EMMI workshop: Neutron Matter in Astrophysics: From Neutron Stars to the r-Process

Thursday 15 July 2010 - Sunday 18 July 2010

GSI

Book of Abstracts

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r-Process Nucleosynthesis and Early Chemical Evolution

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Observations of elemental abundances in metal-poor stars in the Galactic halo and dwarf galaxies are used to shed light on the stellar sources for the elements (1) from Na to Zn, (2) from Sr to Ag, and (3) from Ba to U. The production of Sr, Y, and Zr in the neutrino-driven winds from nascent neutron stars provides a key insight into the diverse sources operating in the early universe. It is shown that a wide range of core-collapse supernovae associated with neutron star and black hole formation are required to account for the observations. A self-consistent framework to explain these data requires low-mass core-collapse supernovae to be the source for the r-process.

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Modeling Hybrid Stars

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We extend the hadronic SU(3) non-linear sigma model to include quark degrees of freedom. The choice of potential for the deconfinement order parameter as a function of temperature and chemical potential allows us to construct a realistic phase diagram from the analysis of the order parameters of the system. These parameters are the chiral condensate, for the chiral symmetry restoration, and the scalar field Φ (as an effective field related to the Polyakov loop) for the deconfinement to quark matter. Besides reproducing lattice QCD results, for zero and low chemical potential, we are in agreement with neutron star observations for zero temperature.

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Single particle spectroscopy of 133Sn via the (d,p) reaction in inverse kinematics

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It is important, both for nuclear structure physics and understanding the synthesis of heavy elements in the cosmos, to determine how single-particle states change as we move away from the valley of stability, especially around shell closures. One powerful method to probe single-particle structure of nuclei is to use single-nucleon transfer reactions. With short-lived exotic nuclei, these reactions need to be performed in inverse kinematics, using a radioactive ion beam and light ion targets. A beam of 132Sn produced at ORNLs Holifield Radioactive Ion Beam Facility was used in a transfer reaction experiment to study single-particle states in 133Sn. The beam impinged on a target of CD2 with effective thickness of around 150ug/cm2. Charged ejectiles were detected in an array of position sensitive silicon detectors, mostly of the new ORRUBA type, with SIDAR detectors at very backward angles. At forward laboratory angles, telescopes of detectors were used to discriminate protons from heavier, elastically scattered particles. From the angles and energies of the protons, the energies of the states populated in the final nuclei were measured. The present work has determined the purity of the low-spin single-neutron excitations in 133Sn. A previously unobserved state in 133Sn has also been measured here for the first time. The simplicity of the structure of 132Sn, and the single-neutron excitations in 133Sn, provides a new touchstone needed for extrapolations to nuclei further from stability, in particular those responsible for the synthesis of the heaviest elements via the r-process.

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Neutron Star Masses and Radii

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Recent observations of thermal emissions from quiescent and isolated cooling neutron stars and of photospheric radius expansions in X-ray bursters can be used to estimate their masses and radii. Although the observational uncertainties for each source are considerable, they can be used to snugly constrain the mass-radius relation if it is assumed that a single such relation fits all neutron stars. In addition, limits to the underlying dense matter pressure as a function of density (i.e., the equation of state) can be deduced if it is appropriately parametrized. Values of the underlying parameters can be inferred with a Bayesian analysis using the combined mass-radius information from observations. It is shown that the subnuclear equation of state is consistent with that of neutron matter from recent estimates. Also, the deduced nuclear incompressibility, skewness and symmetry parameters are surprisingly compatible with nuclear systematics and experiment. The density dependence of the nuclear symmetry energy is predicted to be small, leading to relatively small values for the neutron skin thickness of lead. Furthermore, the neutron star maximum mass, to 90% confidence, is predicted to be greater than 1.85 solar masses.

