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Zero-sound modes for the nuclear equation of state at supra-normal densities

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The meaningful correlations between the zero-sound modes and the stiffness of the nuclear equation of state (EOS) are uncovered in symmetric nuclear matter with the relativistic mean-field (RMF) theory. We found that the high-density zero-sound modes merely exist in models with the stiff EOS. While the soft RMF EOS are usually characteristic of the inclusion of the ω-meson self-interactions (the ω^4 term) [1], the weakened coupling of the ω-meson self-interactions can ensure the appearance of the zero sound at high density. These results suggest that the high-density zero-sound modes can be used to probe the stiffness of the EOS at supra-normal densities that is still subject to large uncertainty [2]. In asymmetric matter, the correlation also exist clearly between the zero-sound modes and the stiffness of the nuclear EOS. On the other hand, it is found that the symmetry energy has the impact on the behavior of zero sound modes. The symmetry energy in RMF models is modified by introducing the isoscalar-isovector ($\omega - \rho$) coupling term. A softer symmetry energy results in a narrower range for low-density zero sound, while the energy of the damped zero sound at high-density moves much closer to the undamped one as the symmetry energy softens. The implications and effects of zero sounds are also discussed in heavy ion collisions and neutron stars.

[1] R. Y. Yang, W. Z. Jiang, S. N. Wei, and D. R. Zhang, Sci. Rep.7, 1 (2017).

[2] J. Ye, J. Margueron, N. Li, and W. Z. Jiang, Phys. Rev. C 108, 044312 (2023).

Nuclear structure, short-range correlations, and clustering from direct reactions / 3

Size Compression of Nucleon Pair On Nuclear Surface

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We investigate the size changing of $2n$, $2p$, and $2d$ during their emission from ^{6}He, ^{6}Be, ^{6}Li, and ^{18}F in the microscopic calculation framework. The average size of the subsystem in the nucleus is defined with the two-dimensional reduced width amplitude (RWA). The results show that all of these nucleon pairs, including the boundary deuteron($2d$) pair, will happen the size compression at the surface of the nucleus. With further investigation into the behavior of the RWA, we propose that the pairing effect is strongly affected by the quantum feature of the wave function.

Short presentations / 4

Study of quasi-projectile properties at Fermi energies in 48Ca projectile systems

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The emission of the pre-equilibrium particles during nuclear collisions at moderate beam energies is still an open question. This influences the properties of the compound nucleus but also changes the interpretation of the quasi-fission process. A systematic analysis of the data obtained by the FAZIA collaboration during a recent experiment with a neutron rich projectile is presented. The full range of charged particles detected in the experiment is within the limit of isotopic resolution of the FAZIA detector. Quasi-projectile (QP) fragments were detected in majority thanks to the forward angular acceptance of the experimental setup which was confirmed by introducing cuts based on the HIPSE event generator calculations. The main goal was to compare the experimental results with the HIPSE simulations after introducing these cuts to investigate the influence of the n-rich entrance channel on the QP fragment properties. More specifically, the lowering of N/Z of QP fragments with beam energy was found to be present since the initial phase of the reaction. Thus, pre-equilibrium emissions might be a possible candidate to explain such an effect.

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 5

Exploring Composition of Neutron Star Matter with Astrophysical Observations

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Astrophysical observations of neutron stars allow us to study the physics of matter at extreme conditions which are beyond the scope of any terrestrial experiments. In this work, we perform a Bayesian analysis putting together the available knowledge from the nuclear physics experiments, observations of different X-ray sources, and gravitational wave events to constrain the equation of state of supranuclear matter. In particular, we employ a relativistic metamodel to explore the uncertainties of the saturation properties of nuclear matter such as the symmetry energy and its higher-order derivatives, incompressibility, skewness, kurtosis etc. We further probe the fractions of different particle species within our model that the interior of a neutron star may contain, particularly the proton fraction in the core and the observational consequences of the allowed compositions. We also incorporate the possible emergence of hyperons in the system and the number of ways that the density functional can accommodate hyperons in the neutron star matter. Finally, we calculate the strangeness content in the star and discuss its observational implications.

Short presentations / 6

Isomeric Structure in 100Sn Region: Possible Competition between beta+ Decay and Proton Emission in Isomeric Unbound Nucleus 97Sn

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The isomeric structure and properties in proton-rich nuclides are crucial for determining the path of the rapid proton capture (rp)-process. For example, bound nuclei inside the dripline can have unbound isomeric states and change the rp-process pathway. The configuration interaction shell model (CISM) is used to investigate nuclei around the $Z = N$ line at the south-west region of ^{100}Sn. The excitation mechanism of $1/2_1^-$ isomers is identified as dominated by exciting one nucleon in the $1p_{1/2}$ orbit to the $0g_{9/2}$ orbit. The study explores the decay properties of both the ground and isomeric states. Remarkably, competitive β^+ decay and proton emission are predicted in the unbound $1/2_1^-$ isomer of ^{97}Sn, suggesting potential influences on the rp-process pathway.

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 8

Bayesian model averaging for nuclear symmetry energy from effective proton-neutron chemical potential difference of neutron-rich nuclei

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The data-driven Bayesian model averaging is a rigorous statistical approach to combining multiple models for a unified prediction. Compared with the individual model, it provides more reliable information, especially for problems involving apparent model dependence. In this work, within both the non-relativistic Skyrme energy density functional and the nonlinear relativistic mean field model, the effective proton-neutron chemical potential difference $\Delta\mu^*_{\rm pn}$ of neutron-rich nuclei is found to be strongly sensitive to the symmetry energy $E_{\rm sym}(\rho)$ around $2\rho_0/3$, with ρ_0 being the nuclear saturation density. Given discrepancies on the $\Delta\mu^*_{\rm pn}$–$E_{\rm sym}(2\rho_0/3)$ correlations between the two models, we carry out a Bayesian model averaging analysis based on Gaussian process emulators to extract the symmetry energy around $2\rho_0/3$ from the measured $\Delta\mu^*_{\rm pn}$ of 5 doubly magic nuclei ^{48}Ca, ^{68}Ni, ^{88}Sr, ^{132}Sn and ^{208}Pb. Specifically, the $E_{\rm sym}(2\rho_0/3)$ is inferred to be $E_{\rm sym}(2\rho_0/3) = 25.6^{+1.4}_{-1.3}$ MeV at 1σ confidence level. The obtained constraints on the $E_{\rm sym}(\rho)$ around $2\rho_0/3$ agree well with microscopic predictions and results from other isovector indicators.

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Theoretical progress in the investigation of the ^{132}Sn and the ^{208}Pb mass regions

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In the last decade the investigation of the ^{132}Sn and the ^{208}Pb mass regions has experienced a great progress either experimentally by the advances of new facilities of radioactive ion beams, or theoretically by the development of different theoretical models and effective interactions.

Within the shell model (SM) framework [1], I will expose the calculated spectroscopic properties and the evolution of the collectivity in nuclei from ^{132}Sn (Z≥50, N≥82) and ^{208}Pb (Z≥82, N≥126) mass regions, where the calculations are carried out by making use of our effective interactions N3LOP [2] and H208 [3]. Some of these results are considered as references in the interpretation of several new measurements [4,5,6,7], which will be widely discussed.

In the second part, I will present a new effective interaction developed for ^{132}Sn mass region, but with the proton particles Z≥50 and neutron holes N≤82. In order to confirm the reliability of the TBME of this new interaction, the low-lying states energies, E2 and M1 transitions, of some nuclei are calculated and compared with the experimental data, with the prediction of some results not observed yet.

[1] E. Caurier, G. Martinez-Pinedo, F. Nowacki, A. Poves, and A.P. Zuker, Rev. Mod. Phys. 77, 427 (2005).
[2] H. Naïdja, F. Nowacki, and B. Bounthong, Phys.Rev.C 96, 034312 (2017).
[3] Houda Naïdja, Phys. Rev. C 103, 054303 (2021).
[4] A Jungclaus, P Doornenbal, J Acosta, et al. Phys.Lett. B 851, 138561(2024).
[5] B. Andel et al., Phys. Rev. C (accepted) (2024).
[6] M. Si, R. Lozeva, H. Naïdja et al.Phys. Rev. C 106, 014302 (2022).
[7] B Moon, A Gargano, H Naïdja, et al. Phys. Rev.C 105, 034334(2022).

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 10

Calibrating global behaviour of equation of state by combining nuclear and astrophysics inputs in a machine learning approach

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Recovering the nuclear matter parameters (NMPs), crucial elements in neutron star equations of state for the nucleonic core configuration, is a significant ongoing task in nuclear astrophysics. This involves utilizing various experimental data and astrophysical observations through a Bayesian approach. However, the conventional method of computing the equation of state (EoS) and solving the Tolman-Oppenheimer-Volkoff (TOV) equations to obtain neutron star (NS) properties is computationally intensive and time-consuming. To address this, we propose a rapid approach, denoted as symbolic regression model (SRM), which provides a preliminary estimation of the underlying NMPs more than 100 times faster than the traditional TOV approach within the same framework. We observe that including constraints from various nuclear experiments and neutron star observations are able reproduce most of the NMPs in a very narrow bounds. Additionally, Our analysis demonstrates that the results obtained using the SRMs closely align with those derived from the actual TOV equations.

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 11

Decoding the nuclear symmetry energy event-by-event in heavy-ion collisions with machine learning

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Inferences of the nuclear symmetry energy from heavy-ion collisions are currently based on the comparison of measured observables and transport model simulations. Only the expectation values of observables over all considered events are used in these approaches, however, observables can be obtained event-by-event both in experiments and transport model simulations. By using the light gradient boosting machine (LightGBM), a modern machine-learning algorithm, we present a framework for inferring the density-dependent nuclear symmetry energy from observables in heavy-ion collisions on the event-by-event analysis. The ultrarelativistic quantum molecular dynamics (UrQMD) model simulations are used as training data. The symmetry energy slope parameter extracted with LightGBM event-by-event from test data also by UrQMD has an average spread of approximately 30 MeV from the truth, and is found to be robust against variations in model parameters. In addition, LightGBM can identify features that have the greatest effect on the physics of interest, thereby offering valuable insights. Our study suggests that the present framework can be a powerful tool and may offer a new paradigm to study the underlying physics in heavy-ion collisions.

Constraints from heavy-ion collisions at relativistic energies / 12

Hyperon and Hypernuclei production in Ag+Ag collisions at 1.58 AGeV beam energy with the HADES experiment

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The HADES experiment was designed for the exploration of the QCD phase diagram at high baryochemical potential and moderate temperatures as well as for hadron physics with proton and pion beams. In A+A collisions at 1-2 AGeV strangeness production is close to threshold, thus becomes a rare observable being sensitive to the dense baryonic matter that has been created.

The most recent, high statistics heavy-ion data sample of nearly 16 billion events of Ag+Ag collisions at 1.58 AGeV beam energy allows for detailed analysis of strange hadrons, in particular baryons. The collision energy is right at the strangeness production threshold. Interestingly, it is not only the Λ that has been produced but also light hyper-nuclei. Thanks to the recent addition of an ECAL to HADES and the upgrade of the RICH detector, the Σ^0 baryon in its $\Lambda\gamma$ channel is measured for the first time in subthreshold (with respect to NN) AA collisions. Resulting multiplicities are compared to the statistical hadronization model and transport models clearly showing an impact of the high baryon density environment for strange baryon production.

Nuclear structure, short-range correlations, and clustering from direct reactions / 13

Intertwined quantum phase transitions in even-even and odd-mass nuclei

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Quantum phase transitions (QPTs) in atomic nuclei are drastic structural changes in the spectrum that are identified as either shape evolution or crossing shell model configurations in a chain of nuclei as a function of nucleon number. This phenomenon is frequently investigated in nuclear physics, both theoretically and experimentally, where many rare isotope beam facilities investigate a plethora of nuclei.
In this talk I will discuss my attempt to understand such phenomenon using algebraic frameworks - the interacting boson model with configuration mixing for even-even nuclei, and the new interacting boson-fermion model with configuration mixing for odd-mass nuclei. I will present my work on the chain of zirconium isotopes ($Z = 40$) with mass numbers *A = 92-110* and the chain of niobium isotopes (*Z = 41*) with mass numbers *A = 93-103*. The spectrum of the two chains discloses the manifestation of intertwined quantum phase transitions (IQPTs). IQPTs represent a situation where two types of QPTs occur in the same chain of nuclei. One is a crossing of two configurations in the ground state, and another is a shape evolution within each configuration. The occurrence of IQPTs in both chains of isotopes can set path for new investigations of this phenomenon in other chains, both even-even and odd-mass.

