, experiments in inverse kinematics at radioactive ion-beam facilities seem to be the only approach to tackle the high-energy range, either via indirect (surrogate) reactions or with direct methods. These topics will be illustrated with several recent examples and future options will be summarized and discussed.

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Atomic computations for astrophysical plasma

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Electronic structure calculations of atoms and ions have a long tradition in physics with applications spectroscopy, astro and plasma physics, and at various places elsewhere. With the Jena Atomic Calculator (JAC), I here present a new implementation of a (relativistic) electronic structure code for the computation of atomic amplitudes, properties and cascades for atoms and ions across the periodic table. JAC [1] is based on Julia, a new programming language for scientific computing, and provides an easy-to-use but powerful platform to extent atomic theory towards new applications in (nuclear) astrophysics.

A primary guiding philosophy in designing JAC was to develop a general and easy-to-use toolbox for the atomic physics community, including an interface that is equally accessible for working spectroscopists, theoreticians and code developers. In addition, I also wish to provide a modern code design, a reasonable detailed documentation of the code and features for integrated testing [2].

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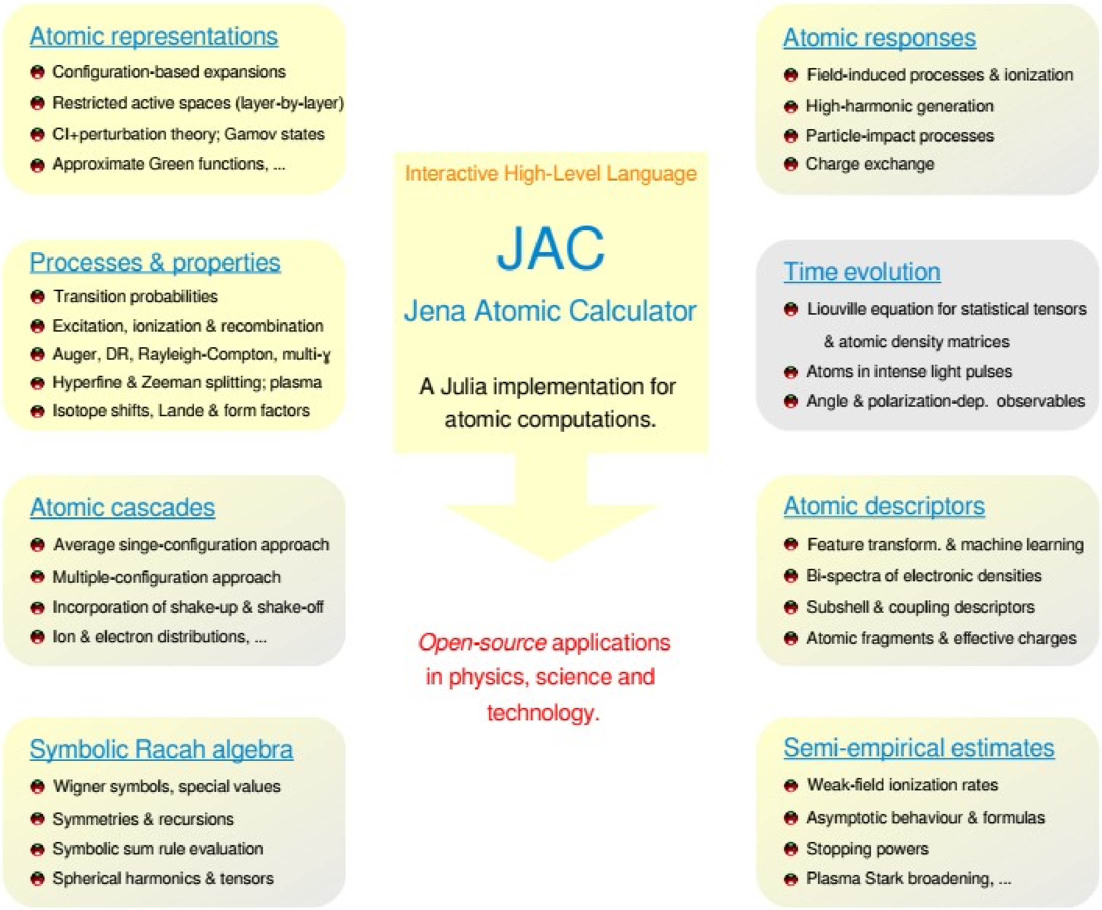

