International Workshop on Multi-facets of EOS and Clustering

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Experimental study of the symmetry energy from 40,48 Ca+ 40,48 Ca reactions at 35 AMeV

Auteur: Quentin Fable[1]

[1] *L2it, CNRS/IN2P3, France*

Auteur correspondant quentin.fable@l2it.in2p3.fr

We investigated the possibility to probe the symmetry energy term of the nuclear equation of state with isoscaling observables from 40,48 Ca+ 40,48 Ca reactions at 35 AMeV . Data were obtained using the unique coupling of the VAMOS high acceptance spectrometer and the 4π INDRA detector. This required a precise study of the trajectory reconstruction in the spectrometer focal plane along with the development of an event normalization procedure. The spectrometer allowed high resolution measurement of charge, mass and velocity of the cold projectile-like fragment (PLF), while the INDRA detector measured almost all remaining charged particles. The detection of the PLF in coincidence with light charged particles (LCP) allows the reconstruction of the mass, charge and excitation energy of the associated initial quasi-projectile nuclei (QP), as well as the extraction of apparent temperatures. Comparisons with filtered AMD model followed by the the statistical decay code GEMINI++ lead to the conclusion that for such reactions, the reconstruction of the primary source helps to apply the isoscaling method. The resulting experimental symmetry energy term C sym is shown to decrease with increasing excitation energy or increase with increasing charge of the reconstructed QP. This may reflect a density dependence of the nuclear symmetry energy and the effect of surface contribution.

Nuclear Dynamics : from fission to multifragmentation / **4**

Negative heat capacity for hot nuclei: confirmation with formulation from the microcanonical ensemble.

Auteur: Bernard Borderie[1]

[1] *IJCLab Orsay, France*

Auteur correspondant bernard.borderie@ijclab.in2p3.fr

B. Borderie et al. - INDRA Collaboration

By using freeze-out properties of multifragmenting hot nuclei produced in quasi-fusion central 129 Xe+ nat Sn collisions at different bombarding energies (32, 39, 45 and 50 AMeV) which were estimated by means of a simulation based on experimental data collected by the 4π INDRA multidetector, heat capacity in the thermal excitation energy range 4 - 12.5 AMeV was calculated from total kinetic energies and multiplicities at freeze-out. The microcanonical formulation was employed. Negative heat capacity which signs a first order phase transition for finite systems is observed and confirms previous results using a different method.

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Clustering phenomena and multi-particle decay / **5**

Alpha, cluster and 2alpha decays with Energy Density Functional method

Auteurs: Florian Mercier[1]; Jie Zhao[2]; Jean-Paul Ebran[3]; Elias Khan[4]; Tamara Niksic[5]; Dario Vretenar[5]

[1] *IJCLab Orsay, France*

[2] *Center for Circuits and Systems, Peng Cheng Laboratory*

[3] *CEA*

[4] *IJCLab*

[5] *University of Zagreb*

Auteur correspondant florian.mercier@ijclab.in2p3.fr

The use of Energy Density Functional (EDF) method within a relativistic framework showed, this last decades, that it can both describe the bulk properties of nuclei (radii, ground state energy, binding energy, …) [1] as well as clusters formation[2]. The study of cluster structures allow for many applications ranging from α or cluster decay to fission or many different kinds of excitations.

During the last decades, cluster decay and fission have been extensively studied within EDF framework[3] leading to both qualitative and quantitative results in agreement with experiments. Still, α radioactivity had yet to be described within this framework. Last year, its description has been achieved using covariant EDF in mid-mass nuclei ^{108}Xe and ^{104}Te [4] opening the possibility to obtain a unified description of the different radioactivity processes. More recently, the joint description of both α and cluster decays has been performed leading to a more global description of radioactivity processes in a single framework.

These studies also lead to the prediction of a new kind of radioactivity process involving not one but two α particles emitted in opposite directions[5]. The lifetimes associated with this decay mode have been computed for two different nuclei and appear to be of the same order of magnitude than the one of cluster decays that have already been experimentally observed. Hence, if it turns out that this mode exists, it would theoretically be possible to detect it with current technologies.

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Nuclear Dynamics : from fission to multifragmentation / 7

AMD with Fermi motion, clustering and 3 body collisions

Auteur: Roy Wada[1]

[1] *Cyclotron Institute, TAMU, USA*

Auteur correspondant wada@comp.tamu.edu

The antisymmetrized molecular dynamics (AMD)[1] is one of the most successful transport models, applied in intermediate heavy ion collisions. AMD usus a frozen (crystal) concept for the initial nuclei and the Fermi motion is taken into account as an average Fermi energy, T0 ~ 9 MeV/nucleon, in the energy calculation. This brings the stability of the initial nuclei in the time evolution, but the quantum fluctuation is lost. In order to restore the quantum fluctuation during the time evolution of the wave packets, a diffusion process is incorporated as a stochastic process in the 1996 version (AMD/D)[2] and enable to reproduce the experimental multifragmentation events reasonably well. Recently it is found that the Fermi motion is also important in the nucleon-nucleon collision process and AMD/D was not able to reproduce the experimental high energy proton yields properly. We incorporated the Fermi motion in the collision term (AMD/D-FM)[3] and successfully reproduced the experimental results measured with the MEDIA detector array[4]. However, when the incident energy is increased around 100 A MeV region, AMD/D-FM also failed to reproduce the experimental high energy proton yields measured at Bevalac in 1980's[5]. Following the pioneer works of Banasera et al. in 1990's[6,7], a 3 body collision term is incorporated in AMD/D-FM, called AMD/D-FM(3N)[8], which can reproduce the experimental high energy proton and neutron data at the incident energies up to 300 A MeV. Currently we are working on the proton and cluster productions with AMDs in 12C+1H at 95 A MeV measured at GANIL[9], incorporating the Fermi motion and clustering. We found that the inverse 12C+1H collisions provide a unique test bench for the Fermi motion and clustering processes in the particle emissions. I will summarize all these recent results in the talk.

Nuclear EoS and Astrophysics / 8

The effect of the energy functional on the pasta-phase properties of catalysed neutron stars

Auteur: Hoa Dinh Thi[1]

Co-auteurs: Anthea Francesca FANTINA [2]; Francesca Gulminelli [3]

[1] *GANIL, France*

[2] *{CNRS}UPR3266*

[3] *LPC/Ensicaen*

Auteur correspondant dinh@lpccaen.in2p3.fr

Nuclear pasta, which is an inhomogeneous distribution of nuclear matter characterized by non-spherical clustered structures, is expected to occur in a narrow spatial region at the bottom of the inner crust of neutron stars, but the width of the pasta layer is strongly model dependent. In the framework of a compressible liquid-drop model, we use Bayesian inference to analyze the constraints on the sub-saturation energy functional and surface tension imposed by both ab-initio chiral perturbation theory calculations and experimental measurements of nuclear masses. The posterior models are used to obtain general predictions for the crust-pasta and pasta-core transition with controlled uncertainties. A correlation study allows extracting the most influential parameters for the calculation of the pasta phases. The important role of high-order empirical parameters and the surface tension is underlined.