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Toward a better characterization of the nuclear equation of state using central collisions at Fermi energy

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The nuclear equation of state (EoS) describes the properties of dense nuclear matter, governing the behavior of nuclei, neutron stars, and energetic astrophysical phenomena.
However, our knowledge of the EoS at high densities remains limited due to the lack of direct experimental constraints.
This study combines the analysis of heavy-ion collision data with Bayesian inference to provide improved constraints on the nuclear EoS. Two phenomenological models, ELIE and HIPSE, are employed. A precise machine learning-based method has been developed to reconstruct the centrality (impact parameter) of Ni+Ni and Xe+Sn collisions from INDRA data in the energy range of 32 to 100 MeV/nucleon, enabling selection of the most central, potentially supra-saturation density events. Bayesian inference is then performed on these central collisions to extract constraints on the nucleon-nucleon cross-section and the nuclear incompressibility in the Fermi energy domain.
The extracted nucleon-nucleon cross-sections are compared against theoretical predictions and phenomenological analyses by D. Coupland & al. (PRC 84, 054603 (2011)) and M. Henry & al. (PRC 101, 064622 (2020)). The incompressibility modulus, a key parameter governing the stiffness of the EoS at high densities, is benchmarked against the compilation of theoretical model values by J. Margueron (PRC 97, 025805 (2018) and PRC 97, 025806 (2018)). This allows us to constrain the maximum densities reached in the heavy-ion collisions.
These empirical comparisons and constraints pave the way toward an accurate determination of the nuclear EoS, crucial for modeling extreme astrophysical phenomena such as neutron stars and supernovae. Our results establish heavy-ion collisions as a powerful terrestrial probe of the high-density EoS, shedding light on fundamental nuclear physics and astrophysics.

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 15

Nuclear equation of state from nuclear experiments and neutron star observations

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The Equation of State (EoS) is crucial for understanding the structure of compact objects such as neutron stars. In the conservative hypothesis of a purely nucleonic composition of neutron star matter, the EoS is fully determined in terms of the so-called nuclear matter parameters (NMPs), which, in principle, can be determined from nuclear theory and experiments, though with error bars. However, present constraints from nuclear data are typically limited to (i) independent analyses of different data sets with limited control over the quality of the simultaneous reproduction of different observables and (ii) independent inferences of single NMPs with limited knowledge of the correlations among parameters.

The main objective of our work is to progress on both limitations. Specifically, we build a reliable probability distribution of the whole set of nuclear matter parameters and investigate the correlations between them using a combined Bayesian inference of a large set of EoS-sensitive nuclear structure data. We then use this distribution to compute the static properties of neutron stars.

To compute a wide selection of precisely measured nuclear observables over the nuclear chart (binding energies, charge radii, spin-orbit splittings, giant resonance energies, dipole polarizability, parity-violating scattering), we employ the hfbcs-qrpa [1] code with standard Skyrme functionals. While ground state properties of nuclei require negligible computational time, observables linked to nuclear response, which are expected to be sensitive to specific nuclear bulk properties are computationally more demanding. In Metropolis sampling, evaluating on the fly is time-consuming, so we resorted to the MADAI package [2], an emulator software for Bayesian inference with slow models.

The final result is a 10-dimensional multivariate probability distribution for the NMPs. Marginalizing the distribution over all parameters but one allows to compare with previous simpler analyses in the literature. The talk will present such a critical comparison and the final predictions on some selected static properties of neutron stars.

We will, in particular, show that the constraints from nuclear experiments are well compatible with the theoretical predictions for infinite pure neutron matter from ab initio modeling, and those constraints additionally indicate the existence of interesting structures in the density dependence of the sound speed in neutron stars.

[1] G. Colò, X. Roca-Maza, arXiv:2102.06562v1 [nucl-th]
[2] MADAI Collaboration (Models and Data Analysis Initiative) https://madai.phy.duke.edu/indexdc37dc37.html?page_id=445

Nuclear structure, short-range correlations, and clustering from direct reactions / 16

The Mainz Radius EXperiment (MREX): setup optimization and uncertainty prediction

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The neutron skin (NS) is a phenomenon of an increased neutron to proton density ratio at the nuclear periphery. It is a prominent probe of the nuclear equation of state, connecting nuclear physics and astrophysics. The PREX experiment was the first to determine the NS in ^{208}Pb through parity-violating electron scattering but had great uncertainty in the resulting NS thickness. The Mainz Radius EXperiment (MREX) aims to repeat this determination and increase its precision. The solenoid geometry of the experimental setup based on the integrating Cherenkov detector makes it necessary to account for many rate-contributing particles at the simulation stage. Apart from the dominant elastically scattered electrons contribution, these include inelastically, quasielastically, and multiply scattered electrons, as well as secondary produced particles. Their detection results in the shift in the measured parity-violating asymmetry and momentum transfer and must be corrected. In this work, we make predictions for the corresponding corrections with the latest version of the developed Monte-Carlo simulation of the experiment. We study the dependence of these corrections on experimental setup adjustments and minimize the systematic uncertainty introduced by them. Finally, we calculate the measuring time necessary for MREX to match or double the PREX-II precision.

Transport model simulations of heavy-ion reactions / 18

Combining mean field and nucleonic degrees of freedom in orthogonal-wave-function dynamics for heavy-ion collisions

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Is it possible to combine a quantum mean-field theory and molecular dynamics within a unique framework for heavy-ion collisions?

Starting from the time-dependent Hartree-Fock scheme and by introducing a dynamical basis of orthogonal fermionic wave functions, we work out a solution to combine the advantages of the two above-mentioned approaches, bypassing a number of usual approximations. Such approximations like, for instance, the non-locality properties of nucleonic wave functions, are one of the essential reasons why current transport approaches may yield different descriptions.

The quantum mean-field description introduces spacial localization properties and it allows to describe densities in terms of an evolving level scheme. Molecular dynamics, on the other hand, involves nucleonic degrees of freedom which could be exploited to introduce nucleon-nucleon collisions and large-amplitude fluctuations, without needing to rely on averages, projections or effective nucleon-nucleon terms. We show, together with a few examples, how a dynamical basis, iteratively perturbed by collision events while ensuring that orthogonality is preserved, could be a possible solution to describe a broad range of energy regimes, from low to Fermi and intermediate energies.

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Nuclear symmetry energy in dilute and dense matter

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The properties of neutron-rich nuclear systems are largely determined by the density dependence of the nuclear symmetry energy. Experiments aiming to measure the neutron skin thickness [1,2] and astronomical observations of neutron stars and gravitational waves [3,4] offer valuable information on the symmetry energy at sub- and supra-saturation densities, respectively.

The KIDS theoretical framework for the nuclear equation of state (EoS) and energy density functional (EDF) [5-7] offers the possibility to explore the symmetry-energy parameters such as J (value at saturation density), L (slope at saturation), Ksym (curvature at saturation), independently of each other and independently of assumptions about the in-medium effective mass. Within this versatile and physically motivated framework, any set of EoS parameters can be transposed into a corresponding EDF and readily tested in microscopic calculations of nuclear properties [6-8]. Related studies of symmetry-energy parameters have utilized both astronomical observations and bulk nuclear properties [8,9] and a comprehensive Bayesian analysis of both isoscalar and isovector nuclear observables including giant resonances [10,11].

I plan to discuss high-order parameters such as Ksym, indications for a model decoupling of the nucleonic fluid from dense and dilute regimes, and first attempts to extend the framework to quarkionic matter [12].

References

[1] T. Aumann et al., Phys. Rev. Lett. 119 (2017) 262501.
[2] D. Adhikari et al. (PREX Collaboration), Phys. Rev. Lett. 126 (2021) 172502;
D.Adhikari et al. (CREX Collaboration), Phys. Rev. Lett. 129 (2022) 042501.
[3] B. P. Abbott et al., Phys. Rev. X 9 (2019) 011001.
[4] M. C. Miller et al., Ap.J.L. 918 (2021) L28.
[5] P. Papakonstantinou et al., Phys. Rev. C 97 (2018) 014312.
[6] H. Gil, P. Papakonstantinou, C. H. Hyun, Y. Oh, Phys. Rev. C 99 (2019) 064319.
[7] H. Gil et al., Phys. Rev. C 100 (2019) 014312.
[8] H. Gil et al., Phys. Rev. C 103 (2021) 034330.
[9] H. Gil, P. Papakonstantinou, C. H. Hyun, Int. J. Mod. Phys. E 31 (2022) 2250013.
[10] Jun Xu, P. Papakonstantinou, Phys. Rev. C 105 (2022) 044305.
[11] Jia Zhou et al., Phys. Rev. C 107 (2023) 055803.
[12] P. Papakonstantinou, C. H. Hyun, Summetry 15 (2023) 683.

Investigations at existing and future accelerator facilities and detectors / 20

KRAB detector for the ASY-EOS II experiment within the R3B infrastructure at GSI

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The only way to study the properties of asymmetric nuclear matter at high densities in the laboratory conditions is to investigate the relativistic heavy ion collisions. A complementary source of information are the astrophysical observations and gravitational waves. The degree of compression and pressures achieved during the heavy ion collision depend on the susceptibility of the nuclear matter to compression, and hence on its equation of state. In particular, the measured angular and energy distributions of the neutrons and protons, light isobars and of the π−and π+emitted form the interaction zone depend on the symmetry energy and its gradients at the attained densities. Precision measurements of the azimuthal distributions of neutrons and protons and light isobars with respect to the reaction plane require specific detectors. The setup for the ASY-EOS II experiment within the R3B infrastructure at GSI will allow for improved resolution flow measurements through the usage of the NeuLAND neutron/proton detector, the KRAB fast multiplicity trigger, reaction plane and centrality detector, of the CHIMERA multidetector at intermediate angles, of two TOFD time of flight walls for flow measurements at very forward angles and for light charged particles hitting NeuLAND and of the KRATTA array for complementary measurement of light charged particles opposite to NeuLAND. The presentation will focus on the KRAB detector constructed to fulfill the special requirements for the multiplicity trigger around the target in the ASY-EOS II setup. Its characteristics and performance measured during the tests at CCB on the proton beam and at GSI on the relativistic Au beams will be presented.

Constraints from heavy-ion collisions at intermediate energies / 21

Symmetry energy constraints from isospin transport: Recent results from the INDRA-FAZIA apparatus

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Heavy-ion collisions at intermediate energies (20-100 MeV/nucleon) are an essential tool for probing the properties of nuclear matter in far-from-equilibrium conditions. Among other topics, they allow the investigation of isospin transport phenomena, which can be interpreted within the framework of the Nuclear Equation of State (NEoS). This area of research holds significant interest due to its implications in both nuclear physics and astrophysics [1].
The INDRA-FAZIA apparatus [2] is particularly well suited to study such phenomena. The coupled apparatus, operating at GANIL since 2019, combines the excellent identification capability of FAZIA, positioned at forward polar angles to detect ejectiles in the quasiprojectile (QP) phase space, with the large angular coverage of INDRA, which is useful to construct global variables for reaction centrality estimation.

Here, we report on the most recent results from the INDRA-FAZIA apparatus. The main focus will be on its first experiment [3,4], which was aimed at studying isospin diffusion by comparing the results of the two asymmetric reactions ^{64,58}Ni+^{58,64}Ni with both the corresponding neutron rich and neutron deficient symmetric systems at Fermi energies, employing the isospin transport ratio technique [5].
The neutron-to-proton content of the heavy QP remnant, directly accessible thanks to the identification performance of FAZIA, is exploited as an isospin observable to highlight the isospin equilibration between asymmetric projectile and target. By applying the impact parameter reconstruction method proposed in [6], we hereby provide a model-independent experimental evaluation of the degree of isospin equilibration taking place in Ni-Ni collisions at 32~MeV/nucleon across varying reaction centralities.
This experimental result can be easily compared with the predictions of any transport model: in this presentation, we also show a first comparison with BUU@VECC-McGill model predictions [7] assuming different NEoS parametrizations, which represents a promising result in view of constraining the symmetry energy behavior at sub- to saturation densities.

[1] A. Sorensen et al., Progr. Part. Nucl. Phys. 134, 104080 (2024).
[2] G. Casini and N. Le Neindre, Nucl. Phys. News 32, 24 (2022).