Atomic representations
- Configuration-based expansions
- Restricted active spaces (layer-by-layer)
- CI+perturbation theory; Gamov states
- Approximate Green functions, ...

Processes & properties
- Transition probabilities
- Excitation, ionization & recombination
- Auger, DR, Rayleigh-Compton, multi-γ
- Hyperfine & Zeeman splitting; plasma
- Isotope shifts, Lande & form factors

Atomic cascades
- Average singe-configuration approach
- Multiple-configuration approach
- Incorporation of shake-up & shake-off
- Ion & electron distributions, ...

Symbolic Racah algebra
- Wigner symbols, special values
- Symmetries & recursions
- Symbolic sum rule evaluation
- Spherical harmonics & tensors

Interactive High-Level Language

JAC

Jena Atomic Calculator

A Julia implementation for atomic computations.

Open-source applications in physics, science and technology.

Atomic responses
- Field-induced processes & ionization
- High-harmonic generation
- Particle-impact processes
- Charge exchange

Time evolution
- Liouville equation for statistical tensors & atomic density matrices
- Atoms in intense light pulses
- Angle & polarization-dep. observables

Atomic descriptors
- Feature transform. & machine learning
- Bi-spectra of electronic densities
- Subshell & coupling descriptors
- Atomic fragments & effective charges

Semi-empirical estimates
- Weak-field ionization rates
- Asymptotic behaviour & formulas
- Stopping powers
- Plasma Stark broadening, ...

Nanoseconds Timing Fusion Reaction Measurements with the STELlar LAboratory

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Fusion of light heavy ions dominates the element production and provides the energy output during light element synthesis. Carbon fusion is exceptional as it bridges a vast mass range along the nucleosynthesis path and therefore represents a bottleneck in the early evolution of massive stars, superburts in x-ray binary systems and type Ia supernovae [1]. The fusion excitation function reveals multiple strong resonances around the Coulomb barrier and continuing onward into the region of interest (ROI) for astrophysics with significant impact on stellar evolution [2, 3]. Those resonances are thought be linked to molecular states in ^{24}Mg [4], whose impact on the fusion mechanism isn't fully explored yet, as their appearance inflicts huge uncertainties on extrapolations of direct experimental measurements from higher energies.

Here we present measurements of ^{12}C+^{12}C with the *mobile STELLA station* at Andromède, Orsay (France) right into the astrophysics ROI. The experimental apparatus is optimized for low background gamma-particle coincidence detection of fusion evaporation residue with nanoseconds timing [5]. The combination of the STELLA particle detection system with $LaBr_3$(Ce) detectors from the UK-FATIMA collaboration enables efficient background suppression with reliable detection of fusion cross sections lower than nano barn [6]. We'll give insight into the detection and analysis techniques for high accuracy exclusive exit channel measurements during extended data taking periods with high intensity ion beam. We'll furthermore sketch the more complex decay pattern of ^{12}C+^{16}O fusion, detail its importance in the astrophysics region and our various developments for reliable direct measurements.

