The Symmetry Energy of the Nuclear Equation of State

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Abstract. The symmetry energy $E_{\text{sym}}$ is the part of the nuclear energy associated with the asymmetry in the neutron/proton content. Its relevance is due to the role that it plays in a large variety of systems and processes in nuclear structure, astrophysics and heavy-ion collisions dynamics. In the last ten years many efforts from different fields have been pursued to constrain its density dependence both below and above the saturation density ($\rho_0 \sim 0.16 \text{fm}^{-3}$). Here we briefly sketch the present status on the knowledge of $E_{\text{sym}}$ at low density, we discuss the ongoing work at suprasaturation one and we present new perspective that are opening up for the role of $E_{\text{sym}}$ in the transition to quark matter at high baryon density.

1. Introduction

The study of the equation of state (EoS) of nuclear matter has been one of the main challenges of nuclear physics in the last 30 years. This endeavor has been performed mainly for nuclear matter with an almost equal numbers of neutrons and protons, but it is known already from the Weisacker mass formula that the difference in the neutron-proton content gives a contribution to energy called symmetry energy, i.e. the energy arising from the breaking of a symmetric neutron-proton content. The symmetry energy $E_{\text{sym}}$ can be defined from the following expansion of the energy density $\epsilon(\rho, I_3) \equiv \epsilon(\rho) + \rho E_{\text{sym}}(\rho) I_3^2 + O(I_3^4) + ...$, with $\rho = \rho_p + \rho_n$ and $I_3 = \rho_p - \rho_n$ being the total and the isospin densities and $I = I_3/\rho$ the isospin [1]. We notice that in general $E_{\text{sym}}$ depends on the density $\rho$ while at each density the contribution to total energy density is usually assumed to be proportional to $I^2$. Such an assumption of the Weisacker formula is confirmed by its wide application to nuclei, but also by all many-body theoretical approaches and in particular by the microscopic Brueckener-Hartree-Fock (BHF) approaches [2], Dirac-BHF[3], the variational method [4] practically for all the range of density of interest.

The interest for the nuclear symmetry energy comes from the role it has in a very broad variety of processes that goes from the nuclear structure of exotic nuclei to the nucleosynthesis, from the dynamics of the supernova explosions to the formation and structure of protostars and neutron stars. Nowadays its role in the supernova explosions and the formation of elements starts to be explicitly studied in both 2D and 3D simulations [5].

The symmetry term gets a kinetic contribution directly from basic Pauli blocking determining different Fermi energies for $n$ and $p$ and a potential part from the highly controversial isospin dependence of the effective interactions. Both at sub-saturation and supra-saturation densities,
predictions based of the existing many-body techniques diverge rather widely\cite{6, 7, 8} as shown in Fig.1 for several relativistic and non-relativistic models. Therefore while $E_{sym}$ is fairly well constrained around the saturation density from nuclear structure \cite{9, 10} its behavior at lower and at higher density is poorly known\cite{7, 1}.

Ab-initio BHF calculations, started with the aim of showing that the EoS can be derived directly from the two-body nuclear interaction by mean of a many-body theory, have shown that two-body nuclear potential is not sufficient to obtain the nuclear matter properties at $\rho_0$. It is indeed necessary a three-body force \cite{11} that cannot be uniquely derived ab-initio but that can be constrained at $\rho < \rho_0$ by nuclear structure study where it plays an important role together with the tensor force. In DBHF it is not clear the necessity of an explicit three-body force and the EoS is generally stiffer \cite{6}. In a variational approach one gets similar results but using a different three-body force \cite{12}. As a general comment however we can say that ab-initio calculations has reached a degree of accuracy that at least around and below $\rho_0$ can be considered quite under control leaving only a limited room for uncertainty. At increasing density of course both the three-body force and the tensor one (in particular in the isospin channels \cite{13}) cannot be constrained and the behavior of $E_{sym}(\rho)$ remains still largely uncertain.

