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Impact of the in-medium conservation of energy on the π^-/π^+ multiplicity ratio

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Abstract

An upgraded version of the isospin dependent Tübingen QMD transport model, which allows the conservation of the total energy, is presented. This is achieved by including in the energy-balance equations of the density, isospin asymmetry and momentum dependent in-medium baryon potential energies. It leads to an effective modification of particle production thresholds with respect to the vacuum ones. Compatible constraints for the symmetry energy stiffness from π^-/π^+ multiplicity ratio and elliptic flow experimental data of Au+Au collisions at 400 MeV/nucleon can be extracted in this case. However, an important dependence of the π^-/π^+ observable on the strength of the isovector part of the $\Delta(1232)$ isobar potential is also demonstrated. The present lack of information on this quantity prevents a precise extraction of the value for the symmetry energy stiffness employing the mentioned observable alone.

1 Introduction

The π^-/π^+ multiplicity ratio (PMR) has been proposed as a suitable observable to constrain the density dependence of the symmetry energy (SE) above the saturation point [1]. Various attempts in this direction [2–5] have resulted in a confusing picture: constraints on the high density dependence of SE ranging from a very soft to stiff have been determined by employing different transport models and/or parametrizations of the symmetry potential. Additionally, most models lead to a contradiction between the

π^-/π^+ multiplicity ratio and neutron/proton elliptic flow ratio extracted constraints. Attempts to find a solution to this problem by studying the impact of in-medium modification of the pion-nucleon interaction [6], of the kinetic part of the SE term [7], neutron skin thickness [8] or particle production thresholds due to the inclusion of self-energy contributions [9,10] on the PMR value have proven unsuccessful.

Transport models that employ momentum or isospin dependent mean-fields do not conserve the total energy at microscopical level, in two-body collision, resonance decay or meson absorption processes. This fact translates into an energy conservation violation at an event by event basis and also when an average is performed over a large number of events. Consequently, an upgrade of the Tübingen transport model, that alleviates this problem, has been developed. All the relevant details of this upgrade together with the most relevant results to the PMR problem have been presented in detail in Ref. [11]. In this conference proceeding we will present in greater detail the motivation that has lead to the mentioned upgrade, some relevant details of the model and end with a few selected results.

2 The model

The starting point for the model employed in this study has been the QMD transport model developed in Tübingen [12] which has been upgraded to accommodate for density dependent cross-sections, various parametrizations of the optical potential and of the isovector part of the equation of state (EoS) of nuclear matter [13]. For the present study the Gogny inspired parametrization of the SE has been used [14], which allows the adjustment of the stiffness of the isovector part of the EoS by the introduction of a parameter denoted x. Positive and negative values of this parameter correspond to a soft and respectively stiff choice for the stiffness of the SE.

The poorly known in-medium baryonic resonance's potentials are chosen as follows. The isoscalar part is set to be equal to that of the nucleon, a choice common to most transport models. The isovector resonance potential is related to that of the nucleon by making use of the decay branching ratios of each isospin quadruplet component into the possible pion-nucleon pairs [15]. The total resonance potential can thus be written as

$$\begin{aligned} V_{\Delta^-} &= V_N + (3/2)\, V_v \\ V_{\Delta^0} &= V_N + (1/2)\, V_v \\ V_{\Delta^+} &= V_N - (1/2)\, V_v \\ V_{\Delta^{++}} &= V_N - (3/2)\, V_v \end{aligned} \tag{1}$$