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Proto-Neutron Star Winds with Magnetic Fields and Rotation

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Core collapse supernovae have long been considered one of the most promising astrophysical sites for r-process nucleosynthesis. Detailed calculations of the neutrino-heated winds from proto-neutron stars, however, find that the ratio of neutrons to seed nuclei is generally too low for the r-process to reach the second or third abundance peaks. Success instead appears to require some combination of lower electron fraction, higher entropy, or more rapid expansion. Although most calculations to date consider slowly rotating, non-magnetized neutron stars, it is now clear that highly magnetized neutron stars ("magnetars") are fairly common and that rapid rotation may be a key ingredient in their formation. I will present one-dimensional MHD calculations of the neutrino-heated winds from magnetized rotating proto-neutron stars. I will use these results to describe how strong magnetic fields and rapid rotation alter the wind conditions (electron fraction, entropy, dynamical timescale) necessary for a successful r-process.

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Neutrinos and Nucleosynthesis in Hot Outflows

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We consider neutrinos and nucleosynthesis in several different environments: supernovae, gamma ray bursts and compact object mergers. We examine the role of neutrinos in the r-process, the p-process and in the formation of Nickel-26. We consider the impact of neutrino general relativistic effects and collective neutrino flavor transformation.

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The r-process nucleosynthesis during the decompression of neutronised matter

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The rapid neutron-capture process, or r-process, is known to be of fundamental importance for explaining the origin of approximately half of the A>60 stable nuclei observed in nature. In recent years nuclear astrophysicists have developed more and more sophisticated r-process models, eagerly trying to add new astrophysical or nuclear physics ingredients to explain the solar system composition in a satisfactory way. The r-process remains the most complex nucleosynthetic process to model from the astrophysics as well as nuclear-physics points of view.
The present contribution emphasizes some important future challenges faced by nuclear physics in this problem, particularly in the determination of the radiative neutron capture rates by exotic nuclei close to the neutron drip line and the fission probabilities of heavy neutron-rich nuclei. These quantities are particularly relevant to determine the composition of the matter resulting from the decompression of initially cold neutron star matter. New detailed r-process calculations are performed and the final composition of ejected inner and outer neutron star crust material is estimated. We discuss the impact of the many uncertainties in the astrophysics and nuclear physics on the final composition of the ejected matter.

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Neutron star matter

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Neutron capture in the r-process

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Recently we have shown that neutron capture rates on nuclei near stability can significantly influence the r-process abundance pattern. We discuss the different mechanisms by which the abundance pattern is sensitive to the capture rates and identify key nuclei whose rates are of particular importance. We compare the behavior of the system in different astrophysical conditions, e.g. an equilibrium ("hot") and non-equilibrium ("cold") r-process. We consider the A=80, A=130, and the rare earth peak.

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Nucleosynthesis in O-Ne-Mg Supernovae

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The site of the r-process has been the most enduring mystery in nucleosynthesis theory since the publication of the seminal papers in this field. Of particular promise (in their times and for some even today) have been the many efforts suggesting Type II supernovae as the site with the relevant conditions arising either in or near the exploding core (initially championed by Burbidge et al.), or in the outer layers, with recent attention focused on aspects of neutrino interactions. We will explore detailed nucleosynthesis in the shocked surface layers of an Oxygen-Neon-Magnesium core collapse supernova to determine if suitable conditions arise for r-process nucleosynthesis. We find no such conditions in an unmodified model, but do find overproduction of N=50 nuclei (previously seen in early neutron-rich neutrino winds) in amounts that, if ejected, would pose serious problems for galactic chemical evolution. A minor modification to the distribution of the neutron excess predicted by the model can alleviate this result, providing for production 64Zn, which has been under-produced in previous surveys of galactic chemical evolution.

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Symmetry energy, neutron star crust and neutron skin thickness

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We perform a systematic analysis of the density dependence of nuclear symmetry energy within the microscopic Brueckner-Hartree-Fock (BHF) approach using the realistic Argonne V18 nucleon-nucleon potential plus a phenomenological three-body force of Urbana type. Our results are compared thoroughly with those arising from several Skyrme and relativistic effective models. The values of the parameters characterizing the BHF equation of state of isospin asymmetric nuclear matter fall within the trends predicted by those models and are compatible with recent constraints coming from heavy ion collisions, giant monopole resonances, or isobaric analog states. In particular we find a value of the slope parameter L=66.5 MeV, compatible with recent experimental constraints from isospin diffusion, L=88±25 MeV. The correlation between the neutron skin thickness of neutron-rich isotopes and the slope L and curvature Ksym parameters of the symmetry energy is studied. Our BHF results are in very good agreement with the correlations already predicted by other authors using nonrelativistic and relativistic effective models. The correlations of these two parameters and the neutron skin thickness with the transition density from nonuniform to β-stable matter in neutron stars are also analyzed. Our results confirm that there is an inverse correlation between the neutron skin thickness and the transition density.

