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Recent highlights from INDRA and FAZIA

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Summary. — In this contribution, we review the recent results from the INDRA and FAZIA Collaborations. It will cover the results from INDRA-VAMOS experiments at GANIL, the first two INDRA-FAZIA campaigns at GANIL and FAZIA experiments at LNS Catania. Recent detector upgrades and developpements will also be discussed. Those results are better explained and more detailed in the following report presentations of this issue and just a brief overview will be mentionned here, with mostly the main conclusions addressed.

1. – Introduction

The nuclear matter equation of state (EoS) is one of the fundamental concepts underlying many areas of research, both in nuclear physics itself and in related fields such as nuclear astrophysics. In this astrophysical context, it governs both the dynamics of core collapse supernovae, as well as the structure of the neutron star that may result from them. Numerous efforts are currently being made to improve our understanding of the EoS, particularly in the case of asymmetric nuclear matter (where the neutron density differs from proton density), where the lack of experimental constraints leads to significant disagreement between different theoretical predictions.

Moreover, when the density of nuclear matter becomes low compared to saturation density, correlations between nucleons increase and clusters appear. The chemical composition changes, which affects the thermodynamic properties of the system. Many theoretical developments have been made recently to describe a mixture of clusters in a nucleon gas. These efforts have been primarily motivated by the need to model supernovae explosions.

It then becomes essential to consider that these clusters are not isolated: unlike the nuclei traditionally studied in the laboratory, they evolve in a highly diluted medium mainly consisting of electrons, protons, and neutrons, which can alter their intrinsic properties. The presence of nuclei in the neutrino-sphere, with binding energy potentially reduced due to interaction with this environment, may modify the electron neutrino absorption cross-section. However, the modification of nuclear properties induced by the interaction of a nucleus with its environment has been studied very little experimentally.

Thus, the main scientific questions underlying the scientific program of the INDRA and FAZIA Collaborations in recent years are as follows:

1) What is the dependence of the nuclear EoS on density, temperature, and isospin?

2) What is the composition of nuclear matter at low density?

3) How are the properties of nuclei modified by the interaction with the surrounding nuclear medium?

In this contribution, we will report on some recent highlights from the INDRA and FAZIA Collaborations since the 2021 edition of IWM-EC.

2. – Isospin transport and EoS

One of the main goals of the INDRA and FAZIA Collaborations is to constrain experimentally the isovector term of the EoS (also called symmetry energy), particularly through the phenomenon of isospin transport observed in semi-peripheral heavy-ion collisions. Most transport models indeed predict that the difference between proton and neutron currents ($\vec{j}_n - \vec{j}_p$) that develops in the presence of an isospin gradient ($\overrightarrow{\nabla} I$) and a density gradient ($\overrightarrow{\nabla}\rho$) can be related to the magnitude of the symmetry energy (S(ρ)) and its derivative with respect to density (ρ):

$$\vec{j}_n - \vec{j}_p \propto S(\rho)\overrightarrow{\nabla} I + \frac{\partial S(\rho)}{\partial \rho}\overrightarrow{\nabla}\rho.$$

Two effects are then expected:

1) migration of neutrons toward the diluted neck region, which can lead to the formation of neutron-rich light fragments between projectile and target, and

2) equilibration of the N/Z ratio between the projectile and the target with different initial N/Z ratios.

The measurement of the isotopic composition of the various fragments produced in such collisions allows us to quantify the proton and neutron currents, which can then be linked to the parameters of the EoS by comparison with transport models. This approach has been implemented in two distinct studies recently published using ^{40,48}Ca + ^{40,48}Ca collisions at 35 MeV/nucleon measured with the INDRA-VAMOS coupling [1, 2] and ^{58,64}Ni + ^{58,64}Ni collisions at 32 and 52 MeV/nucleon measured with the INDRA-FAZIA coupling [3, 4], both in GANIL.