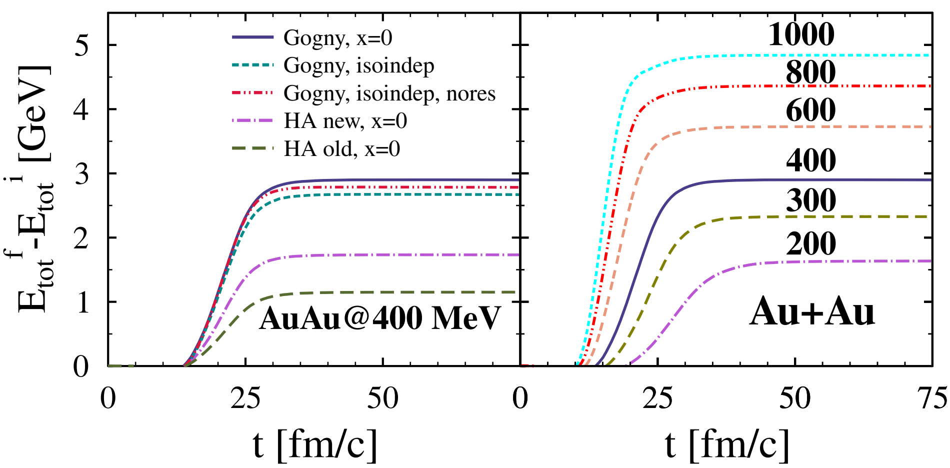

Figure 1: Left Panel: Magnitude of the energy conservation violation in central Au+Au collisions at an impact energy of 400 MeV/nucleon. Results for three different parametrizations of the optical potential are presented: Gogny (full curve), old Hartnack-Aichelin (long dashed-curve) and new Hartnack-Aichelin (dash-dotted curve). Additionally, for the case of the Gogny potential results for the cases when the isovector part of the potential (short dashed curve) and the inelastic channels (dashed double dotted curve) are ignored are presented. Right Panel: Dependence of the magnitude of the energy conservation violation on the impact energy below 1 GeV/nucleon for the Gogny inspired potential.

where V_N is the isoscalar nucleon potential and V_v=δ, with the definition δ=(1/3)(V_n-V_p), V_n and V_p being the isovector components of the neutron and proton potential respectively.

To justify the approximations introduced next, the extent to which the conservation law of total energy is obeyed is investigated, the results being presented in Fig. 1. The left panel presents results for three different parametrizations of the optical potential for central Au+Au collisions at an impact energy of 400 MeV/nucleon: the Gogny inspired one of Ref. [14] and the two parametrization (Hartnack-Aichelin) extracted from the analysis of proton-nucleus scattering data in Ref. [16]. It is observed that the amount of energy conservation violation (ECV) dependents strongly upon the choice of the optical momentum but is it in all cases much larger than the rest mass of the pion. The isospin dependent part of the potential and the inelastic channels are seen to impact the magnitude of ECV rather modestly at this impact energy. The right panel of Fig. 1 presents the dependence of the amount of ECV on the kinetic energy of the projectile nucleus. An monotonically increasing behavior on this quantity is observed, however a saturation phenomenon takes place towards higher impact energies, a trend that can be explained by the same behavior of the optical potential as a function of the momentum of the incident particle.

It is thus clear that transport models that fail to conserve the total energy at the level of few GeV are not appropriate for the description of production of particles with rest masses much smaller than this value. The problem can be alleviated by including in the process of the determination of the kinematics of final states of two-body collisions, resonance decay and meson absorption processes of the in-medium meson and baryon potentials. In this processes elementary two-body reactions lose their local character becoming part of a much more complicated N-body process which allows the conservation of total energy via exchanges mediated by the intermediate and long-range part of the nucleon-nucleon interaction. In a Feynman diagrammatic picture, the leading order contributions are expected to arise from initial-state and final-state interactions, while contributions originating from more complicated diagrams (rescattering terms) are assumed to be much smaller and thus are completely neglected. All the pertinent details of the approximations involved, the invariant masses at which elastic and inelastic channels cross-sections are evaluated, the needed modifications to the detailed balance formula, in-medium effects on cross-sections and numerical approximations required to make such calculations feasible time-wise are presented in Ref. [11].

3 Selected results

The inclusion of contributions of the hadronic potentials in the equation of energy conservation leads to threshold shifts for particle production with respect to their vacuum position [9]. In the case of π mesons the effect is much stronger for the negatively charged pion [11] which leads to a total different dependence of the PMR on the SE stiffness compared with the case when total energy is not conserved: a higher PMR value is favored by a stiffer asy-EoS, a behaviour that was also reported by the study in Ref. [10]. This allows, using the prescription for the in-medium Δ potential of Eq. 1, to extract a constraint for the density dependence of SE above the saturation point which is compatible with the one extracted from experimental data of the elliptic flow ratio of neutrons and protons [11]. Additionally, the

