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ASY-EOS experiment at GSI: Constraining symmetry energy with neutron and proton elliptic flows

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Summary. — The Equation Of State of asymmetric nuclear matter is of fundamental importance for both nuclear physics and astrophysics. However, the present understanding of the EOS is limited, largely due to the poor knowledge of the density dependence of the nuclear symmetry energy. In fact, while considerable progress has been made recently in determining the behaviour of symmetry energy at sub-normal nuclear matter density, much more work is still needed to probe its behaviour at high density. The ASY-EOS experiment at GSI will measure elliptic flow (squeeze-out) of neutrons, protons and light complex particles in reactions of isospin asymmetric systems at pre-relativistic energies, in order to provide quantitative information on the density dependence of symmetry energy at densities larger than the saturation one.

PACS `25.75.Ld` – Collective flow.
PACS `21.65.Ef` – Symmetry energy.
PACS `21.65.Mn` – Equations of state of nuclear matter.

1. – Introduction

A key question in modern nuclear physics is the knowledge of the nuclear Equation Of State (EOS) and, in particular, of its dependence on density and on asymmetry, *i.e.*, on the relative neutron-to-proton abundance [1-4]. The EOS can be divided into a symmetric term (*i.e.* independent of the isospin asymmetry $I = \frac{N-Z}{N+Z}$, where N and and Z are the numbers of neutrons and protons, respectively) and an asymmetric term (also known as the symmetry energy) that is proportional to the square of the isospin asymmetry I [3-5].

Measurements of isoscalar collective vibrations, collective flow and kaon production [1, 6, 7] in energetic nucleus-nucleus collisions have constrained the behaviour of the

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equation of state of isospin symmetric matter for densities up to five times the saturation density ρ_0.

On the other side, the EOS of asymmetric matter is still subject to large uncertainties. Besides the astrophysical interest, *e.g.*, neutron star physics and supernovae collapse [8,9], the density dependence of the symmetry term is of fundamental importance for nuclear physics. The thickness of the neutron skin of heavy nuclei reflects the differential pressure exerted on the core [10] and the strength of the three-body forces, an important ingredient in nuclear-structure calculations [11], represents one of the major uncertainties in modeling the equation of state at high density [1, 12]. Moreover, properties of exotic nuclei, *i.e.*, nuclei far away from stability valley, and the dynamics of nuclear reactions rely on the density dependence of the symmetry energy [3, 4].

In the last decade, measurements of the Giant Monopole [13], Giant Dipole [14] and Pygmy Dipole [15] resonances in neutron-rich nuclei, isospin diffusion [16, 17], neutron and proton emissions [18], fragment isotopic ratios [17, 19, 20] and isospin dependence of competition between deep-inelastic and incomplete fusion reactions [21] have provided initial constraints on the density dependence of the symmetry energy around and below saturation density ρ_0. It results that the best description of experimental data is obtained with a symmetry energy $S(u) = C_{kin}^{sym}(u)^{2/3} + C_{pot}^{sym}(u)^{\gamma}$ with γ in the range 0.6–1.1 [17] ($u = \rho/\rho_0$ is the reduced nuclear density). In the near future, extensions of these measurements with both stable and rare-isotope beams will provide further stringent constraints at sub-saturation densities.

In contrast, up to now, very few experimental constraints exist on the symmetry energy at supra-saturation densities ($u > 1$). This is the domain with the greatest theoretical uncertainty and the largest interest for neutron stars. The behaviour of the symmetry energy at supra-saturation densities can only be explored in terrestrial laboratories by using relativistic heavy-ion collisions of isospin asymmetric nuclei. Reaction simulations propose several potentially useful observable which should be sensitive to the behaviour of the symmetry energy at supra-saturation densities, such as neutron and proton flows (direct and elliptic) [4, 22, 23], neutron/proton ratio [4, 17, 24, 25], π^-/π^+ ratio and flows [4, 22, 26], K^+/K^0 [27] and Σ^-/Σ^+ [26] ratios.