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Study of neutron rich Cadmium isotopes and the possible N=82 shell quenching

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The abundances of r-process nucleosynthesis in the mass A=130 region are largely affected by the nuclear structure properties around the N=82 magic number. Some simulations show a better description of the abundances if a shell quenching of N=82 is assumed. In addition, the

anomalous behavior of the experimental 2+ excitation energies in neutron rich Cd isotopes has been interpreted as an indication of a reduction of the shell gap in this region. In this work we will study the spectroscopic properties of even-even Cadmium isotopes from N=50 to N=82 shells with beyond mean field methods. Our results reproduce nicely both the 2+ energies and B(E2) transitions without adjusting any parameter of the nucleon-nucleon force (Gogny D1S). Furthermore, we do not observe N=82 shell quenching and the anomalous behavior of the 128Cd can be interpreted in terms slight deformation effects.

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High density behavior of the nuclear EoS and properties of massive neutron stars

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Modern constraints from the mass and mass-radius-relation measurements require stiff EoS at high densities, whereas flow data from heavy-ion collisions seem to disfavour too stiff behavior of the EoS. Our aim is to present a nuclear EoS at supernuclear densities which satisfies both the constraints from neutron star (NS) and the heavy ion collision phenomenology. The data from massive NSs and pulsars may provide an important cross-check between high-density astrophysics and heavy-ion physics. The variation of pressure with density for the present EoS is consistent with the experimental flow data confirming its high density behaviour. We find that the large values of gravitational masses (˜2.0 M_solar) for the NSs are possible with the present EoS with the SNM incompressibility K=274.7 (7.4) MeV, which is rather stiff' enough at high densities to allow compact stars with large values of gravitational masses ˜ 2 M_solar while the corresponding symmetry energy issuper-soft' as preferred by FOPI/GSI experimental data. Thus the DDM3Y effective interaction which is found to provide unified description of elastic and inelastic scattering, various radioactivites and nuclear matter properties, also provides excellent description of beta-equilibrated NS matter to allow the recent observations of the massive compact stars.

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Origin of the LEPP nuclei in supernovae

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Observations indicate that r-process elements have at least two components. The heavy r-process nuclei (A>130) are synthesized by rapid neutron capture in a yet unknown site. The second component corresponds to the lighter element primary process (LEPP) or weak r-process. Our nucleosynthesis studies are based on hydrodynamical simulations for core-collapse supernovae and their subsequent neutrino-driven winds. We show that heavy r-process elements cannot be synthesized in these neutrino-driven winds. However, LEPP elements can be formed for a broad range of conditions. We have studied the impact of the electron fraction on the LEPP. This provides constraints on the electron fraction evolution based on the pattern observed in the atmosphere of UMP stars. We have found that the elemental abundances can be reproduced under proton-rich conditions explaining the origin of the LEPP elements found in UMP stars. However, isotopic abundances show that only p-nuclei are produced, discarding proton-rich winds as the origin of LEPP nuclei in the solar system, where also neutron-rich isotopes are expected. Our results show that, in neutron-rich winds, LEPP elements (including all isotopes) are also synthesized, but with the old overproduction problem around A=90. Future observations of isotopic abundances in UMP stars can discriminate between proton- and neutron-rich winds. These will give rise to new insights that can constrain the evolution of the electron fraction and thus of neutrino properties in supernovae.