The paper is organized in three part. Section I, briefly discuss the state of the art in the determination of $E_{sym}(\rho)$ around and below $\rho_0$; Section II, we discuss the issue of the isospin momentum dependent part of the mean field and the particle ratio; Section III, we present more recent ideas on the role of $E_{sym}(\rho)$ in the transition to quark matter of asymmetric nuclear matter.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{symmetry_energy.png}
\caption{Symmetry energy as a function of density as predicted by different models from Ref.\cite{6}. Left panel is a zoom on the low density region.}
\end{figure}

2. State of the art at $\rho < \rho_0$

Most of the efforts to determine the density dependence of the symmetry energy have been concentrated on the density region around and below $\rho_0$. A reference to quantify such a dependence is usually the $\gamma$ factor, that is the power with which the symmetry energy grows, according to the simple parametrization $E_{sym}(\rho) = J(\rho/\rho_0)^\gamma$ where $J \sim 30$ MeV is the value at $\rho_0$. Another common way is to determine the slope parameter that is defined as $L = 3\rho_0dE_{sym}/d\rho|_{\rho=\rho_0}$, that is related to $\gamma$ by the simple relation $L = 3J\gamma$.

Information on $L$ or $\gamma$ have been obtained in the last ten years looking at a large variety of observables from nuclear structure studies on neutron skin thickness, mass formula or pigmy...
resonances to nuclear reaction investigations of pre-equilibrium emission, isospin diffusion and collective flows. A recent collection of the results of such studies can be found in [9] to which one can add also the study of Giant Monopole Resonances and pre-equilibrium dipole emission [14]. Such a study refer to very different physical process and are investigated with diverse theoretical tooos, nonetheless it is appreciable that there is a common overlap region for $\gamma \sim 0.8 \pm 0.2$ corresponding to $L \sim 75 \pm 20$ MeV. More details can be found in the IWM2009 Proceedings [15]. It is worth of note that such a value is well inside the value predicted by ab-initio many-body calculations like BHF including three-body forces [16].

It is certainly necessary to enlarge the systematics of data and theoretical calculations to reduce the uncertainties and validate the current interpretations. A boost in this direction will be offered by the upcoming availability of facilities delivering exotic nuclei [25].

![Diagram](image_url)

**Figure 2.** Momentum dependence of neutron proton potentials at saturation density and asymmetry $I = 0.2$ for the two splitting choices $m^*_n < m^*_p$ (dashed) and $m^*_n > m^*_p$ (solid). Left panel: Asy-soft Iso-Eos. Right panel: Asy-stiff case.

3. **State of the art at $\rho > \rho_0$**

This paper focuses mainly on the open issues for the determination of $E_{sym}(\rho)$ at suprasaturation densities relevant for the neutron star mass-radius relation and its cooling [17], for the hybrid star structure and the transition to a deconfined phase [18] up to the formation of black holes. The quest for the knowledge of the $E_{sym}(\rho)$ at high density is obviously out of reach for nuclear structure studies and can be prusued only by mean of HIC’s intermediate beam energy ($E/A > 400$ MeV) and/or by measurement of neutron star mass-radius relation that are becoming available.

The large energy implied makes more relevant, respect to HIC at Fermi Energies, the role of the momentum dependence of the mean field. In fact it is well known that due to the non-equilibrium initial conditions for the dynamics of HIC it is important not only the EoS but also the specific dependence of the mean field on the nucleons momenta. Such a dependence is fairly well known for the isoscalar part while its isospin dependence is still uncertain [19]. The momentum dependence is usually characterized in terms of the effective masses given by:
Figure 3. n/p ratio for $^{132}$Sn + $^{124}$Sn at 400 AMeV (b=1fm, y < 0.3) vs. the transverse momentum normalized to the projectile one for two different isospin momentum dependences and two choices of $E_{sym}(\rho)$.

\[ \frac{m_q^*}{m} = \left[ 1 + \frac{m}{p} \frac{\partial U_q}{\partial p} \right] , \]