Clustering phenomena and multi-particle decay / 9

Study of the ^{12}C Hoyle state produced by fragmentation

Auteurs: Alex Rebillard-Soulié[1]; Diego Gruyer[2]; Giuseppe Verde[3]

[1] *LPC Caen, France*

[2] *LPC Caen*

[3] *L2I Toulouse, CNRS/IN2P3*

Auteur correspondant rebillard@lpccaen.in2p3.fr

The second 0^+ excited state of ^{12}C, also known as the Hoyle state, has a key role in the synthesis of the elements. It is also believed to possess a rather unusual structure where the dominant degrees of freedom are those of α clusters rather than nucleons [1]. Whereas the understanding of the properties of this state has been the focus of a major experimental activity, its non-radiative decay mode is still debated (i.e. direct decay into three α particles or sequential decay with formation of an intermediate ^{8}Be). Many direct-reaction experiments report a 3α direct decay branching ratio compatible with zero [1-5]. On the other hand, Raduta et al. [6] published in 2011 a large value of 17% for 3α direct decay. In this latter case, excited ^{12}C were produced in the ^{40}Ca+ ^{12}C at 25 MeV/A fragmentation reaction.

In this talk, I will present a new measurement of the direct decay branching ratio of the ^{12}C Hoyle state produced during fragmentation reactions (^{20}Ne+^{12}C at 25 MeV/A). Experimental data were acquired during the FAZIACOR experiment performed at LNS Catania. Excited ^{12}C have been reconstructed using the invariant mass method while the observable proposed in [5] was used to discriminate the different decay modes. The background was evaluated using the ponderated "event mixing" method. The direct decay branching ratio was finally obtained by comparing the experimental reconstructions with a complete simulation of the different decay modes, taking carefully into account the detector response.

We finally obtain a direct decay branching ratio compatible with zero, which is consistent with most of the previous results [1-5] but seems to invalidate the 17% direct decay obtained in [6].

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Isospin Effects and EoS in nuclear reactions / 10

Probing nuclear isospin equilibration : the INDRA-FAZIA experiment in GANIL

Auteur: Joël Quicray[1]

[1] *LPC Caen, France*

Auteur correspondant quicray@lpccaen.in2p3.fr

J. Quicray
On behalf of the INDRA and FAZIA collaborations

Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France

The study of fragmentation reactions produced in heavy-ion collisions has permitted major advances in the understanding of the dynamics and thermodynamics of nuclear matter [1, 2] and is still one of the most promising tools to constrain its equation of state. This fundamental feature in nuclear physics is also a crucial ingredient in the understanding of various astrophysical objects or phenomena: dynamics of supernovae explosion and structure of the remanent neutron star, or interpretation of signals coming from neutron star merger [3, 4]. Up to now, a crucial ingredient was missing in most fragmentation experiments: the isotopic composition of reaction products, it was only accessible for the lightest fragments with existing multi-detectors such as INDRA in GANIL. In this context, the FAZIA collaboration has developed a new generation detector [7, 8] able to measure the charge and mass of fragments up to Z=25 over a broad angular and
energy range. Results of first experiments with FAZIA in stand alone mode have been published by the collaboration on the isotopic distribution of measured fragments [5, 6]. Now, twelve FAZIA modules are mounted in GANIL to replace the forward part of INDRA. This INDRA-FAZIA coupling is one of the
most powerful detector to constrain the nuclear equation of state asymmetry term. The identification quality and large angular coverage also allow to investigate nuclear collision dynamics, clusterization process at low density, and light nuclei structure and decay modes.

The first INDRA-FAZIA experiment at GANIL was performed in 2019. The main goal is to study the isospin tranport properties of nuclear matter by measuring the evolution of the N/Z equilibration between projectile and target of different initial isospin contents as a function of the collision centrality. In this contribution, I will present the context and first results of this experiment.

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Clustering phenomena and multi-particle decay / 11

Population and decay of states of 12C

Auteur: Giuseppe Cardella[1]

[1] *INFN Sez. Catania, Italy*

Auteur correspondant cardella@ct.infn.it

Population and decay of states of 12C
G. Cardella(1), A. Bonasera(2)(3), N.S. Martorana(2)(4), L. Acosta(1)(5), E. De Filippo(1), E. Geraci(1)(4), B. Gnoffo(1)(4), C. Guazzoni(6), L.Lo Monaco(4), C. Maiolino(2), A. Pagano(1), E.V. Pagano(2), M. Papa(1), S. Pirrone(1), G. Politi(1)(4), F. Rizzo(2)(4), P. Russotto(2), D. V. Sicari(6), and M. Trimarchi(1)(7)
1 INFN sezione di Catania, Italy
2INFN-LNS, Italy
3Cyclotron Institute Texas A&M University, college station, Texas, USA
4Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Italy
5Instituto de Física, Universidad Nacional Autónoma de México
6 INFN Sez. Milano e Politecnico Milano
7 Dipartimento di Scienze MIFT, Università di Messina, Italy

By using the CHIMERA detector, we have measured the alpha andgamma decay width of excited states of 12C important for the carbon production in astrophysical environments. Gamma rays were detected in CsI stages of the CHIMERA (Si-CsI) telescopes. Inelastically scattered beam particles, carbon recoils and alpha-particles from the decay of excited states were detected and identified with DE_E and Time of flight methods. In the same experiment, we directly compared all decay modes of the excited levels, so decreasing systematic errors. We have checked the efficiency for gamma-ray decay measurement by well-known levels, such as the 15.1 and 12.7 MeV obtaining a good agreement between observations and expectations. With the simultaneous measurement of scattered beam, recoiling carbon and decay gamma-rays we reduced considerably the background of the measurement. We observed for the first time in a direct way the gamma-ray decay of the 9.64 MeV level, with a signal to noise ratio around 2 with a decay probability of only 5.5x10-5[1]; the most recent indirect observation of this decay mode [2] obtained a similar result but with a much worse signal to noise ratio. The observed decay width is more than one order of magnitude larger than the expected upper limits reported in literature from previous measurements [3] with a very large background. Evidently, our result has a significant consequence on the carbon production rate, for instance in supernova explosions. A gamma-ray decay width larger than previous observations was measured also for the Hoyle state. In addition, we investigated on the recently proposed population of an Efimov state at 7.458 MeV [4], as a possible alternative explanation for the observed large decay width. The investigation was done by an accurate analysis of the alpha decay width of the region near the Hoyle state. Preliminary results will be shown.
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Nuclear EoS and Astrophysics / 12

Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions

Auteur: Arnaud Le Fèvre[1]

Co-auteurs: Sabrina Huth [2]; Peter T. H. Pang [3]; Ingo Tews [4]; Tim Dietrich [5]; Achim Schwenk [6]; Wolfgang Trautmann [7]; Kshitij Agarwal [8]; Mattia Bulla [9]; Michael W. Coughlin [10]; Van Den Broeck Chris [11]

[1] *GSI, Darmstadt, Germany*

[2] *Technische Universität Darmstadt, Germany*

[3] *Nikhef, The Netherlands*

[4] *Theoretical Division, Los Alamos National Laboratory, USA*

[5] *Institut für Physik und Astronomie, Universität Potsdam, Germany*

[6] *ExtreMe Matter Institute, GSI Helmholtzzentrum, Darmstadt*

[7] *GSI Helmholtzzentrum Darmstadt, Germany*

[8] *Physikalisches Institut, Eberhard Karls Universität Tübingen, Germany*

[9] *Stockholm University, Sweden*

[10] *University of Minnesota, Minneapolis, USA*

[11] *Utrecht University, The Netherlands*

Auteur correspondant a.lefevre@gsi.de

Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear densities. However, our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, dense matter is not only probed in astrophysical observations, but also in terrestrial heavy-ion collision experiments. In this work, we use Bayesian inference to combine data from astrophysical multi-messenger observations of neutron stars and from heavy-ion collisions of gold nuclei at relativistic energies with microscopic nuclear theory calculations to improve our understanding of dense matter. We find that the inclusion of heavy-ion collision data indicates an increase in the pressure in dense matter relative to previous analyses, shifting neutron-star radii towards larger values, consistent with recent NICER observations. Our findings show that constraints from heavy-ion collision experiments show a remarkable consistency with multi-messenger observations and provide complementary information on nuclear matter at intermediate densities. This work combines nuclear theory, nuclear experiment, and astrophysical observations, and shows how joint analyses can shed light on the properties of neutron-rich supranuclear matter over the density range probed in neutron stars.

Isospin Effects and EoS in nuclear reactions / 14

Status of data analysis and preliminary results of the CHIFAR experiment

Auteur: Paolo Russotto[1]

[1] *INFN-LNS Catania, Italy*

Auteur correspondant russotto@lns.infn.it

The CHIFAR experiment [1] was carried out at LNS in November 2019. Reactions between beams of 124Sn,124Xe and 112Sn, accelerated at 20 AMeV by the CS, and targets of 64Ni, 64Zn and 58Ni were studied by using the CHIMERA multi-detector [2] coupled to 10 telescopes of the FARCOS array [3]. The ten FARCOS telescopes, grouped in 5 couples, were arranged in a ring-like configuration covering about ¾ of the 2\pi azimuthal range at polar angles, in the laboratory, between 16 and 30 deg. Main topics of the experiment are the competition between reaction mechanisms and the Intermediate Mass Fragment production phenomenon, aiming to extend towards the low energy regime the studies performed in the REVERSE and InKiIsSy experiments, carried out at beam energy of 35 AMeV [4]. Status of data analysis and preliminary results will be presented.

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New Experimental Tools, Detection Techniques and Facilities / 15

Recent results on the construction of a new correlator for neutrons and charged particles

Auteur: Emanuele Vincenzo Pagano[1]

Co-auteurs: giuseppe cardella [2]; Enrico De Filippo [3]; Elena Geraci [4]; Brunilde Gnoffo [5]; Chiara Guazzoni [6]; Concettina Maiolino [7]; Nunzia Simona Martorana [8]; Angelo Pagano [9]; Sara Pirrone [10]; Giuseppe POLITI [11]; Fabio Risitano [12]; Francesca Rizzo [13]; Paolo Russotto [14]; Marina Trimarchi [15]

[1] *INFN - LNS Catania, Italy*

[2] *infn sezione di catania*

[3] *INFN Catania, Italy*

[4] *INFN, Sezione di Catania & Dipartimento di Fisica ed Astronomia, Università di Catania,*

[5] *INFN, Sezione di Catania, & Dipartimento di Fisica ed Astronomia, Università di Catania,*

[6] *Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and INFN Sezione di Milano*

[7] *LNS-INFN*

[8] *Dipartimento di Fisica e Astronomia "Ettore Majorana", Università degli Studi di Catania and INFN-LNS, Catania, Italy*

[9] *INFN, Sezione di Catania*

[10] *INFN Sezione di Catania*

[11] *Dipartimento di Fisica e Astronomia - Università di Catania - ITALY*

[12] *Università degli Studi di Messina*

[13] *INFN, Laboratori Nazionali del Sud, Dipartimento di Fisica ed Astronomia, Università di Catania*

[14] *INFN-LNS*

[15] *INFN, Sezione di Catania, Dipartimento di Scienze MIFT, Università di Messina*

Auteur correspondant epagano@lns.infn.it

With the advent of new facilities for radioactive ion beams mainly rich in neutrons, like SPES @ LNL, FRAISE @ LNS and FAIR @ GSI just to give some examples, the detection of neutrons, in conjunction with charged particles, in Heavy on collisions with radioactive beams becomes mandatory. Neutron detection requires both high angular and energy resolutions. Consequently, the construction of new detection systems suitable for these experimental purposes becomes an important goal. The

contribution includes two correlated sections:
the first section presents, the results of recent tests performed using a new plastic material the EJ276 both in the "green-shifted" and in the ordinary version, coupled with PMT and Si-PMT will be shown. These experimental works aim at the construction of a prototype of a detector for neutrons and charged particles with high angular and energy resolutions.
The second section discusses, the recent results about FARCOS (Femtoscope Array for COrrelation and Spectroscopy) used in the CHIFAR experiment will be discussed. The experiment was performed at LNS at the end of 2019. FARCOS was coupled with CHIMERA in order to study the neutron rich system 124Sn+64Ni, the neutron poor one 112Sn+58Ni and, in addition, the 124Xe+64Zn system isobaric to the neutron rich one, but with the same isospin of the neutron poor, at the bombarding energy of 20 MeV/u.