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Dipole response of exotic nuclei and the equation of state

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The properties of exotic nuclei are ideally studied in inverse-kinematics experiments at high beam energies using the FRS-LAND facilities at GSI, allowing exclusive measurements of all projectile-like residues following the electromagnetic excitation of the projectile in a high-Z target (Pb). At beam energies of ˜500 AMeV electromagnetic excitations are dominated by dipole transitions. In an experiment utilizing secondary beams of neutron-rich Sn isotopes 129-132Sn and neighbouring nuclei with similar A/Z ratio we have observed a substantial fraction of dipole strength at energies below the giant dipole resonance (GDR). For 130Sn and 132Sn this strength is located in a peak-like structure around 10 MeV and exhibits a few percent of the Thomas-Reiche Kuhn (TRK) sum-rule strength [1]. Several calculations (see e.g.[2,3]) predict the appearance of dipole strength at low excitation energies in neutron-rich nuclei, often referred to as pygmy dipole resonance (PDR). In a macroscopic picture, the PDR is discussed in terms of a collective oscillation of excess neutrons out of phase with the core nucleons. Recent random-phase-approximation calculations show a strong correlation of the PDR strength to the density dependence of the symmetry energy and thus a link to the neutron skin size [4,5]. We will discuss consequences from the experimental findings in 130Sn, 132Sn [5] and 208Pb [6] for the neutron-skin sizes, the symmetry energy and the neutron equation of state (EoS).
Using the same setup and detection technique the Nickel isotopic chain was investigated utilizing relativistic secondary beams of 57-72Ni, with energies of approximately 500 AMeV, enabling the access to the dipole strength distribution in the continuum. Cross sections for selected isotopes will be presented.
In order to investigate the appearance of the pygmy-strength over a wide range of A/Z ratios, we decided to examine the case of 32Ar, a so-called "proton-rich" nucleus. Several calculations predict the appearance of pygmy-strength for this nucleus [7,8]. In Summer 2008 an experiment was carried out addressing the dipole response of 32-34Ar at the LAND-FRS setup after a recent upgrade. We will report on the status of data analysis and statistics to be expected.
[1] P. Adrich et al., Phys. Ref. Lett. 95, 132501 (2005) [2] D. Vretenar, Nucl. Phys. A, 264c (2005), and references therein [3] D. Sarchi et al., Phys. Lett. B 601, 27 (2004) [4] J. Piekarewicz, Phys. Rev. C 73, 044325 (2006) [5] A. Klimkiewicz et al., Phys. Rev. C 76, 051603(R) (2007) [6] N. Ryezayeva et al., Phys. Rev. Lett. 89, 272501 (2002) [7] N. Paar et al., Phys. Rev.Lett. 94, 182501 (2005) [8] C. Barbieri et al., Phys. Rev. C 77, 024304 (2008)

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Neutron-Capture Element Observations in Low-Metallicity Stars: Joys and Frustrations

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Neutron-capture elements often are extremely overabundant in metal-poor halo stars. In some cases we have been able to determine accurate abundances or significant upper limits to over 30 elements with Z>30. These detailed abundance distributions can provide significant constraints on neutron- capture nucleosynthesis predictions. But how well do we really know the neutron-capture abundances? What can we trust, and what must be viewed with a lot of caution? In this talk, the view from a stellar spectroscopist's perspective, I will try to demonstrate which abundances are probably rock-solid, which have significant uncertainties, and which are more hopeful than assured. Cautions for the consumer, and suggested avenues for future improvements will be provided.

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Clusters in nuclear matter

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Thermodynamical properties and the composition of nuclear matter are strongly affected by correlations, in particular the formation of clusters. At very low densities and finite temperatures the system can be described by the virial equation of state that is based on experimental data. With increasing density medium effects become important that modify the properties of the clusters. At densities around and above nuclear saturation density clusters are dissolved and mean-field concepts can be used to describe the matter. In this contribution a generalized relativistic mean-field model is presented that allows a smooth interpolation between the low-density phase dominated by few-body correlations and the homogeneous phase above saturation.

