Symposium Fathoming Stellar Evolution with Laboratory Precision (SYSE)

jointly organized by
the Mass Spectrometry Division (MS),
the Atomic Physics Divison (A),
the Extraterrestrial Physics Division (EP),
the Molecular Physics Division (MO), and
the Quantum Optics and Photonics Division (Q)

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Precision experiments in different areas of physics have recently become very useful to understand various aspects of stellar evolution from the interstellar medium to neutron-star matter. The rate of generation of molecular hydrogen during the epoch of the formation of the first stars has been determined by associative-detachment reaction studies, stability measurements of molecular anions ameliorate our understanding of interstellar molecular clouds, and experiments with electron beam ion traps give insight into EUV and X-ray spectra from highly excited regions of our Universe. Different theoretical approaches have shown the possible impact of laboratory experiments on modern theory of stellar evolution. Constraining the neutron-matter equation of state and the properties of neutron-rich matter are such examples. With the use of microscopic mass models, precise mass determinations can be used to probe the elemental composition in the outer crust of neutron stars.

Overview of Invited Talks and Sessions

(Lecture room: Audimax)

Invited Talks

SYSE 1.1	Wed	14:00–14:30	Audimax	**Addressing open questions of stellar evolution with laboratory experiments** — •Almudena Arcones
SYSE 1.2	Wed	14:30–15:00	Audimax	**Methods and problems of the modern theory of stellar evolution** — •Achim Weiss
SYSE 1.3	Wed	15:00–15:30	Audimax	**Photoabsorption and opacity in the X-ray region: The role of highly charged ions** — •José R. Crespo López-Urrutia
SYSE 1.4	Wed	15:30–16:00	Audimax	**Neutron-rich matter: From cold atoms to neutron stars** — •Achim Schwenk

Sessions

SYSE 1.1–1.4	Wed	14:00–16:00	Audimax	**Fathoming Stellar Evolution with Laboratory Precision**
SYSE 2.1–2.5	Wed	16:30–18:15	DO24 1.205	**Fathoming Stellar Evolution (Part 2)**

SYSE 1: Fathoming Stellar Evolution with Laboratory Precision

Time: Wednesday 14:00–16:00 Location: Audimax

Invited Talk SYSE 1.1 Wed 14:00 Audimax
Addressing open questions of stellar evolution with laboratory experiments — •Almudena Arcones — Technische Universität Darmstadt, Institut für Kernphysik, Germany — GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany

After several hydrostatic burning stages, massive stars end their life as core-collapse supernova explosions. These high-energy events enrich the interstellar medium with elements formed during the stellar life, produce new heavy elements, and are the birthplace of neutron stars. An exciting stage in the life of neutron stars is the merger with another neutron star or a black hole. Both, core-collapse supernovae and neutron star mergers are sources of heavy elements in the universe. Elements from Sr to Ag can be synthesized in neutrino-driven winds after core-collapse supernovae via charged particle reactions through nuclei relatively close to stability. Heavier elements are produced in rare supernovae and neutron star mergers via the rapid neutron capture process (r-process). In this talk, the role of nuclear masses will be presented showing how further experimental information is highly necessary to constrain the nucleosynthesis and the still uncertain theoretical models. In addition, the r-process can be directly observed after a neutron star merger in the form of a light curve (kilonova) triggered by the radioactive decay of neutron-rich nuclei. In order to obtain the maximum information from such events more atomic data are required to calculate the opacities for r-process ejecta. Therefore, precision experiments are critical to understand supernova, neutron star mergers and their implication in the chemical history of the universe.

Invited Talk SYSE 1.2 Wed 14:30 Audimax
Methods and problems of the modern theory of stellar evolution — •Achim Weiss — Max-Planck-Institut für Astrophysik, Garching

The theory of (hydrostatic) stellar evolution has developed into a mature field of astrophysics. We basically understand the structure and evolution of most stars. The most important input physics is accurate enough to model successfully the nuclear and photometric evolution of stars. I will, in the first part, review this canonical theory, and present a few highlights. A closer look on and into stars, that has become available due to observational progress in the fields of spectroscopy and asteroseismology, reveals, however, that fundamental physical effects, connected mostly with hydrodynamical processes and matter flows, are far from being understood. The second part of this overview will present some of the observational challenges and discuss attempts to improve our theoretical models. The importance of more accurate stellar models for other fields of astrophysics will also be discussed.