where we use the index $q = p, n$ to underline that, in general, they are different for proton and neutrons. We see from Eq.(1) and in Fig. 2) that a smaller effective mass means a larger slope of the $U(\rho, k)$ mean field around the fermi momentum $p_F$. In the case $m_n^* < m_p^*$ the high-momentum neutrons will see a more repulsive field with respect to the high-$p_t$ protons. The opposite will happen in the $m_n^* < m_p^*$ case. The fast nucleon emission will be directly affected: in the $m_n^* < m_p^*$ case it has been found a larger n/p yield for nucleons emitted in central collisions and a larger neutron squeeze-out (elliptic flow) in semicentral collisions in heavy-ion reactions at intermediate energies, in particular for high-$p_t$ (transverse momentum) selections. A detailed analysis can be found in Ref.[19]. In Fig.3 we show only the n/p ratio exhibiting a strong dependence on the sign of the splitting of the effective massesfor $p_t/p_{proj} > 1$. The key point of this result is that especially at high $p_t$ the effect is almost independent on the stiffness of $E_{sym}$ allowing to disentangle the dependence on the momentum from that on the density. Instead, for lower beam energies and in the low momentum region the pre-equilibrium emission is found to depend significantly on both the stiffness of $E_{sym}$ and the isospin MD.

The search for $E_{sym}$ at high density, implying the exploit of HIC at high energy, involves a new phenomena not considered at Fermi energies that is the excitation of the lower mass mesonic states, namely pions and kaons. Therefore symmetry energy effects are transferred to the production of mesons. In Ref.[20] it was suggested that the $\pi^-/\pi^+$ ratio is sensitive to $E_{sym}(\rho)$. Using a relativistic transport approach (Relativistic Boltzmann-Ühling-Uhlenbeck, RBUU[21]) we have analyzed pion and kaon production in central $^{197}$Au + $^{197}$Au collisions in the 0.8 – 1.8 AGeV beam energy range, comparing models with the same “soft” EoS for symmetric matter and with different effective field choices for $E_{sym}$. In Fig.4 (left) a slight increase in the $\pi^-/\pi^+$ ratio is observed when going from a NL-RMFT model without isovector fields (NL) to one with a $\rho$ meson (NL$\rho$) and with $\rho$ and $\delta$ mesons (NL$\rho\delta$), i.e. with increasing stiffening of $E_{sym}$. The effect becomes larger when going to low energy close to threshold production. A first comparison without filtering effects can be done with the data from FOPI Collaboration [22] (full triangles in Fig. 4). It can be seen that the estimated increase of the $\pi^-/\pi^+$ ratio with RBUU appears too strong, however as shown in Ref.s[22, 23] with IQMD there is the opposite problem. Furthermore within an isospin and momentum dependent transport model (IBUU) it has been shown that an agreement with data can be achieved only with a very soft $E_{sym}(\rho)$ is
considered corresponding to a $\gamma \sim 0$ around $\rho_0$ and with a negative slope above $\rho_0$ [26]. This would be in disagreement with all the ab-initio calculations and also in strong disagreement with other studies that exploit the elliptic flow to extract the slope of above the saturation density [27]. However more recently using a ImQMD model [24] it has been found that a comparison to data needs a quite stiff $E_{sym}(\rho)$ corresponding to a $\gamma \sim 1 \sim 2$. From such a simple comparison we can say that at the moment it is clear a disagreement among different studies. Therefore there are circumstantial reasons to be careful. Indeed, the physics involved in the in-medium particle production has many aspects and a comprehensive and self-consistent approach is necessary before extracting the isospin dependence of the interaction.

The effect described in Ref.[26] essentially is due to the fact that a stiff $E_{sym}$ causes a neutron-rich emission of nucleons in the early stages of the reaction leaving the system too symmetric in isospin content to reproduce the $\pi^-/\pi^+$ ratio of FOPI. On the other hand, if one employs an $E_{sym}(\rho)$ that just above $\rho_0$ decreases with density generating an isospin force that is attractive for the neutrons it is possible to get close to the data. However, we note that it is mandatory to check if one can reproduce at the same time the $n=p$ emission especially at the high $p_t$ relevant for pion production. This would be a first test of the claim for a very soft $E_{sym}$ and in case of failure it will provide evidence that there are other mechanism determining the in-medium meson production. Indeed, we already know that there are at least three other effects competing with the mean field effect on the $n/p$ emission. These are the so-called ”threshold effects” emphasized by the calculation of Ref.s [21], the momentum dependence of the isospin-dependent cross sections, and the the isospin mass shift of pions due to in medium interaction[29]. These will be discussed in the following subsection.