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Thermal Evolution of Hybrid Stars modeled with an SU(3) non-linear Sigma Model

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The thermal evolution of hybrid stars is investigated. The structure and composition of these objects are obtained by means of an exteded hadronic and quark SU(3) non-linear sigma model. Within this model the degrees of freedom of the system change naturally from quarks to hadrons, allowing a more natural description of hybrid stars. In this work we will focus on the thermal evolution of these objects. Furthermore speciall attention will be given to the possible effects that spin-down may have on the cooling of these stars.

Session 4: The r-process in core-collapse supernovae I / 22

Integrated Neutrino Driven Wind Nucleosynthesis

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Although they are but a small fraction of the mass ejected in core-collapse supernovae, neutrino-driven winds (NDWs) from nascent proto-neutron stars (PNSs) have the potential to contribute significantly to supernova nucleosynthesis. In previous works, the NDW has been implicated as a possible source of r-process and light p-process isotopes. I will present time-dependent hydrodynamic calculations of nucleosynthesis in the NDW which include accurate weak interaction physics coupled to a full nuclear reaction network. Using two published models of PNS neutrino luminosities, we predict the contribution of the NDW to the integrated nucleosynthetic yield of the entire supernova. For the neutrino luminosity histories considered, no true r-process occurs in the most basic scenario. At most, it contributes to the production of the $N = 50$ closed shell elements and some light p-nuclei. In doing so, it may have left a distinctive signature on the abundances in metal poor stars, but the results are sensitive to both uncertain models for the explosion and the masses of the neutron stars involved.

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Shear viscosity and the nucleation of antikaon condensed matter in hot neutron stars

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The shear viscosity plays an important role in damping gravitational wave driven instabilities in old and accreting neutron stars. We discuss the shear viscosity in the presence of an antikaon condensate in neutron stars, using Boltzmann kinetic equation in the relaxation time approximation. The calculation of shear viscosity involves the equation of state (EoS) as an input, that we construct for antikaon condensed matter at finite temperature within the framework of relativistic field theoretical model. We consider a first order phase transition from charge neutral and beta-equilibrated nuclear matter to K- condensed phase in a hot neutron star after the emission of trapped neutrinos.
Antikaons, which form a s-wave (p = 0) condensation, do not take part in momentum transfer during collisions with other particles. However, with the onset of K- condensation, electrons and muons are rapidly replaced by them. This influences the proton fraction and EoS which, in turn, have important consequences for the electron, muon and proton shear viscosity. We find that the electron and muon shear viscosities drop steeply after the formation of the K- condensate in neutron stars. Hence, the total shear viscosity decreases in the K- condensed matter due to the sharp drop in the lepton shear viscosities. However, the proton shear viscosity whose contribution to the total shear viscosity was negligible compared to the leptonic contribution in nucleons only matter, now becomes significant in the presence of the K- condensate. The proton shear viscosity may even exceed the neutron as well lepton shear viscosities at higher densities.
Further the shear viscosity might control the nucleation rate of bubbles in first order phase transitions. The thermal nucleation time is inversely proportional to the shear viscosity. In this connection we discuss the effect of shear viscosity on the nucleation process of bubbles of K-condensed phase in neutron stars.

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BETA-DECAY OF NUCLEI NEAR N=126 CLOSED NEUTRON SHELL

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Within the Generalized Energy-density Functional method we have systematically calculated the beta-decay total energy releases, half-lives and beta-delayed neutron emission branchings for near-spherical nuclei with charge numbers Z = 60 - 80 near the neutron shell at N = 126. Together with our previous calculations this provides a basic set of the weak rates for the r-process modeling. Our half-lives predictions can provide a benchmark for the experiments on the production of heavy neutron-rich nuclei close to N = 126 and measuring their beta half-lives at the fragment separator FRS-ESR at the GSI, Darmstadt. A reasonable agreement with the half-lives recently measured in GSI justify our predictions for the half-lives of the N = 126 r-process waiting-point nuclei. We will specifically discuss a principal contribution of first-forbidden transitions to the half-lives and Pn-values near N = 126.

