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The Density Dependence of the Symmetry Energy in Heavy Ion Collisions

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The density dependence of the nuclear symmetry energy is important from very low densities in supernova explosions, to the structure of neutron rich nuclei around saturation density, and to several times saturation density in neutron stars. Heavy ion collisions are the only means to study this density dependence in the laboratory. We discuss the knowledge and uncertainty of the symmetry energy and the parameterizations used in heavy ion collisions. Transport theories are necessary to extract the symmetry energy from heavy ion collisions and we discuss their uncertainties and challenges. We finally study in detail two examples, which relate particularly to the high density symmetry energy, which is of particular interest today. These are the pre-equilibrium emission of nucleons and light clusters, and the π^-/π^+ yield ratios. For the last case we point out the inconsistencies in the theoretical analyses of different groups and we discuss the open problems.

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1. Introduction

The nuclear symmetry energy together with the Coulomb energy governs the composition of nuclear systems from stable and exotic nuclei to astrophysical objects. Thus the symmetry energy (SE) is not only of interest around saturation density as in nuclei but also for very dilute matter as in supernovae to several times saturation density in the interior of neutron stars. Therefore the density dependence of the SE is a topic of great interest today and considerable experimental as well as theoretical efforts are devoted to put constraints on it[1].

From the study of nuclei one may gain information on the value of the SE at saturation and also on the slope at saturation, which is proportional to a symmetry pressure. It is strongly correlated to many nuclear properties, like the shift of isobaric analog states (IAS), the pygmy dipole resonance (PDR), and, in particular, to the difference of neutron and proton radii, the so-called neutron skin, of heavier nuclei, and substantial efforts are being undertaken to determine it as model-independently as possible[2, 3].

To investigate a wider range of densities heavy ion collisions (HIC's) are the prime opportunity in the laboratory. One may choose the density regime by variation of incident energy and impact parameter, and vary within limits the asymmetry of the system. The advent of intense secondary radioactive beams will substantially widen the opportunities. On the other hand HIC's are a strongly non-equilibrium processes and require a thorough and reliable modeling of the collision dynamics via transport theories.

Increasingly stringent constraints on the density dependence of the SE come from ever more refined observations of neutron stars[4]. The recent observation of a two solar-mass neutron star with a very small error sets a stringent limit on many models, together with increasingly tight limits on neutron star radii[5]. For the determination of the density dependence of the SE a close cooperative effort from heavy ion collisions and astrophysics is desirable.

This contribution aims to give a brief overview of the conditions and challenges in the determination of the SE in HIC's. We will first discuss the knowledge and parameterizations of the density dependence of the SE, to clarify the relation between them. We will then discuss the challenges to transport descriptions of HIC's. Finally we will give two examples to illustrate these, the pre-equilibrium emission of nuclei and light clusters, and the production of pions. This work results from a longtime collaboration with the Catania group, referenced in more detail in the Acknowledgement.

2. The Nuclear Symmetry Energy

The nuclear SE is best known from the Bethe-Weizsäcker mass formula via the symmetry term $a_s(N-Z)^2/A^2$, which parametrizes the global asymmetry dependence of the binding energy (BE) of nuclei. The density dependent SE is defined via the expansion of the BE per nucleon in infinite nuclear matter (without Coulomb interactions) $E(\rho,\beta) = E_{nm}(\rho) + E_{sym}(\rho)\beta^2 + \mathscr{O}(\beta^4)$ in terms of the asymmetry $\beta = (\rho_n - \rho_p)/\rho$. Then $E_{nm}(\rho)$ is the equation-of-state (EOS) of (symmetric) nuclear matter, and $E_{sym}(\rho)$ is the density dependent SE due to the strong interaction, which is the quantity of interest here. The observation that in empirical parameterizations of the SE one usually has $a_s \approx E_{sym}(0.6\rho_0)$, where $\rho_0 \approx 0.16 fm^{-3}$ is the saturation density, i.e. the minimum of $E_{nm}(\rho)$, is due to the fact that finite nuclei are not uniform in density.