[3] C. Ciampi et al., Phys. Rev. C 106, 024603 (2022).
[4] C. Ciampi et al., Phys. Rev. C 108, 054611 (2023).
[5] F. Rami et al., Phys. Rev. Lett. 84, 1120 (2000).
[6] J. D. Frankland et al., Phys. Rev. C 104, 034609 (2021).
[7] S. Mallik et al., J. Phys. G: Nucl. Part. Phys. 49, 015102 (2022)

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 22

Determination of the Equation of State from Nuclear Experiments and Neutron Star Observations

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With recent advances in neutron star observations, major progress has been made in determining the pressure of neutron star matter at high density. This pressure is constrained by the neutron star deformability, determined from gravitational waves emitted in a neutron-star merger, and measurements of radii of two neutron stars, using a new X-ray observatory on the International Space Station. Previous studies have relied on nuclear theory calculations to provide the equation of state at low density. Here we use a combination of 15 constraints composed of three astronomical observations and twelve nuclear experimental constraints that extend over a wide range of densities. Bayesian Inference is then used to obtain a comprehensive nuclear equation of state. This data-centric result provides benchmarks for theoretical calculations and modeling of nuclear matter and neutron stars. Furthermore, it provides insights on the composition of neutron stars and their cooling via neutrino radiation.

Nuclear structure, short-range correlations, and clustering from direct reactions / 23

Nuclear clustering - from the edge of stability to the Fermi energy domain

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Loosely bound nuclei are currently at the center of interest in low-energy nuclear physics. The deeper understanding of their properties provided by the shell model for open quantum systems changes the comprehension of many phenomena and offers new horizons for spectroscopic studies of nuclei from the driplines to the valley of β-stability, for states in the vicinity and above the first particle emission threshold [1,2]. Systematic studies in this broad region of masses and excitation energies will extend and complete our knowledge of atomic nuclei at the edge of stability.

In this talk, I will briefly review the recent progress in open quantum system shell model description of nuclear states and their decays. I will discuss the nature of the proton-decaying 0_2^+ resonance of

α particle [3], and the chameleon properties of near-threshold resonances due to the alignment of their wave functions with the decay channel, leading to the emergence of clusters [4]. The quantum nature of clustering in this regime will be illustrated on chosen examples of the chameleon nature of near-threshold resonances, and the systematic appearance of near-threshold resonances.

In the next step I will briefly comment on the evolution from the purely quantum regime of clustering at the edge of nuclear stability with respect to the particle emission, to the semi-classical mechanism at higher excitation energies and, finally, to the classical statistical clustering mechanism at the Fermi energy domain and above which is rooted in the Central Limit Theorem of Mathematics.

[1] N. Michel, M. Ploszajczak, Gamow Shell Model - The
Unified Theory of Nuclear Structure and Reactions, Lecture Notes in Physics 983 (Springer, Cham, 2021).

[2] N. Michel, W. Nazarewicz, M. Ploszajczak and T. Vertse, J. Phys. G: Nucl. Part. Phys., 36 (2008) 013101.

[3] N. Michel, W. Nazarewicz and M. Ploszajczak, Phys. Rev. Lett. 131 (2023) 242502.

[4] J.P. Linares Fernandez, N. Michel, M. Ploszajczak and A. Mercenne, Phys. Rev. C 108 (2023) 044616.

[5] R. Botet and M. Ploszajczak, Unuversal Flustuations - The Phenomenology of Hadronic Matter, World Scientific Lecture Notes, Vol. 65 (2002).

Constraints from heavy-ion collisions at intermediate energies / 24

Using Molecular Dynamics Codes to Quantify Neutron-Proton Equilibration

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Previous studies at the Cyclotron Institute at Texas A&M University have experimentally shown that neutron-proton equilibration in heavy-ion collisions evolves exponentially [1,2]. The two heaviest fragments originating from the dynamically deformed, excited projectile-like fragment evolve to become more similar as its angle of rotation increases. Results were compared to Constrained Molecular Dynamics and Anti-symmetrized Molecular Dynamics simulations varying the density dependences of the asymmetry energy term of the nuclear equation of state. The results indicate better agreement with a softer interaction.

Constraints from heavy-ion collisions at intermediate energies / 25

Systematic measurement of charged pion production in HIC with RI beams at RIKEN-RIBF

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Charged pion production in HIC is one of the possible probes to study the density dependent symmetry energy. In 2016, the experiments for the measurement of charged pion ratio in neutron-rich and in neutron-deficient Sn+Sn system at the beam energy of E/A=270 MeV were conducted at RIKEN-RIBF.
A constraint on the symmetry energy around the nuclear density of \rho ~ 1.5\rho_0 was given based on this charged pion measurement.
In addition to Sn RI beam, there are several RI beams were produced and HIC data with those beams were taken at the same time.
In this talk, we will present the analysis status of systematic pion measurement in such reactions, where the charged pion ratio data of the asymmetry delta range of = abs(N-Z)/A : 0.086 - 0.226, and the energy range of E/A : 249 - 285 MeV can be expected.
Status of the new 124,136Xe+112,124Sn Spirit experiments will also be discussed.

Constraints from heavy-ion collisions at intermediate energies / **26**

Study of nuclear symmetry energy from isospin transport in intermediate energy heavy-ion reactions

Auteur: Swagata Mallik[1]

Co-auteurs: Caterina Ciampi [2]; Francesca GULMINELLI [3]; John Frankland [4]; Diego Gruyer [5]; Abdelouahad Chbihi [2]; Rémi Bougault [5]; Nicolas Leneindre [6]

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One of the most exciting challenges in modern nuclear physics and astrophysics is to understand the behavior of nuclear matter under extreme conditions. Intermediate energy heavy-ion reactions provide a unique opportunity to enrich our knowledge about the nuclear equation of state (EoS) at sub-saturation densities [1,2]. In particular, the isospin transport in heavy-ion reactions at intermediate energies is directly correlated to the density dependence of the nuclear symmetry energy [3]. Recently, a Boltzmann-Uehling-Uhlenbeck equation based transport model of heavy ion reactions (BUU@VECC-McGill) [4,5] was upgraded by including a meta-modelling equation of state based on a density development around saturation [6], with parameters that can be tuned to reproduce ab-initio functionals from many-body perturbation theory. Based on this BUU@VECCMcGill transport model, isospin diffusion is studied for the 58,64Ni+58,64Ni reactions that are presently experimentally analyzed by INDRA-FAZIA collaboration at GANIL [7]. The comparison of isospin transport ratio from different isospin sensitive observables will be presented. The sensitivity of the isospin transport ratio on nuclear symmetry energy at saturation, its slope and curvature will be discussed. Finally, the dependence of isospin diffusion on the uncertainty still affecting the nuclear equation of states [8] will be described.

References:
[1] B.-A. Li and W.-U. Schroder, Isospin Physics in Heavy-Ion Collisions at Intermediate Energies (Nova Science, New York, 2001).
[2] S. Das Gupta, S. Mallik and G. Chaudhuri, Heavy Ion Reaction at Intermediate Energies: Theoretical Models (World Scientific Publishers, Singapore, 2019).
[3] M. B. Tsang et al., Phys. Rev. Lett. 92, 062701 (2004).
[4] G. F. Bertsch and S. Das Gupta, Phys. Rep. 160, 189 (1988).
[5] H.Wolter et.al, Prog. Part. Nucl. Phys. 125, 103962 (2022).

[6] S. Mallik, G. Chaudhuri and F. Gulminelli, Phys. Rev. C 100, 024611 (2019)
[7] C. Ciampi et al., Phys. Rev. C 106, 024603 (2022).
[8] S. Mallik, F. Gulminelli and D. Gruyer, Jour. Phys. G: Nucl. Part. Phys 49, 015102 (2021)

Short presentations / **27**

Comparison of collective flow variables for different isotopic combinations in Xe + Sn collisions from 65 to 150 AMeV

Auteur: Seon ho Nam[1]

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The nuclear symmetry energy indicates the binding energy of the nuclear matter depending on the isospin composition. It is a crucial parameter for the structure and stability of dense nuclear matter which exists in astronomical objects such as the neutron stars. Despite the dedicated efforts for the last several decades using the various collision systems in a wide beam-energy range, the detailed understanding of the nuclear symmetry energy is far from complete due to the experimental and theoretical limitations.
We have performed the multi-dimensional analysis for the directed and elliptic flow parameters in 129Xe + 124Sn collisions at 65 to 150 AMeV and the 129,124Xe + 124,112Sn at 100 AMeV, which were obtained at GSI by using the INDRA detector system in 1998. To reveal any effects that originated from the nuclear symmetry energy, the collective flow parameters between the neutron-rich system and the neutron-poor system have been carefully compared. In this presentation, the recent status of the analysis and the comparison with the model calculations results are presented.

Nuclear structure, short-range correlations, and clustering from direct reactions / **28**

Implications of PREX-II and CREX experiments for relativistic nuclear energy density functionals

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The nuclear energy density functional (NEDF) theory represents a unified approach to studying properties of nuclei along the nuclide map and the equation of state of nuclear matter. Significant progress has been made in constructing NEDFs using both relativistic and non-relativistic frameworks. NEDFs have primarily been parameterized using experimental data related to ground-state properties (e.g., masses, charge radii, spin-orbit splitting) of nuclei. However, these observables are insufficient to fully constrain the effective interaction, particularly its isovector component. The isovector part of the EDFs is crucial for understanding neutron-rich drip line nuclei and determining the density dependence of the nuclear symmetry energy.

Recently, we have constrained new NEDFs based on the relativistic density-dependent point coupling model. While optimizing these new functionals, we have incorporated not only nuclear ground-state properties but also weak-charge form factors from the PREX-II [1] and CREX [2] experiments. By integrating weak-charge form factor data into the optimization procedure, we have uniquely constrained the isovector channels of the effective interactions for each functional for the first time [3]. In this talk, I will first discuss the importance of the symmetry energy in nuclear physics studies, with a primary focus on the neutron-rich side of the nuclear landscape and drip lines [4]. Then, I

will discuss the contradictory findings arising from these new functionals and their implications for predictions of nuclear properties [3].

[1] D. Adhikari and PREX Collaboration, Phys. Rev. Lett. 126, 172502 (2021).
[2] D. Adhikari and CREX Collaboration, Phys. Rev. Lett. 129, 042501 (2022)
[3] E. Yüksel and N. Paar, Physics Letters B, 836, 137622, (2023).
[4] A. Ravlić, E. Yüksel, T. Nikšić, N. Paar, Physical Review C 108 (5), 054305 (2023).

Constraints from heavy-ion collisions at intermediate energies / 29

Signatures of Short-Range Correlations in collisions of intermediate energy projectiles

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Short-range nucleon-nucleon correlations (SRC), fluctuations when nucleons form pairs with high relative momentum and small center of mass momentum for short periods of time, provide important information on large relative momentum and short distance properties of nuclear wave functions. This information is important in theoretical models to understand the density dependence of symmetry energy at both sub and supra saturation densities. Characteristics and properties of SRCs have historically been investigated at GeV scale energies. However, recent theoretical calculations of lower intermediate energy heavy ion collisions have shown that signatures of SRC may be observed. To pursue this interesting idea, we have analyzed energy spectra of protons at forward angles in intermediate energy heavy ion reactions of various projectile target combinations. We show that this analysis indicates evidence of observation of high momentum tails at these intermediate energies and shows a dependence on projectile energy as well as the mass/charge asymmetry of projectile and target.

Constraints from heavy-ion collisions at intermediate energies / 30

Heavy-ion collisions and the low-density neutron star equation of state: from the lab to space

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Light nuclear clusters are expected to be ubiquitously present in astrophysical environments and play an important role in different astrophysical phenomena involving ultra-dense baryonic matter, but the estimation of their abundancy demands to correctly estimate the in-medium modification of their binding energy.
In the original measurements, Equilibrium Constants were extracted detecting clusters emitted by a hot expanding source identified in the mid-rapidity region in central heavy-ion collisions. The measured Equilibrium Constants for 2H, 3H, 3He, 4He and 6He were compared to a relativistic mean-field model, and seen to be reasonably compatible with a universal correction of the attractive σ-meson coupling.
Recently the data/model confrontation was analysed again by using a Bayesian analysis in order to reproduce the isotope mass fractions. This new analysis will be presented.
From the experimental point of view, different entrance channels, reaction mechanisms and incident energies have to be explored to validate the results and heavier clusters (Z>2) should also be considered to challenge the theoretical hypothesis of universal couplings. This is why a new experiment

has been carried out in order to analyse vaporization-like events of heavy ion reactions measured at GANIL using the INDRA-FAZIA multi-detector. We propose to present these new results within the Bayesian approach that has already been settled.