To this day the problem is still open. Few works have provided constraints on symmetry energy behaviour at supra-saturation densities. The double ratio $(K^+/K^0)_{\mathrm{Ru}}/(K^+/K^0)_{\mathrm{Zr}}$ was measured in $^{96}\mathrm{Ru} + {}^{96}\mathrm{Ru}$ and $^{96}\mathrm{Zr} + {}^{96}\mathrm{Zr}$ collisions at 1528 MeV/nucleon using the FOPI detector at GSI [28]; the experimental results show good agreement with the prediction of a thermal model in the case of the assumption of a soft symmetry energy for infinite nuclear matter. More realistic simulations in the frame of transport theory, for finite nuclear matter, show a similar good agreement with the data, but also exhibit quite an insensitivity to the symmetry term. However, it has recently been pointed out that more experimental and theoretical work is needed to establish the effectiveness of the K^+/K^0 ratio in probing the symmetry energy [4].

The single ratio π^-/π^+ was measured in $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$ [29] and analyzed using the hadronic transport model IBUU04 [30]. The results suggest that the symmetry energy is rather soft at supra-saturation densities; this finding, symmetry energy reaches its maximum at a density between ρ_0 and $2\rho_0$ and then starts decreasing at higher densities, is not consistent with the density dependence deduced from fragmentation experiments probing nuclear matter near or below saturation density [17] and with the slightly softer density dependence resulting from the analysis of the pygmy dipole resonance in heavy nuclei [15]. Moreover, other theoretical works [31] suggest a reduced sensitivity of π^-/π^+

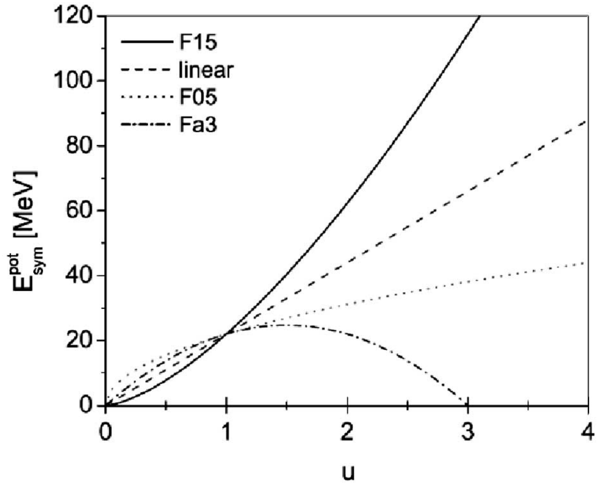

Fig. 1. – Asy-Stiff (F15) and Asy-Soft (F05) parameterizations of symmetry potential energy of nucleons as a function of the reduced nuclear density u, as used in UrQMD calculations; from ref. [36].

ratio to the symmetry energy. Recently, the same set of FOPI data has been analyzed in the framework of the Improved Isospin dependent Quantum Molecular Dynamics (ImIQMD) [32]; it results a very stiff symmetry energy of the potential term proportional to u^γ with $\gamma \simeq 2$, just the opposite of the results of ref. [30]. It follows that also for the π^-/π^+ ratio further work is needed to establish the effectiveness in probing the symmetry energy. In-medium absorption and re-emission of pions can distort the asymptotic experimental signal and it is not clear which density of matter is explored by the pions signal. The analysis of another set of FOPI data is described in the third section of this paper.

