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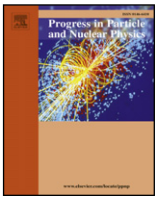

Review

The high-density symmetry energy in heavy ion collisions

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ABSTRACT

The nuclear symmetry energy as a function of density is rather poorly constrained theoretically and experimentally both below saturation density, but particularly at high density, where very few relevant experimental data exist. We discuss observables which could yield information on this question, in particular, proton–neutron flow differences, and the production of pions and kaons in relativistic heavy ion collisions. For the meson production we investigate particularly ratios of the corresponding isospin partners π^-/π^+ and K^0/K^+, where we find that the kaons are an interesting probe to the symmetry energy. In this case we also discuss the influence of various choices for the kaon potentials or in-medium effective masses.

1. Introduction

The symmetry energy E_{sym} is that part of the nuclear equation of state (EOS), which depends on the isovector density $\rho_3 = \rho_p - \rho_n, \epsilon(\rho, \rho_3) = \epsilon(\rho) + \frac{E_{sym}}{A}\rho_3^2/\rho + \cdots$ [1]. It has been found that the quadratic approximation in ρ_3 is a very good assumption at a wide range of density (but may break down at very low density due to the importance of cluster correlations). While the symmetry is fairly well constrained around saturation density from the Bethe–Weizsäcker mass formula, its behavior both at lower and at higher densities is of great recent interest both theoretically and experimentally [2,3]. At low densities it is important for the structure of exotic nuclei as well as in the neutron star crust and in supernova explosions. For high densities it is crucial for the structure of neutron stars, in particular as to the question, whether strange or deconfined hadronic matter exists in the center of neutron stars [4].

Heavy ion collisions provide a unique opportunity to explore the density dependence of the symmetry energy in the laboratory, because one is able to choose the asymmetry via the collision partners, and the density range via the collision energy and centrality. On the other hand, one does not measure the equation of state, and thus also not the symmetry energy, directly in a heavy ion collision, which is a violent non-equilibrium process. Rather one has to perform transport calculations of the collision process, into which the EOS (and the in-medium cross section, which are also isospin-dependent) enter, and compare observables which are sensitive to the symmetry energy with experiment. The search for such sensitive observables is one of the great challenges in this field.

A broader view of the investigation of the symmetry energy in heavy ion collisions is given in the contribution of M. Di Toro in this issue [5]. There is also an extensive recent review on the symmetry energy in heavy ion collisions by B.A. Li, et al. [6]. Here we concentrate on the high density symmetry energy, which is investigated in relativistic heavy ion

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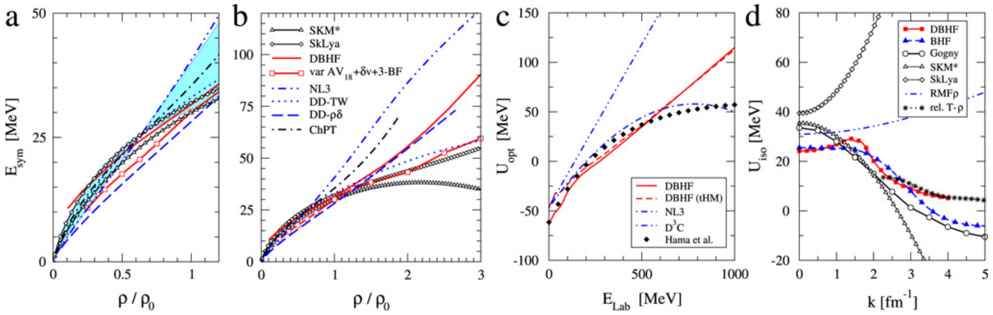

Fig. 1. (a, b) Symmetry energy as a function of normalized density in various theoretical nuclear matter models (panel (a) detail for low density). The theoretical models are labeled in panel (b), and and given explicitly in Ref. [2]. (c) Real part of optical potential for symmetric nuclear matter as a function of energy, and (d) isospin part of optical potential (Lane potential) for asymmetric nuclear matter as a function of momentum, in some of the theoretical models identified in the panels, see Ref. [2].