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DUST PROPERTIES AROUND ASYMPTOTIC GIANT BRANCH STARS: IRAS 20263+4245 UNDER IRIS, AKARI AND WISE SURVEY

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This work present the physical properties of dust across the far infrared cavity candidate region around an AGB star namely IRAS 20263+4245 was found to be located centered at R. A. (J2000) = 20^h 28^m 6.20^s and Decl. (J2000) = $+42^\circ$ 55' 5.33" at a distance 3038.60 pc. Physical properties have been studied at 60 μm and 100 μm in IRAS, 90 μm and 140 μm in AKARI and 12 μm and 22 μm in WISE survey. In order to find the possible candidate of cavity structure around AGB star in which dust properties not yet studied, we used SIMBAD database to specify discrete information in the region. Presents work show the distribution of flux density, dust color temperature, dust mass, Planck's function, visual extinction and spectral distributions around the cavity. The dust color temperature is found to be in the range of 23.92 ± 0.92 K to 28.46 ± 0.92 K using IRIS data, 13.91 ± 0.53 K to 19.74 ± 0.53 K using AKARI data and 305.15± 4.37 K to 327.26 ± 4.37 K using WISE data. The average value of dust mass and Planck's function are 0.12 $M_\odot$ and 1.41×10^{-15} $Wm^{-2}sr^{-1}Hz^{-1}$ using IRIS data, 0.81 $M_\odot$ and 4.73×10^{-16} $Wm^{-2}sr^{-1}Hz^{-1}$ using AKARI data and 3.65×10^{-5} $M_\odot$ and 4.72×10^{-12} $Wm^{-2}sr^{-1}Hz^{-1}$ using WISE data. The average value of visual extinction using IRIS, AKARI and WISE data are found to be 1.69×10^{-11} mag, 1.12×10^{-10} mag and 5.06×10^{-11} mag respectively. From three surveys, it was observed that flux, dust color temperature, and Planck's function have virtually identical distribution trends, although dust mass and visual extinction have an inverse relationship with the first three parameters.

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Experiments at the Low-Energy Heavy Ion Storage Ring CRYRING@ESR

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As a first completed facility of the FAIR project, the heavy ion storage ring CRYRING@ESR is in operation since 2020 and is serving as experiment platform for the SPARC collaboration. The ring is optimized for low-energy storage and beam cooling, and with access to all ion species available from the GSI accelerator chain or from a local RFQ injector. This offers a unique access to study the dynamics of slow collisions and for precision spectroscopy in highly charged ions. To realize these experiments, CRYRING@ESR has four straight sections where experimental setups can be installed: for merged-beams electron-ion collisions spectroscopy at the electron cooler, in a collinear laser spectroscopy setup, in a 'free' experimental section for various setups provided from the collaboration, and an extracted beam for single pass experiments, such as surface modifications [1]. Thus, in the recent years, researchers from atomic physics, nuclear reactions and materials science have been able to commence their experiment program. While the data analysis from these first experiments is largely still ongoing, we are finding that the very high expectations on achievable resolution have been fulfilled [2].

With this poster, we will be giving an overview of the CRYRING@ESR facility, discuss our presently available experimental installations, their performance, and the boundary conditions for beam operation. We present selected results from first experiments, preview our program for the next few years, and invite for a discussion of novel ideas.

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Activation experiments using decay chains

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The most important contribution to the nucleosynthesis of proton rich nuclei, that cannot be produced through neutron capture processes – the p-nuclei – is provided by the ɣ-process which encompasses tens of thousands of reactions across approximately 2000 different and predominantly radioactive nuclei [1]. Modeling these vast reaction networks requires the extrapolation of nuclear properties to little known regions of the nuclear chart [2]. While radioactive beam experiments could provide crucial insights into the behavior of nuclei in these regions, precise data from stable beam experiments is also indispensable.

Among the most precise and best-established methods of obtaining nuclear reaction cross sections is the activation technique, based on the consecutive irradiation of a target and the observation of ɣ-rays produced in the decay of the reaction product [3]. The applicability of this method is strongly limited by the half-life of the reaction product, the existence of isomeric states, the characteristic decay radiation produced by the decay of the product nucleus, and a variety of other experimental considerations.

Many of these limitations can be circumvented if the daughter nucleus of the reaction product is unstable as well. Using time resolved decay curves for the second decay in a decay chain enables the use of the activation technique even in cases where the first decay cannot be observed. This approach expands the scope of accessible reactions, mitigating several experimental challenges.