New Experimental Tools, Detection Techniques and Facilities / 16

THE NEW FRAGMENT IN-FLIGHT SEPARATOR AT INFN-LNS

Auteur: Nunzia Simona Martorana[1]

[1] *Dipartimento di Fisica e Astronomia "Ettore Majorana", Università degli Studi di Catania and INFN-LNS, Catania, Italy*

Auteur correspondant martorana@lns.infn.it

N.S. Martorana [1,2], C. Altana[2], A. Amato [2], L. Calabretta [3,2], G. Cardella [4], A. Caruso [2], L. Cosentino [2], M. Costa [2], E. De Filippo [4], G. De Luca [2], E. Geraci [1,4], B. Gnoffo [1,4], C. Guazzoni [5], L. Lo Monaco [1], C. Maiolino [2], E.V. Pagano [2], S. Pirrone [4], G. Politi [1,4], S. Pulvirenti [2], F. Risitano [6,4], F. Rizzo [1,2], A.D. Russo [2], P. Russotto [2], D. Santonocito [2], A. Trifir\'o[6,4], M. Trimarchi [6,4], S. Tudisco [2], G. Vecchio [2]

[1] Dipartimento di Fisica e Astronomia Ettore Majorana, Universit\'a degli Studi di Catania, Italy
[2] INFN-LNS, Catania, Italy
[3] INFN-LNL, Legnaro, Italy
[4] INFN-Sezione di Catania, Italy
[5] DEIB Politecnico Milano and INFN Sez. Milano
[6] Dipartimento MIFT, Universit\'a di Messina, Italy

Since 2001, the In-Flight Fragmentation method allows the production of Radioactive Ions Beams (RIBs) at Laboratori Nazionali del Sud of INFN (INFN-LNS) [1-3]. An ambitious and massive upgrade project of the k800 Superconducting Cyclotron (POTLNS) is in progress at INFN-LNS. One of the goals of the upgrade is to deliver light and medium masses nuclei with a power up to $\approx$ 10 kW. This project opens further perspectives to produce RIBs. A future dedicated facility of a new fragment separator FRAISE (Fragment In-flight Separator) is on the way, to exploit the primary beams, with a power of $\approx$ 3-4 kW, for the production of high-intensity and high-quality RIBs [1-3]. The high beam intensity achieved with FRAISE requires the use of diagnostics and tagging systems able to operate in a strong radioactive environment and in a wide intensity range. For this reason, we are investigating the possibility to use an array of detectors based on the SiC technology. In this framework, an intense R&D program has been started with the aim to develop the FRAISE facility, as well as a new diagnostics system and a new tagging device. The latter will be especially useful for the CHIMERA multidetector beam line. In this contribution, we report the status and the perspectives of the FRAISE facility as well as the status of the diagnostics and tagging systems.

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Nuclear Dynamics : from fission to multifragmentation / 17

Probing the nucleon effective mass with n/p ratios using Bayesian analysis

Auteur: Chi-En Teh[1]

Co-auteur: Betty Tsang [2]

[1] *Michigan State University, USA*

[2] *FRIB, MSU*

Auteur correspondant teh@frib.msu.edu

Abstract: In this study, we analyze the experimental data from heavy-ion collision (HIC) using 40Ca and 48Ca beams at 140 MeV/u impinging on 58Ni and 64Ni targets. The experimental set up includes a charged particle array HiRA10 and the neutron wall array, LANA. From the charged particles, we construct coalescence invariant ratios of pseudo-neutrons and protons as a function of transverse momentum. The data is compared with nuclear transport model predictions using Bayesian analysis technique to infer the correlations of nucleon effective masses.

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Isospin Effects and EoS in nuclear reactions / 18

Isoscaling effect with Z=1 and 2 particles in Sn+Sn at 270 AMeV

Auteur: Jung Woo Lee[1]

[1] *Korea University, South Korea*

Auteur correspondant ejungwoo@korea.ac.kr

Isoscaling effect with Z=1 and 2 particles in Sn+Sn at 270 AMeV

J. W. Lee for SπRIT collaboration
Korea University, Seoul, Korea

The mechanism of the fragmentation in heavy ion collision is studied with particle yields of light nuclei. In the thermal equilibrium view, the primary fragment yield can be predicted using the partition function of each fragment. However, the fragments go through the secondary decays before they are detected. The effects of the secondary decay are largely canceled in the ratios of particle yields between the two systems with similar size and temperature. These ratios of the particle yields show the exponential relation in neutron and proton number, which is known as isoscaling. We explore this phenomenon in the neutron rich ^{132}Sn+^{124}Sn and neutron deficient ^{108}Sn+^{112}Sn systems. The radioactive Sn isotopes at 270 AMeV were produced from the Radioactive Isotope Beam Factory (RIBF) at RIKEN, and the particles were measured with the SπRIT Time Projection Chamber. At this energy, the light particles with $Z \leq 3$ and the pions are well identified. In this presentation, Z =1 and 2 particles are used to explore the isoscaling properties, and the experimental data are compared to the Statistical Multifragmentation Model (SMM) and Antisymmetrized Molecular Dynamics (AMD) calculations.

This work is partly supported by U.S. Department of Energy (Office of Science) under Grant Nos. DE-SC0014530, the Japanese MEXT, Japan KAKENHI (Grant-in-Aid for Scientific Research on Innovative Areas) Grant No. 24105004 and by the National Research Foundation of Korea (NRF) under grant No. 2018R1A5A1025563.

Isospin Effects and EoS in nuclear reactions / 20

Understanding isospin transport ratio: influence of fast emissions and statistical de-excitation

Auteur: Alberto Camaiani[1]

[1] *IKS - KU Leuven, Belgium*

Auteur correspondant alberto.camaiani@kuleuven.be

Isospin transport ratio is a powerful method to estimate the neutron-proton (n-p) equilibration in heavy-ion collisions, and extensively used to obtain information on the asy-stiffness of the nuclear Equation of State. In fact such a ratio is expected to bypass any perturbations introducing a linear transformation of the chosen observable. In particular, it is supposed to overcome contributions due to emission, either of dynamical or statistical nature, from the primary fragments formed during the collisions. In this talk we explore the validity of this assumption, looking at the quasi-projectile n-p ratio (N/Z) in peripheral and semi-peripheral events for Ca+Ca reactions at 35 MeV/nucleon, simulated via the Antisymmetrized Molecular Dynamics transport model, coupled to different statistical decay codes. The investigation has shown that both the statistical de-excitation of primary fragments and the "fast dynamical"emissions can influence the observed n-p equilibration via isospin transport ratio, mainly in two distinctive ranges of centrality.

