Proposal for Beam-time
for Constraining the
Symmetry Energy at High Densities from
Neutron/Proton Flow Excitation Functions

Spokespersons: P. Russotto*, A. Le Fèvre, J. Łukasik
   *russotto@lns.infn.it
   INFN-LNS, Catania, Italy

Ion Species: $^{197}$Au @ 250, 400, 600, 1000 AMeV

Main Experimental/Scientific goals

• Determination of the high density behavior of the symmetry energy through the simultaneous measurement of elliptic flow excitation functions of neutrons, protons and light clusters. The elliptic flow developed in relativistic heavy ion collisions has been proven theoretically and experimentally to have a unique sensitivity and robustness in probing the symmetry energy up to around $2\rho_o$. The knowledge of the density dependence of the symmetry energy in a broad range of densities will provide a missing link for astrophysical predictions of the neutron star mass-radius relation. In particular, the data will provide tighter constraints on the slope parameter $L$ and entirely new limits on $K_{sym}$, the currently poorly constrained symmetry energy curvature parameter.

• Enforcement of tight constraints on nuclear transport theories by providing new data on the symmetry energy and the inter-related phenomena of clustering and neutron and proton emissions as well as correlations among them.

The proposed campaign represents a unique set of measurements, presently possible only at the GSI/FAIR facility, because of the available range of beam energies and the existing instrumentation.
Symmetry energy at high densities from neutron/proton flow excitation functions

Spokespersons: P. Russotto1, A. Le Fèvre2, J. Łukasik3
Principal Investigators: K. Boretzky2, M.D. Cozma4, E. De Filippo5, I. Gašparić6, A. Le Fèvre2, Y. Leifels2, I. Lihtar7, J. Łukasik3, S. Pirrone3, G. Politi5,8, P. Russotto1, W. Trautmann2
Institutions: 1INFN-LNS, Catania, Italy; 2GSI, Darmstadt, Germany; 3IFJ PAN, Kraków, Poland; 4IFIN-HH, Bucharest, Romania; 5INFN-Sezione di Catania, Italy; 6RBI, Zagreb, Croatia; 7Univ. of Zagreb, Croatia; 8Università di Catania, Italy;

Abstract

The proposed experimental program aims at putting new and more stringent constraints on the density dependence of the symmetry energy at supra-saturation densities. Densities toward 2ρo, indispensable for obtaining the constraints relevant for astrophysics, are expected to be reached in the proposed central heavy ion collisions. Proposed systems: Au+Au at 250, 400, 600 and 1000 AMeV. Such an energy scan can currently be performed only at the GSI/FAIR facility. Key observables: excitation function of the neutron, proton elliptic-flow ratios, directed and elliptic flows for n, p and isotropically resolved light clusters, yields and ratios, energy and angular distributions, correlation functions. The experimental setup will be based on the NeuLAND detector for measuring neutrons, protons and light charged clusters emitted from mid-rapidity. The main novelty of this proposal consists in using NeuLAND to obtain well resolved proton spectra allowing to probe effectively about 30% higher densities than with only elemental resolution. The setup will include also the KRAB plastic barrel surrounding the target for providing the multiplicity trigger and for estimating the centrality and the reaction plane orientation by covering polar angles beyond 30°, four double-rings of CHIMERA, and the R3B New Time-of-Flight Wall TOFD for extracting event-by-event the centrality and the orientation of the reaction plane at polar angles up to 30°. The START detector placed upstream of the target will provide the reference signal for the time of flight measurement and trigger. The KRATTA triple telescopes and the FARCOS array will be placed near the target for measuring light charged particles at mid-rapidity and at backward angles, respectively. Expected value added in nuclear and astrophysics: providing new constraints on the symmetry energy up to 2ρo from simultaneous measurement of n, p and isotropically resolved light charged particles. Specifically, the new measurement is expected to provide tighter constraints on the slope parameter L and entirely new ones on the, up to now very weakly constrained, curvature parameter Ksym. Probing the densities toward 2ρo is indispensable for meaningful comparisons with modern nuclear theories. The new data on flow patterns and correlations, and on competition between cluster and neutron and proton emissions will provide valuable constraints for the transport models aiming at describing and explaining these phenomena. Proposed measurement will provide results complementary to those obtained with the ground and satellite based X-ray telescopes and with the gravitational wave interferometers. The results are also expected to be competitive in terms of precision. The knowledge of the Symmetry Energy in a broad range of densities will provide a missing link for realistic simulations of astrophysical objects and processes. Expected instrumental value added: commissioning of the KRAB and FARCOS detectors.

Scientific Context and Motivation. The nuclear matter Equation of State (EoS) is one of the central topics in contemporary nuclear physics. In general, it describes the relation between density, pressure, energy, temperature and the isospin asymmetry δ = (ρn - ρp)/ρ, where ρn, ρp, and ρ are the neutron, proton and nuclear matter densities, respectively. For cold nuclear matter it is conventionally split into a symmetric normal nuclear matter density, ρν, leading to the following expression:

\[ E_{\text{sym}}(\rho) = E_{\text{sym,0}} + \frac{L}{3} \left( \frac{\rho - \rho_o}{\rho_o} \right)^3 + \frac{K_{\text{sym}}}{18} \left( \frac{\rho - \rho_o}{\rho_o} \right)^2 + \ldots \]

(1)

where the value of the symmetry energy at normal density \(E_{\text{sym,0}}\) = \(E_{\text{sym}}(\rho = \rho_o)\), the slope parameter \(L \equiv 3\rho_o \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \bigg|_{\rho=\rho_o}\), and the curvature parameter (symmetry compressibility) \(K_{\text{sym}} \equiv 9\rho_o^2 \frac{\partial^2 E_{\text{sym}}(\rho)}{\partial \rho^2} \bigg|_{\rho=\rho_o}\).

