THE SYMMETRY ENERGY AT HIGH DENSITY: EXPERIMENTAL PROBES*

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The symmetry energy, *i.e.* the difference between the energy densities of pure neutron matter and of symmetric matter, is essential for nuclear physics and astrophysics but still insufficiently known, in particular, at high density. Heavy-ion reactions at relativistic energies offer unique possibilities for studying compressed nuclear matter in the laboratory. The elliptic flow in collisions of neutron-rich heavy-ion systems has been identified as an observable sensitive to the strength of the symmetry energy at supra-saturation densities. First results obtained by comparing ratios or differences of neutron and hydrogen flows with predictions of transport models favor an approximately linear density dependence, consistent with *ab initio* nuclear-matter theories.

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1. Introduction

The symmetry energy is known to us from the Bethe–Weizsäcker formula in which it accounts for the dependence of atomic masses on the isotopic composition. More refined mass-formulae exhibit individual bulk and surface terms, reflecting the dependence of the symmetry energy on density. In the Fermi-gas model, the density dependence is given by a proportionality to $(\rho/\rho_0)^\gamma$ with an exponent $\gamma = 2/3$ ($\rho_0 \approx 0.16$ nucleons/fm^3 is the saturation density). The coefficient of this so-called kinetic contribution to the symmetry energy is $\epsilon_{\rm F}/3$, where $\epsilon_{\rm F} \approx 28$ MeV is the Fermi energy. The kinetic part thus represents only about 1/3 of the symmetry term of ≈ 30 MeV for nuclear matter at saturation. The major contribution is given by the potential term reflecting properties of the nuclear forces.

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For nuclear matter, the symmetry energy $E_{\rm sym}$ is defined as the coefficient of the quadratic term in an expansion of the energy per particle in the asymmetry $\delta = (\rho_n - \rho_p)/\rho$, where ρ_n, ρ_p, and ρ represent the neutron, proton, and total densities, respectively,

$$E/A(\rho,\delta) = E/A(\rho,\delta=0) + E_{\rm sym}(\rho)\,\delta^2 + \mathcal{O}\left(\delta^4\right)\,. \tag{1}$$

In the usual quadratic approximation, the symmetry energy is the difference between the energies of neutron matter ($\delta = 1$) and symmetric matter ($\delta = 0$).

A variety of predictions for the nuclear equation of state has been obtained from microscopic many-body theory [1]. The examples shown in Fig. 1 for the symmetry energy demonstrate that, overall, the results are quite compatible among each other, except for densities exceeding saturation for which the predictions diverge. The uncertainty is mainly related to our lacking knowledge of the short-range behavior of the nucleon–nucleon force [1, 2].

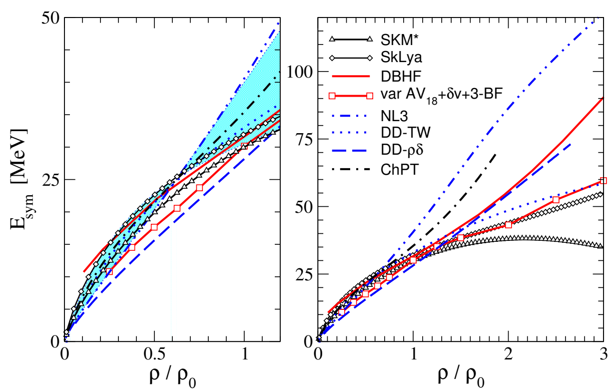

Fig. 1. Symmetry energy as a function of density as predicted by different models. The left panel zooms the low density range up to saturation. The full lines represent the DBHF and variational approaches using realistic forces (from Ref. [1], reprinted with kind permission from Springer Science+Business Media).

The symmetry energy influences properties of nuclei in their ground states and collective modes and governs properties of neutron stars, such as their internal structures, their radii and moments of inertia, and their cooling rates after formation in a supernova collapse. Understanding and modeling these processes requires knowledge of the symmetry energy over a wide range of densities [3]. As the symmetry energy appears in nearly every aspect of nuclear structure and reactions, many constraints exist in the density regime near and below saturation [4]. Experimental information on the high-density behavior has recently emerged from studies of the elliptic flow in collisions of neutron-rich heavy-ion systems (see Ref. [5] for a brief introductory review).