3.1. Isospin dependence of thresholds and spectral functions
The ”threshold effect” is due to the fact that the masses of nucleons and $\Delta$’s are modified in the medium. The unknown self-energies of the $\Delta$’s are usually specified in terms of the neutron and proton ones by the use of Clebsch-Gordon coefficients for the isospin coupling of the $\Delta$’s to nucleons [20, 21]. These medium modifications are isospin dependent, Eq.(2), affecting the phase-space available for meson production in a nucleon-nucleon (NN) collision, because they modify the difference between the invariant energy in the entrance channel $s_{in}$ and the production threshold $s_{th}$. This effect is, of course, present in general for all meson productions, but for brevity we concentrate here on one inelastic channel: $nn \rightarrow p\Delta^-$, mainly responsible for $\pi^-$ production. From Eq.(1) the invariant energy in the entrance channel and the threshold...
energy are given, respectively, by

\[ \sqrt{s_{th}}/2 = \left( E_n + \Sigma_n^0 \right) \overset{\text{vac}}{\overset{\text{in}}{\rightarrow}} \left[ m_N^* + \Sigma_0^p + \Sigma_0^p + \Sigma_0^p \right] > m_N^* + \Sigma_0^0 \]

\[ \sqrt{s_{in}} = \left[ m_p^* + m_{\Delta^-} + \Sigma_0(p) + \Sigma_0(\Delta^-) \right] = m_N^* + m_{\Delta} + 2\Sigma_0 \]

where \( m_N^*, m_{\Delta} \) are the isospin averaged values and \( \Sigma^0 \)'s are the self-energy associated to the different scalar-vector fields [28]. The last equality for the threshold energy is valid due to the prescription for the Delta self-energies noted above, which leads to an exact compensation of the isospin-dependent parts, hence the threshold \( s_{th} \) is not modified by isospin dependent self-energies. Generally in a self-consistent many-body calculation higher order effects can destroy this exact balance. On the other hand, the energy available in the entrance channel, \( s_{in} \), is shifted in an explicitly isospin dependent way by the in-medium self-energy \( \Sigma_0^p + \Sigma_0 > 0 \). Especially, the vector self-energy gives a positive contribution to neutrons that increases the difference \( s_{in} - s_{th} \) and hence increases the cross section of the inelastic process due to the opening up of the phase-space, especially close to threshold.

A similar modification but opposite in sign is present in \( s_{in} - s_{th} \) for the \( pp \rightarrow nn\Delta^{++} \) channel that therefore is suppressed by the isospin effect on the self-energies. Hence, due to the described threshold effect the ratio \( \pi^-/\pi^+ \) increases with the stiffness of which is associated with a large \( \Sigma_0(p) + \Sigma_0(\Delta^-) \). This is at the origin of the result in Fig. 4. Of course, the RBUU calculation contains also the mean field effect on the pre-equilibrium emission like in [26] but the final result appears to be dominated by the threshold effect. However a critique can be moved about self-consistency, in fact there are at least two other physical aspects that have to be considered.

Another key point in the study of the isospin effects is the isospin dependence of the cross section for the inelastic processes. In fact in medium self-energies discussed above should also modify the cross section of the pertinent inelastic processes. It is likely that simultaneously taking into account the isospin dependence of the cross section can damp the effect of self-energies on \( s_{in} - s_{th} \).

Another effect is the in-medium modification of the pion spectral function which in an asymmetric medium becomes isospin dependent. The effect has been pointed out in Ref. [29], where it is shown that the interaction in dense asymmetric nuclear matter modifies the expected thermal \( \pi^-/\pi^+ \) ratio with respect to the one with vacuum masses. The effect goes in the direction: that a larger \( E_{sym} \) implies smaller \( \pi^-/\pi^+ \) ratios. It would be important to include such an effect in the transport models, even if it means to go beyond the simple quasi-particle approximation. We notice that the inclusion of such an effect in the transport simulation of Ref.[26] would imply an even softer \( E_{sym} \) toward a stronger disagreement with ab-initio calculations. On the contrary it would move the results of Ref.[21] with NL\( \rho \) closer to data.