A theoretical determination of the nuclear EoS from first principles by microscopic calculations is challenging and a subject of current scientific research since several decades [2]. In fact, microscopic calculations of the density functional of nuclear matter employing different approaches to the nucleon-nucleon interaction predict...
rather different forms of the EoS. In particular, the dependence of $E_{\text{sym}}$ on density $\rho$ shows very different behaviors. Most calculations coincide at or slightly below normal matter density, which demonstrates that constraints from finite nuclei are active for an average density smaller than $\rho_0$ and surface effects play a role. In contrast to that, extrapolations to supra-normal densities diverge dramatically, calling for more tight experimental constraints in this region. However, significant progress is currently being made: recently, calculations based on chiral effective field theory ($\chi$EFT), combined with advanced statistical methods, have been able to predict the $E_{\text{sym}}$ at $2\rho_0$ with about 5% precision [3]. Nevertheless, heavy-ion laboratory experiments and astrophysical measurements, see below, are needed to validate theoretical findings.

The density dependence of the $E_{\text{sym}}$ is an important constituent for the determination of the drip lines, masses, densities, and collective excitations of neutron-rich nuclei [4, 5], for flows and multi-fragmentation in heavy-ion collisions at intermediate energies [1, 2], but also for astrophysical phenomena like supernovae, neutrino emission, and neutron stars [7], where knowledge on the high-density dependence of the $E_{\text{sym}}$ is most important.

In fact, one of the key question of modern physics is the determination of the mass vs radius relationship of neutron stars. While the (maximum) mass of neutron stars is mainly governed by the isoscalar nuclear matter equation of state, $E(\rho, 0)$, the radius of a neutron star is governed by the symmetry energy behavior at high density, around $2\rho_0$ [6]. In fact, the pressure of neutron matter at $2\rho_0$ is what is basically needed to determine the radius of a canonical neutron star; in [7], using a multitude of EoS obtained by polytrope expansion, a very tight correlation between pressure at $2\rho_0$ and radius of a $1.4M_\odot$ neutron star was obtained. A similar result was obtained in ref. [8] using about 100 EoSes of different kind. In [9] masses and radii of neutron stars were calculated from equations of state based on recent high-quality chiral nucleon-nucleon potentials. For a $1.4M_\odot$ neutron star predictions fall between 10.8 and 12.8 km. Moreover it was shown that the radius of a $1.4M_\odot$ neutron star is nearly insensitive to extrapolation beyond $2\rho_0$.

The main aim of this proposal is to determine the Symmetry Energy in the density region toward $2\rho_0$ which is relevant for realistic simulations of astrophysical objects and processes.

The discovery of gravitational waves has permitted a significant step-forward in this field. In binary neutron star merger events, like the one observed in the first evidence of gravitational wave GW170817 [12], one of the key observable is the so called tidal polarizability $\Lambda$, strictly correlated to the neutron stars radii. It follows that observation of GW opened-up new opportunities for determining radii of neutron stars, possible in the past only in few cases and with larger errors. Thus, the opening of multi-messenger astronomy including gravitational waves makes the study of the symmetry energy at high density even more intriguing than in the past, allowing now a direct and stringent comparison of data from terrestrial laboratories with astrophysical observations. A second event of binary neutron star merger GW190425 has been recently reported in [13]: there a pressure of $19-80\text{ MeV/fm}^3$ was estimated for neutron star matter at $2\rho_0$.

A large amount of studies have been recently published, where the constraint on symmetry energy from GW observation are compared with the ones early obtained in terrestrial laboratory; thus, relevant step-forward arises from comparison of results coming from nuclear and astro-physicists communities. As an example, in [14] Zhang and Li produced a restricted EoS parameter space using observational constraints on the radius, maximum mass, tidal polarizability and causality condition of neutron stars, resulting in an estimation of the Symmetry Energy at $2\rho_0$ of $46.9 \pm 10.1\text{ MeV}$. It is interesting to note that in a subsequent paper [15], the authors show that the observation of the 2.17 $M_\odot$ neutron star reduces the error to $\pm 9\text{MeV}$ and mention that it is unlikely that even heavier neutron stars will be observed because the value 2.17 $M_\odot$ is already close to the theoretical maximum according to several studies. In [16] a Bayesian analysis of GW170817 and quiescent low-mass X-ray binaries radii suggested the symmetry energy at $2\rho_0$ to be in the interval $31-51\text{MeV}$. In [17] the authors stated that while the tidal polarizability $\Lambda$ depends strongly on the details of the symmetry energy, different trends of $E_{\text{sym}}(\rho)$ lead to very similar values of $\Lambda$. Thus, measuring $\Lambda$ alone may not determine completely the density dependence of the symmetry energy; both nuclear laboratory experiments and astrophysical observations are therefore necessary to break this degeneracy and determine precisely the details of the symmetry energy. A similar conclusion comes from [19] where it was shown how observations of gravitational waves from binary neutron star mergers can be combined with insights from nuclear physics to obtain useful constraints on EoS of dense matter between one and two times the nuclear saturation density. Moreover, first results for the radius of a $1.4M_\odot$ neutron star from X-ray pulse-profile modeling have been reported by the NICER (Neutron star Interior Composition Explorer) collaboration very recently [20, 21]. It will be interesting to see the impact of the comparably large values of 12.7 km or 13.0 km with errors of $\pm 1.2$ km in comparison with the data from other sources.