From the above definition the SE is given as $E_{sym} = \frac{1}{2}\frac{\partial^2 E(\rho,\beta)}{\partial \beta^2}$. In the approximation that the higher order terms in β^2 are small, it can also be defined as the difference between the energy of pure neutron matter ($\beta = 1$) and that of symmetric nuclear matter $E_{sym}(\rho) = E(\rho,1) - E(\rho,0)$. In this definition the SE is different if for larger β there are deviations from the quadratic behavior. This, e.g. has been observed in very dilute matter, where clustering effects become important. Usually the last form of the SE is accepted as the more general definition.

Two parametrization have been widely used to characterize the SE near saturation density in a simple way:

$$E_{sym}(\rho) = S + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + ..., \tag{2.1}$$

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho) + E_{sym}^{pot}(\rho) = \frac{1}{3}\varepsilon_F(\rho-\rho_0)^{\frac{2}{3}} + C\left(\frac{\rho}{\rho_0}\right)^{\gamma}. \tag{2.2}$$

The first is to expand the SE around the saturation density, with S, the SE, L the symmetry slope (or symmetry pressure) and K_{sym} the symmetry incompressibility. The second representation writes the SE with a kinetic and a potential contribution, where the kinetic term resulting from the difference in the Fermi energies of neutrons and protons is given in the Fermi gas model. The parametrization of the potential term as a power γ in the density is purely phenomenological. Both forms are two-parameter representations of the SE in the neighborhood of ρ_0, and, of course, there is a correspondence $(C,\gamma) \leftrightarrow (S,L)$.

The values of L, resp. γ, determine, how rapidly the SE rises with density. Accordingly the SE is termed as stiff (asy-stiff) for larger values of L or $\gamma > 1$, and soft (asy-soft) in the opposite case. One should note that for the same S a stiff SE has smaller values than a soft one for $\rho < \rho_0$, and opposite for $\rho > \rho_0$. Thus the qualitative effects of a stiff/soft SE change at ρ_0. Many effects in nuclear structure depend on both S and L, and constraints from observations have been expressed as correlations between S and L. In particular, from fits to nuclear masses, a strong correlation between S and L appears[6]. Often in such correlation diagrams also constraints from observables that probe very different density regimes away from ρ_0 are included. Obviously, such extrapolations to ρ_0 are only valid within a given model of $E_{sym}(\rho)$ and are therefore of limited general validity.

More realistic parameterizations of the SE have been developed in the framework of Skyrme functionals[7]. Such versions are used by the Texas group[1] and are characterized by a parameter x, which changes the symmetry energy without changing the isoscalar EOS, and by the Catania group in the generalization by Bombaci[8]. A common feature of these functionals is that they include a momentum dependence not only of the symmetric EOS but also of the SE, and thus also of the Lane potential, the difference between neutron and proton potentials, even though the experimental data are rather limited here. The momentum dependence can also be expressed in terms of the effective masses, which are given as $\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$, where the index q stands for neutrons and protons. A momentum dependent symmetry potential thus leads to different neutron and proton effective masses. The effective masses effect will become more important for the higher energies, i.e. at those energies where one explores the higher densities. Thus for the investigation