Nuclear EoS and Astrophysics / 21

Towards a global and multi-purpose EoS: quasi-clusters for an explicit treatment of short-range correlations

Auteurs: Stefano Burrello[1]; Stefan Typel[1]

[1] *Technische Universitat Darmstadt, Fachbereich Physik, Institut fur Kernphysik, Darmstadt, Germany*

Auteur correspondant burrello@lns.infn.it

The formation of nuclear clusters constitutes an essential feature for the construction of global equation-of-state (EoS) tables. They emerge as many-body correlations, which can be attributed to the nucleon-nucleon (NN) interaction, and exist at sub-saturation densities in nuclear matter. Phenomenological models that make use of energy density functionals (EDFs) offer a convenient approach to account for the presence of these bound states of nucleons when clusters are introduced as additional degrees of freedom. However, these models are constructed in such a way that clusters dissolve when the density approaches the nuclear saturation density, so that only nucleons survive as independent quasi-particles at higher densities. These models reveal thus inconsistencies with recent findings that evidence the existence of sizeable NN short-range correlations (SRCs) even at a larger density, in a regime where the cluster dissolution is usually predicted. It would be advisable to include these features to improve EoS models. In our work, we propose a novel approach which allows, within the EDF framework, for an explicit treatment of SRCs at supra-saturation densities, by using effective clusters immersed in dense matter as a surrogate for correlations. Our idea is to embed the SRCs within generalized relativistic energy density functionals through the introduction of suitable in-medium modifications of the cluster properties. As a first exploratory step, the example of a quasi-deuteron in a relativistic mean-field model with density dependent couplings is currently explored. In contrast to previous studies, a relativistic deuteron wave functions is introduced with an effective in-medium interaction that consistently describes the cluster as well as characteristic properties of nuclear matter.
Implications in the widest scope of astrophysical applications are envisaged and the impact of these studies for general aspects of reactions dynamics, such as the clustering processes emerging in heavy-ion collisions will be also discussed.

Nuclear Dynamics : from fission to multifragmentation / 22

Comparison of heavy ion transport simulations for mean-field dynamics

Auteur: Maria Colonna[1]

[1] *INFN-LNS Catania, Italy*

Auteur correspondant colonna@lns.infn.it

Within the transport model evaluation project (TMEP collaboration) of simulations for heavy-ion collisions, the mean-field dynamics of local density fluctuations is examined in several transport models widely employed to describe nuclear reactions.

The results of transport codes belonging to two families (BUU-like and QMD-like) are compared among each other and to exact calculations. For BUU-like codes, employing the test particle method, the results depend on the combination of the number of test particles and the spread of the profile functions that weight integration over space. These parameters can be properly adapted to give a good reproduction of analytical results of the mean-field dynamics.

QMD-like codes, using molecular dynamics methods, are characterized by large damping effects, attributable to the fluctuations inherent in their phase-space representation. Moreover, for a given nuclear effective interaction, they generally lead to slower mean-field response, as compared to BUU-like codes [1].

The significance of these results for the description of heavy-ion collisions is discussed. In particular, a proper reproduction of the mean-field dynamics is instrumental to extract reliable information on nuclear EoS features from the study of reaction mechanisms at Fermi energies.

[1] M.Colonna et al., Phys. Rev. C 104, 024603 (2021).

Isospin Effects and EoS in nuclear reactions / 23

Isospin influence on the thermal characteristics in the reactions 78,86Kr+ 40,48Ca at 10 AMeV

Auteur: Brunilde Gnoffo[1]

[1] *Univ. Catania and INFN Sez. Catania, Italy*

Auteur correspondant brunilde.gnoffo@ct.infn.it

B. Gnoffo1,2, S. Pirrone2, G. Politi1,2, L. Acosta2,3, G. Cardella2, E. De Filippo2, E. Geraci1,2, L. Lo Monaco1, C. Maiolino4, N.S. Martorana1,4, A. Pagano2, E.V. Pagano4, M. Papa2, F. Risitano2,5, F. Rizzo1,4, P. Russotto4 and M. Trimarchi2,5

1) Dipartimento di Fisica e Astronomia E. Majorana, Università di Catania, Italy
2) INFN-Sezione di Catania, Italy
3) Instituto de Fisica, Universidad Nacional Autònoma de México
4) INFN-LNS, Catania Italy
5) Dipartimento di Scienze MIFT, Univ. di Messina, Messina, Italy

The features of alpha particles, emitted in coincidence with Evaporation Residues, produced in the reactions 78Kr + 40Ca and 86Kr + 48Ca at 10 AMeV, have been investigated by using the high capabilities of 4π CHIMERA multidetector.
The thermal evaporation from compound nucleus has been studied within the thermometric method, based on the kinematic approach.
The data analyses show the independence of the energy spectra of evaporated alpha particles from the emission angle in the frame of centre mass and a Maxwellian shape, as it is expected in the case

of emission by an equilibrated source. These characteristics have been confirmed, from the comparison with the theoretical prediction of the statistical code GEMINI++.
The values of the temperature, for both systems, have been extracted from these spectra.
Higher temperature has been found for the system with higher neutron enrichment, suggesting that this thermal characteristic is sensitive to the N/Z ratio.

Nuclear EoS and Astrophysics / 24

Machine learning at the nexus of EoS and astrophysics

Auteur: Thomas Chen[1]

[1] *Association for Computing Machinery, USA*

Auteur correspondant thomaschen7@acm.org

In this review, we seek to synthesize the current literature in terms of works that harness machine learning for the understanding of the nuclear EoS in astrophysics. Furthermore, we propose future areas of work at this exciting interdisciplinary nexus. Model types and approaches include regression, clustering, decision trees, ensemble models, and neural networks (computer vision). There are, however, many challenges in this area, including the gathering of large quantities of data for training, in addition to the interpretability of models. We seek to call for more astrophysicists to incorporate machine learning techniques in their work, for they can yield results that would be impossible to obtain using conventional methods.

Nuclear Dynamics : from fission to multifragmentation / 25

Collective and dissipative effects in a common microscopic dynamical description

Auteur: Hung Dinh Viet[1]

Co-auteur: Paolo Napolitani [2]

[1] *IJCLab Orsay, France*

[2] *IPN Orsay*

Auteur correspondant hung.dinh-viet@universite-paris-saclay.fr

Depending on the energy regime, the dynamics of heavy-ion collisions reveals a variety of different mechanisms which are attributed to the combination of collective and dissipative effects.
Whereas at low and high energies only one of the two contributions tends to prevail, the description of Fermi-to-intermediate energy regimes imposes to address the interplay between collective and chaotic processes.
Semiclassical approaches have been successful in describing chaotic regimes at Fermi-energies but they gradually lose precision when extending to collective behaviours and in general when low-energy features becomes more determinant in the dynamics.
To improve on this description, we propose a theoretical approach starting from the TDHF scheme.
A multiple-ensemble representation has been worked out in order to give a simplified solution to handle the evolution in time and to introduce beyond-mean-field extensions and stochastic contributions.
In particular, we can treat collisional correlations and large-amplitude fluctuations in order to address clusterisation processes, which characterise the out-of-equilibrium dynamics of dissipative heavy-ion collisions.
Selected applications to Ar+Ni and Ca+Ca reactions at Fermi-energies will be addressed.

Isospin Effects and EoS in nuclear reactions / 26

Constraints on the symmetry energy at supra-saturation density from Pion Spectral Ratios

Auteur: William Lynch[1]

[1] *NSCL/FRIB Dept. of Physics and Astronomy Michigan State Univ., USA*

Auteur correspondant lynch@nscl.msu.edu

Pion spectral ratios and double ratios are measured for neutron rich 132Sn+124Sn and neutron deficient 108Sn+112Sn collisions. Both pi-/Pi+ single spectral ratios for the two systems and double ratios obtained by combining both systems can be described by a dcQMD calculations. These comparisons provide a correlated constraint on L and on the neutron-proton effect mass difference. This represents a step forward towards constraining the symmetry energy at supra-saturation densities with pion production. Future steps to better constrain the symmetry energy at supra-saturation densities will be discussed.