The last two decades, meaningful constraints for the nuclear EoS have been obtained by laboratory experiments. Many results of nuclear structure and nuclear reaction measurements as well as astrophysical observations were collected and compared in [22] and [23]. Rather precise values of $E_{\text{sym}}$ have been evaluated for $\rho/\rho_0 \sim 0.6-0.7$ in [24] and [25] by fitting the properties of doubly closed-shell nuclei. Together with the results
of an analysis of isobaric analogue states [26] and from heavy ion reaction data [6], one obtains a quite consistent behavior of $E_{sym}$ at low densities [27].

As mentioned above, the $E_{sym}$ above $\rho_0$ can be accessed either by the determination of the masses and radii of neutron stars [23] or by employing observables in heavy ion collisions which are related to the early, high density phase of the reactions. A multitude of observables have been proposed to be sensitive to the $E_{sym}$ at supra-saturation densities (for a review see [1]): ratio of multiplicities or spectra of isospin partners (e.g. $\pi^-/\pi^+$, n/p or $^3/^4$He) and the comparison of their flows. The ratio of positively and negatively charged pions, as measured in the 1 AGeV regime for various collision systems by the FOPI collaboration [28], were well reproduced with the IBUU4 transport code [29] but only with a super-soft density dependence of $E_{sym}$. The incorporation of in-medium effects like mass-shifts of the pions, potentials, s-wave production of pions, and the properties of intermediate $\Delta$ resonances has been shown to lead to different and even opposite conclusions [30, 31], while describing the experimental data equally well, indicating a strong model dependence in the interpretation of the pion ratio. As a solution, it has been proposed to study not the integrated pion yield ratios but the ratios of pion spectra at high kinetic energies in the center of mass (CM) reference frame [32].

Experiments with this aim have been carried out at RIKEN with the SAMURAI magnet and the SPIRIT TPC in 2016 [33], and $\pi^-/\pi^+$ ratios in neutron rich and neutron poor Sn+Sn collision have been measured at 270 AMeV. The sensitivity to the symmetry energy is high around the pion production threshold but the range of densities effectively probed will be centered below saturation density [34]. In parallel to this experimental activity, a strong theoretical effort is being made, comparing pion predictions from several models within the code comparison project aiming to better understand and eventually reduce systematic differences between model predictions [35, 36, 37]. The aim is to support the interpretation of this new set of pion data.

Other observables which are known to be sensitive to $E_{sym}$ at supra-normal densities are collective flows. At energies below 1.5A GeV the reaction dynamics is largely determined by the nuclear mean field. The resulting pressure produces a collective motion of the compressed material whose strength will be influenced by $E_{sym}$ in isospin-asymmetric systems. The strengths of collective flows in heavy ion collisions are usually expressed with a Fourier expansion of the azimuthal distributions of particles around the reaction plane: $d\sigma(y)/d\phi \propto 1 + 2(v_1(y)\cos\phi + v_2(y)\cos 2\phi,....)$. The side flow of particles is characterized by the coefficient $v_1$ and the elliptic flow by $v_2$. The value of $v_2$ around mid-rapidity is negative at incident beam energies between 0.2 and 5 AGeV which signifies that matter is squeezed out perpendicular to the reaction plane. At intermediate energies (below 1.5A GeV), the elliptic flow of protons and composite charged particles emitted at midrapidity in heavy-ion collisions shows the strongest sensitivity to the nuclear equation of state (EoS) [38]. Thus, $v_2$ is a strong tool for constraining the strength of the mean field, of both isoscalar and isovector contributions. In fact, as an example, the EoS of symmetric matter was strongly constrained in [39] by the elliptic flow $v_2$ of protons, deuterons, tritons, $^3He$ and $^4He$ emitted around mid-rapidity in Au+Au collisions [40]. This study concluded in favor of a soft momentum dependent EoS when comparing with the IQMD model predictions [11]. This result has been more recently confirmed in a similar comparison, using UrQMD transport model calculations [42]. For the case of asymmetric matter, the ratio $v_2^{n}/v_2^{p(ch)}$ of the elliptic flow strengths of neutrons with respect to that of protons or light charged particles was recommended in [43] as a robust observable sensitive to the stiffness of the $E_{sym}$.

**Previous Experiments and Background.** The first attempt to constrain the $E_{sym}$ at high densities has been done in [43] by re-analyzing the existing FOPI-LAND data [44] on neutron and Hydrogen emissions obtained with the LAND [45] detector. The re-analysis yielded a moderately soft $E_{sym}$ dependence on density, with the slope parameter $L = 83 \pm 26$ MeV. Despite a large uncertainty, the result made it possible to rule out the extremely soft or stiff density dependencies of the symmetry energy [47]. It was, in particular, also possible to demonstrate that the effects of isoscalar-type parameters affecting the individual flows in the calculations largely cancel in the predictions for the flow ratios.