2. – Neutron and proton elliptic flows

One of the most promising probe of the symmetry energy strength at supra-saturation densities is the difference of the neutron and proton (or hydrogen) elliptic flows [33-35]. This has emerged mainly from calculations based on the Ultra-Relativistic Quantum Molecular Dynamics model (UrQMD) [37]. We report here some results obtained using UrQMD for the $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$ collision at 400 MeV/nucleon. The calculations have been performed using both Asy-Stiff ($\gamma = 1.5$) and Asy-Soft ($\gamma = 0.5$) potential symmetry energies, indicated as F15 and F05, respectively, in fig. 1. A realistic description of the clustering processes during the evolution of the reaction is crucial for predicting dynamical properties of free neutrons, protons and light charged particles. In the UrQMD, the clustering algorithm is based on the evaluation of the proximity of nucleons in the phase space by using two parameters: the relative nucleon coordinates (Δr) and the relative momenta (Δp). The results presented here have been obtained using the cluster distributions built after a reaction time of 150 fm/c. The proximity parameters were: $\Delta r = 3.0\,\mathrm{fm}$ and $\Delta p = 275\,\mathrm{MeV}/c$ which are typical for QMD models [38]. As an example of the clusterization procedure, the charge distribution obtained for central collisions of Au + Au is shown in fig. 2 in comparison with the data of Reisdorf *et al.* [39].

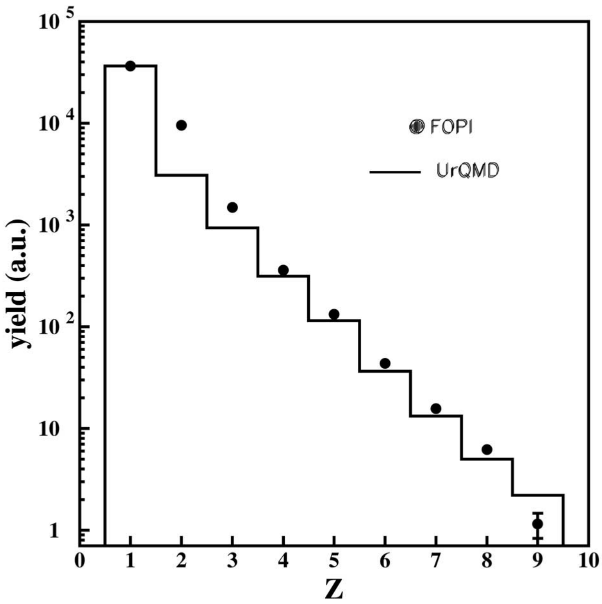

Fig. 2. – Fragment yields, integrated over the 4π solid angle, in central (equivalent to impact parameter $b < 2.0\,\mathrm{fm}$) collisions of $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$ at 400 MeV/nucleon as a function of Z (dots, from ref. [29]) in comparison with UrQMD predictions normalized at $Z = 1$ (histogram); adapted from ref. [40].

With a normalization at $Z = 1$, the overall dependence on Z is rather well reproduced but the yields of $Z = 2$ particles are underpredicted by about a factor 3. The strong binding of ^{4}He particles is beyond the phase-space clustering criterion used in the model. However, also the 4π integrated yields of deuterons and tritons in central collisions are underestimated by similar factors of 2 to 3.

The UrQMD predictions for the elliptic flow of neutrons, protons, and hydrogen as a function of rapidity in laboratory reference system Y_{lab} for mid-peripheral collisions (impact parameter $5.5 < b < 7.5\,\mathrm{fm}$) and for the two choices of the density dependence of the symmetry energy, are shown in fig. 3. We remind here that direct (v_1) and elliptic (v_2) flows are obtained by the azimuthal particle distributions with the usual Fourier expansion

$$f(\Delta\phi) \propto 1 + 2 \cdot v_1 \cos(\Delta\phi) + 2 \cdot v_2 \cdot \cos(2 \cdot \Delta\phi) \tag{1}$$

with $\Delta\phi$ representing the azimuthal angle of the emitted particle with respect to the reaction plane [41]. The dominant difference is the significantly larger neutron squeeze-out in the Asy-Stiff case (upper panel) compared to the Asy-Soft case (lower panel). The proton and hydrogen flows respond only weakly, and in opposite direction, to the variation of γ within the interval of interest.