collisions. The observables discussed here, are, of course, the same which are discussed to investigate the EOS generally, i.e. the isospin symmetric part of the energy density: flow observables, pre-equilibrium emission of nucleons and light clusters, and the production of mesons. However, here we are looking for isospin differences, i.e. proton/neutron flow differences, or differences in the production of isospin partners, e.g. π^+ vs. π^- or K^0 vs. K^+. It is clear, that these differences will be much smaller than effects of the symmetric EOS, and thus the signatures of the symmetry energy are difficult to grasp. This may also be the reason, why only very few experimental data are available at present, which look directly for isospin differences. However, this situation should improve in the future, when more intense radiactive beams become available at facilities such as FAIR, RIKEN, FRIB, etc.

2. Models of the symmetry energy and transport

Theoretical models for nuclear matter have been formulated non-relativistically or relativistically in phenomenological models (Skyrme-type, resp. Relativistic Mean Field (RMF)) or in microscopic models (Brueckner HF or Dirac-Brueckner HF (DBHF)). A connection between the phenomenological and the microscopic approaches can be seen in the density functional approach: the density functional of the phenomenological models is guided (or taken directly) from the density dependence of the mean field of the microscopic models. These observations are true for the symmetric EOS as well as for the symmetry energy. However, the symmetric EOS is much more constrained from properties of nuclear matter and finite nuclei, than the symmetry energy. Consequently there is a large theoretical uncertainty about the density behavior of the symmetry energy.

This is demonstrated in Fig. 1: In panels (a) and (b) the symmetry energy is given in various phenomenological and microscopic models (detailed references to these models are found in Ref. [2], from which these figures are taken). One may distinguish between symmetry energies which rise more or less strongly around saturation density (asy-stiff, resp. asy-soft). It is seen that most of the realistic models cross not at ρ_0, but rather around $0.6\rho_0$. This points to the fact, that in fitting asymmetric nuclei the asymmetry of the surface has a large influence. For densities below saturation the realistic models of the symmetry energy do not deviate very strongly; however, this still has important consequences, as demonstrated in Ref. [5]. It is clear, however, that dramatic differences in the symmetry energy exist for higher densities. One may also notice, that the behavior of the symmetry energy for low and high density is not necessarily connected. E.g. the symmetry energy in DBHF calculations is rather soft for low densities but behaves stiff at higher densities [2].

In Fig. 1, panels (c) and (d), the energy, resp. momentum dependence of the real part of the optical potential is shown for symmetric nuclear matter (c) and the Lane potential for asymmetric nuclear matter from various calculations [2]. In (c) the calculations are compared to the empirical potential (Hama et al.), and it seen that the energy dependence is too strong in RMF (NL3) or DBHF models, but can be reproduced in a recently developed RMF model with density and derivative dependent coupling (D^3C, [7]). Again the Lane potential shows much larger deviations already for not so high momenta. Experiments indicate that the Lane potential is decreasing with energy, but the accuracy is not enough to essentially constrain the momentum dependence of the symmetry energy. The momentum dependence of the symmetry energy can also be discussed in terms of effective masses, here specifically of the difference of proton and neutron effective masses [2,5].

Heavy ion collisions are simulated in this work, using a relativistic transport code with finite size test particles, for details see Ref. [8]. We propagate protons and neutron separately, but also particles produced in inelastic NN collisions, such as Δ resonances, pions and kaons. The self energies for the nucleons are specified in the RMF model, which includes non-linearity in the σ-field, and in the isovector sector either ρ mesons, or ρ and δ mesons (models $NL\rho$ and $NL\rho\delta$, respectively) [9]. An issue has been the specification of the mean field for the kaons [10]. It has been modeled in chiral perturbations theory (ChPT, Nelson and Kaplan, [11]) or in the one-boson exchange model (OBE, [12]), and we test both options here, as discussed below (for details see Ref. [13]). Here we discuss in particular the isospin partners of the strange kaons (K^+, K^0), since the anti-strange kaons have a much larger final state interaction. The effective kaon mass for the two models is shown in Fig. 2;