Motivated by this finding, an attempt was made to improve the accuracy with a new experiment that was conducted at the GSI laboratory in 2011 (ASY-EOS experiment S394 [48]). The experimental setup followed the scheme developed for FOPI-LAND by using LAND as the main instrument for neutron and charged particle detection. For the event characterization and for measuring the orientation of the reaction plane, three detection systems had been installed, the ALADIN Time-of-Flight (AToF)Wall [49], four double rings of the CHIMERA multidetector [50] carrying together 352 CsI(Tl) scintillators in forward direction and four rings with 50 thin CsI(Tl) elements of the Washington University Microball array [51] surrounding the target. A detailed description of the set-up of the ASY-EOS experiment and of the data analysis procedure is available in [48]. Constraints on the symmetry energy were obtained by comparing the experimental $v_2^{n}/v_2^{p(ch)}$ ratios, neutron over charged-particles, with those from the UrQMD simulations. Being not able for technical reasons to well identify protons has been one of the main drawback of that measurement, reducing also the maximum density effectively probed. A soft iso-scalar EoS was assumed for the simulations and the $E_{sym}$ was parametrized with
Figure 1: Left panel: constraints deduced for the density dependence of the symmetry energy from the ASY-EOS (orange band) and FOPI-LAND (yellow band) experiments, compared also to some low-density results. Right panel: Elliptic flow ratio of neutrons over charged particles measured in the same acceptance range for central ($b < 7.5$ fm) Au+Au collisions at 400 AMeV as a function of transverse momentum, $p_t/A$. The black squares represent the ASY-EOS experimental data. The green triangles and purple circles represent the UrQMD results employing a stiff and soft density dependence of the $E_{\text{sym}}$. The solid line is the result of a linear interpolation between the predictions leading to the indicated $\gamma = 0.75 \pm 0.10$. From ref. [48].

A Fermi-gas-like formula:

$$E_{\text{sym}}(\rho) = E_{\text{sym}}^{\text{pot}}(\rho) + E_{\text{sym}}^{\text{kin}}(\rho) = 22(\rho/\rho_0)^\gamma + 12(\rho/\rho_0)^{2/3} \text{ MeV}$$

with $\gamma = 0.5$ and $\gamma = 1.5$ corresponding to a soft and a stiff density dependence, respectively.

The main results of the experiment are shown in Fig. 1. From the fit of the measured flow ratios with a linear interpolation between the soft and stiff model predictions the exponent $\gamma = 0.75 \pm 0.10$ was obtained (right panel of Fig. 1). After taking into account all corrections and systematic uncertainties, the final value was found to be $\gamma = 0.72 \pm 0.19$, corresponding to a slope parameter $L = 72 \pm 13$ MeV [48]. The corresponding density dependence of the Symmetry Energy is shown in left panel of Fig. 1. It confirms the FOPI-LAND result and represents an improvement of the accuracy by a factor of two. The sensitivity of the measurement to the density that is probed with the flow ratio in the studied reaction is shown in Fig. 2. It is centered at approximately saturation density and extends beyond twice that value. The sensitivity distribution indicates that the flow ratio $v_2^2/v_3^3$ at this bombarding energy is well suited to measure the density dependence of the symmetry energy slightly above the saturation density $\rho_0$.

The ASY-EOS constraints suggest the 51-60 MeV interval for the $E_{\text{sym}}$ at $2\rho_0$ in partial overlap with above cited values of the Refs. [14, 16]. The obtained slope parameter $L = 72 \pm 13$ MeV, corresponding to a symmetry pressure $p_0 = 3.8 \pm 0.7$ MeV fm$^{-3}$, was used to estimate the pressure in neutron star matter at density $\rho_0$ [48]. The obtained value $3.4 \pm 0.6$ MeV fm$^{-3}$ is located inside the pressure interval obtained with 95% confidence limit by Steiner et al. from the observation of eight neutron-stars [52] and inside the 90% confidence interval of the pressure-density relation presented by the LIGO and Virgo collaborations [53]. The known tight correlation between the symmetry pressure $p_0$ and the radius $R_{1.4}$ of a canonical neutron star of 1.4 $M_\odot$ [9] has, furthermore, been used and a value $R_{1.4} = 12.6 \pm 0.7$ km was obtained [54]. It is in amazingly good agreement with the recently published radii $12.7 \pm 1.2$ km [20] and $13.0 \pm 1.2$ km [21] of the NICER collaboration, and the errors are very competitive. The ASY-EOS $R_{1.4}$ estimation agrees also with the values of Ref. [11] above reported. Since both GW and X-rays direct observation are in a starting phase, and ASY-EOS estimations in the $2\rho_0$ region should be taken as an extrapolation, these agreements should be considered as preliminary.

The comparisons illustrate the value of terrestrial measurements of the EOS of asymmetric matter to complement and possibly support astrophysical observations whose uncertainties are related to the complexity of the applied methods [55] or to serve as starting points for extrapolations to high densities exceeding $2\rho_0$ [56]. It has to be emphasized, however, that the UrQMD analysis of the ASY-EOS flow ratios relies on two assumptions. The expression for $E_{\text{sym}}$ (Eq. 2) assumes $E_{\text{sym}}(\rho_0) = 34$ MeV, leading to the sharp cross over of the error bands visible in Fig. 1. It does not reflect the present uncertainty of approximately 3 MeV of our knowledge of the symmetry energy at saturation [22, 57]. $E_{\text{sym}}(\rho_0) = 31$ MeV in the analysis reduces the resulting slope parameter to $L = 63 \pm 11$ MeV as reported in the ASY-EOS publication [48]. The second assumption is that of the functional form of a power law (Eq. 2) that, with the present results, is equivalent to assuming -70 MeV to -40 MeV for $K_{\text{sym}}$, an interval that does not at all correspond to our limited knowledge of the curvature term.
However, as shown by Cozma [58], these difficulties can be overcome with measurements performed at different energies and by exploiting the dependence of the sensitivity to density on the type of charged particles whose flow is selected for the comparison with the neutron flow (Fig. 2). The proposed measurements are intended to serve that purpose. Thus, a new experiment probing with high effectiveness the region toward $2\rho_0$ will allow to get better and more reliable constraints from terrestrial laboratories to be compared with new and more systematic data coming from astrophysical observations.