Another interesting observable is the ratio of neutron and proton yields as a function of the transverse momentum pt (*i.e.* the component of momentum perpendicular to the beam direction); as an example, fig. 4 shows UrQMD predictions for the neutron/proton yields ratio as a function of transverse momentum in Au + Au central (impact parameter

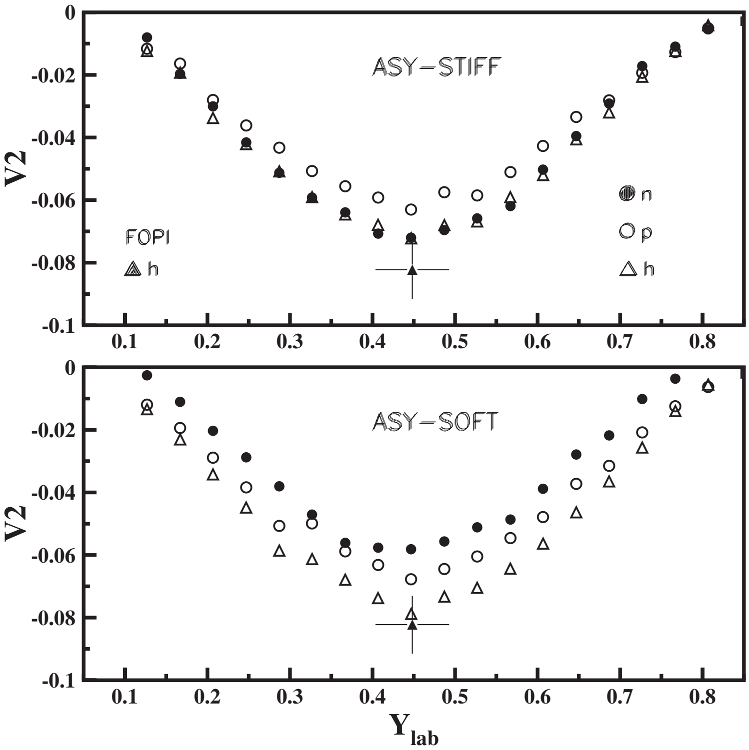

Fig. 3. – Elliptic flow parameter v_2 for mid-peripheral (impact parameter $5.5 < b < 7.5\,\mathrm{fm}$) $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$ collisions at 400 MeV/nucleon as calculated with the UrQMD model for neutrons (dots), protons (circles), and all hydrogen isotopes ($Z = 1$, open triangles), integrated over transverse momentum pt, as a function of the laboratory rapidity Y_{lab}. The predictions obtained with a stiff and a soft density dependence of the symmetry term are given in the upper and lower panels, respectively. The experimental result from ref. [42] for $Z = 1$ particles at mid-rapidity is represented by the filled triangle (the horizontal bar represents the experimental rapidity interval); adapted from ref. [40].

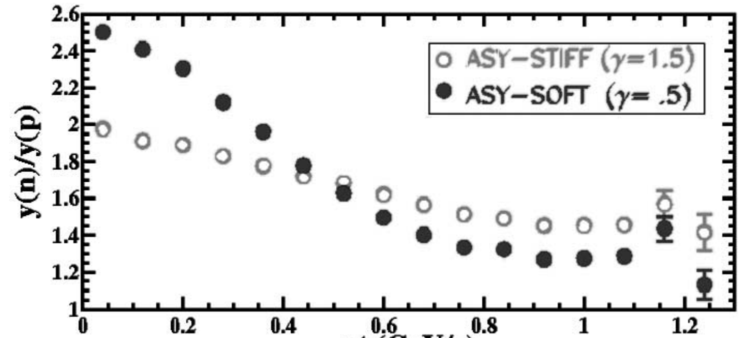

Fig. 4. – UrQMD predictions for the neutron/proton yield ratio, as a function of transverse momentum pt in Au + Au central (impact parameter $b < 3\,\mathrm{fm}$) collisions, for stiff (empty circles) and soft (full circles) parametrization of symmetry energy.