This method will be illustrated using the ^{55}Mn(α,n)^{58}Co^{m+g} and ^{58}Fe(p,n)^{58}Co^{m+g} reactions for which cross sections for the production of the metastable-state and the ground-state of ^{58}Co were determined without having to detect the 25 keV transition from the metastable to the ground state.

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Study of decay properties on neutron-rich nuclei around mass A=160 relevant for the formation of the r-process rare-earth peak (REP)

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[6]*www.wiki.edu.ac.uk/display/BRIKEN/Home*

The rapid neutron capture process (the r-process) produces nearly half of the nuclei heavier than iron in explosive stellar scenarios. Above the mass number A = 100, two main peaks in the r-process solar-system abundances are located at A ≈ 130 and A ≈ 195. Between these peaks lies the so called Rare-Earth Peak (REP), a distinct but small peak at mass number A ≈ 160 that arises from the freeze-out during the final stages of neutron exposure. According to theoretical models and sensitivity studies, half-lives ($T_{1/2}$) and β-delayed neutron emission branchings (P_{xn}) of neutron-rich nuclei, in the mass region A ≈ 160 for 55 ≤ Z ≤ 64, are critical for the formation of the REP [1,2]. The BRIKEN project [3, 4] conducted an extensive measurement program of beta-decay properties of nuclei involved in the r-process at the Radioactive Isotope Beam Factory (RIBF) located in the RIKEN Nishina Center, Japan. The BRIKEN-REP experiment has measured $T_{1/2}$ and P_{1n}-values of nuclei from Ba to Eu (A ≈ 160), belonging to the region that is most influential to the REP formation [5,6]. In this contribution, we will present the final experimental results of new P_{1n} branchings and $T_{1/2}$ within the Ba to Nd region. Furthermore, we will discuss how this new experimental data may help to constrain uncertainties in recent nuclear model calculations used for r-process simulations of the REP.

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Proton capture measurements on stored ions for the γ-process nucleosynthesis

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After two successful campaigns of proton-capture measurements on stored stable beams at the Experimental Storage Ring (ESR) at GSI in 2009 and 2016 [1-2], new experiments have been carried out in 2020 and 2021 using a radioactive ion beam. The complex spatial ion hit distributions recorded by a UHV-compatible double sided silicon strip detector (DSSSD) was modeled with Monte-Carlo based ion-optical simulations using the MOCADI code [3]. The sensitivity for the ions of interest is maximized by the application of the novel “Elimination of the Rutherford elAStic scattEring” (ERASE) technique. The suitability of the method was demonstrated in 2020 and in 2021.

In this contribution, the measured ion-hit spectra of the DSSSD will be presented focusing on the effects of the ERASE technique. ERASE is a powerful tool to efficiently study the proton capture on nuclei hardly accessible in large quantities.

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Dielectronic recombination plasma rate coefficients of Na-, Mg- and Al-like iron ions: the role of the 2(s + p) → 4l, nl′ and 3(s + p) → 5l, nl′ resonances

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The important role played by dielectronic recombination (DR) of M-shell Fe ions in the observed absorption X-ray spectra of Seyfert galaxies [1,2] have encouraged a thorough investigation of the related plasma DR rate coefficients in support of astrophysical observations. So far, theoretical modeling of such processes has accounted for the sole contributions due to Δn = 0,1 excitation channels (see, for instance, [1]). However, it was pointed out that at reasonably high temperatures even the neglected Δn = 2 channels may remarkably contribute to the total temperature-dependent DR rates [3]. This has spurred us to investigating the contribution of the Δn = 2 excitation channels for the 3 → 5 electron excitations to the plasma rate coefficients of initially Na-like and Mg-like Fe ions in the 105 – 109 K temperature range, by means of the Multi-Configurational Dirac-Hartree-Fock method. As a result, the contribution to the total plasma DR rates due to this excitation channel was found to be relevant and comparable to the Δn = 0,1 analogs.