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Equation of State in the era of new nuclear physics and multimessenger constraints

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Over the past decade, a widely rich variety of data pouring in from laboratory experiments as well as astrophysical observations, including the detection of gravitational waves from binary neutron star mergers and the observations of a subsequent electromagnetic signal have raised new challenges in modelling equation of state of dense matter, and in physics in general. In this contribution, I will start with an overview of different types of equation of state modelling in the Bayesian formalism, to demonstrate the impact of different experimental and observational constraints. Further, I will present equations of state at finite temperature obtained with Brussels-Skyrme-on-a-Grid (BSkG) energy density functionals developed at Brussels, which are unified across the crust and core of the neutron star environment. These models have demonstrated remarkable accuracy over the whole nuclear chart on the masses, and fission barriers of nuclei, but at the same time they also satisfy recent astrophysical constraints. I will outline the impact of our calculations at finite temperatures on the composition of the crust in the neutron stars. Our immediate future goal is to apply these equations of state in the simulation of binary neutron star mergers.

Theory of supernovae, neutron stars, and neutron star mergers / 32

Resonant shattering flares as asteroseismic tests of chiral effective field theory

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χEFT is a powerful framework to construct models for the equation of state of low-density neutron star (NS) matter. However, there are currently only limited probes of NS matter that can reliably be used to test χEFT and the models it produces. While constraints on bulk NS properties can be inferred from various observables, these properties are mainly sensitive to the NS core, where χEFT may be inapplicable as exotic phases of matter could appear. Asteroseismology on the other hand allows us to probe lower-density matter within these compact objects, as different normal modes are sensitive to various properties throughout the star. Resonant shattering flares in particular could provide reliable constraints on the frequency of the crust-core interface mode, which is sensitive to the composition of matter around half saturation density. I will examine how measurements of this mode's frequency could be used to infer the equation of state of nuclear matter at sub-saturation densities, and subsequently investigate its use as a test of χEFT. While reliable measurements of this

frequency require the multimessenger detection of gravitational waves alongside a resonant shattering flare, I will also asses short gamma-ray bursts precursor flares identified in the literature under the optimistic assumption that most are resonant shattering flares, providing some early insight into the properties of the interface mode.

Nuclear structure, short-range correlations, and clustering from direct reactions / 33

Microscopic determination of the isospin symmetry breaking energy density functional

Auteur: Tomoya Naito[1]

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The isospin symmetry breaking terms of the nuclear interaction is a small part of the whole, while it gives important contributions to some physical observables of nuclear properties. For instance, we showed that the isospin symmetry breaking terms affect the estimation of the slope parameter of the symmetry energy using the neutron-skin thickness and the charge radii difference of the mirror nuclei. Nevertheless, it depends on the strengths of the isospin symmetry breaking energy density functional. In this talk, we will show how to pin down the strength of the isospin symmetry breaking energy density functional using microscopic theories.

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 34

Alpha-decay half-lives and symmetry energy in KIDS model

Auteurs: Yong-Beom Choi[1]; Hana Gil[2]; Chang Ho Hyun[1]; Chang-Hwan Lee[3]

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We studied alpha-decay half-lives of 84 <= Z <= 92 in the semiclassical WKB approximation frame work using the density-dependent cluster model and the density distribution described by various Korea-IBS-Daegu-SKKU (KIDS) models. Main goal of this work is to find a correlation between alpha-decay half-lives and the stiffness of the symmtery energy. Parameters of KIDS model are determined to reproduce the nuclear data (energy and charge radii of 40Ca, 48Ca and 208Pb) and the neutron star observations including constraints by NICER, tidal deformability from GW170817, and the maximum mass limit of neutron star observations. We used the KIDS models (A-D) which have distinctive values for the parameters controlling the stiffness of the nuclear matter equation of state. We found that alpha-decay half-lives increase systematically from KIDS-A model to KIDS-D

model. This implies a correlation between alpha-decay half-lives and the symmetry energy. In this talk, we present our results and discuss their implications.

Investigations at existing and future accelerator facilities and detectors / 35

Status of LAMPS for nuclear symmetry energy at RAON

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A new radioactive-ion beam (RIB) accelerator facility, RAON, is under construction in Korea. It consists of two RIB production systems, namely, isotope separation online (ISOL) and in-flight fragmentation (IF) and will eventually combine them to provide more exotic ion beams closer to the neutron drip line.
The large acceptance multi-purpose spectrometer (LAMPS) is one of the experimental systems for nuclear physics at RAON. The main goal of the LAMPS is to investigate the nuclear equation of state (EoS) and, especially, the symmetry energy (SE) of the compressed nuclear matter, which is essential for the effective nuclear interactions and structure of the neutron stars.
The LAMPS detector system has two independent systems: the fixed system at the high-energy experimental hall and another set of detectors mainly for the low-energy experiments. The high-energy LAMPS consists of the beam diagnostic system with the starting counters (SC) and beam drift chambers (BDC), time-projection chamber (TPC), barrel and forward time-of-flight arrays (BTOF and FTOF), forward neutron detector array (NDA), and superconducting solenoid magnet. For the low-energy experiments, the fast-timing gamma array KHALA, active-target time-projection chamber (AT-TPC) with a superconducting solenoid, and Si-CsI charged particle telescope are being procured.
In this presentation, the overview of the present status of LAMPS and the readiness of the detector components will be given with some perspectives.

Astrophysical, multi-messenger observations / 36

More neutron star radius measurements from NICER to understand dense nuclear matter

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The question of the nuclear symmetry energy is of great importance in physics, with numerous implications for a variety of fields. There exist different approches to solve this question, either experimentally, theoretically, or with astrophysical observations. For the latter, neutron stars are unique laboratories to probe nuclear-rich matter beyond saturation density, and therefore to help understand the nuclear symmetry energy. measurements of neutron stars masses and radii are direct probes of the interior of these compact objects, and therefore on the composition and behaviour of dense nuclear matter. Mass measurements have been accessible from radio pulsars in binary systems since the discovery of the Hulse-Taylor pulsar in the 1970s, providing exquisite precisions for neutron stars between 1.2 and about 2.1 solar masses. In the past two decades, X-ray observatories have provided some measurements of neutron star radii, but with limited precision in comparison to the mass measurements. The results from the NICER Observatory have, however, showed the most promising, robust and precise measurements. In this talk, I will present the key and most recent results from the NICER mission of the measurements of three neutron stars, as well as the implications for the equation of state of dense matter. The talk will also include a discussion of expected constraints from future observatories.

Short presentations / 37

A new paradigm in the consistent extraction of nuclear symmetry energy and related properties using the relativistic application of coherent density fluctuation model

Auteur: Praveen Kumar Yadav[1]

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Since the advent of nuclear physics, traditional bulk properties such as binding energy, shell correction, and deformations have facilitated the prediction of shell closure near the β-stability region. However, moving away from the stability region towards the dripline, the isospin-asymmetry (neutron-proton asymmetry) starts to dominate. For enhancing the understanding of this region, it is required the use an observable dependent on isospin-asymmetry. The nuclear symmetry energy is one such observable [1-2]. However, it comes with a caveat. Being a quantity associated with nuclear matter, it is usually defined in the momentum space, while finite nuclei are defined in the coordinate space. As a remedy, the coherent density fluctuation model (CDFM) was proposed to consistently translate symmetry energy and related nuclear matter quantities from momentum space to coordinate space [1-4]. Moreover, with the recent incorporation of relativistic energy density functional within the CDFM formalism, we have successfully addressed the Coester-Band problem that plagued Brückner's prescription [4]. In addition, a novel method has been suggested to compute the surface and volume terms of symmetry energy, yielding better constraint results. This facilitates a comprehensive exploration of the entire nuclear landscape while validating the established experimental shell closures and predicting novel shell closures. In the present work, we examine the presence of novel shell closure along various isotopic chains in medium mass regions, which helps cater to our current understanding of the variation of surface properties in the exotic regions of the nuclear chart.

References:

[1] M. K. Gaidarov *et al.*, Physical Review C **85**, 064319 (2012).
[2] M. K. Gaidarov *et al.*, Physical Review C **104** (2021) 044312.
[3] P. K. Yadav *et al.*, Chinese Physics C **46** (2022) 084101.
[4] P. K. Yadav *et al.*, Euro Physics Letter **146** (2024) 14001.

Constraints from heavy-ion collisions at relativistic energies / 38

Nuclear processes in ltrarelativistic, ultraperiprheral Pb+Pb collisions

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The ultrarelativistic Pb+Pb collisions are the source of many interesting processes. One of them is creation of the virtual photons by two moving electromagnetic fields generated by charged spectators. Moreover, these photons can excite the Pb nuclei and excite them substantially. The Pb

Our study focuses on the photon induced Pb spectator and its various channels of dexcitation. We calculate cross sections for single and any number of n, p, α, γ in UPC (b > R1 + R2) for LHC energies. We analysis deexcitation of excited 208Pb for excitation energies E_{exc} ∈ (0,500) MeV within Hauser-Feshbach formalism as encoded in the cascade program GEMINI++. At low excited energies we observe emission of neutrons and photons. At higher excitation energies E_{exc}

100 MeV we observe multiple emission of neutrons and photons, emission of single or in pairs of protons and alpha particles. Also fission channels open at larger excitation energies. The particles of a few MeV energy in the nucleus rest frame are emitted in a narrow cone in the laboratory (overall CM) frame after appropriate Lorentz boost (η> 10). We address a question whether such particles could be measured at the LHC. So far only neutrons are measured by the ZDCs. We calculated
energy spectra of the different particles. The energies of photons are rather small, below appropriate threshold. Protons and α particles could be measured by forward proton spectrometer. We estimated photoproduction cross section in Pb-Pb collision for single and multiple particles emission. Results are compared with existing ALICE data for neutron multiplicities at $\sqrt{s_{NN}}$=2. 76 and 5.02 TeV.

Theory of supernovae, neutron stars, and neutron star mergers / 39

Exploring robust correlations between fermionic dark matter model parameters and neutron star properties: A two-fluid perspective

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We investigate the probable existence of dark matter in the interior of neutron stars.
Despite the current state of knowledge, the observational properties of neutron stars have not definitively ruled out the possibility of dark matter. Our research endeavors to shed light on this intriguing mystery by examining how certain neutron star properties, including mass, radius, and tidal deformability, might serve as constraints for the dark matter model.

In our investigation, we adopt a two-fluid approach to calculate the properties of neutron stars. For the nuclear matter EOS, we employ several realistic EOS derived from the relativistic mean field model (RMF), each exhibiting varying stiffness and composition. In parallel, we look into the dark matter EOS, considering fermionic matter with repulsive interaction described by a relativistic mean field Lagrangian. A reasonable range of parameters is sampled meticulously.

Our study primarily focuses on exploring correlations between the dark matter model parameters and different neutron star properties using a rich set of EOSs. Interestingly, our results reveal a promising correlation between the dark matter model parameters and stellar properties, particularly when we ignore the uncertainties in the nuclear matter EOS. However, when introducing uncertainties in the nuclear sector, the correlation weakens, suggesting that the task of conclusively constraining any particular dark matter model might be challenging using global properties alone, such as mass, radius, and tidal deformability.

Notably, we find that dark-matter admixed stars tend to have higher central baryonic density, potentially allowing for non-nucleonic degrees of freedom or direct Urca processes in stars with lower masses. There is also a tantalizing hint regarding the detection of stars with the same mass but different surface temperatures, which may indicate the presence of dark matter. With our robust and extensive dataset, we delve deeper and demonstrate that even in the presence of dark matter, the semi-universal C-Love relation remains intact. This captivating finding adds another layer of complexity to the interplay between dark matter and neutron star properties.

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Exploring nuclear structures using fast neutrons at NFS

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Systematic studies of nuclear reactions are essential to the development of nuclear physics.
Understanding and predicting the evolution of nuclear structure and the novel phenomena in atomic nuclei has long been a pursuit of scientific curiosity.
Conventional methods such as charged particle probes, β-decay, Coulombic-excitation, and heavy-ion fusion evaporation reactions have been employed so far in the phase space of Shell structure, magic numbers, angular momentum, and excitation energy. However, the horizon of possibilities expands when we delve into the uncharted territories of fast-neutron probes. The (n,xn) reactions are a long-standing reaction mechanism used in the cross-section data evaluation, but rarely used in the framework of nuclear structure.
This might unveil a treasure trove of reactions, particularly the (n,xn) reactions with high production thresholds, which, until now, have not been looked at from the eye of nuclear structures.
As a result, we know very little about their reaction mechanisms.