In [58], Cozma reported a more complete analysis of FOPI flow data, FOPI-LAND and ASY-EOS by using a QMD type transport model supplemented by a phase-space coalescence model fitted to FOPI experimental multiplicities of free nucleons and light clusters. Considering that calculation has proven that neutron-to-proton and neutron-to-charged particles elliptic flow ratios probe on average different densities, see below, and anchoring symmetry energy parametrization at the precise value available for $\rho = 0.1\text{fm}^{-3}$, Cozma extracted both the slope $L$ and curvature $K_{sym}$ parameters of the Symmetry Energy, as $L = 85 \pm 22(\text{exp}) \pm 20(\text{th}) \pm 12(\text{sys})$ MeV and $K_{sym} = 96 \pm 315(\text{exp}) \pm 170(\text{th}) \pm 166(\text{sys})$ MeV. Measuring at the same time yields and flow of LCP, as we plan to do, is a way to reduce the systematic error arising from light-cluster multiplicities not well reproduced by the models. Also a value of $L$, free of systematical theoretical uncertainties, was extracted from the neutron-to-proton elliptic flow ratio alone, $L = 84 \pm 30(\text{exp}) \pm 19(\text{th})$ MeV.

For the Au+Au case at 400A MeV, the specific density region tested by the flow ratio observable has been explored in [58] within the TüQMD model [59]. Two calculations have been performed there using a moderately soft and a stiff $E_{sym}$ dependencies up to a given density threshold and using a common intermediate dependence on density above that threshold. The Difference of Elliptic Flow Ratios, $DEFR$, with these two parametrizations has been then defined as an “observable” measuring the sensitivity of the density region below the threshold on the stiffness of the $E_{sym}$. The left top panel of Fig. 2 shows the $DEFR$ function for the $v_2$ ratios of neutrons to charged particles. It can be seen that the sensitivity achieved with the elliptic flow ratios increases with the density threshold and then saturates going toward the $2\rho_0$ region. To evaluate this more carefully, bottom panel shows the derivative of the $DEFR$ (solid line), to be used as a quantitative estimator of the sensitivity of the $v_2$-ratio observable to a given density region. Dashed and dash-dotted line report the same quantity but for $v_2$-ratio of neutrons with respect to Hydrogen’s or protons, respectively. For the Au+Au case at 400 AMeV, $v_2$-ratio of neutrons with respect to charged-particles or Hydrogen’s is mainly sensitive to a region centered slightly above saturation density, while the $n/p$ ratio sensitivity is centered around $1.4\rho_0$.

Thus, the direct measurement of $n/p$ ratio, instead of $n/\text{charged particles ratio}$, will enable more effective probing of much higher density region than was possible so far. This will be a very big step forward.

![Figure 2: Left panel: (top) TüQMD predictions of the $DEFR$ function for the ratio of elliptic flows of neutrons and charged particles for the Au+Au system at 400A MeV; (bottom) corresponding sensitivity density (solid line) together with the ones obtained from elliptic-flow ratios of neutrons over all hydrogen isotopes (dashed line) and neutrons over protons (dash-dotted line). From Ref. [48]. Right panel: IQMD predictions of the incident energy dependence of the average reduced density $<\rho/\rho_0>$ of protons in semi-central (impact parameter $b = 3\text{fm}$) collisions of $^{197}\text{Au} + ^{197}\text{Au}$ (with the soft momentum-dependent EoS "SM" which best reproduced the experimental data), for various space-time selections: (triangles) maximum value reached in the central volume of the collision, (circles) maximum value for protons ending-up in the phase space selected for constraining the EoS in [59] (reduced transverse velocity $u_0 > 0.4$ and reduced rapidity $|y_0| < 0.8$), (error bars) spread distribution (one sigma) of the time averaged value weighted by the force of the mean field felt by protons falling in the same phase space selection. See [39] for more details.](image)

This observation gives rise to the expectation that with an isotopic resolution sufficient for unambiguous
proton identification one should be able not only to constrain the slope of the $E_{\text{sym}}$, $L$, but also its curvature, $K_{\text{sym}}$, see eq. [11]. The latter is the least constrained experimentally and theoretically observable so far. The experimental constraint of [60] yields $K_{\text{sym}} = -50\pm200$ MeV. Another compilation [61] locates the theoretical value of $K_{\text{sym}}$ between $-400$ and $+466$ MeV and its experimental value in a range from $-566\pm1350$ MeV to $+34\pm159$ MeV. The results of Cozma [58] are given above. In Fig. 13 of this work it was also shown that for Au+Au semi-central collisions neutron-proton elliptic flow ratio sensitivities to L and $K_{\text{sym}}$ attain maxima at 600 and 250 AMeV, respectively, thus at quite different energies. Note that the potential terms that are proportional to L and $K_{\text{sym}}$ have different dependencies on density and, consequently, the forces generated by these two terms attain their maximum effectiveness at different regions of density; simplifying, the L term is proportional to the isospin asymmetry $\delta$, while the $K_{\text{sym}}$ term to $\delta\rho$. This explains why the maximum sensitivity for L and $K_{\text{sym}}$ do not occur for the same incident energies. This is another strong reason for measuring excitation function of neutron-proton elliptic flow observable.