Nuclear Dynamics : from fission to multifragmentation / 27

Interplay between surface and volume instabilities in heavy-ion collisions examined within mean-field extensions

Auteurs: Paolo Napolitani[1]; Hung Dinh Viet[2]

[1] *IJCLab Orsay, France*

[2] *IJCLab, Université Paris-Saclay*

Auteur correspondant napolita@ipno.in2p3.fr

In the transition from nuclear matter to finite nuclei, complex finite-size effects which characterise open systems arise, in relation with either the nuclear surface or the bulk. In addition, the non-equilibrium character of the process, typical of violent heavy-ion collisions (from Fermi energy to the intermediate-energy domain) adds up as well. The resulting dynamics is the combination of surface and volume unstable modes which trigger large-amplitude fluctuations. As a result, a rich variety of fragmentation patterns may arise, ranging from collimated streams of nuclear clusters to the split of stretched nuclear complex into few large fragments. They imply different conditions of density and surface tension, and result in different chronologies. Such phenomenology has been observed in experiments, but it is often difficult to recognise and disentangle the underlying types of instabilities.

To draw some example, selected processes, related to extremely deformed nuclear systems produced below and above Fermi energy, will be followed microscopically from the collision to the rupture or disintegration into fragments and clusters, within extended mean-field approaches.

New Experimental Tools, Detection Techniques and Facilities / 28

Impact parameter determination using Machine learning algorithms

Auteur: Chun Yuen Tsang[1]

[1] *NSCL, Michigan State University, USA*

Auteur correspondant tsangc@nscl.msu.edu

Determination of impact parameter is a challenge for experimentalists because it cannot be measured directly. Using transport model simulations, it has been demonstrated that machine learning algorithms can infer impact parameter from experimental observables. However, unlike simulations, detection limitations such as geometric efficiencies and energy thresholds of the detector may affect the ability of machine learning to infer impact parameters. In this talk, we will discuss the impact parameter determination using machine learning in the collisions of 132Sn + 124Sn system at 270 MeV/u using charged particles detected by the SpiRIT Time Projection Chamber. We will also discuss how we validate that the impact parameters determined from machine learning is indeed more accurate than that obtained by various experimental observables.

Nuclear Dynamics : from fission to multifragmentation / 29

Density evaluation in neck fragmentation at the Fermi energies

Auteurs: Angelo Pagano[1]; Enrico De Filippo[2]; Giuseppe Cardella[2]; Elena Geraci[3]; B. Gnoffo[4]; C. Maiolino[5]; N.S. Martorana[6]; E.V. Pagano[5]; M. Papa[7]; Sara Pirrone[7]; Giuseppe Politi[8]; F. Rizzo[9]; Paolo Russotto[5]; M. Trimarchi[10]

[1] *INFN Sez. Catania, Italy*

[2] *INFN Sez. di Catania, Italy*

[3] *Dipartimento di Fisica e Astronomia E. Majorana, Universita di Catania, Italy and INFN SeZ. di Catania, Italy*

[4] *ipartimento di Fisica e Astronomia E. Majorana, Università di Catania, Italy and INFN sezione di Catania, Italyd*

[5] *INFN-LNS, Catania Italy*

[6] *Dipartimento di Fisica e Astronomia E. Majorana, Università di Catania, ItalIy and INFN-LNS, Catania Italyy and*

[7] *INFN sezione di Catania, Italy*

[8] *Dipartimento di Fisica e Astronomia E. Majorana, Università di Catania, Italy and INFN sezione di Catania, Italy*

[9] *Dipartimento di Fisica e Astronomia E. Majorana, Università di Catania, Italy and INFN-LNS, Catania Italy*

[10] *Dipartimento di Scienze MIFT, Univ. di Messina, Messina, Italy and INFN sezione di Catania, Italy*

Auteur correspondant angelo.pagano@ct.infn.it

Density determinations for neck fragmentation (ternary reactions) has been shown [1] for the reaction 124Sn + 64Ni at 35 AMeV, as investigated by using the CHIMERA multi-detector [2]. The analysis is now applied to the system 112Sn + 58Ni and the reactions induced by 124Xe on 64Zn and 64Ni targets at the same incident energy. In these last cases the two systems differ only for the target atomic number Z and, consequently, for the isospin N/Z ratio [3]. This permits to check further the sensitivity of the method for density determination and to evaluate its dependence on N/Z of the reactions products.

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[3] P. Russotto et al., Eur. Phys. J. A56, 12 (2020)

Clustering phenomena and multi-particle decay / 30

Status of the CLIR experiment at LNS

Auteur: Fabio Risitano[1]

[1] *Univ. Messina and INFN Sez. Catania, Italy*

Auteur correspondant farisitano@unime.it

F. Risitano 1,2,* , L. Acosta 1,3 , G. Cardella 1 , E. De Filippo 1 , D. Dell'Aquila 4,5 , F. Favela 1,3 , E. Geraci 1,6 , B. Gnoffo 1,6 , I. Lombardo 1 , C. Maiolino 5 , N.S. Martorana 5,6 , A. Pagano 1 , E.V. Pagano 5 , M. Papa 1 , S. Pirrone 1 , G. Politi 1,6 , F. Rizzo 5,6 , P. Russotto 5 , A. Trifirò 1,2 , M. Trimarch i1,2

1) INFN-Sezione di Catania, Italy
2) Dipartimento MIFT, Università di Messina, Italy
3) Instituto de Física, Universidad Nacional Autónoma de México, Mexico
4) Dipartimento di Chimica e Farmacia, Università di Sassari, Sassari, Italy
5) INFN –LNS, Catania, Italy
6) Dipartimento di Fisica e Astronomia "Ettore Majorana", Università degli Studi di Catania, Italy

*e-mail: farisitano@unime.it

The CLIR (Clustering in Light Ion Reactions) experiment performed at INFN Laboratori Nazionali del Sud (LNS) aims at investigating cluster structures of neutron-rich nuclei via break-up reactions on a light target. The radioactive ions of interest were produced at the FRIBs@LNS facility [1], through the In-Flight Fragmentation technique. A 18O (55 MeV/u) primary beam was fragmented on a 1500 µm thick 9 Be target, producing a cocktail beam of several radioactive isotopes. These included many species such as 6He, 8,9Li, 11Be, 13,14,15B, 17C and, in particular among the others, the 16C and 10Be isotopes, for which cluster structures have been already studied at LNS [2]. Identification of the cocktail beam was performed by the ΔE-TOF method, using a 150 µm thick Si detector. A C2H4 polyethylene (protons) target was used to trigger the break-up reactions and the produced fragments were detected by the high-granularity femtoscope array FARCOS [3] coupled with the CHIMERA 4π multidetector [4]. Calibrations have been performed for the tagging detector, and the CHIMERA and FARCOS arrays. Very preliminary results of this analysis will be presented.