While the structure of ^{56}Ni has been previously investigated using charged particle and heavy ions collisions as shown in Fig.1.

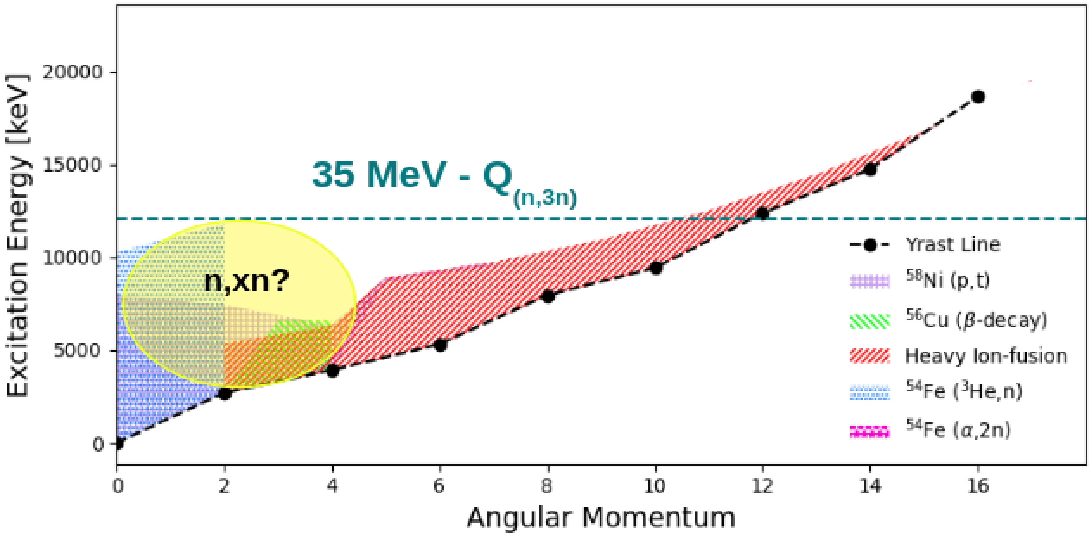

Figure 1: Yrast Diagram

, a pure neutron probe was never used.
For the first time, using the unprecedented neutron flux at ∼20 - 40 MeV at the Neutrons for Science (NFS) facility of GANIL–Spiral2, ^{56}Ni can be populated from ^{58}Ni in a (n,3n) reaction which has a cross-section of 2 mb at ∼30 MeV, opening a new probe and possibly new aspects of the nuclear structure of this doubly magic nucleus.
The TALYS cross-section calculation as a function of incident neutron energy is shown in Fig.2.

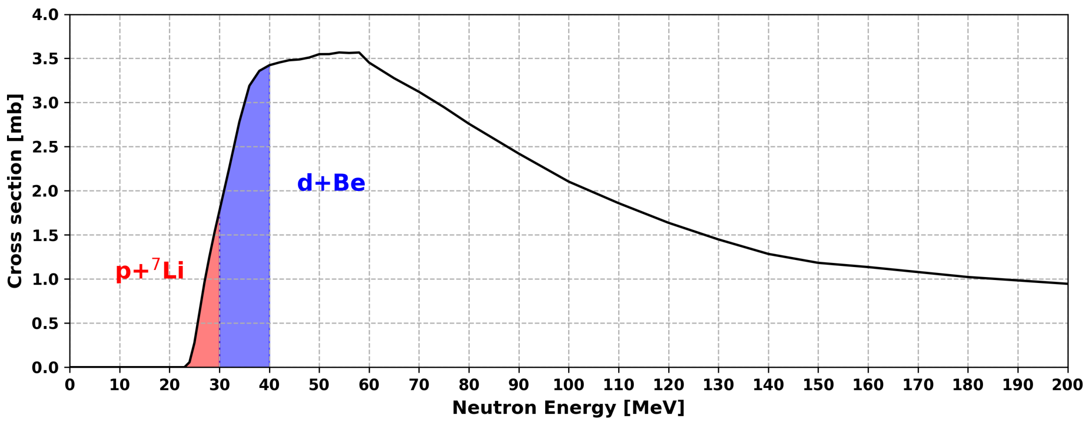

Figure 2: ^{56}Ni cross-section

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The maximum cross-section is predicted to be at 40 MeV, slightly higher than the end-point of NFS. p + Li / Be allows reaching the [20-30] MeV range, whereas d + Be allows up to a broader [25-40] MeV range.
With ^{58}Ni target, studying pure neutron channels is the main interest alongside Co isotopes that are produced from (n,p/d/t) reaction.

The nuclei near ^{56}Ni are of particular interest as they are amenable to different microscopic theoretical treatments while studying the competition between single-particle and collective excitations. The collective states in ^{56}Ni involve multiparticle multi-hole excitations across the $N = Z = 28$ shell gap from the 1f$_{7/2}$ shell to the 2p$_{3/2}$, 1f$_{5/2}$, and 2p$_{1/2}$ orbits. Excitation to the higher lying 1g$_{9/2}$ orbit are necessary to explain the observed rotational bands in Cu and Zn. At high excitation energies, reaction studies have revealed evidence for hyper-deformed resonances in the ^{56}Ni compound.

In this project, we performed prompt-γ spectroscopy of ^{56}Ni using the EXOGAM array at NFS.
From nuclear structure's point of view, the main motivation is the search for low spin (J=2 or 4) states from 3 to 10 MeV excitation energy possibly populating the 0^+ states at 3956 keV, 6654 keV and 7903 keV observed only in ^{58}Ni(p,t)^{56}Ni and ^{58}Ni(^{3}He,n)^{56}Ni reactions. New spectroscopic information that will be collected is also relevant for nuclear reaction mechanism formalism (like TALYS) and nuclear data evaluation libraries.

The experiment was carried out in October 2023. During an effective beam time of ~11 days, a high energy neutron beam produced by a primary beam of 10 μAmps of ^{2}H, bombarded a 1mm thick Ni target.
The prompt gamma rays selected on the fastest neutron using the Time of Flight information have been detected by 12 EXOGAM clovers placed at 15 cm off the beam axis.
About 1.6×10^{10} $\gamma\gamma$ coincidences have been sorted after the AddBack procedure.
The ^{56}Ni decay was observed and a large number of $\gamma\gamma$ coincidences for ^{57}Ni and Co isotopes were sorted.
The very preliminary analysis of the experiment, focusing mainly on the pure neutron channels, will be presented.
The (n,2n) channel that produces ^{57}Ni has a much larger cross-section, reaching a maximum of $\sim$90 mb at around 23 MeV, making it easier to study. Additionally, ^{57}Ni is only one neutron away from the doubly magic ^{56}Ni, making spectroscopy of single particle, core-coupled, and collective states of great interest. The primary focus of the talk will be to provide a comprehensive description of its level scheme and excitation functions. This isotope has a half-life of 35.6 hours and undergoes β^+ decay to produce ^{57}Co in the system, which interestingly is also populated by the (n,d) and (n,n′p) channels.
The question of whether large germanium volume detectors can be used for γ spectroscopy in a high flux high neutron energy environment will also be addressed.

This experiment is a pioneering work in the study of the nuclear structure studies using large gamma array and fast neutron and is only possible at GANIL-Spiral2 as of today.
If successful, this program will open a new door for nuclear structure studies.

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The symmetry energy between 0.1 and 2 times nuclear saturation density from nuclear and astrophysical theory and measurements nuclear using unified equations of state

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We have entered the era of multi-messenger nuclear astrophysics; bringing a host of astrophysical observations and nuclear experimental data to collectively measure the properties of neutron star matter and the nuclear force in neutron-rich systems. In order to combine disparate data sets with meaningful uncertainty quantification, over the past decade the statistical inference techniques employing ensembles of models have been increasingly employed. In order to minimize systematic model uncertainty, where possible the same underlying model should be used to construct neutron star and nuclear models. We present an example of such an approach, using an Energy-Density Functional to model bulk properties of neutron stars such as the maximum mass, radii, tidal deformabilities and moments of inertia, crust properties of neutron stars, and nuclear properties including nuclear masses, neutron skins and dipole polarizabilities. We allow independent variation of the first four parameters of the symmetry energy and account for possible variation in the symmetric nuclear matter parameters; we fit surface parameters of the crust model to mass fits and semi-infinite matter calculations. We extend the model beyond 2 times nuclear saturation density using both polytropic and speed of sound parameterizations of the high density EOS. We demonstrate how different observ-

ables constrain the symmetry energy in different density ranges, and discuss some of the remaining model uncertainties.

Transport model simulations of heavy-ion reactions / **42**

Constraints on EoS from study of light clusters and strange hadrons in heavy-ion collisions

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Authors: S. Glässel, V. Kireyeu, G. Coci, V. Voronyuk, M. Winn, J. Aichelin, C. Blume, and E. Bratkovskaya

We present the latest results on the constraints on the equation-of-state (EoS) of strongly interacting hadronic and partonic matter created in heavy-ion collisions from study of the light clusters, hypernuclei and strange hadrons (hyperons and strange mesons). Our study is based on the Parton-Hadron-Quantum-Molecular Dynamics (PHQMD) microscopic transport approach (PHQMD) [1-4]. The PHQMD is a microscopic n-body transport model based on the QMD propagation of the baryonic degrees of freedom, where the clusters are formed dynamically during the entire heavy-ion collision by potential interaction between nucleons and deuteron production by hadronic kinetic reactions.

We employed different EoS realized via potential interaction - a static interaction between nucleons vis Skyrme potential as well as via a {\bf momentum dependence interaction}. We investigate the influence of EoS on the collective dynamics of hadronic matter. The comparison of PHQMD results on directed and elliptic flow coefficients v_1 and v_2 of nucleons, light clusters and strange baryons with HADES, FOPI and STAR data allows to make a constraints on the EoS of nuclear matter probed in heavy-ion collisions at SIS and FAIR energies.

1 J. Aichelin, E. Bratkovskaya, A. Le F'evre, V. Kireyeu, V. Kolesnikov, Y. Leifels, V. Voronyuk and G. Coci, Phys. Rev. C 101 (2020) no.4, 044905 [arXiv:1907.03860 [nucl-th]].
2 S. Gl¨aßel, V. Kireyeu, V. Voronyuk, J. Aichelin, C. Blume, E. Bratkovskaya, G. Coci, V. Kolesnikov and M. Winn, Phys.Rev. C 105 (2022) no.1, 014908 [arXiv:2106.14839 [nucl-th]].
3 V. Kireyeu, J. Steinheimer, J. Aichelin, M. Bleicher and E. Bratkovskaya, Phys. Rev. C 105 (2022) no.4, 044909 [arXiv:2201.13374 [nucl-th]].
[4] G. Coci, S. Gläßel, V. Kireyeu, J. Aichelin, C. Blume, E. Bratkovskaya, V. Kolesnikov and V. Voronyuk, Phys. Rev. C 108 (2023) no.1, 014902 [arXiv:2303.02279 [nucl-th]].
[5] V. Kireyeu, G. Coci, S. Gl¨aßel, J. Aichelin, C. Blume and E. Bratkovskaya, Phys. Rev. C 109 (2024) no.4, 044906

Nuclear structure, short-range correlations, and clustering from direct reactions / **43**

Nuclear structure inputs to constrain the symmetry energy –The complex pattern of the pygmy resonance

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The pygmy dipole resonance (PDR) is a vibrational mode described as the oscillation of a neutron skin against a core symmetric in number of protons and neutrons. The PDR has been the subject of numerous studies, both experimental and theoretical [1,2,3]. Indeed, the study of the PDR has been and still is of great interest since it allows to constrain the symmetry energy, an important ingredient of the equation of state of nuclear matter that describes the matter within neutron stars [4]. However, despite numerous experiments dedicated to the study of the PDR, a consistent description is still discussed. In this context, various experimental approaches have been tried out. In particular, we have proposed to study the PDR using a new probe: the neutron inelastic scattering reaction (n,n'g). This type experiment is now feasible thanks to the high-intensity proton beam of the new accelerator SPIRAL2 at GANIL and the NFS (Neutron For Science) facility.