Invited Talk SYSE 1.3 Wed 15:00 Audimax
Photoabsorption and opacity in the X-ray region: The role of highly charged ions — •José R. Crespo López-Urrutia — Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Within the radiative zone of stars, the contribution to opacity by highly charged ions is the dominant one. In such a dense and hot environment, X-ray opacity determines radiation transport and radiation pressure. It strongly influences the hydrostatic equilibrium, and thus the structure and dynamic evolution, e. g., oscillations and collapse, of a star. Even minor amounts of iron present there play a key role: They are essential to explain the temperature profile of the Sun and main sequence stars. Highly charged iron ions make the star core almost completely opaque to X-rays, slowing down the energy flux. On the theoretical side, opacity calculations for astrophysics require the use of approximations, and until now very few accurate experimental benchmarks have been reported for them. Recently, with the use of electron beam ion traps at X-ray sources such as free-electron lasers and synchrotron facilities, new methods have been developed for detailed studies of such X-ray photoabsorption process. The results of these experiments test the values of cross sections and resonance energies for ions in charge states which had hitherto been beyond reach, and the experimental results achieve accuracies surpassing that of current theory.

Invited Talk SYSE 1.4 Wed 15:30 Audimax
Neutron-rich matter: From cold atoms to neutron stars — •Achim Schwenk — Institut für Kernphysik - Theoriezentrum, TU Darmstadt — ExtreMe Matter Institute EMMI, GSI, Darmstadt

There are many synergies between neutron matter and ultracold Fermi gases with resonant interactions. This talk will discuss the physics of neutron-rich matter starting from universal properties at low densities to dense matter in neutron stars. We will focus on the similarities of these systems and on the current frontiers in describing neutron-rich systems in the laboratory and in stars.

SYSE 2: Fathoming Stellar Evolution (Part 2)

Time: Wednesday 16:30–18:15 Location: DO24 1.205

Invited Talk SYSE 2.1 Wed 16:30 DO24 1.205
Mass spectrometry of exotic nuclear species for the study of neutron stars — •David Lunney — CSNSM/IN2P3 – Université de Paris Sud, Orsay

A large fraction of stars end their lives in dramatic explosions forming ultra-compact objects with a density exceeding that of the atomic nucleus. These resulting neutron stars have a complex composition that requires a wide range of physics to model. Of particular interest is the neutron-star crust, which may contain exotic nuclear species that can be detected by astronomers.

The recent observation of a "kilonova" (an explosion larger than a nova but smaller than a supernova) has been associated with gravitational mergers involving neutron stars and hints at tantalizing evidence for the production of heavy elements from the rapid capture of abundant neutrons (the *r* process). Modeling the neutron star and its composition, as well as an associated *r* process, requires the knowledge of nuclear binding energies. These quanties are obtained by precision mass spectrometry at radioactive beam facilities.

This presentation will explain the neutron-star model and describe the ISOLTRAP spectrometer at CERN-ISOLDE that produces the mass data necessary for the neutron-star composition and *r*-process modeling, along with some results.

Invited Talk SYSE 2.2 Wed 17:00 DO24 1.205
High-resolution spectroscopy of (deuterated) molecular ions — •Oskar Asvany, Sandra Brünken, Sabrina Gärtner, Pavol Jusko, Lars Kluge, Alexander Stoffels, and Stephan Schlemmer — I. Physikalisches Institut, Universität zu Köln, Köln, Germany

One phenomenon in the initial phases of star formation is the deuteration of molecules and ions observed in many different environments. Since several decades there is a vivid interplay between astronomical detections and laboratory measurements in this field, recent examples being the tentative observation of CH_2D^+ towards Orion IRc2 and the firm detection of para-H_2D^+ towards I16293 in Ophiuchus using the GREAT receiver on the SOFIA airplane.

This talk concentrates on the laboratory methods to obtain rotational and rovibrational spectra of mass-selected molecular ions of astronomical interest. High-resolution is achieved by cooling and trapping a few thousand ions in a multipolar trap, while using narrow-band IR or mm-wave sources for their excitation. This excitation is detected by action spectroscopy, laser induced reactions (LIR) being the main workhorse in our laboratory.

Recently, the arsenal of action spectroscopy methods has been enriched by the newly developed method of Laser Induced Inhibition of Cluster Growth (LIICG), in which attachment of He atoms to ionic species below 10 K is hindered by resonant excitation. Advantages of LIICG are operation at 4 K, its apparent applicability to any ion, and response to any sort of excitation (rotational/vibrational/electronic), as will be shown on selected examples (CD_2H^+, H_3^+, CO^+).