Microscopic transport calculations predict that for a short time period ($\sim 20 \text{ fm/c}$) densities of up to $\sim 3$ times the saturation density can be reached in the central zone of a heavy-ion collision even at moderate incident energies $\sim 1\text{ A GeV}$, as demonstrated in Fig. 3. As an example, the right panel of Fig. 2 provides also convincing arguments that the maximum densities in the innermost center of the collision may reach up to $3.5\rho_0$ at 1.5 A GeV, while the densities probed by the mid-rapidity protons during the heavy ion collision may extend up to twice the saturation density, irrespectively of the transverse momentum cut. This finding comes from [39] and was obtained by analyzing the elliptic flow data of charged particles and employing the Quantum Molecular Dynamics code IQMD [41] for Au+Au collisions up to 1.5 AGeV. Analogously to the above mentioned DERF function used with TüQMD calculations, this study has given IQMD predictions of ranges of densities that are probed by the effect of the mean field in the elliptic flow, that is the "force-weighted" average density shown as error bars in the right panel of Fig. 2. It shows that for Au+Au collisions at 1A GeV, the typical densities directly influencing the flow by the way of the mean field span between $\rho_0$ and $2.2\rho_0$. Nevertheless, as demonstrated in [38], higher densities reached in the compressed central region of the colliding system (dubbed as "fireball") play also an indirect role in the strength of the elliptic flow, because they determine how fast the later expansion of the fireball will occur and modify the elliptic flow by the interplay between expanding fireball and flying away spectators. And the speed of this expansion is ruled by the strength of the mean field. Therefore, at 1A GeV, the influence of the EoS at $3\rho_0$ on $v_2$ cannot be ruled out. This conclusion applies also to the isovector part of the EoS. In the most compressed phase of the collision, it is expected that due to the symmetry energy, the neutron part in excess of the fireball will expand faster than protons, then will interact differently with the spectators, which will result in a different elliptic flow.

![Figure 3: Evolution of the central baryon density in $^{132}$Sn+$^{124}$Sn collisions at beam energies from 200 to 2000 AMeV for $b = 1 \text{ fm}$, as predicted by the hadronic transport model of [62].](image)

Therefore, according to the models, it is possible to access the $E_{\text{sym}}$ at higher densities by raising the beam energy. However, as the incident energy is increased the fraction of nucleons excited into baryonic resonances, mainly $\Delta(1232)$ at energies of 1 AGeV and below, in the highly compressed phase of the collision reaches values in the neighborhood of 20% [63] with potential impact on the time evolution of the reaction that may leave a comparable imprint on the $E_{\text{sym}}$ at 2-3 $\rho_0$ depending on the chosen observables. Thus, one should be aware that the highest density reached during a heavy-ion collision is not necessarily equivalent to the density that can safely be probed, i.e. without the occurrence of unmanageable systematic theoretical uncertainties, for the purpose of constraining the high density dependence of the $E_{\text{sym}}$, as discussed in [18, 39] and [38]. The ASY-EOS II measurements will provide powerful data to explore these delicate aspects.

**New Approach and Relevance to the Field.** The main novelty of the proposal consists in using the NeuLAND detector for measuring neutrons, isotopically resolved H and He isotopes in a broad energy range within the same acceptance. This will be the first measurement of this kind and quality, allowing the high density $E_{\text{sym}}$ to be pinned down with an unprecedented precision. Using the 12 double planes of NeuLAND to obtain isotopically well resolved proton spectra will allow us to effectively probe about 30% higher densities than was possible so far. New detectors, KRAB and FARCOS, will improve the precision and quality of the data as detailed below. Measuring excitation functions of flow observables will provide additional constraints
on $E_{\text{sym}}$ by scanning through a broad range of densities.

New tight constraints on the symmetry energy for densities reaching $2\rho_0$ will complement the results obtained with the X-ray telescopes and with the GW interferometers and are also expected to be competitive in terms of precision. The knowledge of the symmetry energy in a broad range of densities will provide the missing information for astrophysical predictions of the neutron star mass–radius relation and for realistic simulations of neutron stars, supernova explosions and nucleosynthesis.

Precise data on the symmetry energy and the inter-related phenomena of clustering and neutron and proton emissions as well as correlations between them will present strong constraints to nuclear transport theories. The data should allow theorists to address problems such as delta and pion production and dynamics, importance of three-body forces at high densities, cluster formation, and effective neutron and proton mass splitting related to the momentum dependence of the nuclear mean field.

OBJECTIVES, EXPECTED RESULTS AND THEORY BACKGROUND. The ASY-EOS experimental results proved the effectiveness of the $v_2^p/v_2^n$ ratio in constraining the high-density behavior of the $E_{\text{sym}}$. The method appears to be very robust and precise; we can notice that statistical errors smaller than 10% can be obtained. As seen in Fig. 2 (right panel), although the accurate ASY-EOS determination of the $E_{\text{sym}}$ is estimated to have reached the supra-saturation density region, which was already a unique achievement, there remains a strong need for constraining it further, with an even better precision given by the more effective $v_2^p/v_2^n$ ratio, toward $\sim 2\rho_0$. SIS@GSI provides a unique tool to probe such densities with heavy-ion collisions. Simulations of semi-central Au+Au collisions at 250, 400, 600, 800, 1000 and 1500 AMeV and, for comparison, neutron rich $^{132}\text{Sn}+^{124}\text{Sn}$, $^{124}\text{Sn}+^{24}\text{Sn}$ and Pb+Pb systems at 400, 600 and 800 AMeV have been carried out by using the same version of the UrQMD transport model already used in [18]. The neutron-to-proton elliptic flow ratio, $v_2^p/v_2^n$, at mid-rapidity ($0.4 < y_{\text{lab}}/y_{\text{proj}} < 0.6$), with a stiff ($\gamma=1.5$) and a soft ($\gamma=0.5$) parametrization of the potential part of the $E_{\text{sym}}$ for semi-central ($b_{\text{cent}} < 0.54$) collisions is shown, as a function of the incident beam energy, in the left panel of Fig. 4. The difference of such $v_2^p/v_2^n$ ratios between the stiff and soft choices can be taken as the sensitivity of the proposed observable, and is shown in the right panel of the same figure.