Short presentations / 44

Study of Pygmy Dipole Resonance using neutron inelastic scattering at GANIL-SPIRAL2/NFS : Status of the analysis

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Giant dipole resonance is a collective excitation mode of the nucleus that exhaust most of the dipole excitation strength. But additionnal low lying dipole strength has been observed in neutron-rich nuclei, called the Pygmy Dipole Resonance (PDR). Both experimental and theoretical studies [1,2,3] have been performed on the PDR, which is often described as the oscillation of a neutron skin against a symmetrical neutron-proton core.
The study of the PDR is interesting in many ways: it allows to constrain the symmetry energy (a term in the nuclear equation of state that drives the neutron skin and the description of nuclear matter in neutron stars) [4], and predictions show that this mode can play a key role in the astrophysical r-process [5]. However no coherent description on the nature of the PDR has been achieved yet.

In this context, the study of the PDR using a new probe, the neutron inelastic scattering reaction (n;n'γ), has been proposed. The high-intensity proton beam of the SPIRAL2 accelerator at GANIL [6], and the NFS (Neutron For Science) facility [7] have made this study possible. The experiment to study the PDR in 140Ce via the (n;n'γ) reaction was performed in Sept 2022. The new generation multi-detector PARIS [8] has been used for the detection of the γ from the deexcitation of the PDR, and MONSTER modules [9] were set for the scattered neutrons detection.

The characterization of the PARIS and MONSTER detectors and results on the elastic scattering will be presented, as well as preliminary results on the (n;n'γ) channel.

1 D. Savran, T. Aumann, A. Zilges, Prog. Part. Nucl. Phys. 70, 210-245 (2013)
2 A. Bracco, E.G. Lanza, A. Tamii, Prog. Part. Nucl. Phys. 106, 360-433 (2019)
3 E. G. Lanza, L. Pellegri, A. Vitturi, M. V. Andrés, Prog. Part. Nucl. Phys. 129, 104006 (2023)
[4] A. Carbone et al., Phys. Rev. C 81, 041301(R) (2010)
[5] S. Goriely, E. Khan, M. Samyn, Nucl. Phys. A 739, 331-352 (2004)
[6] A. K. Orduz et al., Phys. Rev. Accel. Beams, 25 (2022)
[7] X. Ledoux et al., Eur. Phys. J. A, 57 (2021)
[8] A. Maj et al., Acta Phys. Pol. B40, 565 (2009)
[9] A. R. Garcia et al., JINST 7, C05012 (2012)

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 45

An overview of existing and new nuclear and astrophysical constraints on the equation of state of neutron-rich dense matter

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Through continuous progress in nuclear theory and experiment and an increasing number of neutron-star observations, a multitude of information about the equation of state (EOS) for matter at extreme densities is available. Here, we apply these different pieces of data individually to a broad set of physics-agnostic candidate EOSs and analyze the resulting constraints. Specifically, we make use of information from chiral effective field theory, perturbative quantum chromodynamics, as well as data from heavy-ion collisions and the PREX-II and CREX experiments. We also investigate the impact of current mass and radius measurements of neutron stars, such as radio timing measurements of heavy pulsars, NICER data, and other X-ray observations. We augment these by reanalyses of the gravitational-wave (GW) signal GW170817, its associated kilonova AT2017gfo and gamma-ray burst afterglow, the GW signal GW190425, and the GRB211211A afterglow, where we use improved models for the tidal waveform and kilonova light curves. Additionally, we consider the postmerger fate of GW170817 and its consequences for the EOS. This large and diverse set of constraints is eventually combined in numerous ways to explore limits on quantities such as the typical neutron-star radius, the maximum neutron-star mass, the nuclear symmetry-energy parameters, and the speed of sound. Based on the priors from our EOS candidate set, we find the radius of the canonical 1.4 M⊠ neutron star to be 12.27+0.83-0.94 km and the TOV mass 2.26 +0.45 - 0.22, at 95% credibility, when including those constraints where systematic uncertainties are deemed small. A less conservative approach, combining all the presented constraints, similarly yields the radius of the canonical 1.4 M⊠ neutron star to be 12.20+0.53-0.50 km and the TOV mass 2.31 +0.08 - 0.20.

https://docs.google.com/presentation/d/1zV6YfZBue6czA_dXZHkE4uW9WDq2cN8NJ4hpP7b-EcQ/edit?usp=sharing

Nuclear structure, short-range correlations, and clustering from direct reactions / 46

Possibility to examine the transportation model by charge-changing reactions at intermediate energies

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Projectile fragmentation at several hundred MeV/nucleon has been crucial to exploring the world of nuclear physics.
One of the reactions in the projectile fragmentation is the charge-changing reaction cross sections (CCCS), which are the total removal probabilities
of one or more protons during the collisions with target nuclei. The reactions have been used to determine the ⊠⊠⊠ proton radii for the most exotic nuclei.
Along with reaction cross sections, it can provide the first hint of exotic structures and phenomena of unstable nuclei and can be used to constrain the nuclear symmetry energies.
I will present our recent CCCS measurements of p-sd shell nuclei on carbon, hydrogen, silver, and lead targets at about 900 and 300 MeV/nucleon at GSI/Germany and HIRFL/China. Benefiting from the large data set, we show the deficiency in the current understanding of the charge-changing reaction mechanism and demonstrate a robust and novel correlation of CCCS with the separation energy of the projectile nuclei. This robust correlation, independent of the reaction energy, helps derive reliable ⊠⊠⊠ proton radii when addressing the exotic nuclei. I will further show that the IQMD+GEMINI works well to predict such reactions and can help reveal the underlying reaction mechanisms.
This, in turn, may open a new way to examine various transportation models in the market.

Theory of supernovae, neutron stars, and neutron star mergers / 47

Disorder and clustering in the (Proto-)Neutron Star crust and the contribution of nuclear experiments

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A number of phenomena and signals from compact stars involve transport phenomena in nuclear matter at densities below saturation, where matter is known to be clusterized. This concerns core-collapse supernova dynamics at high temperature, where matter is in a liquid phase and the energy transport is ruled by the interaction of neutrinos with the different nuclear species, but also the magneto-thermal evolution of neutron stars through the presence of impurities in the crust.
In this talk we will review the two key aspects of the problem, namely (i) the theoretical prediction of the composition of the multi-component plasma matter in the different thermodynamic conditions; (ii) the effective treatment of in-medium modifications to the clusters energies in the dense stellar medium.
For this latter point, we will employ a relativistic mean-field formalism where light clusters are treated as independent quasi-particles with coupling constants calibrated on heavy-ion collisions measured by the INDRA-FAZIA collaboration. A full Bayesian inference estimation of the binding energy shifts without any prior assumption of the thermal parameters of the model will be presented, showing that light cluster abundancies are expected to decrease with temperature faster than previously estimated. The possible microscopic origin of the crustal resistivity from a disordered structure due to the presence of clusters will also be discussed.

Nuclear structure, short-range correlations, and clustering from direct reactions / 48

Investigations on the Pygmy Dipole Resonance and implications on the EOS symmetry energy

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Studies of the low-lying E1 strength around the nucleon binding energy, historically known as Pygmy Dipole Resonance (PDR), are among the most intriguing nuclear structure issues. The PDR is an excitation mode connected to the neutron excess in nuclei, and its strength is more intense in nuclei far from the stability with respect to the stable ones. The interest in a deep understanding of this mode arises also for the strong connection with the neutron skin and with the symmetry energy term of the equation of state of the nuclear matter (EoS) [1-3]. One of the major task of experimental and theoretical investigations is the determination of a consistent density parametrization of the symmetry energy, which can provide a unified picture of nuclear properties. Indeed, several features of nuclei as well as of the neutron stars can be obtained through the constrain of the symmetry energy term [4]. One of the most important feature of the PDR is the isospin mixing effect [1-3]. Due to this effect, as shown in several stable nuclei and in few unstable ones, the PDR excitation can be populated with both isoscalar and isovector probes [2-3]. However, some of its properties, as the degree of collectivity, are still under debate. In order to better understand the nature of the PDR it is necessary to perform investigations using both probes in different mass regions and above and below the neutron emission threshold. In this contribution, results about PDR studies, within its implications on the symmetry energy, will be discussed. Furthermore, a special focus will be given on the measurement performed in Catania, at INFN-LNS, studying the PDR ⊠-decay in 68Ni [5]. Future perspectives aiming at a better understanding of the PDR using the FRaISe facility, in construction at INFN-LNS, will be discussed. A new SiC tagging system, developed in the framework of INFN-Sezione di Catania activities in the SAMOTHRACE ecosystem, will be presented in detail [6-7]. This work has been partially supported by SAMOTHRACE ecosystem [7].

1 C. Agodi, F. Cappuzzello, G. Cardella et al. Eur. Phys. J. Plus 138, 1038 (2023) and references therein
2 A. Bracco et al., Progr. in Particle and Nuclear Physics 106, 360-433 (2019) and references therein
3 D. Savran et al., Progr. in Particle and Nuclear Physics 70, 210-245 (2013)
[4] A. Sorensen et al., Progr. in Particle and Nuclear Physics 134, 104080 (2024) and references therein
[5] N.S. Martorana et al., Physics Letters B 782, 112 116 (2018)
[6] N.S. Martorana et al., Frontiers in Physics, 10 (2022) and references therein
[7] www.samothrace.eu

Theory of supernovae, neutron stars, and neutron star mergers / 51

Equation of State of Dense Matter in Neutron Star Cores

Auteurs: Bao-An Li[1]; Bao-Jun Cai[2]; Zhen Zhang[3]

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Given an Equation of State (EOS) for neutron star (NS) matter, there is a unique mass–radius sequence characterized by a maximum mass Mmax at radius Rmax. We first show analytically that the Mmax and Rmax scale linearly with two different combinations of the NS central pressure and energy density, by dissecting perturbatively the dimensionless Tolman–Oppenheimer–Volkoff (TOV) equations governing NS internal variables. The scaling relations are then verified via 104 widely used and rather diverse phenomenological as well as microscopic NS EOSs with/without considering hadron–quark phase transitions and hyperons, by solving numerically the original TOV equations. The EOS of the densest NS matter allowed before it collapses into a black hole is then obtained. Using the universal Mmax and Rmax scalings and Neutron Star Interior Composition Explorer and XMM-Newton mass–radius observational data for PSR J0740+6620, a very narrow constraining band on the NS central EOS is extracted directly from the data for the first time, without using any specific input EOS model. By similar analysis, we demonstrate that the ratio of pressure to energy density in NSs is generally upper bounded as P/e≤0.374, generalizing the apparent requirement (P/e≤1) set by the principle of special relativity (causality). Finally, the strong gravity in general relativity (GR) is found to play a twofold role in the peaked structure in the speed of sound squared: it compresses NS matter and modifies the pressure/energy density ratio from small values in Newtonian stars showing no s^2 peak to large ones for massive NSs possessing a peak in their s^2 profiles, and eventually takes away the peak in extremely compact/massive NSs approaching the causality limit.

Constraints from heavy-ion collisions at relativistic energies / 52

Strangeness in equation of state studies at high density

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Because of strangeness conservation, strange hadrons are produced in pairs through the so-called associated production. As a result, they have small production cross sections and are also not likely to be destroyed after their production in nuclear collisions. With their relatively large masses, their yields in nuclear collisions at energies below their production thresholds in free space are sensitive to the stiffness of the nuclear equation of state (EOS) at high densities as shown in Ref. 1, where a factor of three difference in the kaon yield is obtained between soft and stiff EOS. This effect had led to the extraction of a soft nuclear EOS from the kaon yield by the KaoS Collaboration from nuclear collisions at subthreshold energies [2,3]. The extension of using subthreshold production of strange hadrons for studying nuclear symmetry energy at high densities was subsequently carried out theoretically for the yield ratios K^0/K^+ [4], Σ^-/Σ^+ [5], and Ξ^-/Ξ^0 [6]. In this talk, I will review these results and discuss the challenges in using strangeness for EOS studies at high densities.

1 J. Aichelin and C. K. Ko, Phys. Rev. Lett. 55, 2661 (1985).
2 F. Laue et al., Phys. Rev. Lett. 82, 1640 (1999); C. Sturm et al., ibid. 86, 39 (2002);
3 C. Fuchs, A. Faessler, E. Zabrodin, and Y. M. Zheng, Phys. Rev. Lett. 86, 1974 (2001).
[4] G. Ferini, M. Colonna, T. Gaitanis, and M. Di Toto, Nucl. Phys. A 762, 147 (2005).
[5] Q. Li, Z. Li, E. Zhao, and R. K. Gupta, Phys. Rev. C 71, 054907 (2005).
[6] G. C. Yong, B. A, Li, Z. G. Xiao, and Z. W. Lin, Phys. Rev. C 106, 024902 (2022).