SYSE 2.3 Wed 17:30 DO24 1.205
Entwicklung von zwei-, drei- und vierstufigen Anregungssche-

mata für höchste Ionisationseffizienz am Palladium — •Tobias Kron[1], Susanne Kreim[2,3], Fabian Schneider[1], Sven Richter[1] und Klaus Wendt[1] — [1]Institut für Physik, Johannes Gutenberg-Universität Mainz — [2]Max-Planck-Institut für Kernphysik, Heidelberg — [3]CERN, Genf, Schweiz

Untersuchungen der Eigenschaften des Atomkerns entlang der Palladium-Isotopenkette, sowie hochpräzise Massenmessungen im Bereich des N=82-Schalenabschlusses sollen wertvolle Informationen zur noch immer nicht vollständig geklärten astrophysikalischen Nukleosynthese der Elemente schwerer als Eisen liefern und ermöglichen damit wichtige Tests verschiedener Theoriemodelle.

Zur Produktion isobarenreiner Ionenstrahlen dieser kurzlebigen Isotope an Online-Ionenquellen, wie ISOLDE (CERN), wird die resonante Laserionisation genutzt. Die Effizienz dieses hochselektiven Ionisationsprozesses hängt dabei vorrangig von der genutzten Leiter optischer Dipolübergänge zwischen den elementspezifischen Energieniveaus ab. Am Offline-Massenseparator RISIKO wurden Schemata mit zwei bis vier Anregungsschritten weiterentwickelt und hinsichtlich ihrer Ionisationseffizienz verglichen. Die Spektroskopie mehrerer Rydbergserien oberhalb des ersten Ionisationspotenzials ermöglichte die Wahl des optimalen finalen Ionisationsübergangs, was die Ionisationseffizienz deutlich erhöht. Die anschließenden Messungen der Effizienz mittels kalibrierter Proben geben Aufschluss über die zu erwartende Teilchenrate bei der zukünftigen Online-Anwendung.

SYSE 2.4 Wed 17:45 DO24 1.205

Detecting Supernova Dust on the Earth's Sea Floor with AMS — •Jenny Feige[1], Anton Wallner[2], Dieter Breitschwerdt[3], L. Keith Fifield[2], Gunther Korschinek[4], Silke Merchel[5], Georg Rugel[5], Peter Steier[1], Steve Tims[2], Stephan R. Winkler[1], and Robin Golser[1] — [1]University of Vienna, Austria — [2]ANU Canberra, Australia — [3]TU Berlin, Germany — [4]TUM, Germany — [5]HZDR, Germany

An ^{60}Fe anomaly was detected with accelerator mass spectrometry (AMS) - a very sensitive method to measure extremely low isotopic ratios - in a 2 Myr old layer of a ferromanganese crust (Knie et al., 2004). This signal is assumed to be of supernova origin and might be linked to the observation of our solar system being located in a region of thin, hot interstellar medium. This region, called the Local Bubble, was presumably formed by multiple supernova explosions starting ∼14 Myr ago. Calculations suggest that at least one of these supernovae occured close enough to the solar system to leave a detectable ^{60}Fe trace on Earth.

New AMS measurements are performed in deep-sea sediments from the Pacific Ocean. An international collaboration of different AMS facilities searches for signatures of the long-lived radionuclides ^{26}Al, ^{53}Mn, and ^{60}Fe in a time range from 1.7 to 3.1 Myr. Magnetostratigraphic dating of the samples is confirmed by measurements of the cosmogenic radionuclide ^{10}Be. All ^{10}Be and ^{26}Al measurements are finished, ^{53}Mn and ^{60}Fe is in progress. First results will be presented and discussed.

SYSE 2.5 Wed 18:00 DO24 1.205

Tracing back the Local Bubble's formation from isotopic anomalies in the deep ocean crust — •Michael Schulreich and Dieter Breitschwerdt — Zentrum für Astronomie und Astrophysik, TU Berlin, Berlin, Germany

Supernova explosions responsible for the creation of the Local Bubble (LB) and its associated HI cavity should have caused geological isotope anomalies via deposition of debris on Earth. The discovery of a highly significant increase of ^{60}Fe (a radionuclide which is exclusively produced in explosive nucleosynthesis) in layers of a deep sea ferromanganese crust, corresponding to a time of 2.2 Myr before present, appears very promising in this context. We report on our latest results in relating these measurements to the formation of the LB by means of 3D hydrodynamical adaptive mesh refinement simulations of the interstellar medium in the solar neighborhood. These calculations are based on a sophisticated selection procedure for the LB's progenitor stars and take advantage of passive scalars for modeling the turbulent chemical mixing process.