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Nuclear Dynamics : from fission to multifragmentation / **31**

Quenched production of neutron-rich nuclei in fragmentation reactions of medium- mass and heavy projectiles

Auteur: Jose Benlliure[1]

[1] *Univ. Santiago de Compostela, Spain*

Auteur correspondant j.benlliure@usc.es

J. Benlliure 1 , J. Díaz 1 , H. Alvarez-Pol 1 , T. Aumann 2 , C.A. Bertulani 3 , B. Blank 4 , E. Casarejos 1 , D. Cortina 1 , D. Dragosavac 1 , V. Fohr 5 , A. Gargano 6 , M. Gascón 1 , W. Gawlikowicz 7 , A. Heinz 5 , K. Helariutta 8 , A. Kelic 5 , F. Montes 5 , L. Pienkowski 7 , J.L. Rodríguez-Sánchez 1 , K.-H. Schmidt 5 , M. Staniou 5 , K. Subotic 9 , K. Summerer 5 , J. Taieb 10 , A. Trzcinska 7

1 Universidade de Santiago de Compostela, Spain,
2 Technische Univeritat Darmstadt, Germany,
3 Texas A&M University Commerce, USA,
4 Centre d'Etudes Nucleaires Bordeaux-Gradignan, France,
5 GSI Darmstad, Germany, 6 INFN Napoli, Italy,
7 Heavy Ion Laboratory, University of Warsaw, Poland,
8 University of Helsinki, Finland,
9 Institute of Nuclear Sciences Vinča, University of Belgrade, Serbia,
10 CEA Arpajon, France

Fission of 238U and fragmentation of 132 Xe projectiles at relativistic energies have been used at GSI to produced medium-mass nuclei around 132Sn [1]. The first section of the Fragment Separator made it possible the unambiguous identification of those nuclei, while the second section was used to identify the residual nuclei produced in proton and neutron removal reactions induced on a beryllium target installed at the intermediate image plane of the separator.

The one neutron removal cross sections are in good agreement with recent measurements at RIKEN for 134Sn [2], showing a clear reduction at N=84 explained by the N=82 closed shell. All measured cross sections are rather well explained by model calculations based on particle-hole excitations from shell model configurations and initial- and final-state interactions.

The proton removal cross sections are also in agreement with previous measurements [3,4]. The observed reduction in the cross sections for N=83 nuclei (133Sn and 134Sb) is explained as due to the N=82, while the relative difference between those two nuclei is attributed to the shell Z=50. The same model calculations describing the neutron removal show the observed reduction produced by the closed shells, but in general overestimate the measured cross sections by around a 40%. This quenching of the proton removal channels corresponds to a reduction of the production cross sections of neutron-rich nuclei compared to the predictions obtained with fragmentation models.

The presence of 20% short-range correlated (SRC) nucleon pairs in nuclei, and the recent confirmation of the dominance of neutron-proton SRC pairs [5] provide a possible explanation for the observed reduction in the proton-removal cross sections. The relative large number of SRC protons in neutron-rich nuclei (~30% in 132Sn), and the fact that the removal of any of those protons causes the ejection of the companion neutron because of the large relative momentum between both, would explain the 40% reduction in the cross section of the final A-1 residual nuclei produced in the single proton removal process.

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Nuclear Dynamics : from fission to multifragmentation / **32**

Progress in the characterization of the fission fragments in microscopic theory

Auteur: Guillaume Scamps[1]

[1] *Bruxelles Univ., Belgium*

Auteur correspondant gscamps@ulb.ac.be

The complete microscopic description of the fission process is still a challenge for nuclear theory. Density functional theory (DFT) and Time-Dependent DFT are tools of choice to describe fission. However, it can be difficult to extract information about the fragments that are needed for comparison with experience or as input for the r-process model.

In this presentation, I will discuss the recent progress that has been made on the description of the properties of the fragments. I will show how the octupole shape of the fission fragment at the scission plays a role to determine the asymmetry [1]. How we can determine the distribution of charge and mass of the fission fragments using the projection technique in the time-dependent generator coordinate method (TDGCM) [2]. Important progress has also been made in the determination of the spin of the fragments using particle projection on the angular momentum in static and dynamical approaches [3,4]. A model that describes directly the fission starting from the fission fragments is the scission-point model [5], I will discuss recent advances and the possibility to include the octupole degree of freedom in the model using machine learning.

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Nuclear Dynamics : from fission to multifragmentation / **33**

The asymmetry dependence of temperatures measured in fusion-evaporation reactions and in multi-fragmentation reactions

Auteur: Alan B. McIntosh[1]

[1] *Texas A&M, USA*

Auteur correspondant amcintosh@comp.tamu.edu

The nuclear caloric curve is an emergent property of the nuclear equation of state. Some models predict the caloric curve depends on the neutron excess, but the magnitude and even sign of this dependence varies between models. We aim to characterize the asymmetry dependence of the nuclear caloric curve experimentally. Since the caloric curve emerges from the microscopic interaction, knowledge of the asymmetry dependence of the caloric curve may constrain the asymmetry energy in the nuclear equation of state. We have extracted the temperatures of compound nuclei formed in fusion-evaporation reactions of Kr+C. The results are compared to our previous results obtained in multifragmentation reactions.

This work is supported by the U.S. Department of Energy (DE-FG02-93ER40773) and the Robert A. Welch Foundation (A-1266).

Introduction / **34**

Recent highlights from INDRA-FAZIA

Auteur: J. D. Frankland[1]

[1] *GANIL, France*

Auteur correspondant john.frankland@ganil.fr

Introduction / **35**

Recent highlights from CHIMERA

Auteur: Elena Geraci[1]

[1] *Univ. Catania and INFN Sez. Catania, Italy*

Auteur correspondant elena.geraci@ct.infn.it

Welcome Address / **36**

Welcome address by GANIL direction

Auteur correspondant navin.alahari@ganil.fr

Isospin Effects and EoS in nuclear reactions / **37**

Theoretical aspects: Isospin effects and EOS in nuclear reactions

Auteur correspondant bao-an.li@tamuc.edu

The isospin dependence of in-medium nuclear effective interactions is a fundamental issue in nuclear physics and has broad ramifications in astrophysics. Its uncertainties, especially the difference of neutron-proton interactions in the isosinglet and isotriplet channels, affect significantly the density and momentum dependence of the isovector single-nucleon potential and nucleon-nucleon short-range correlation in neutron-rich matter. Consequently, the neutron-proton effective mass splitting and the density dependence of nuclear symmetry energy are still rather uncertain. Heavy-ion reactions especially those involving rare isotopes is a useful tool for probing the isospin dependence of nuclear effective interactions through (1) the neutron-skin in coordinate and proton-skin in momentum of the initial state of colliding nuclei, (2) the density and momentum dependence of especially the isovector nuclear mean-field as well as (3) the isospin dependence of in-medium nucleon-nucleon cross sections. Experimental observables that are potentially good probes of the isospin dependence of in-medium nuclear effective interactions include the degree (stopping power) and time scale isospin equilibrium, relative yields and differential flow of neutrons and protons or light mirror nuclei as well high-energy/momentum particles such as hard photons. In this talk, several selected theoretical aspects of these issues will be discussed.