The obtained sensitivity decreases with increasing the beam energy, because the mean-field contribution decreases at higher energies where the two-body collisions start to dominate. Nevertheless, up to 1 AGeV the sensitivity of the proposed observable is $\sim 15\%$, while a measurement can easily reach a $\sim 5\%$ accuracy, allowing clear discrimination between stiff and soft choices.

A similar conclusion can be drawn from a recent paper [61] where UrQMD simulation with 11 selected Skyrme forces was performed. In Fig. 3 of that paper, the ratio between the elliptic flow parameter of free neutrons and protons was plotted as a function of the slope parameter L for Au+Au collision from 400 to 1000 AMeV. The highest sensitivity was there obtained at 400 AMeV, while sensitivity at 1000 AMeV was reduced by a factor 2.

Sensitivity of the Au+Au systems is similar to the one of the other neutron rich systems, even in the case of $^{132}\text{Sn}$ radioactive ion beams. Heavier systems, Pb and Au, present smaller statistical errors, for the same numbers of simulated events. It is also important to stress the differences in trends (slopes) observed in left panel of Fig. 3. For the soft EoS the ratios increase with the energy while for the stiff EoS the trend is opposite. This proves the needs for measuring the excitation functions of these observables and the importance of using neutron rich beams where the effect is stronger. We have verified that by filtering the simulations for the acceptance of the common neutron and proton detector (NeuLAND, see below) does not change the results.
shown for the sensitivity of the proposed observable.

In order to convince ourselves that this level of sensitivity to the symmetry energy is not just peculiar to the UrQMD approach, we have performed simulations with other transport models, among them with the IQMD [11]. We show predictions in left panel of Fig. 5 for the same systems as in Fig. 4. Comparing with UrQMD, we observe qualitatively similar trends, except for a higher predicted sensitivity for the highest incident energy. The right panel of Fig. 5 shows the predictions of the TiQMD transport model [59] which have been performed within the acceptance cut of the FOPI-LAND experiment, but using two extreme cases for the $E_{sym}$ parametrizations, i.e. the $x=-2$ super-stiff and $x=2$ super-soft cases. Also in this case we find a decreasing sensitivity with the increasing beam energy, with a strong sensitivity of the flow ratios even at the highest beam energies between the two extreme super-stiff and super-soft choices. Note here that when using hydrogen isotopes instead of protons, this sensitivity is reduced. This emphasizes again the necessity to experimentally separate the hydrogen isotopes.

![Figure 5: Left panel: same as right panel of Fig. 4 but with the predictions of the IQMD model [11] at $b=6$ fm. Right panel: Similar to right panel of Fig. 4 with the predictions of the TiQMD model [59] for mid-central collisions ($b < 7.5 \text{ fm}$) of the Au+Au system. The magenta curve provides in addition the flow ratio obtained when taking all hydrogen isotopes instead of protons.](image)

Measuring the excitation functions will provide an additional constraint on $E_{sym}(\rho)$ through the trends. Availability of the high resolution neutron detector with a capability to resolve LCPs and relativistic stable heavy ions makes the upcoming FAIR-Phase-0 facility a unique place to perform proposed measurements. In the future, once the new R3B-cave will be available, we plan to pursue this kind of studies by profiting from the radioactive heavy ions and detectors there installed.

**Experimental Design, Methods, Set-Up, Technical Requirements**

The set-up that we propose to use in the experiment is sketched in Fig. 6. Eight rings of CsI(Tl) of CHIMERA [59], covering the polar angular regions. The outstanding calorimetric properties of NeuLAND will allow protons and other hydrogen isotopes to be relatively well separated, and will give access to the neutron vs proton observables. The NeuLAND demonstrator was a part of the SPIRIT experiment [33] carried out at RIKEN in 2016 and the capability of resolving both protons and neutrons was clearly demonstrated there. The identification plot of hydrogen isotopes in the demonstrator (4 double planes, 40 cm total thickness) is presented in the left panel of Fig. 7. The p, d, t lines are clearly resolved up to the punch through energy (about 260 MeV for protons) above which the characteristic back-bendings occur.
The foreseen 12 double planes of NeuLAND, resulting in a total depth of 120 cm, will assure stopping of protons up to about 500 MeV. A simulated identification plot for the Au+Au collisions at 400 AMeV is presented in the right panel of Fig. 7. Indeed, no punch-through segments are observed at this energy and the p, d, t lines clearly stick out of the secondary reaction and multi-hit background. The simulations include tracking, the secondary reaction losses, multiple Coulomb scattering, light propagation in plastic scintillators and quenching effects. The estimated efficiency for proton identification amounts to about 64% at 200 MeV and 36% at 400 MeV. Taking into account the thickness of the NeuLAND calorimeter and the secondary reaction and scattering probability, the estimated efficiencies are still impressive. The identification capability within the punch-through segments at higher energies can be improved by applying statistical methods including regularized decomposition as shown in [66].