Nuclear structure, short-range correlations, and clustering from direct reactions / 53

PREX and CREX: Evidence for Strong Isovector Spin-Orbit Interaction

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The recent PREX-2 and CREX data on the model-independent extraction of the charge-weak form factor difference ΔF in Pb208 and Ca48 challenge modern nuclear energy density functionals (EDFs) as well as our present understanding on the neutron skin and nuclear symmetry energy. Within the Skyrme-like EDFs, we demonstrate that the isovector spin-orbit interaction can strongly change the ΔF in Ca48 while it has essentially no influence on the ΔF in Pb208, mainly due to the eight spin-orbit unpaired 1f7/2 neutrons in Ca48. To simultaneously describe PREX-2 and CREX data in 1σ error, we find the strength of isovector spin-orbit interaction should be larger than about four times of that in the conventional Skyrme-like EDFs, implying the neutrons and protons have significantly different spin-orbit interaction. To further reconcile the data on electric dipole polarizability in Pb208 and Ca48, we obtain L≈55 MeV for the slope parameter of the symmetry energy, Δr(Pb208)≈ 0.19 and Δr(Ca48)≈0.12 fm for the neutron skin thickness. The implications of the strong isovector spin-orbit interaction are discussed.

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Probing the neutron skin and nuclear symmetry energy with relativistic isobar collisions

Auteurs: Haojie Xu[1]; Fuqiang Wang[2]

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Neutron structure and skin thickness in nuclei have been traditionally measured by low-energy scatterings where the nuclei are only gently disturbed. Their precision has been limited by theoretical uncertainties in modeling the nuclear force. Here, we propose an unconventional approach to probe the neutron skin by smashing isobar nuclei completely apart at relativistic energies. We demonstrate that the small difference in several observables between isobar collisions, together with state-of-the-art calculations of nuclear structure, can provide an exquisite sensitivity to the poorly constrained neutron density distributions and skin thickness, which can in turn put stringent constraints on the nuclear symmetry energy.

Constraints from heavy-ion collisions at intermediate energies / 55

Pion potentials and its effect on pion production in heavy-ion collisions

Auteur: Natsumi Ikeno[1]

Co-auteurs: Akira Ono ; Che Ming Ko

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To study the pion production in heavy-ion collisions, we developed the transport model 1 which combines the nucleon dynamics obtained by the antisymmetrized molecular dynamics (AMD) model with a newly developed transport code which we call sJAM. In the previous work 1, we treated the collision terms of the $NN \leftrightarrow N\Delta$ and $\Delta \leftrightarrow N\pi$ processes with the rigorous conservation of energy and momentum under the presence of momentum-dependent potentials for the initial and final particles of the process. The potentials affect not only the threshold condition for the process but also the cross section in general as a function of the momenta of the initial particles, which is treated in a natural way. We found that the momentum dependence of the neutron and proton potentials has a significant impact on the $NN \rightarrow N\Delta$ process, and this information is strongly reflected in the charged pion ratio (π^-/π^+). However, the pion potentials were not included in the previous work~1. In the present work, we include the pion potentials in the AMD+sJAM model to study the effect of the pion potential on the pion production in heavy-ion collisions. We find that the pion potentials not only directly affect the $\Delta \rightarrow N\pi$ process and the mean field propagation of pions, but also the Δ production such as $NN \leftrightarrow N\Delta$ due to the change in the Δ spectral function and the Δ decay width. We will discuss how the pion potentials affect the pion observables in the heavy-ion collisions.

1 N. Ikeno and A. Ono, Phys. Rev. C 108, 044601 (2023).

Theory of supernovae, neutron stars, and neutron star mergers / 56

The hyperon puzzle in neutron stars : status and possible solutions.

Auteur: Fiorella Burgio[None]

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In my talk I will review the role of hyperons on the properties of neutron stars, discussing the so-called "hyperon puzzle". I will revise some of the solutions proposed to solve it, and discuss its implications with respect to the most recent measurements of unusually high neutron star masses.

Short presentations / 57

Astrophysics and Nuclear Physics Informed Interactions in Dense Matter: Inclusion of PSR J0437-4715

Auteur: TUHIN MALIK[1]

Co-auteurs: Constança Providência [2]; Veronica Dexheimer [3]

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We investigate how vector-isoscalar and vector-isovector interactions can be determined within the density regime of neutron stars (NSs), while fulfilling nuclear and astrophysics constrains. We make use of the Chiral Mean Field (CMF) model, a SU(3) nonlinear realization of the sigma model within the mean-field approximation, for the first time within a Bayesian analysis framework. We show that neutron-matter χEFT constraints at low density are only satisfied if the vector-isovector mixed interaction term is included, e.g., a $\omega^2\rho^2$ term. We also show the behavior of the model with respect to the conformal limit. We demonstrate that the CMF model is able to predict a value for the parameter d_c related to the trace anomaly and its derivative takes values below 0.2 above four times saturation density within a hadronic version of the model that does not include hyperons or a phase transition to deconfined matter. We compare these effects with results from other (non-chiral) Relativistic Mean Field models to assess how different approaches to incorporating the same physical constraints affect predictions of NS properties and dense matter equations of state. We also include data from the gravitation wave event GW230529 detected by the LIGO-Virgo-Kagra collaboration and the most recent radius measurement of PSR J0437-4715 from the NASA NICER mission. Our analysis reveals that this new NICER measurement leads to an average reduction of approximately ~ 0.1 km radius in the posterior of the NS mass-radius relationship.

Theoretical (microscopic) calculations of neutron rich dense nuclear matter / 58

Microscopic equation of state constraints and Bayesian uncertainty quantification

Auteur: Christian Drischler[1]

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In recent years, significant advances have been made in constraining the dense matter equation of state (EOS) from, e.g., multi-messenger astronomy, chiral effective field theory (EFT), novel experimental campaigns such as PREX-II and CREX, and heavy-ion collisions. However, many key questions remain, especially regarding the composition and EOS of the dense matter in the inner cores of heavy neutron stars.

In this talk, I will review recent advances in microscopic nuclear matter calculations with chiral two- and three-nucleon interactions and Bayesian methods for rigorous uncertainty quantification. Benchmarks of chiral EFT in terms of empirical saturation properties and their implications for the nuclear symmetry energy and density dependence will be discussed. I will also demonstrate the efficacy of Bayesian model mixing (BMM) in combining EOS predictions from chiral EFT at low and perturbative QCD at very high densities to construct globally predictive, microscopic EOS models that cover all densities probed by neutron stars.

Transport model simulations of heavy-ion reactions / 59

Consistent description of clusters and fragments within upgraded transport models

Auteurs: Maria Colonna[1]; Rui Wang[2]; Stefano Burrello[3]

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[2] *INFN - Catania*

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The formation of nuclear clusters, which emerge as many-body correlations at sub-saturation densities in nuclear matter, is essential for constructing a reliable equation of state (EOS). Phenomenological models utilizing energy density functionals (EDFs) provide a convenient approach to account for these bound states of nucleons by introducing clusters as additional degrees of freedom (DOF). In a recent work, we extended these EDF-based models to incorporate recent experimental findings on the existence of nucleon-nucleon short-range correlations at supra-saturation densities by using effective clusters immersed in dense matter as surrogates 1.
In this talk, we propose a novel approach to include light cluster DOF and associated in-medium effects at sub-saturation densities within an upgraded time-dependent framework employing EDFs. Our work represents the first attempt, following a linearized Vlasov approach 2 or a hydrodynamical perspective 3, to describe the formation of intermediate mass frag ments and light clusters within a unified theoretical picture. This formation occurs during the dynamics of out-of-equilibrium processes characteristic of heavy-ion collisions.
The potential to use upgraded transport models to extract valuable information on the EOS, which is also of great interest for modeling astrophysical objects and gravitational wave signals, will be explored and discussed.

References
1 S. Burrello, S. Typel, Eur. Phys. J. A 58, 120 (2022).
2 R. Wang, S. Burrello, M. Colonna, arXiv:2405.02157v1 [nucl-th], accepted as Letter on PRC.
3 S. Burrello, S. Typel, in preparation.

Investigations at existing and future accelerator facilities and detectors / 60

Plans for Symmetry Energy research within the INDRA-FAZIA collaborations

Auteur: Nicolas Leneindre[1]

[1] *Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France*

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The road map for the INDRA & FAZIA collaborations will be presented in this talk, focusing on studies on nuclear symmetry energy and various observables to constraint it. New developements and perspectives will be discussed too.

Transport model simulations of heavy-ion reactions / 61

Understanding of expanding and clustering matter: Cluster correlation and momentum fluctuation in AMD

Auteur: Akira Ono[None]

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In heavy-ion collisions at several hundred MeV/nucleon, a compressed nuclear system is formed to about twice the saturation density and then rapidly expands. It has been a theoretical challenge to extract information about nuclear matter properties such as the EOS of isospin-asymmetric nuclear matter. Since light clusters and heavier fragment nuclei are abundantly produced, they can influence the global collision evolution.

The antisymmetrized molecular dynamics (AMD) model, with an extension for cluster formation in the final state of each NN collision, can reasonably reproduce the overall multiplicities of light clusters such as d, t, 3He and 4He. However, the comparison of the three-dimensional momentum distributions of clusters with the SpiRIT data for collisions at 270 MeV/nucleon has shown that the cluster production is systematically underestimated by AMD around the center of the expanding system. Varying the inmedium NN matrix element does not solve this problem. This suggests some insufficiency of momentum fluctuation.

In this talk, I will present recent advances in the interpretation and treatment of the momentum width inherent in Gaussian wave packets in AMD. In the improved method, the momentum width is activated to appropriately influence the time evolution, by introducing wave packet splitting for nucleons and clusters as the isolation of the wave packet increases due to mean-field propagation. The momentum width is also activated at NN collisions. In nucleon knockout reactions, we have confirmed that this method significantly improves the momentum distribution of the residual nucleus.

In central heavy-ion collisions, the momentum fluctuation significantly increases cluster formation around the center of the system. The remaining deviation of the triton yield in the neutron-rich 132Sn + 124Sn system may indicate an unexpectedly large N/Z ratio in the central region or some other anomaly in triton production.

Constraints from heavy-ion collisions at intermediate energies / 62

Constraints from FOPI and ASY-EOS flow measurements

Auteur: Arnaud Le Fèvre[1]

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The equation-of-state (EoS) of nuclear matter is of fundamental interest and has been the object of intense theoretical efforts since several decades. The interest is boosted by the fact that it is an important ingredient in modelling astrophysical phenomena such as compact stars and core collapse supernovae. A method to approach the nuclear equation-of-state, practiced since the mid-eighties, is the use of heavy-ion collisions over a wide range of incident energies, system sizes and compositions. From FOPI and ASY-EOS experimental data on elliptic flow of neutrons, protons and other light charged particles, one could extract constraints for the EoS of compressed (a-)symmetric nuclear matter up to about 2.5 times saturation density, using transport models. We will address the importance of taking into account momentum dependent interactions in the modelling of nuclear potentials, and of the determination of probed densities. This latter is strongly related with the origin of the elliptic flow that we measure in experiments, an origin explaining its sensitivity on the EoS.

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The search for the nuclear equation of state by transport approaches

Auteur: Joerg Aichelin[1]

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I present the experimental observables which have been identified by present transport approaches as being sensitive to
the potential among nucleons and explicitly to the nuclear equation of state. This is followed by a discussion
which conclusions can be drawn presently and which variables are presently considered as most promising to come to firm conclusions about the different parts of the nucleon-nucleon interactions.

Investigations at existing and future accelerator facilities and detectors / 64

Overview of heavy ion collision program at FRIB

Auteur: Zbigniew Chajecki[1]

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The Facility for Rare Isotope Beams (FRIB) is at the forefront of research into the fundamental properties of nuclear matter, utilizing heavy ion collisions to explore the physics of rare isotopes and the nuclear equation of state. This talk will provide an overview of the heavy ion collision program at FRIB, highlighting its scientific program and key experimental initiatives including detector development. The program's scientific focus includes probing the density dependence of the symmetry energy, which is crucial for understanding the structure and dynamics of neutron stars.