2. High-density probes

Densities of up to twice or three times normal nuclear density may be reached in central heavy-ion collisions at incident energies of several hundred MeV to one GeV per nucleon [6]. The search for observables suitable for extracting relevant information on the high-density matter produced during the brief initial collision phase has mainly concentrated on collective flows and meson production [7, 8]. They appear as promising candidates also for the study of asymmetric matter.

Transport theory, required to follow the temporal evolution of the collision, uses simplified parameterizations of the symmetry energy in order to keep the calculations on a tractable level. In the ultrarelativistic QMD (UrQMD) model of the group of Li and Bleicher [9], the potential part of the symmetry energy is defined with two parameters, the value at saturation density, typically 20 to 22 MeV, and the power-law coefficient γ describing the dependence on density as $(\rho/\rho_0)^\gamma$. In other models, the nuclear potential of Das *et al.* [10] with explicit momentum dependence in the isovector sector is used. Examples of these parameterizations and of results obtained from the analysis of experimental reaction data are given in Fig. 2.

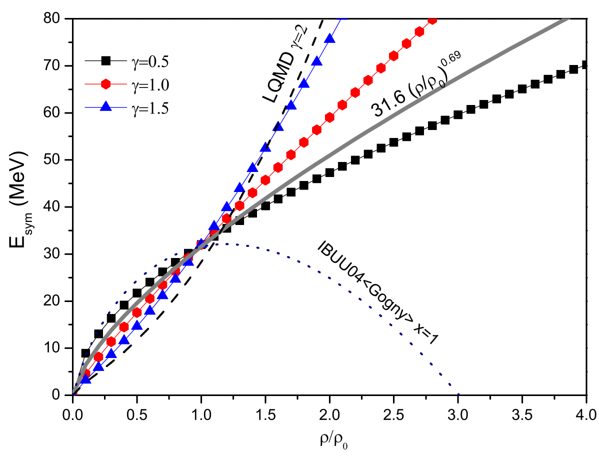

Fig. 2. Parameterizations of the nuclear symmetry energy as used in the UrQMD (Ref. [9]) with power law coefficients $\gamma = 0.5, 1.0$, and 1.5 (lines with symbols as indicated), the result with $\gamma = 0.69$ obtained in Ref. [11]), and the super-soft and stiff parameterizations deduced from the π^-/π^+ yield ratios with the IBUU04 (dotted line, Ref. [12]) and the ImIQMD (dashed line labeled LQMD, Ref. [13]) transport models (from Ref. [14], reprinted with kind permission from Springer Science+Business Media).

Probes considered as very promising as, *e.g.*, K^+/K^0 production ratios have turned out to be only weakly sensitive to the density dependence of the symmetry energy when measured double ratios were compared to transport calculations [15]. An even more puzzling situation was encountered in the analysis of the π^-/π^+ yield ratios measured at a variety of energies up to 1.5 GeV per nucleon and for several symmetric collision systems up to ^{197}Au + ^{197}Au by the FOPI Collaboration [16]. The conclusions were found to be highly model dependent, ranging from a rather stiff to a super-soft behavior of the symmetry energy [12, 13, 17].

The motivation for studying elliptic flows has been provided by UrQMD calculations which indicated a significant sensitivity of elliptic flow to the assumptions made for the density dependence of the symmetry energy [18]. Calculations with different choices for the power-law parameter γ predicted a larger neutron squeeze-out in the a-stiff ($\gamma = 1.5$) than in the a-soft case ($\gamma = 0.5$). Relative to each other, the neutron and proton elliptic flows were found to vary by about 15%. Squeeze-out refers to collective emissions perpendicular to the reaction plane.