2˙1. *INDRA-VAMOS*. – Isospin transport has been investigated with ^{40,48}Ca+^{40,48}Ca reactions at 35 MeV/nucleon, measured with the coupling of the VAMOS high-acceptance spectrometer and the INDRA charged particle multidetector at GANIL.

Firstly, isospin diffusion was studied by means of the isospin transport ratio of the quasi-projectile residue [1]. A clear evolution towards isospin equilibration with increasing dissipation was demonstrated. In addition, using the isotopic composition of light charged clusters ($Z \leq 4$), a systematic neutron enrichment of the mid-rapidity region (neck emissions) with respect to the forward-emitting region (quasi-projectile emissions) was evidenced and interpreted as a consequence of isospin migration. The excellent isotopic identification capabilities of the VAMOS spectrometer also allows for a detailed study of the isoscaling properties of the quasi-projectile residue (see fig. 1).

In a second article [2], the experimental data were compared with filtered transport model calculations, focusing on isospin diffusion. We applied a newly proposed method of impact parameter reconstruction [5], demonstrating its relevance over the whole impact parameter domain and allowing for a direct comparison with transport models. Our results demonstrated the importance of considering cluster formation to reproduce observables used for isospin transport and centrality studies. A benchmark of global observables is proposed to assess the relevance of the Antisymmetrized Molecular Dynamics (AMD) model coupled to GEMINI++ in the study of dissipative collisions. The results presented in this work constitute a further step to improve the comparison protocol employed in the study of isospin transport and of the nuclear EoS. More details can be found in Fable's contribution to this workshop.

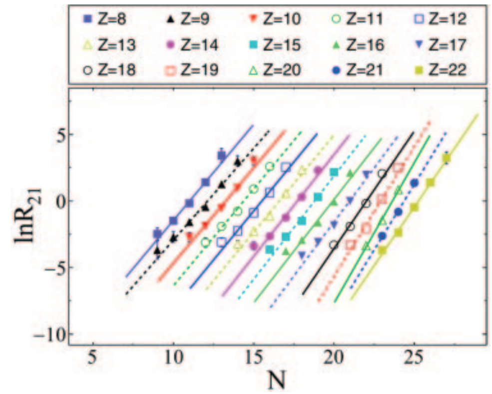

Fig. 1. – Example of experimental isoscaling plots using an expanded Z range for the ^{48}Ca+^{48}Ca system relative to the ^{40}Ca + ^{40}Ca using the fully reconstructed quasi-projectile. Adapted from [1].

2˙2. *INDRA-FAZIA*. – The first INDRA-FAZIA experiment in GANIL was performed in 2019 (E789). During this experiment, we measured the ^{58,64}Ni + ^{58,64}Ni reactions at 32 and 52 MeV/nucleon. The first publication concerning these data focuses on quantifying the isospin diffusion [3]: both the neutron to proton content of the quasi-projectile residue and that of the light ejectiles coming from the quasi-projectile evaporation have been used as probes of the dynamical process of isospin diffusion between projectile and target for the asymmetric systems. The relaxation of the initial isospin imbalance with increasing centrality has been clearly evidenced (see fig. 2). The isospin equilibration appears stronger for the reactions at 32 MeV/nucleon, as expected due to the longer projectile-target interaction time than at 52 MeV/nucleon. Coherent indications of isospin equilibration have been observed from the quasi-projectile residue characteristics and from particles ascribed to the quasi-projectile decay.

The same data have also been used to compare the quasi-projectile evaporation and breakup channels. It was observed that for the same centrality, greater relaxation of initial isospin imbalance occurs in the breakup channel compared to the binary output, suggesting a selection of specific dynamical features. This was interpreted as being due to longer projectile-target contact times in the breakup channel, supported by molecular dynamics simulations [4].

This analysis has been pursued with a proper estimate of the impact parameter distribution associated to the different centrality selection allowing for a direct comparison with transport model calculations. This part is described in the contributions of Ciampi and Mallik (in these proceedings).