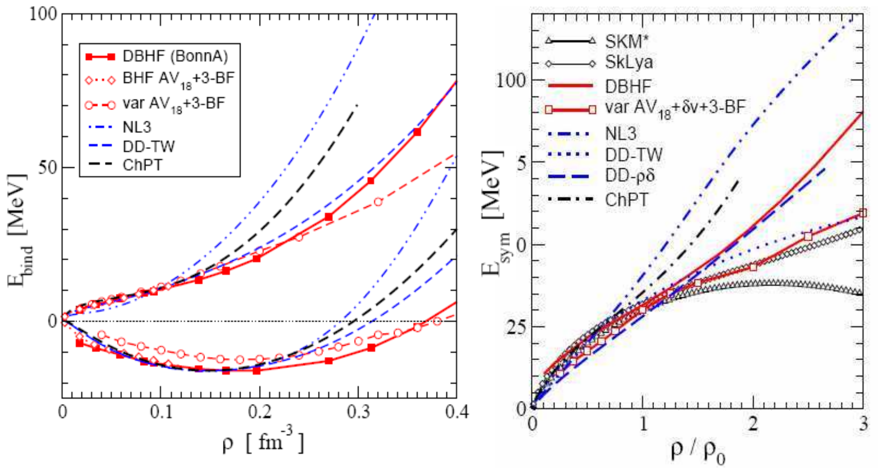

Figure 1: (left) The energy density for symmetric nuclear matter (lower curves) and for pure neutron matter (upper curves) for different theoretical approaches given in the legend. On the right the corresponding symmetry energy densities.

of the high density SE the momentum dependence or the effective mass effect has to be taken into account, as will be seen below.

There have been and continue to be intense discussions about the density dependence of the SE from the viewpoint of microscopic many body calculations. A compilation of several of such results[9] is given in Fig. 1, in the left panel separately for neutron and nuclear matter, and in the right panel for the SE as the difference between the two. The approaches represented range from variational calculations, Brueckner-HF theories, Chiral perturbation theory and phenomenological RMF or Skyrme forces. It is evident that for nuclear matter the theories agree fairly well for $\rho < \rho_0$, where they are constrained by nucleon-nucleon and nuclear data. There are more deviations above ρ_0, but from the study of HIC's over many years the EOS of symmetric nuclear matter has been fairly well constrained as soft-momentum dependent. However, for the SE the microscopic approaches deviate from each other much more strongly. They cross at a density somewhat below ρ_0 due to the constraints of finite nuclei as mentioned above. Thus the deviations are less severe but still important below ρ_0. However, there are drastic differences in the predictions for the high density SE, which is the area of prime concern today. Generally one could say that the microscopic SE's fall into the range of stiff to medium soft $(0.5 < \gamma < 1.)$. Note also, that these results do not necessarily show the behavior of simple power law, as seen e.g. for the DBHF result. The question, why microscopic calculations of the SE are so uncertain is being extensively discussed. It seems to be linked to the asymmetry dependence of the short range correlations[10], i.e. to the tensor forces, or, expressed differently, by the medium mass dependence of the ρ-meson[11]. Another approach has been made in the framework of chiral effective field theory[12].

3. The Symmetry Energy in Heavy Ion Collisions

The prime method to investigate the density dependence of the SE in the laboratory are HIC's. However, the EOS and thus also the SE are equilibrium concepts, while HIC's are strongly dynamical processes, which need to be interpreted within a non-equilibrium description. The main method to do so have been transport theories. They describe the temporal evolution of the one-body phase-space distribution function $f(\mathbf{r},\mathbf{p},t)$ under the action of a mean field potential $U(\mathbf{r},\mathbf{p})$, possibly momentum dependent, and 2-body collisions with the in-medium cross section$\sigma(\Omega)$[13]

$$\begin{aligned}\frac{df_i}{dt} &= \frac{\partial f_i}{\partial t}+\frac{\mathbf{p_i}}{m}\nabla^{(r)}f_i-\nabla^{(r)}U_i(\mathbf{r},\mathbf{p})\nabla^{(p)}f_i-\nabla^{(p)}U_i(\mathbf{r},\mathbf{p})\nabla^{(r)}f_i \\ &= \sum_{j,i',j'}\int d\mathbf{p_j}d\mathbf{p_{i'}}d\mathbf{p_{j'}}v_{ij}\sigma_{i,j\to i',j'}(\Omega)\delta(\mathbf{p_i}+\mathbf{p_j}-\mathbf{p_{i'}}-\mathbf{p_{j'}}) \\ &\quad \times[(1-f_i)(1-f_j)f_{i'}f_{j'}-f_if_j(1-f_{i'})(1-f_{j'})]. \end{aligned} \tag{3.1}$$

Here the indices (i,j,i',j') run over neutrons and protons, such that these are coupled equations via the collision term and indirectly via the potentials. If the production of other particles is considered, like Δ's, nucleon resonances or π and K mesons, these have their own dynamical equations coupled through the corresponding inelastic cross sections. The EOS enters through the mean field potentials U_i and the isospin effects enter via the differences in neutron and proton potentials and the isospin dependent cross sections. One should keep in mind, that the isospin effects are always small relative to the dominant isoscaler potentials and cross sections. Thus in order to obtain information on the SE one often resorts to difference observables between isospin partners, in order to become independent as much as possible from uncertainties in the isoscalar part.