3. Elliptic flow from FOPI/LAND

A data set to test these predictions has been available from earlier experiments of the FOPI/LAND Collaboration. It was originally collected and shown to provide evidence for the squeeze-out of neutrons emitted in ^{197}Au + ^{197}Au collisions at 400 MeV per nucleon [19]. The capability of the Large Area Neutron Detector LAND used in these experiments of detecting neutrons as well as charged particles permitted the differential analysis of the observed flow patterns in the form of flow ratios [18] or flow differences [20], expected to enhance isovector with respect to isoscalar effects in the reaction dynamics. The elliptic flow is conventionally expressed in the form of the parameter v_2 which is the second-order coefficient of a Fourier decomposition of the azimuthal distributions measured with respect to the orientation of the reaction plane (see, *e.g.* Refs. [18, 21]).

The measured ratio of neutron *versus* hydrogen flows is shown in Fig. 3 as a function of the transverse momentum p_{t}. The results of the UrQMD model for the two cases a-stiff ($\gamma = 1.5$) and a-soft ($\gamma = 0.5$) reflect the sensitivity to the density-dependent symmetry energy. The experimental ratios, even though associated with large errors, scatter within the interval given by the two calculations. A linear interpolation between the predictions yields $\gamma = 1.01 \pm 0.21$. After assessing statistical and systematic uncertainties, a value $\gamma = 0.9 \pm 0.4$ was adopted by the authors, representing a moderately soft to linear density dependence of the symmetry energy. It is compatible with experimental results for densities below saturation and supports predictions of microscopic calculations using realistic forces (*cf.* Fig. 1).

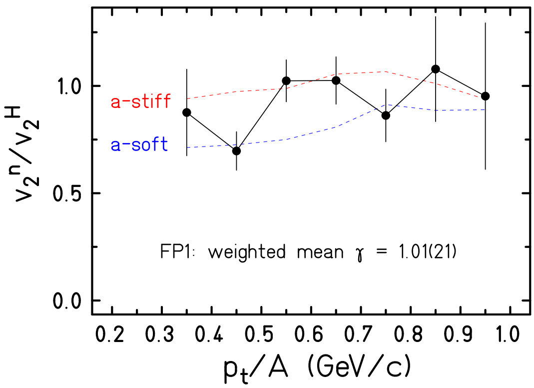

Fig. 3. Ratio of the elliptic flow parameters v_2 for neutrons and hydrogen isotopes for moderately central ($b < 7.5$ fm) collisions of ^{197}Au + ^{197}Au at 400 MeV per nucleon as a function of the transverse momentum per nucleon p_t/A. The symbols represent the experimental data. The UrQMD predictions for $\gamma = 1.5$ (a-stiff) and $\gamma = 0.5$ (a-soft) obtained with the FP1 parameterization for elastic nucleon–nucleon cross sections [22] are given by the dashed lines (adapted from Ref. [18], Copyright (2011), with permission from Elsevier).

In an independent analysis, Cozma [20] has used data from the same experiment and investigated the influence of several parameters on the difference between the elliptic flows of protons and neutrons using the Tübingen version of the QMD transport model. A super-soft behavior of the symmetry energy was confirmed to be excluded by the comparison with the experimental flow data. More recently, a thorough investigation of the parameter dependence led to the conclusion that the overall model dependence is small enough to prevent it from concealing the sensitivity of the differential flows to the strength of the symmetry energy at high density [23].

4. Conclusion and outlook

The consensus emerging from studies near or below saturation, indicating a moderately soft density dependence of the symmetry energy, is very encouraging [4]. However, more direct observables probing nuclear matter at higher densities will still be needed. The squeeze-out observed in ^{197}Au + ^{197}Au collisions at 400 MeV per nucleon indicates a moderately soft to linear behavior of the symmetry energy that is consistent with the density dependence deduced from heavy-ion reactions at lower energies and from nuclear structure experiments. The statistical uncertainty of the existing data is, however, larger than the systematic effects investigated so far. Highly improved results may thus be expected from the new experiment conducted by the ASY-EOS Collaboration at the GSI Laboratory [24, 25].

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