### 3.2. Kaons

The idea of using pions to determine the symmetric part of the EoS has suffered from the fact that pions strongly interact with nucleons and are produced during the whole evolution of the collision system making it difficult to associate their production to a specific density reached during the collision. In that context it was suggested by Aichelin and Ko [30] that kaons are a better probe of the EoS. The reason is twofold. Kaons have a higher threshold energy, hence they are produced only in the high density phase, see Fig. 3.1. Moreover, once produced they...
interact weakly with nucleons and their width with respect to the mass is quite small making a quasi-particle approximation more reliable. After nearly 20 years the effort to determine the symmetric EoS by kaon production has been successful and is summarized in Ref.[31]. Following the same line of thinking the Catania group has suggested to investigate the $K^0/K^+$ ratio as a better probe of the $E_{sym}$ at high density [21, 32] (the other isospin pair with anti-kaons $\bar{K}_0/\bar{K}^-$ suffers from the strong coupling to the medium).

Fig.3.1 reports the temporal evolution of $\Delta^{\pm,++}$ resonances, pions ($\pi^{\pm,0}$) and kaons ($K^{+0}$) for central Au+Au collisions at 1 AGeV [21] It is clear that, while the pion yield freezes out at times of the order of 50 fm/c, i.e. at the final stage of the reaction (and at low densities), kaon production occurs within the very early (compression) stage, and the yield saturates at around 15 fm/c, when the nucleon and $\Delta$'s densities reach their maximum value. In addition from Fig.4 (right) we see that kaon ratio is more sensitive to $E_{sym}$. However even if kaons can be considered a more clean and sensitive probe the various issues that are involved in the determination of the $\pi^-/\pi^+$ are partially present also for $K^0/K^-$ ratios. Therefore more generally there is a need for theoretical improvements in the transport models to match the upcoming availability of experiments able to scrutiny more precisely the isospin dependence of observables in heavy ion collisions.

4. Role of Symmetry Energy on the Transition to Quark Matter
Some suggestions are already present about the possibility of interesting isospin effects on the transition to a mixed hadron-quark phase at high baryon density [18, 32]. This seems to be a very appealing physics program for the new facilities, FAIR at GSI-Darmstadt [33] and NICA at JINR-Dubna [34], where heavy ion beams (even unstable, with large isospin asymmetry) will be available with good intensities in the 1-30 AGeV energy region. The weak point of those predictions is the lack of a reliable equation of state that can describe with the same confidence the two phases, hadronic and deconfined. On the other hand this also represents a strong theory motivation to work on more refined effective theories for a strongly interacting matter.

A nice qualitative argument in favor of noticeable isospin effects on the hadron-quark transition at high density can be derived from the Fig.6, where we compare typical Equations of State (EoS) for Hadron (Nucleon) and Quark Matter, at zero temperature, for symmetric ($\alpha \equiv (\rho_n - \rho_p) / \rho_B = 0.0$) and neutron matter ($\alpha = 1.0$), where $\rho_{n,p}$ are the neutron/proton densities and $\rho_B = \rho_n + \rho_p$ the total baryon density.
Figure 6. Zero temperature EoS of Symmetric/Neutron Matter: Hadron (NLρ), solid lines, vs. Quark (MIT-Bag), dashed lines. α_H,Q represent the isospin asymmetry parameters respectively of the hadron, quark matter: α_H,Q = 0, Symmetric Matter; α_H,Q = 1, Neutron Matter.

The energy density and the pressure for the quark phase are given by the MIT Bag model (two-flavor case), with the bag constant taken as a rather standard value from the hadron spectra (B = 85.7 MeV fm\(^{-3}\), no density dependence) [8, 35].

The boundary of the mixed phase region will appear below the crossing points of the two EoS. We see that such crossing for symmetric matter (α_H = α_Q = 0): 0 is located at rather high density, \(ρ_B ≈ 7ρ_0\), while for pure neutron matter (α_H = α_Q = 1.0) it is moving down to \(ρ_B ≈ 3ρ_0\). Of course Fig.6 represents just a simple energetic argument to support the hadron-quark transition to occur at lower baryon densities for more isospin asymmetric matter.

The structure of the mixed phase instead is obtained by imposing the Gibbs conditions for chemical potentials and pressure and by requiring the conservation of the total baryon and isospin densities [8, 35]. We get the binodal surface which gives the phase coexistence region in the \((T;B;\rho_3)\) space. For a fixed value of the total asymmetry \(T = 3 = B\rho_3\), we will study the boundaries of the mixed phase region in the \((T;ρ_B)\) plane. Since in general the charge chemical potential is related to the symmetry term of the EoS [1] \(μ_3 = 2E_{sym}(ρ_B)\frac{ρ_3}{ρ_B}\), we expect the transition densities rather sensitive to the isovector interaction in the two phases.