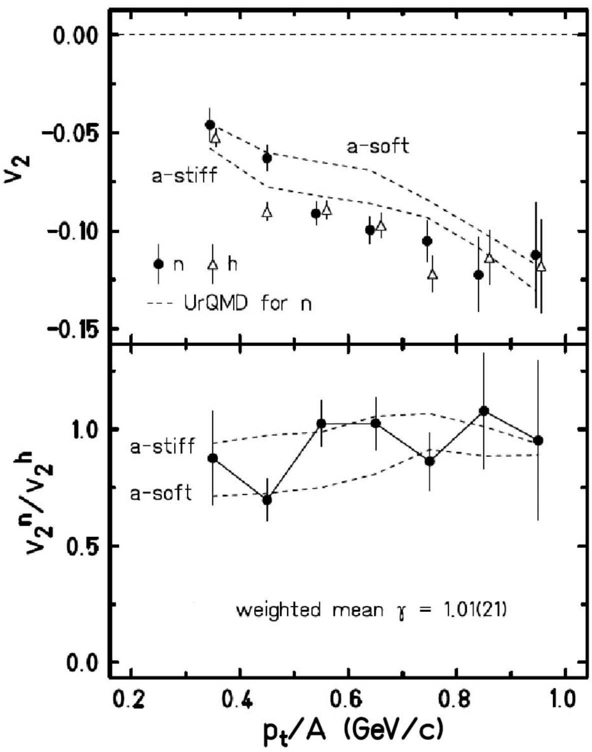

Fig. 5. – Differential elliptic flow parameters v_2 for neutrons (dots) and hydrogen isotopes (open triangles, top panel) and their ratio (lower panels) for moderately central ($b < 7.5\,\mathrm{fm}$) collisions of $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$ at 400 MeV/nucleon, as a function of the transverse momentum per nucleon pt/A. The symbols represent the experimental data. The UrQMD predictions for $\gamma = 1.5$ (Asy-Stiff) and $\gamma = 0.5$ (Asy-Soft) obtained for neutrons (top panel) and for the ratio (bottom panel) are given by the dashed lines; adapted from ref. [33, 35].

$b < 3\,\mathrm{fm}$) collisions, for the two different parameterizations of symmetry energy. The ratio of the yields shows a clear dependence on the parameter describing the effective behaviour of the symmetry energy.

3. – First constraint from elliptic flow in $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$

Neutron and proton directed and elliptic flows were measured in $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$ collisions from 400 to 800 MeV/nucleon using the LAND neutron detector and the FOPI Phase 1 forward wall [43, 44]. We have reanalyzed the data to extract the neutron and proton direct and elliptic flows [33-35]. The results have been compared with predictions of the UrQMD model with the aim of providing constraints on the symmetry energy at supra-saturation densities. The dependence of the elliptic flow parameter v_2 on the transverse momentum per nucleon, pt/A, is shown in fig. 5, upper panel, for the combined data set of collisions with impact parameter $b < 7.5\,\mathrm{fm}$; the impact parameter has been estimated from the total charged particle multiplicity registered in FOPI forward wall. The increase of v_2 in absolute magnitude is nearly linear and the measured values for neutrons and hydrogen isotopes follow approximately the UrQMD predictions. For neutrons, the predictions are different by 20%, on average, for the main part of the pt