The lhs of the above equation can be derived in a semi-classical approximation to the Wigner transform of the non-local quantum-mechanical density matrix, with the collision term added "by hand". A more rigorous derivation starts from a non-equilibrium quantum transport theory such as the Kadanoff-Baym equation[14]. This derivation also clarifies the relation between the mean fields and the in-medium cross sections. These are, in fact, not independent but are derived from the same generalized self-energies. A common approximation is to specify these in the T-matrix approximation, by which the cross section and the mean field are derived from the same in-medium T-matrix. However, in many practical implementations the two inputs are chosen independently and empirically.The above derivation also involves the so-called quasi-particle approximation, which puts the momenta of all particles on-shell. However, in a non-equilibrium situation all particles have finite widths due to collisions and possibly decay. This may be of importance in the production of particles near thresholds, as e.g. Δ's or mesons, but has not been widely investigated[14].

The solution of these non-linear integro-differential equations is usually performed with the so-called test-particle method, which amounts to a simulation of the reaction in terms of (many) particles with Hamiltonian dynamics and stochastic 2-body collisions, subject only to the Pauli principle. The densities reached in a HIC depend on the incident energy and the impact parameter. Thus different density regimes can be investigated, albeit only for short times. Observables have to be identified, which, ideally, are sensitive to this particular phase in the evolution.

Let us briefly discuss the influence of the SE in the different density regimes and some of the informations obtained. In central reactions at Fermi energies moderate densities are reached. Of particular interest has recently been the study of the expansion phase of such reactions, where very low densities of about 1/10 to 1/100 of ρ_0 prevail. By studying isotope ratios (so called ISO-scaling) in these situations the SE at very low densities has been determined[15], which is important for the

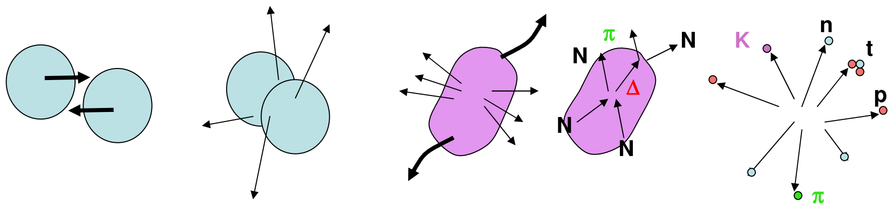

Figure 2: Schematic representation of an intermediate energy semi-central heavy ion collision with the processes important for the determination of the symmetry energy.

simulation for supernova explosions. In this density regime few-body clustering effects become important. A theoretical investigation has shown that the SE in fact is finite a very low densities, and this has been shown to be in agreement with the experiments[16].

At Fermi energy collisions one observes the phenomenon of multi-fragmentation. The distribution of the isospin to the different fragments ("isospin fractionation"), has been used to obtain information on the SE for $\rho < \rho_0$[17]. In more peripheral collisions one observes isospin transport through the low-density neck ("isospin diffusion"), which has been very important to fix the SE below ρ_0[18]. As discussed above in studies of nuclear structure and low energy nuclear excitations the density region around ρ_0, in particular the slope of the SE at saturation, is explored, see also the contribution of W. Trautmann to this conference.

In collisions at energies between about 100 MeV and a few GeV per nucleon densities up to a few times saturation density can be reached. This is the primary interest in the following. Let us briefly note that also at higher energies the influence of the SE has been discussed. There are suggestions that the deconfinement transition may be substantia lly influenced by the difference in the SE between the hadronic and partonic phase, and may in fact, occur at lower density in asymmetric systems[19].