Clustering phenomena and multi-particle decay / **39**

Transport model approach for clusters in heavy-ion collision dynamics

Auteur: Akira Ono[1]

[1] *Tohoku University, Japan*

Auteur correspondant ono@nucl.phys.tohoku.ac.jp

Clusters are the dominant products in heavy-ion collisions (HICs) in a wide energy range from the Fermi energy domain to higher energies of several hundred MeV/nucleon. Correlations in such highly excited nuclear many-body systems are of particular interest, and strong correlations can affect the global dynamical evolution of HICs. Also studies of EOS of symmetric and asymmetric nuclear matter by HIC observables require a good understanding of cluster correlations. For example, a recent analysis of the SpiRIT data for Sn+Sn collisions at 270 MeV/nucleon indicates that the triton-to-proton ratio as a function of the rapidity carries information on symmetry energy at high densities. On the theoretical side, the description of HIC dynamics is a highly challenging problem, and one usually relies on transport models. Since transport models are based on one-body dynamics (plus two-nucleon collision term), they have to be extended in some way to include clusters, such as with a cluster recognition or coalescence prescription and with a more dynamical way by extending the collision term. I will give an overview on these subjects, including theoretical efforts to improve transport models and collaborations to understand implications of experimental data

Clustering phenomena and multi-particle decay / 40

Clustering effects in nuclear reactions at low and medium energies

Auteur: Ivano Lombardo[1]

[1] *INFN Sez. di Catania, Italy*

Auteur correspondant ivano.lombardo@ct.infn.it

In this talk, I will review some recent achievements in the study of clustering in light and medium mass nuclei. In particular, I will discuss some results in the rush to the discovery of possible direct decays of the Hoyle state in 12C, that has been performed both by using nuclear reactions at low and medium energies. I will also discuss some results obtained in the analysis of 13C and 20Ne structure with low energy nuclear reactions, and their connection with symmetries in nuclear physics and nuclear astrophysics. Finally, I will briefly show
some possible effects linked to clustering in the low energy fusion of heavy ions.

Nuclear EoS and Astrophysics / 41

The equation of state of dense matter and nuclear physics constraints

Auteur: Francesca Gulminelli[1]

[1] *LPC Caen, France*

Auteur correspondant gulminelli@lpcaen.in2p3.fr

The exceptional progress of multi-messenger astronomy on different astrophysical sources of dense matter has very recently led to quantitative measurements of various properties of neutron stars, such as the correlation between mass and radius from X-ray timing with NICER and the tidal polarizability from gravitational wave LIGO/Virgo data. These observations, together with the plethora of upcoming data, are expected to unveil in the next future exciting open questions such as the structure and degrees of freedom of baryonic matter in extreme conditions, and in particular the presence of phase transitions and the existence of deconfined matter in the core of neutron stars.

This direct connection between astrophysical measurements and the microphysics of dense matter is due to the well-known fact that, under the realm of general relativity, there is a one-to-one correspondence between any static observable and the dense matter equation of state. However, the task is complicated by the uncertainty on the effective energy functional, and similar equations of state can be obtained under different hypotheses on the underlying microphysics.

To identify the observables pointing towards more exotic constituents, it is important to quantitatively evaluate the space of parameters and observables compatible with the nucleonic hypothesis. We will review the different theoretical and experimental constraints that can be used to restrict the space of parameters, and show that both nuclear observables in the sub-saturation and super-saturation regime are needed to achieve a quantitative description of static astrophysical observables that will be challenged by the upcoming measurements.

Nuclear EoS and Astrophysics / 42

Binary neutron stars: from gravitational to particle physics

Auteur: Luciano Rezzola[1]

[1] *Frankfurt University, Germany*

Auteur correspondant rezzolla@itp.uni-frankfurt.de

I will argue that if black holes represent one the most fascinating implications of Einstein's theory of gravity, neutron stars in binary system are arguably its richest laboratory, where gravity blends with astrophysics and particle physics. I will discuss the rapid recent progress made in modelling these systems and show how the gravitational signal can provide tight constraints on the equation of state for matter at nuclear densities, as well as on one of the most important consequences of general relativity for compact stars: the existence of a maximum mass. Finally, I will discuss how the merger may lead to a phase transition from hadronic to quark matter. Such a process would lead to a signature in the post-merger gravitational-wave signal and open an observational window on the production of quark matter in the present Universe.

New Experimental Tools, Detection Techniques and Facilities / 43

Probing the structure of exotic nuclei with protons targets

Auteur: Anna Corsi[1]

[1] *IRFU Saclay, France*

Auteur correspondant acorsi@cea.fr

Proton induced quasi-free scattering is a tool of choice to probe the nuclear single particle structure. When dealing with radioactive beams in inverse kinematics, the use of liquid hydrogen targets is a very natural choice. In this talk I will describe two devices, MINOS and COCOTIER, which are used at RIBF RIKEN and GSI, respectively, to pursue the study of the structure of radioactive nuclei

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Satatus of the RI accelerator facility in Korea and experimental preparations

Auteur: Kevin Insik Hahn[1]

[1] *Center for exotic nuclear studies, IBS, Daejon, Korea*

Auteur correspondant ishahn@ewha.ac.kr

The radioactive ion (RI) beam accelerator facility called RAON is under construction in Korea. It will produce RI beams by both the ISOL and In-flight methods. One of the experimental facilities called KoBRA is expected to carry out nuclear astrophysics and nuclear structure experiments in the early phase of RAON. Several experiments using both stable and RI beams of tens of MeV/u are considered for understanding explosive nuclear synthesis in stellar sites such as X-ray bursts and novae as well as the origin of proton-rich elements in the rp-process. Current activities and prospects of early experiments at RAON will be discussed.

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Concluding remarks

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Awards for the best talk by a young physicist

Auteurs correspondants: marek.lewitowicz@ganil.fr, lopezo@in2p3.fr

NUPECC prizes given by M. Lewitowitz, chair of NUPECC

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Welcome Address by LPC direction

Auteur correspondant bougault@lpccaen.in2p3.fr