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A Laser-Accelerated Th Beam is Used to Produce Neutron-Rich Nuclei Atround the N=126 Waiting Point of the r-Process Via the Fission-Fusion Reaction Mechanism

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Radiation Pressure Acceleration (RPA) with solid state density ion bunches, which are about 1E15 times more dense then classically accelerated ion bunches, allow for a high probability that generated fission products fuse again, when the thorium beam strikes a second close Th target. The fission fragments have a 1/sin(Theta) angular distribution and thus are predominantly emitted in beam direction and stay within the cylinder volume defined by the small spot diameter of the first Th target. In this double reaction neutron-rich light fission fragments of the beam fuse with neutron-rich light fission fragments of the target and we can reach more neutron-rich nuclei than with classical radioactive beams only. The produced beam of new radioactive nuclei will be analyzed with a classical velocity filter, where the technical optimization is well known. The small repetition rate of the 30 PW APPOLON lasers of about 0.02 Hz with very short production pulses is stretched by the Beta-decay half-lives of the produced nuclei to counting rates acceptable to nuclear detectors. Very neutron-rich nuclei still have small production cross sections, because weakly bound neutrons are evaporated easily. The velocity filter has to suppress the many fused nuclei close to the valley of stability. Here we want to look specifically for nuclei close to the waiting point at N=126 of the r-process, which is decisive for the astrophysical production of heavy elements and was not accessible until now.We estimate sufficient rates for these interesting nuclei. We envision having behind the velocity filter a gas stopping cell and a Penning trap to measure accurately the masses of these nuclei.

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R-process Nucleosynthesis in the Long-Term Simulation of Magnetically Dominated Core-Collapse Supernovae

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We investigate r-process nucleosynthesis during magneto-hydrodynamic supernova explosions driven by rapid rotations and strong magnetic fields. These types of supernovae are very important not only for magnetar formation sites, but also for astronomical r-process sites in astrophysics. Our r-process nucleosynthesis simulations are based on the astronomical supernova explosion models, which follow the long-term evolution in special relativistic magneto-hydrodynamic simulations. We perform an r-process nucleosynthesis simulation for magneto-hydrodynamic jet supernova models based on a large nuclear reaction network including fully nuclear reactions. In our results, we find that a jet-like supernova explosion model with strong magnetic field can occur successful r-process nucleosynthesis.

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Broad-band mass measurements in storage rings

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Recent experiments with stored exotic nuclei, that have been performed at the Experimental Storage Ring ESR in Darmstadt, Germany, will be discussed in this contribution. Broad-band

Schottky (SMS) and Isochronous (IMS) mass spectrometry are extremely powerful methods for simultaneous measurements of big numbers of nuclear masses in one experiment. The former method is applied to electron-cooled beams and can therefore address nuclides with half-lives longer than about one second. The shortest lifetimes that can be measured with the second method are in the few-ten microseconds range. Both methods are sensitive to single stored ions. Large-scale explorations of the nuclear mass-surface have been done in the last years providing a vast information on nuclear structure properties, such as the limits of nuclear existence, nucleon separation energies, nucleon-nucleon interactions, etc. Several new long-lived isomeric states and new neutron-rich isotopes have been discovered. The present status of the experiments and some preliminary results will be presented. Plans for future experiments including the prospects for the new storage ring facility CSRm-CSRe in Lanzhou will be outlined.

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Neutron-rich nuclei, neutron matter and constraints on neutron star structure from chiral effective field theory interactions

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This talk will discuss the impact of chiral three-nucleon forces on neutron-rich nuclei and on neutron-rich matter. I will show that three-nucleon forces lead to repulsive contributions to the interactions among valence neutrons that change the location of the neutron drip line from 28O to the experimentally observed 24O. This three-nucleon mechanism provides the first microscopic explanation of the oxygen anomaly in the neutron drip line and can impact the prediction of the most neutron-rich nuclei and the synthesis of heavy elements in neutron-rich environments. In addition, our microscopic calculations based on the same interactions constrain the properties of dense matter below nuclear densities to a much higher degree than is reflected in current neutron star modeling. Combined with observed neutron star masses, our results lead to a radius R = 11.8 +/- 2.1 km for a M = 1.4 M_sun neutron star, where the theoretical error is due, in about equal amounts, to uncertainties in many-body forces and to the extrapolation to high densities.