3. – Clustering

Nuclear matter at low density and finite temperature, as can be found during supernova explosions, is not homogeneous: clusters appear which can affect the thermodynamic properties of the system. However, these clusters are not isolated. Unlike the nuclei traditionally studied in the laboratory, they evolve in a highly diluted environment that can alter their intrinsic properties. One of the main interests of the INDRA and FAZIA Collaborations in recent years has been to study the appearance of clusters and to characterize the chemical composition of a diluted system of nucleons and light clusters

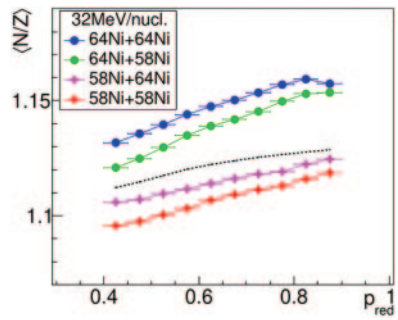

Fig. 2. – Experimental average neutron to proton ratio of the quasi-projectile residue as a function of its reduced momentum for the four ^{58,64}Ni + ^{58,64}Ni reactions at 32 MeV/nucleon. Adapted from [3].

under different thermodynamic conditions. These problems have been tackled both from a dynamic or a thermodynamic point of view.

3˙1. *Dynamic approach: cluster formation.* – Cluster production in excited light systems produced in ^{32}S + ^{12}C and ^{20}Ne + ^{12}C at 25 and 50 MeV/nucleon collisions has been investigated, comparing experimental data with transport model calculations [6].

Experimental fragment multiplicities, angular distributions and energy spectra have been compared with Monte Carlo simulations, *i.e.*, the antisymmetrized molecular dynamics (AMD) and the heavy-ion phase space exploration (HIPSE) models. These models were combined with two different afterburner codes (HFl and SIMON) to describe the decay of the excited primary fragments. All models provide a reasonable reproduction of the general features observed in the experimental data. In the case of AMD, the effect of including the clustering and interclustering processes to form bound particles and fragments is discussed and a clear confirmation of the role of the cluster aggregation in the reaction dynamics and particle production for these light systems (see fig. 3), for which the importance of the clustering process increases with bombarding energy, is obtained.

Recently, a new Bayesian analysis of the same dataset has been carried out. The experimental data are compared with AMD calculations where both the clustering strength and the in-medium nucleon-nucleon cross-section are varied. This study is described in the contribution of Piantelli (in these proceedings).

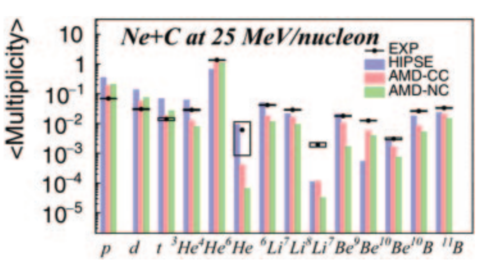

Fig. 3. – Comparison of experimental light particle multiplicities, measured in ^{20}Ne + ^{12}C reactions at 25 MeV/nucleon, with HIPSE and AMD calculations with and without dynamical cluster production. Adapted from [6].

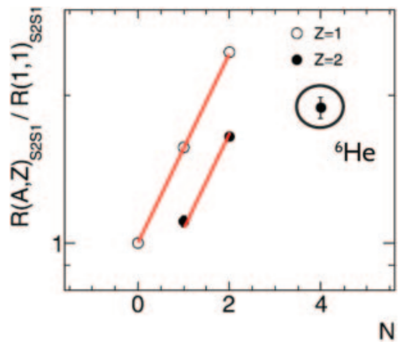

Fig. 4. – Isoscaling for a given statistical ensemble from ^{136}Xe + ^{124}Sn (S2) and ^{124}Xe + ^{112}Sn (S1) reactions. Adapted from [9].