interval (dashed lines) and show tendency to converge at high pt at which the yields become small and the statistical errors large. For the quantitative evaluation, the ratio of the flow parameters of neutrons versus hydrogen isotopes is proposed to be used. The results for the ratio v_2^n/v_2^h, *i.e.* with respect to the integrated hydrogen yield, are shown in fig. 5 (lower panel). They exhibit once more the sensitivity of the elliptic flow to the stiffness of the symmetry energy predicted by the UrQMD. The experimental ratios, even though evaluated with large errors, are found to scatter within the intervals given by the calculations for $\gamma = 0.5$ and 1.5. Linear interpolations between the predictions, averaged over $0.3 < pt/A < 1.0\,\mathrm{GeV}/c$, yield $\gamma = 1.01 \pm 0.21$ for the exponent describing the density dependence of the potential term. The same analysis has been also performed for different parametrization of the momentum dependence of the elastic in medium nucleon-nucleon cross section [45], for the v_2 ratios of free neutrons with respect to free protons, and for different bins of total charged particle multiplicity-impact parameter, resulting in a preliminary value of $\gamma = 0.9 \pm 0.3$.

It is obvious that data with higher statistical precision are highly desirable, allowing to follow the evolutions of Isopin signal with impact parameter, transverse momentum and particle type more accurately.

4. – ASY-EOS experiment at GSI

The experiment S394, "Constraining the Symmetry Energy at Supra-Saturation Densities With Measurements of Neutron and Proton Elliptic Flows", will be devoted to measurements of neutron and proton elliptic flows in isospin asymmetric systems $^{197}\mathrm{Au} + {}^{197}\mathrm{Au}$, $^{96}\mathrm{Ru} + {}^{96}\mathrm{Ru}$ and $^{96}\mathrm{Zr} + {}^{96}\mathrm{Zr}$ at 400 MeV/nucleon. Simultaneous measurements of neutron-proton yield ratio, flow and isotopic ratio for light fragments will also be performed; all these measurements will allow to compare the symmetry energy as extracted by using several different nucleon-based observable.

The Au + Au system is heavy and neutron-rich. Simulations with UrQMD predict large sensitivity of the symmetry energy on the neutron-proton observable for this system. Using Ru + Ru and Zr + Zr systems will allow us to compare neutron-rich and neutron-deficient systems; the ^{96}Ru and ^{96}Zr combination is unique among available stable isotopes in that it is mass symmetric and isobaric. The measurement with these systems are very important in order to reduce systematic errors. Besides, the new data will provide important information to pin up effects related to the size, the total charge and the surface of the nuclear system. The proposed new experiment aims to achieve high quality of the analysis by increasing the statistics by factor expected to be around 20–30 compared to the previous experiment; statistical errors will be thus reduced by a factor 4–5, allowing us to well constrain theoretical calculations. The experiment (see fig. 6 for a schematic view) will use LAND [46] time-of-flight detector for high energetic neutrons and light charged particles in a similar geometry like in [43] to measure neutron squeeze-out. LAND will be positioned around $\theta_{lab} \sim 45°$, to cover the mid-rapidity for a large transverse momentum region. Protons can be separated by employing the calorimetric properties of the neutron detector and the measured proton observable can be compared directly to the FOPI data measured in a similar angular acceptance.

The simultaneous measurement of the atomic number Z and the azimuthal angle for fragment emissions in the forward direction will be essential for a precise determination of the modulus and orientation (reaction plane) of the impact parameter; this task will be accomplished by using a detection system with high granularity at forward angles consisting of 8 CsI rings of the CHIMERA multi-detector [47] and the ALADIN

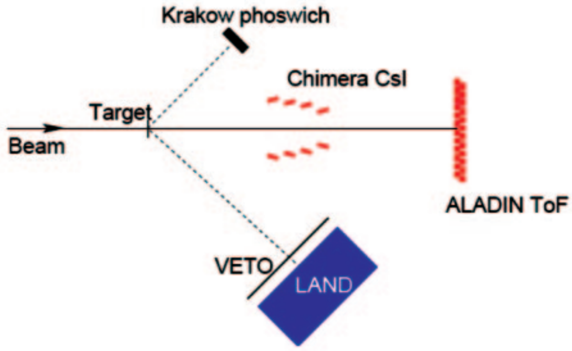

Fig. 6. – Schematic view of the experimental setup.