The situation at intermediate energies is qualitatively sketched in Fig. 2. In the initial phase of the collision (b) pre-equilibrium emission of high energy particles and light fragments occurs. The yield ratios of isotopic partners, like n/p or $^3He/t$, contain information on the relative strengths of the neutron and proton potentials. In the compression phase (c) originate several complementary observables, which finally become manifest in the decomposition of the system (d). The repulsion and pressure generate flow, more precisely in-plane (directed) and out-of-plane (elliptic) flow (c1). Neutron-proton difference or differential flow observables have up to now been the most reliable means to extract information on the high density SE. This is discussed in detail in the contribution by W. Trautmann. On the other hand, inelastic NN collisions lead to the production of Δ resonances, which may decay into pions or lead to the production of strangeness (c2). The observables in (c1) and (c2) are complementary in the sense, that e.g. a stiffer SE has for $\rho < \rho_0$ a more repulsive potential for neutrons and thus favors pre-equilibrium emission of neutrons. This leaves the residue less n-rich, such that the production of the more negative resonances $\Delta^{0,-}$ is reduced, lowering also the π^-/π^+ ratio.

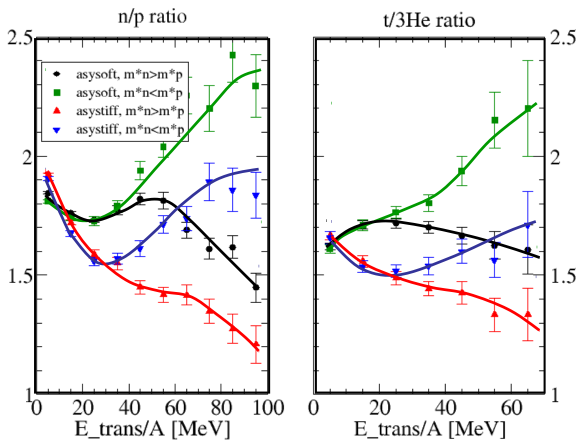

Figure 3: (left) The neutron-proton ratio calculated $^{136}Xe + ^{124}Sn$ collisions at 100 AMeV for different choices of the symmetry energy and the effective masses, as indicated in the legend. On the right the corresponding tritium over ^{3}He ratio. Error bars represent statistical uncertainties of the calculation.

4. Pre-equilibrium emission

As mentioned above the neutron to proton ratio of emitted particles should be sensitive to the SE. It has been measured at MSU for $Sn+Sn$ systems at 50 and 35 AMeV, and a systematic analysis of these data and other observables has yielded rather good limits on the γ exponent around $\gamma \approx 0.6$[18]. Other analyses of the n/p ratio agree with the trend of the data (higher n/p ratio for the softer SE), but do not agree on the magnitude of the effect[8, 20]. For this observable at higher energies the momentum dependence of the SE, i.e. the proton-neutron effective mass splitting, becomes important as first pointed out by Giordano et al.[21] A systematic study of this effect for nucleons and light clusters has been undertaken by our group for INDRA data of different Xe+Sn reactions at energies between 32 and 150 AMeV. A preliminary result from these calculations is shown in Fig. 3 for $^{136}Xe + ^{124}Sn$ in central collisions at 100 AMeV. On the left panel is shown the n/p ratio as a function of transverse energy of the particles, on the right the corresponding result for $t/^{3}He$. The calculations are performed for all combinations of a stiff/soft SE ($\gamma \approx 0.6$, resp. 1.0) and ordering of the effective mass ($m_n^* > m_p^*$, resp. $m_n^* < m_p^*$). One observes a clear pattern in Fig. 3, namely that the stiffness of the SE governs the lower part of the transverse energy spectrum, such that the softer SE yields a larger n/p ratio (densities in this case still lower than ρ_0). On the other hand, the higher part of the spectrum is dominated by the effective mass ordering, such that a smaller neutron effective mass favors the emission of neutrons and increases the ratio. Thus this observable should serve as a promising probe to disentangle the density and momentum dependences of the SE at higher density. Since it is more difficult to measure neutrons, we also checked the ratio for $t/^{3}He$, shown on the right panel, and we observe a very similar pattern. A qualitative comparison with the data (not shown) favors a stiff SE with $m_n^* > m_p^*$, qualitatively in agreement with the flow data. Collision systems with other N/Z ratios and also double ratios of yields are under study.