3·2. *Thermodynamic approach: cluster-medium coupling.* – The question of cluster formation can also be tackled from a thermodynamic point of view. In this case, nuclear collisions must be carefully selected so that they are compatible with statistical ensembles that meet chemical and thermal equilibrium conditions. We then obtain a collection of statistical ensembles in which the chemical composition is measured. These experimental measurements can then be used to calibrate phenomenological models of infinite matter, in which a number of parameters are unknown. In the work carried out by the collaboration, we primarily used a relativistic mean-field (RMF [7]) model which describes a system of inhomogeneous matter at finite temperature, where the coupling constant between light clusters and the surrounding medium needs to be calibrated.

The first contribution to this topic within our collaborations comes from the work of Bougault and Pais on Xe + Sn collisions at 32 MeV/nucleon measured with the INDRA multidetector [7, 8]. A careful analysis of the isoscaling properties of $Z = 1$ and $Z = 2$ particles [9] has recently confirmed the validity of the hypothesis of chemical equilibrium in the event sets, except for ^{6}He that seems to suffer from finite size effects (see fig. 4).

Until recently, these analyses were conducted on INDRA data considering only particles produced in the mid-rapidity region and focusing on the lightest isotopes (up to ^{4}He). The availability of the INDRA-FAZIA coupling in GANIL opens up the possibility of expanding the range of isotopes considered and allows the study of this issue in central collisions at higher energy, where the thermodynamic conditions are different. An experiment has been performed in this sense in 2022 (E818). The first results of this experiment, concerning the contribution of secondary decay to the total light particle yield, is presented in the contribution of Rebillard-Soulié (in these proceedings).

4. – Reaction mechanism

The experimental data measured with FAZIA at LNS Catania led to two publications concerning reaction mechanism.

The first article [10] presents an analysis of the asymmetric reactions ^{40,48}Ca + ^{12}C at 25 and 40 MeV/nucleon. These data were collected with six blocks of the FAZIA array. The analysis focuses on the breakup channel of sources produced in dissipative collisions, partially corresponding to incomplete fusion processes. The study was performed both on detected fragments and on some resonances reconstructed by means of particle-fragment correlations, with a focus on the evolution of the breakup channel with the beam energy and the neutron content of the system. It shows that also carbon fragments reconstructed by means of particle correlations can be in large part interpreted as the light partner of a scission.

The same dataset was also used to study reactions with the ^{48}Ca neutron-rich projectile on various targets [11]. The goal was to compare experimental results with HIPSE event generator simulations to study the effect of a neutron-rich entrance channel on the properties of quasi-projectile fragments. The FAZIA detector's resolution captured the full isotopic range of charged particles, and most quasi-projectile fragments were detected and identified, as confirmed by HIPSE calculations. The study observed a decrease in the N/Z ratio of quasi-projectile fragments with increasing beam energy, potentially due to pre-equilibrium neutron emissions.

5. – Upgrades and R&D

5˙1. *INDRA upgrade*. – Between 2020 and 2022, the full INDRA electronics (both for data acquisition and power supply) has been completely renovated. Technical details are described in the proceedings of the previous edition of IWM-EC [12]. In addition, most silicon detectors were also replaced. In 2022, we performed the first INDRA-FAZIA experiment using the resurrected version of INDRA (E818). The overall identification performances of INDRA were strongly improved as illustrated in fig. 5. In addition, the new electronics and DAQ system allow to drastically reduce the INDRA deadtime which is now comparable to the FAZIA deadtime (10–15 μs), allowing for a much easier coupling between the two detector acquisitions.

5˙2. *FAZIA detectors and electronics*. – In recent years, the FAZIA Collaboration continued improving the performances of the detector. In view of operating FAZIA at higher energies at GANIL, RAON and FRIB, the second layer of silicon (500 μm) of the inner FAZIA blocks were replaced with thicker ones (750 μm). This led to a significant improvement in terms of isotopic identification as illustrated in fig. 6.