Time-Of-Flight wall [48]. In addition, flow of light fragments will be measured with the Krakow telescope array positioned on the opposite side of LAND, at angles $\theta_{lab} \sim 30°$.

The proposed experimental program would greatly benefit from using radioactive isotope beams, since they will allow to explore wider isospin asymmetries into the reaction. As an example, secondary beams of ^{106}Sn and ^{132}Sn (on ^{112}Sn and ^{124}Sn targets, respectively) will allow one to explore N/Z asymmetries much larger than those available with stable beam/target combinations. It is important to notice that using stable beam for these kind of pioneer experiments is also important in order to collect a data base of observable acting as standard for future investigations with exotic beams. GSI is currently upgrading the existing accelerator complex and radioactive beams with good intensities will be available soon; in the future FAIR @ GSI will be an unique opportunity to pursue these investigations, as it will be the only facility worldwide to produce radioactive isotopes beams with energies up to 1–2 GeV/nucleon and with intensities high enough to allow reaction dynamics studies.

In November 2010, during a beam test performed at GSI, 8 rings (352 modules) of CHIMERA CsI detectors have been tested, using collisions induced by Au beam at 400 MeV/nucleon on a Pb target. Preliminary results revealed a charge identification performance for light charged particles using the fast-slow technique in the CsI detectors (fig. 7) and capabilities of reconstructing the reaction plane. The use of digital acquisition techniques [49] in about 10% of the detectors, in parallel to standard analogical one, has been of fundamental importance allowing us to store directly the shape the electronic signals; an off-line analysis is then useful in order to study the best processing system and to develop new electronic solutions.

5. – Conclusions

New experiments on symmetry energy at supra-saturation densities are expected to take place during the next few years, in Europe as well as worldwide. It is likely that providing definitive constraints on the symmetry energy will require simultaneous measurements of several observable. However, the isospin signals at supra-saturation densities appear to be controversial and strongly model dependent; to clarify these points, we need a better understanding of volume, Coulomb and surface effects, production and reabsorption of resonances, reaction dynamics, in-medium nucleon-nucleon cross section,

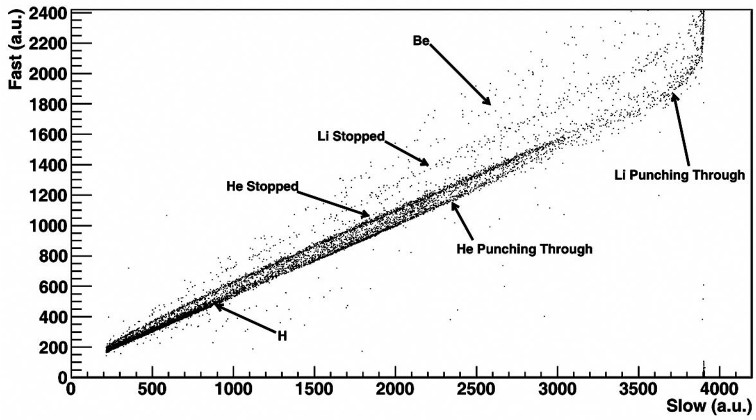

Fig. 7. – Fast *vs.* Slow component scatter plot as obtained in a CHIMERA CsI(Tl) scintillator placed at a polar angle $\theta_{lab} \sim 9^\circ$ for Au + Pb reactions at 400 MeV/nucleon at GSI; lines of particles stopped and passing through CsI detector are indicated by arrows.

splitting of neutron and proton effective masses in momentum-dependent iso-vectorial interactions.

Neutron and proton elliptic flows appear to be as one of the most interesting observable with strong sensitivity to symmetry energy. The ASY-EOS experiment at GSI will measure such and other isospin sensitive observable in reactions of isospin asymmetric systems at pre-relativistic energies, in order to provide quantitative information on the density dependence of symmetry energy at supra-normal saturation density.

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