5. Particle Production

As discussed above the n/p content of the compressed system will also influence the ratio of newly produced particles, which can thus also serve as indicators of the SE in the high density phase. In particular, pions are produced predominantly via the Δ resonances as $NN \to N\Delta$ inelastic processes and the subsequent decay $\Delta \to N\pi$. The ratio of the isospin partners π^-/π^+ can thus serve as a probe of the isospin content of the compressed source and thus of the high density SE. There are simple estimates of how this ratio depends on the asymmetry of the source[22]: In chemical equilibrium the ratio is given as $\pi^-/\pi^+ \simeq exp(2(\mu_n - \mu_p)/T) = exp(8\beta E_{sym}(\rho)/T)$, and is thus directly connected to the SE. For typical conditions of density and temperature T in HIC's one could expect values of order 10 for this ratio. However, in non-equilibrium the ratios are expected and found too be much lower. Another limit is the isobar model, which links the pion yields to the isospin Clebsch-Gordan coefficients in the $\Delta \to N\pi$ decay and gives $\pi^-/\pi^+ \simeq (\frac{N}{Z})^2$, which is closer to observed values[23]. Altogether the π^-/π^+ ratio should be a good probe; moreover, extensive data are available from the FOPI collaboration at intermediate energies, including π^-/π^+ ratios[24].

Qualitatively two effects depending on the SE govern the pion ratio in real HIC's: One is the effect of the different neutron and proton mean fields already discussed above. For a stiffer SE and for $\rho > \rho_0$ pre-equilibrium neutron are preferentially emitted, leaving the residue less n-rich, which decreases the π^-/π^+. The other is the threshold effect for Δ production via the energy-momentum conservation for inelastic $NN \to N\Delta$ collisions, which is modified in the medium by the N and Δ self energies. A careful analysis of these threshold conditions in Ferini et al.[22] using a simple model for the Δ self energies, shows that for a stiffer SE the π^-/π^+ ratio increases. Thus the two effects compete with each other and the net result may be sensitive to assumptions on the two mechanisms. Note that the threshold effect is absent in equilibrium and therefore the ratio can attain much bigger values.

In Fig. 5 we have collected in the right panel results from different recent theoretical analyses (for short called "models" in the following) of this ratio using different program codes and different parameterizations for the SE. They are compared to the FOPI data. In the left panel we show the corresponding SE's. For each model the results for two SE's of different stiffness are shown (stiffer - blue, softer - red). As is seen, the results of the different models are very different and not consistent with each other as briefly summarized now.

The first model of the group of B.A. Li (solid lines) with the IBUU04 code[23] uses a GBD momentum dependent force with a moderately soft ($x = 0$) and a very soft ($x = 1$) SE. The $x = 0$ SE under-predicts the experimental data for the ratio and only the very soft $x = 1$ SE comes close. This evidence for a super-soft SE at high density has raised many discussions and disagrees strongly with the analyses of the FOPI flow data mentioned above. The second model of the Catania group (dotted lines) uses a relativistic transport model (RBUU) with a non-linear Relativistic Mean Field (RMF) parametrization, where the SE is controlled by including two isovector mesons, a ρ (vector) and a δ (scalar)[25]. This SE is relatively stiff at high densities (also the one with only a ρ meson). It is compared to calculation without any potential part of the SE, which is thus effectively soft. While the stiff SE (and similarly one with only a ρ) strongly over-predict the data, only the unrealistic case with $E_{sym}^{pot} = 0$ comes close. Thus the stiffer SE gives a larger ratio, opposite to