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Nuclear effect on angular and polarization behaviors of characteristic x rays following electron-impact excitation of highly charged ions with non-zero nuclear spin

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For atoms or highly charged ions with nonzero nuclear spin, the hyperfine interaction of nuclear magnetic moment with those of bound electrons leads to splitting of their fine-structure levels and, thus, affects their excitation and decay properties. In this contribution, we present a most general density-matrix formalism to explore angular and polarization behaviors of characteristic x rays following electron-impact excitation of atoms or highly charged ions with arbitrary nuclear spin, which can account for depolarization of energy levels and multipole mixing of radiation fields [1]. It is then applied to angular distribution and linear polarization of the $K\alpha_1$ line radiated from heliumlike ions with nuclear spin I=1/2. As an example, detailed calculations are performed for $^{207}\mathrm{Tl}^{79+}$ ions using the multi-configurational Dirac-Hartree-Fock method and the relativistic distorted-wave theory. It is found that the effect of the hyperfine interaction depends dominantly on impact electron energy. For low impact energies close to the excitation threshold, the hyperfine interaction contributes to making the $K\alpha_1$ line more anisotropic and linearly polarized. In contrast, such an effect diminishes quickly with increasing impact energy and even vanishes at intermediate and high energies, which is rather different from the case of radiative electron capture [2]. The present study is experimentally accessible at both electron-beam ion traps and ion storage rings and, thus, accurate angular or polarization measurements of the $K\alpha_1$ line at low impact energies are expected to probe the hyperfine interaction in highly charged few-electron ions.

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Development of new combined jet and extended gas target system for the Felsenkeller underground accelerator laboratory

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For direct cross-section measurements in nuclear astrophysics, in addition to suitable ion beams and detectors, also highly pure and stable targets are needed. Here, using a gas jet as a target offers an attractive approach that combines high stability even under significant beam load with excellent purity and high localization. Such a target is constructed and commissioned at the Felsenkeller underground ion accelerator lab for nuclear astrophysics in Dresden, Germany.

This setup combines a highly localized gas wall jet and an extended, static, windowless gas target. The target thickness of the jet will be measured by optical interferometry, allowing an in-situ thickness determination including also beam-induced effects.

The contribution will report on the technical details and characterization of jet and windowless gas target and outlines possible applications in nuclear astrophysics.

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New physics opportunities at the Rare-RI Ring facility

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A new storage ring facility, Rare-RI Ring (R3), has been constructed at the RI Beam Factory (RIBF) in RIKEN [1] and the first result of mass measurements concerning astrophysical rapid-neutron capture process has recently been published [2].

At the R3, exotic nuclei are produced via the in-flight fission reaction of intense ^{238}U beam from the RIKEN cyclotron complex. They are separated and identified at the BigRIPS fragment separator [3]. Thanks to the event-by-event analysis with the standard detector setup and the newly-developed fast kicker magnet system, only a single ion of interest is injected into the storage ring, where the precise isochronous ion-optical condition ensures the mass-to-charge ratio proportional to the revolution time of the stored ion.

With the excellent mass resolving power of the R3, isomer beam experiments are now possible as well as the storage ring mass spectrometry. I will discuss new physics opportunities of the R3, where examples are exotic decay modes of highly charged ions, total reaction cross sections of well-deformed excited states, and so on. Ongoing technical developments will also be presented.

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Ground-state mass of ^{22}Al, ^{26}P and ^{28}S

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The ground-state mass excess (ME) of the T_z=-2 dripline nuclei ^{22}Al,^{26}P and ^{28}S are measured for the first time using the newly-developed Bρ-defined isochronous mass spectrometry at the cooler storage ring in Lanzhou. The new ME value of ^{22}Al allows to determine the mirror energy differences (MEDs) in the ^{22}Al-^{22}F pair. Besides, The ground-state mass excess of the T_z=-5/2 nuclei ^{23}Si,^{27}S and ^{31}Ar are also measured in this work.