One major goal of the FAZIA Collaboration is to produce four FAZIA blocks to be operated at RAON in Republic of Korea. This implied developping new Front End

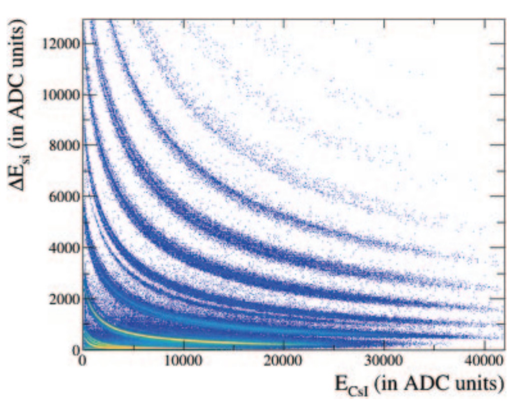

Fig. 5. – Typical Si-CsI matrix measured in Kr + Sn reactions at 68 MeV/nucleon with the new INDRA electronics and silicon detectors.

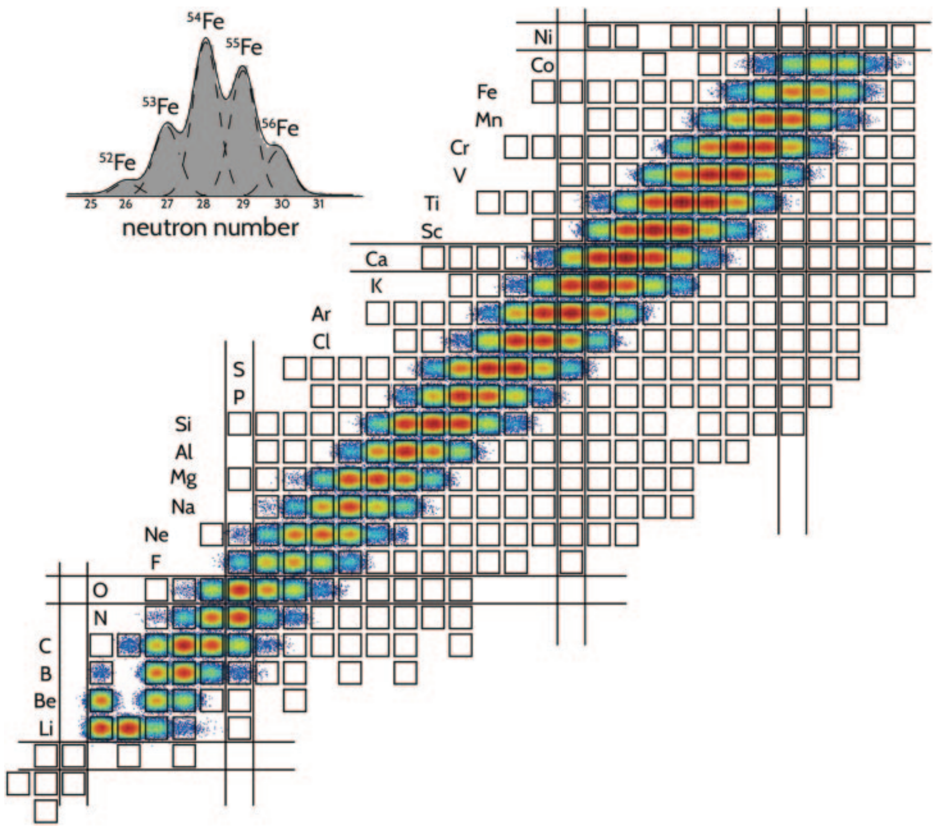

Fig. 6. – Population of the nuclear chart as seen by a typical FAZIA telescope (using ΔE-E identification techniques). The data are coming from the ^{58}Ni+^{58}Ni reaction at 74 MeV/nucleon measured during the E818 experiment at GANIL. The inset illustrate the identification quality for iron isotopes.

cards based on the existing design but updating most of the components. New silicon detectors, both thinner and thicker have also been produced. These blocks will be ready soon in order to participate in the commissioning phase of RAON. The FAZIA activities dedicated to RAON are described in more details in the contribution of Kim (in these proceedings).

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