Transport model simulations of heavy-ion reactions / 65

Challenges for correlation measurements for EoS studies at GSI and FRIB energies

Auteur: Giuseppe Verde[1]

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An overview of challenges and perspectives offered by correlation measurements at facilities with beams over E/A=100 MeV will be presented. Focus on observables and possible multi-purpose setups, including strategies for using transport model simulations are key for the advance of our community engaged in the study of nuclear matter under extreme conditions and its implications in the most challenging astrophysical investigations of neutron stars and supernovae explosions. The status of existing femtoscopy and resonance decay data and possible developments will be presented and discussed in view of an international synergy between different groups and institutions.

Transport model simulations of heavy-ion reactions / 66

Equation of state of nuclear matter from collective flows in intermediate energy heavy-ion collisions: an update

Auteur: Dan Cozma[1]

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The equation of state of nuclear matter, momentum dependence of the optical potential and in-medium modification of elastic nucleon-nucleon cross-sections have been previously studied by comparing theoretical predictions for collective flows and stopping observables in intermediate energy heavy-ion collisions to experimental data gathered by the FOPI Collaboration1. The study is extended to include experimental data for neutron-to-hydrogen 2 and neutron-to-charged particles flow ratios 3. The impact on sensitivity of neutron skins, threshold effects and isospin asymmetry dependence of in-medium elastic nucleon-nucleon cross-sections is presented in detail. Nucleonic observables (stopping, directed and elliptic flows) measured recently by the SπRIT Collaboration [4] are also added to the analysis and a comparison with existing studies is discussed.

1. M.D. Cozma, arXiv:2407.16411;
2. P. Russotto et al., Phys. Lett. B 697, 471 (2011);
3. P. Russotto et al., Phys. Rev. C 94, 034608 (2016);
4. C.Y. Tsang et al., Phys. Lett. B 853, 138661 (2024).

Investigations at existing and future accelerator facilities and detectors / 67

Current and future experiments at SAMURAI in RIBF RIKEN

Auteur: Mizuki Kurata-Nishimura[1]

[1] *RIKEN*

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We want to review the findings from the 2016 SpiRIT experiment and provide an update on the experiment's status as of spring 2024. We will also introduce upcoming projects utilizing the SAMURAI magnet at RIBF. Additionally, we will showcase the planned upgrades to the RIBF facilities.

Transport model simulations of heavy-ion reactions / 68

Transport Model Evaluation Project (TMEP): Status and Perspectives

Auteur: Hermann Wolter[1]

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Heavy-ion collisions and their interpretation by transport model simulations can make a significant contribution to the study of the nuclear EOS, complementary to nuclear structure studies, astrophysical observations and microscopic many-body calculations, since they allow to control to a wide extent the thermodynamical conditions and give information on the composition of the system, in particular having access to the important regime of several times saturation density. However, in view of a strong model dependence of the results, the TMEP started from the idea to improve the significance of transport model studies by comparing simulations of different codes under as much as possible identical conditions in box calculations and simulations of real nucleus-nucleus collisions. Codes of the two main families of transport codes, BUU and QMD, and a significant selection of presently used codes were included in the comparisons in several publications in the last years. From the box calculations new and significant lessons for simulations have been derived, particularly on the influence of fluctuations (which differ significantly in BUU and QMD approaches) on many aspects of simulations. Still, in heavy-ion collisions the codes could not be made to converge sufficiently in some cases, relative to the pertinent questions on the EOS, mainly because collisions are open systems where different effects interact and small effects may lead to large final differences. In the future the focus thus will have to shift from convergence to a quantification of the model differences of transport model analyses as a whole. Attempts in this direction with Bayesian model averaging will be discussed. Moreover, as the previous comparisons were largely done in simplified models of the physics of the collision, closer contact to experiments has to be made with more realistic models, including, momentum-dependent potentials of all constituents, studies the sensitivity of observables to the symmetry energy, including the clustering effect, and introducing microscopic input into transport. Finally, these efforts should be seen in the context of other approaches to quantify the uncertainty of EOS studies, either by not limiting the comparisons only the collisions, or by attempting to construct a universal transport code in a modular approach.

Constraints from heavy-ion collisions at relativistic energies / 69

Probing nuclear symmetry energy in high-energy heavy-ion collisions at RHIC and LHC

Auteur: Giuliano Giacalone[1]

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In an ultra-relativistic heavy-ion collision, the geometry of the interaction region is shaped by the (random) positions of the nucleons that populate the colliding nuclei during the ultra-short duration of the collision process. As the created system expands hydrodynamically to the final state, the details of the spatial distributions of these nucleons (clustering, deformations, skin diffuseness) leave specific imprints in the the collective flow of the produced hadrons. Thanks to advanced Bayesian analysis tools, we are today able to extract, with quantified uncertainties, information about the structure of the colliding nuclei from the measured hadron distributions. Recently, we have extracted the neutron skin of the nucleus ^{208}Pb from LHC data, which has lead to the first determination of the slope parameter of the symmetry energy, L, in this context. Similar results will come in future from isobar collisions involving ^{96}Ru and ^{96}Zr nuclei performed at RHIC. In this contribution, I review the basic features of high-energy nuclear collisions that enable us to connect information on nuclear structure to features of the final-state particle spectra. I discuss prospects for refined extractions of the nuclear symmetry energy and other fundamental nuclear properties from high-energy data.

Astrophysical, multi-messenger observations / 70

Exploring Neutron stars with Gravitational waves: current observations and future challenges

Auteur: Lami Suleiman[1]

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Highly dense and isospin asymetric matter is partly out of the reach of nuclear laboratories on Earth but comprises the deepest shells of the highly compact astrophysical objects that are Neutron Stars. An entire field of nuclear astrophysics, which includes multi-messenger astronomy, is devoted to exploring dense matter by observing neutron stars from their birth in core collapse supernovae to their deiths in mergers. A boost to this field recently occured with the construction of several gravitational wave detectors that can observe the ripples of space time orginating from the coalescence of black holes and neutron stars.
In this presentation, we discuss the sources gathered in the recent catalogue GWTC-3 of the first three runs of the LIGO-Virgo-KAGRA collaboration. We shall particularly consider the few merger events involving neutron stars and how the imprint of the star's deformation on the gravitational waveform has taught us about dense matter. We also discuss a very recent event that occured during the first part of the fourth observing run of the LIGO-Virgo-KAGRA collaboration, a merger between a neutron star and a mass-gap black hole, and its impact on our understanding of heavy-element nucleosynthesis.
Finally, we shall discuss what to expect from future observations and the next generation of gravitational wave detectors, the proposed projects of Cosmic Explorer and Einstein Telescope. Particularly, we shall mention some of the challenges we will face in an era of high precision gravitational waves detections.

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Welcome

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Welcome from GANIL direction

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Seminar - The Webb telescope and the exoplanets

On December 25, 2021, the James Webb Space Telescope (JWST), the largest and most complex telescope ever built, was launched from Kourou (Guyana) by an Ariane 5 rocket. Two weeks later, the telescope was fully deployed and by the end of January, it was in orbit around the Lagrange point L2 (1.5 million km from the Earth). Then, the 18 hexagons that constitute the primary mirror were co-phased and the four instruments put into operation. The performances are outstanding and most often better than specified.
In July 2022, scientific observations began. Thanks to its vast collecting area (25 square meters) and its large wavelength coverage (from 0.6 to 28 microns), this NASA flagship mission with the participation of Europe and Canada, has already a considerable impact on many astrophysical fields. In this talk, I will focus on the study of exoplanets. JWST brings a unique way to characterize the atmosphere of exoplanets. After having given an overview of where we stand in terms of exoplanets studies, I will focus on the latest discoveries made with the JWST, especially on rocky exoplanets.

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Concluding remarks

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Status, problems, and perspectives on symmetry energy

Auteur: Pawel Danielewicz[1]

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The status of current constraints on the symmetry energy and generally nuclear equation of state (EoS) from laboratory measurements and astrophysical observations is discussed. Determination of the symmetry energy from data requires knowledge of the EoS of symmetric matter, and the heavy-ion collisions (HIC) are the only means of constraining EoS experimentally at supranormal densities. Improving the constraints requires, on the one hand, a reduction in theoretical inference uncertainties and, on the other, the development of more constraining experimental observables, e.g., by employing Machine-Learning techniques in data analysis. Improving upon direct extraction of the symmetry energy from HIC requires simultaneous constraining of sensitivity to isospin of different transport ingredients, including mean-fields and collision and new particle production rates. Overlap of interests in EoS from the neutron-star (NS) and HIC sides creates novel opportunities for HIC inferences as there is interest from the NS side in the momentum-dependence of interactions and finite-temperature EoS.

Astrophysical, multi-messenger observations / 76

Constraining the EOS and Symmetry Energy with Neutron Star Mergers

Auteur: David Tsang[1]

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Neutron stars are the sites of the densest, most extreme matter in the Universe, and are natural laboratories in which to explore dense matter physics. I will discuss constraints on the equation of state and the nuclear symmetry energy available through current and future multimessenger observations of neutron star mergers, and how these can complement terrestrial collider experiments.

Investigations at existing and future accelerator facilities and detectors / 77

Status of the RAON Facility

Auteur: Taeksu Shin[1]

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The construction of the RAON (Rare Isotope Accelerator complex for ON-line experiments) facility was launched in 2011 as the Rare Isotope Science Project (RISP). The RAON was designed to produce a variety of stable and rare isotope beams to be used for basic science research and applications. The RAON consists of a heavy ion superconducting linear accelerator (SCL2) as the driver for the In-flight Fragmentation (IF) system, a proton cyclotron as the driver for the ISOL (Isotope Separation On-Line) system, and a superconducting linac (SCL3) for the post-acceleration of ISOL beams. The ISOL and IF systems can be operated independently, while the rare isotopes produced by the ISOL system can be injected to the superconducting linac SCL3 and then to the SCL2 for further acceleration to produce even more exotic rare isotopes through a two-step method (ISOL+IF). This combined scheme (ISOLIF) for producing more exotic rare isotopes in sequence is the uniqueness of the RAON facility.

The first phase of the RISP, constructing the superconducting linear accelerator SCL3, cryo-plant systems, an ISOL system with a cyclotron, supporting facilities, buildings, and seven experimental systems is completed. The construction of the superconducting linac SCL2 to deliver a wide range of heavy ion beams, e.g. uranium beams of 200 MeV/u with a beam current of 8.3 pμA will be done as a second phase.

The first beam commissioning of the SCL3 was carried out successfully by accelerating the Argon beam through 22 QWR modules up to 2.5 MeV/u with 34 μA, and then through 32 HWR modules to accelerate Ar beams to 17 MeV/u with 21 μA. The accelerated Ar beams were delivered to the KoBRA (Korea Broad acceptance Recoil Spectrometer and Apparatus) system to produce rare isotopes.

The ISOL system was commissioned by bombarding the SiC target with proton beams to generate radioactive isotopes such as Na and Al. The beam commissioning of other low-energy experimental facilities such as the MMS (Mass Measurement System), CLS (Colinear Laser Spectroscopy), and NDPS (Nuclear Data Production System) are underway. The current status of the RAON facility will be presented.

Theory of supernovae, neutron stars, and neutron star mergers / 78

Equation of state in dense nuclear matter controlled by nuclear data

Auteur: Jerome Margueron[1]

Co-auteurs: Betty Tsang [2]; Elias KHAN [3]; Pawel Danielewicz [4]; Rohit Kumar [5]; william lynch [6]

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I will present two recent analyses of nuclear data, i.e. flow data from heavy ion collision (HIC) and giant monopole resonances (GMR). These data provide constraints to nuclear matter with an equal number of neutrons and protons. To do so, the model for dense nuclear matter equation of state (EoS) is enriched in order to be sensible to properties close to saturation density, i.e. the curvature of the energy per particle represented by the nuclear empirical parameter Ksat, as well as to its properties as the density departs further from saturation density and represented by the skewness parameter Qsat. These two parameters control the density dependence of the EoS for nuclear densities. Employing IQMD to model HIC and a Bayesian approach to confront it to flow data, we find that the EoS is preferred to be soft around saturation density and to stiffen above. In a complementary way, GMR data also prefer soft EoS around saturation density. These recent results advocate for a more systematic use of the Bayesian approach to confront EoS and nuclear data.

Combined analysis of nuclear and astrophysics information, Bayesian approach, and machine learning / 80

The Spirit project

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