With NeuLAND in its start-up version, consisting of 120 cm detector depth (12 double planes), the one neutron interaction probability is about 70% at 400 MeV [67]. Taking into account also the reconstruction efficiency a five-neutron event is recognized with correct neutron multiplicity with a probability of about 20 to 30% (200 to 1000 MeV).

NeuLAND will be placed 5.8 m away from the target covering effectively the mid-rapidity regions, i.e., the polar angles between $33^\circ$ and $57^\circ$. In order to better discriminate neutrons from protons/LCP a second TOFD will be placed at a distance of 2 m from the target, in geometrical correspondence with the NeuLAND, playing a role of the veto wall.

The KRAB (KRAkow Barrel) detector [68] has been designed to provide a fast trigger signal based on the multiplicity threshold as well as precise azimuthal distributions for charged particles beyond the angular
acceptance of the CHIMERA+TOFD setup. The main features of the KRAB detector are: 5 rings of $4 \times 4 \text{ mm}^2$ fast scintillating fibers (BCF-10, SciFi) read out by the MicroFJ-30035-TSV SiPMs, covering polar angles from $30^\circ$ to $165^\circ$ with $\sim 87\%$ geometrical efficiency and with $\sim 5\%$ multi-hit probability. It will be sufficiently large for radioactive beams and sufficiently small and lightweight in order not to disturb neutrons, having the min and max internal radii of 6.9 and 11.5 cm and a length of $\sim 50 \text{ cm}$. It will consist of $4 \times 160$ segments in forward rings and 96 segments in the backward ring with a total of 736 channels. The mechanical structure holding the SciFi segments and the front end electronics has been 3D-printed with the ABS filament. The SiPMs will be read out and controlled using the 32 channel CITIROC ASICs. In the ASY-EOS experiment the backward region was covered by the MicroBall detector consisting of 50 CsI(Tl) crystals arranged in 4 rings. It was used to roughly define the reaction-plane orientation in the backward region. In addition the correlation between the impact vectors deduced from the backward and forward azimuthal distributions measured by the MicroBall and CHIMERA detectors was found to be of fundamental importance to efficiently reject the off-target upstream reactions in air. Thanks to its high segmentation, the KRAB detector will allow to measure precisely the azimuthal distributions which are indispensable for high resolution estimates of the reaction plane. It will also produce a fast trigger based on total multiplicity in an angular region of $\theta > 30^\circ$ where a strong correlation between the multiplicity and the magnitude of the impact parameter is expected from the model predictions. This will allow for more precise centrality estimates than with the CHIMERA detector alone. Moreover, the design of KRAB assumes construction of a “helium sleeve”, with the target holder inside. Simulations indicate that this should reduce the number of unwanted hits caused by delta-electrons by a factor of about 30. Thus, it is expected that KRAB should greatly improve the quality of the data with respect to the first ASY-EOS experiment. The design and the actual view of the KRAB detector are presented in Fig. 8.

Figure 8: Left panel: The design of the KRAB detector including the CITIROC boards; Right panel: The actual view of the KRAB as of the end of March 2020.

In addition, yields and flows of LCPs at mid-rapidity and at backward angles will be measured by using the KRATTA triple telescope array \cite{69} and the Femtoscope Array for Correlations and Spectroscopy (FARCOS) \cite{70}, respectively. Measuring precisely yields and isotopic compositions of clusters emitted at mid-rapidity and from the target-spectator is of fundamental importance for advanced tuning of clusterization algorithms used in the transport models to get more realistic predictions from them. In fact clustering influences also the predictions of neutron/proton yields and flows, with clusters acting as absorbers of the otherwise free nucleons. Moreover, transport models predict a sensitivity of the ratio of yields and flows of light isobar nuclei to the high density behavior of the $E_{sym}$\cite{71}, and measuring isotopic composition of clusters will allow the use of thermodynamic methods (thermometry) to study properties of the emitting sources, such as their temperature. The high angular resolution of FARCOS, $\sim 0.25^\circ$ will perfectly suit the measurements of particle-particle correlation functions \cite{72} and, through interferometry, will allow for characterization of space-time properties of emitting sources.

**Justification of Beamtime Request.** The system/energies we want to measure in the proposed campaign are:

$^{197}\text{Au} + ^{197}\text{Au}$ at 250, 400, 600, 1000 AMeV

Motivation of the 4 energies is the following:

- the 250 AMeV energy, according to calculations shown in Fig. 13 of \cite{58}, is the energy showing the highest sensitivity on $K_{sym}$; this energy corresponds to the dynamic range of KRATTA assuring clean p, d, t identification without punch-through segments;
- the 400 AMeV energy is the one measured in the past ASY-EOS experiment and is necessary as a reference
point, capable of unveiling systematic difference between the new and old measurements; this is the energy of the maximum squeeze-out, it also assures no punch-through segments in NeuLAND identification maps;

- the 600 AMeV energy, according to calculations shown in Fig. 13 of [58], is the energy showing the highest sensitivity on L;

- the 1000 AMeV energy is the energy allowing to explore the highest densities where the neutron/proton elliptic flow observable keeps a significant sensitivity (\(\sim 15\%\)) to symmetry energy parametrization, according to the UrQMD calculations of Fig. [3].

Let us stress again the importance of measuring all these energies to provide additional constraint on the Symmetry Energy through the observed trends, which are expected to be opposite for the soft and stiff assumptions (see Fig. [4]).

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