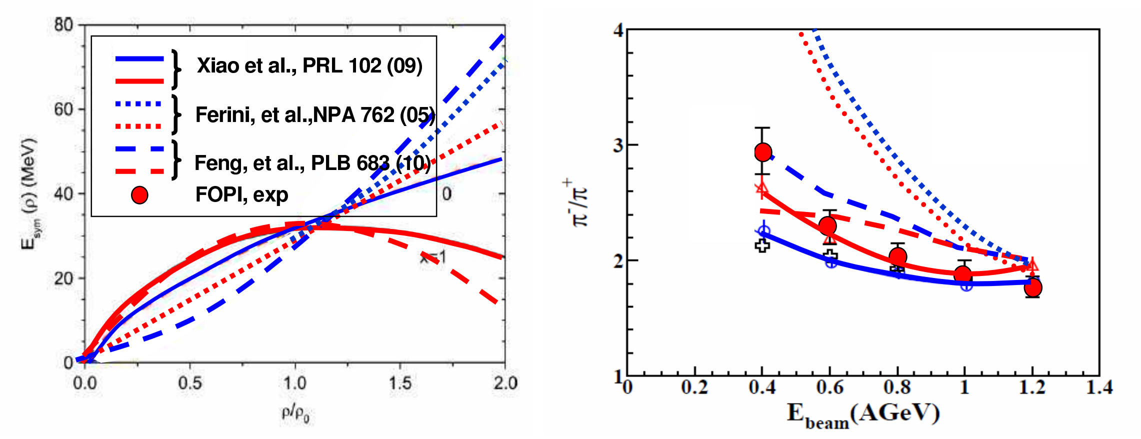

Figure 4: The π^-/π^+ ratio in $Au+Au$ collisions as a function of incident energy as measured by the FOPI collaboration, and as calculated by different groups. (left) Models for the symmetry energy used in the calculations as indicated in the legend. Blue curves are for the stiffer and red ones for the softer behavior in each case. (right) Corresponding results for the π^-/π^+ ratio.

model 1. A third model of Feng et al.[26] (dashed lines) with a variant of the IQMD code uses a very stiff ($\gamma = 2$) and a very soft SE Here again the very soft SE is closer to the data, but quite different in shape to model 1, even though the SE's are similar. As a trend in all models the softer SE's (red curves) are closer to the data (but differ substantially in shape), but the ratio for a stiffer SE is sometimes higher, sometimes lower. Thus, unfortunately, theoretical simulations are not consistent in their predictions of the pion ratio. This is an issue that needs urgent clarification in view of the potential utility of the pion observables and the excellent data situation. A reason may lie in the treatment of the Δ dynamics, which may be modeled differently in the different approaches. We also remarked above, that in the pion ratio two competing effects, the mean field and the threshold effects, are at work and slightly different treatments of these might lead to large differences.

It has also been suggested, that the ratio of the anti-strange kaon isospin partners, K^0/K^+ could be a useful observable for the SE[27]. Indeed, kaon production has been one of the most useful observables to determine the EOS of symmetric nuclear matter. The anti-strange kaons also have the advantage that they weakly interact with nuclear matter and are thus a direct probe of the dense matter where they are produced. Theoretical analyses show similar if not larger sensitivity to the SE compared to pion ratios[27]. Experimentally only double kaon ratios, i.e. ratios of K^0/K^+ ratios for different collision systems, could determined, because of the very different phase space coverages of the two kaon species. However, double ratios seem to reduce the sensitivity to the SE. More experimental and theoretical work is needed, but kaon observables remain an interesting observable for the SE.

6. Conclusions and Outlook

In this brief overview of the determination of the nuclear SE in HIC's we have first discussed the relation of various representations of the symmetry energy. HIC's are interpreted with transport theories and we have discussed some of the challenges in such descriptions with respect to the SE. Generally today a picture emerges where the information on the SE from HIC's, nuclear structure, and neutron stars increasingly converges. In contrast, here we have emphasized current problems in the determination of the SE in heavy ion collisions, where a more thorough understanding of the mechanism is needed. In the end it is desirable to obtain a consistent picture of many observables in heavy ion collisions.

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