In the hadron sector we use the NL-RMF models[1] with different structure of the isovector part: i) NL, where no isovector meson is included and the symmetry term is only given by the kinetic Fermi contribution, ii) NLρ when the interaction contribution of an isovector-vector meson is considered and finally iii) NLρδ where also the contribution of an isovector-scalar meson is accounted for. At high baryon densities the symmetry energy is stiffer \(E_{sym}(ρ)\) going from NL to NLρδ.

A relatively simple calculation can be performed at zero temperature. The isospin effect (asymmetry dependence) on the Lower (\(χ = 0.0\)) and Upper (\(χ = 1.0\)) transition densities of the Mixed Phase are shown in Fig.7(Left Panel) for various choices of the Hadron EoS. The effect of a larger repulsion of the symmetry energy in the hadron sector, from NL to NLρ and to NLρδ, is clearly evident on the lower boundary with a sharp decrease of the transition density even at relatively low asymmetries.

We note from Fig.7 (left panel), that in the more repulsive NLρδ case the lower boundary
is significantly lowered already for not too large asymmetry $\alpha \sim 0.2$. The conclusion seems to be that for a stiffer symmetry term in a heavy-ion collision at intermediate energies during the compression stage we can have a better chance to probe the mixed phase, although in a region with small weight of the quark component. We notice that the results are rather independent on the isoscalar part of the used Hadron EoS at high density, that is chosen to be rather soft in agreement with collective flow and kaon production data [39, 21]. A reduction of the Bag-constant with increasing baryon density, as suggested by various models, see ref.[36], will also go in the direction of an “earlier” (lower density) transition, as already seen in ref.[18]. At variance, the presence of explicit isovector interactions in the quark phase could play an important role, as shown in the following.

Can we expect some signatures related to the subsequent hadronization in the following expansion? An interesting possibility is coming from the study of the asymmetry $\alpha^Q$ in the quark phase. In fact since the symmetry energy is rather different in the two phases we can expect an Isospin Distillation (or Fractionation), very similar to the one observed in the Liquid-Gas transition in dilute nuclear matter [1], this time with the larger isospin content in the higher density quark phase. This is the neutron trapping effect. We expect a signal of such large asymmetries, coupled to a larger baryon density in the quark phase, in the subsequent hadronization. We could predict an enhancement of the production of isospin-rich nucleon resonances and subsequent decays, i.e. an increase of $\pi^-/\pi^+$, $K^0/K^+$ yield ratios for reaction products coming from high density regions, that could be selected looking at large transverse momenta, corresponding to a large radial flow.

If such kinetic selection of particles from the mixed phase can really be successful also other mixed phase signatures would become available. One is related to the general softening of the matter, due to the contribution of more degrees of freedom, that should show up in the damping of collective flows [37]. A further signature could be the observation, for the selected particles, of the onset of a quark-number scaling of the elliptic flow: a property of hadronization by quark coalescence that has been predicted and observed at RHIC energies, i.e. for the transition at $\mu_B = 0$ [38].
5. Conclusions
The determination of the density dependence of $E_{sym}(\rho)$ is important for a large variety of phenomena going from nuclear structure, nucleosynthesis to supernova explosions and neutron star structure. At densities around and below $\rho_0$ there is a general convergence from both nuclear structure and nuclear reaction studies around a value of the slope $L \sim 75 \pm 20$ MeV. The availability of exotic nuclei beams will allow to reduce the uncertainties. At supersaturation density the study has been started more recently looking mainly at the neutron proton elliptic flow and at the isospin particle ratios $\pi^-/\pi^+$. First studies do not show a convergence over a slope parameter and several theoretical issue are still open. On the other hand there are only sparse data and several facilities are planning experiments to solve the open issues. Finally new perspectives are opening about the role of $E_{sym}$ on the phase transition to Quark Matter. First studies would indicate a lowering of the baryon density at which the mixed phase begins for asymmetric nuclear matter.

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