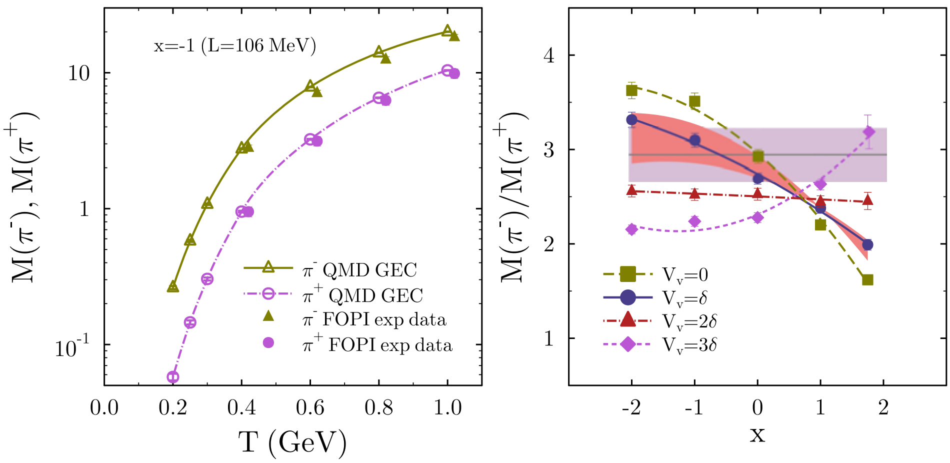

Figure 2: Left Panel: Comparison between theoretical and experimental π^- and π^+ multiplicities for impact energies below 1.0 GeV/nucleon. Theoretical predictions for sub-threshold impact energies are also provided. Right Panel: Sensitivity of the PMR to variations of the strength of the isocalar (band) and isovector (curves) $\Delta(1232)$ potentials at an impact energy of 400 MeV/nucleon as a function of the stiffness parameter x. The experimental value is depicted by the horizontal band. Both panels display results for central ^{197}Au+^{197}Au collisions.

dependence of the PMR on model parameters like compressibility modulus of the isoscalar part of the EoS, parametrization of the optical potential, inclusion or exclusion of medium effects on elastic and inelastic elementary cross-sections is found to be small [11]. A comparison of theoretical and experimental data for the charged pion multiplicities up to values of the impact energy of 1.0 GeV/nucleon shows a good agreement (left panel of Fig. 2). The PMR is however found to be extremely sensitive to the strength of the isovector Δ potential and to a smaller extent to its isoscalar component, as shown in the right panel of Fig. 2. By changing the strength of the isovector Δ potential from 0 to 3 times that of Eq. 1 almost any values for the stiffness parameter x can be extracted from a comparison with the experimental data.

In conclusion, the conservation of the total energy in transport models is a mandatory ingredient if a consistent description of particle production is to be achieved. In particular, the multiplicities and multiplicity ratio of charged pions in heavy-ion collisions close to or slightly above the vacuum pion production threshold are greatly impacted by imposing this constraint consistently. Constraints for the symmetry energy dependence on density compatible with the ones extracted from others heavy-ion observables (most notably flows) can be extracted only within this scenario. However, it was also demonstrated that PMR is extremely sensitive to the strength of the unknown isovector Δ potential, which hinders at present the use of this observable for the purpose of determining the density dependence of the symmetry energy above the saturation point.

References

[1] B. A. Li, G. C. Yong and W. Zuo, *Phys. Rev. C*, **71** (2005) 014608.

[2] Z. Xiao, B. A. Li et al., *Phys. Rev. Lett.*, **102** (2009) 062502.

[3] Z. Q. Feng and G. M. Jin, *Phys. Lett. B*, **683** (2010) 140.

[4] W. J. Xie, J. Su, L. Zhu et al., *Phys. Lett. B*, **718** (2013) 1510.

[5] J. Hong and P. Danielewicz, *Phys. Rev. C*, **90** (2014) 024605.

[6] J. Xu, L. W. Chen, C. M. Ko et al., *Phys. Rev. C*, **87** (2013) 067601.

[7] B. A. Li, W. J. Guo and Z. Shi, *Phys. Rev. C*, **91** (2015) 044601.

[8] G. F. Wei, B. A. Li, J. Xu et al., *Phys. Rev. C*, **90** (2014) 014610.

[9] G. Ferini, T. Gaitanos et al., *Phys. Rev. Lett.*, **97** (2006) 202301.

[10] T. Song and C. M. Ko, *Phys. Rev. C*, **91** (2015) 014901.

[11] M. D. Cozma, arXiv:1409.3110 [nucl-th] Preprint (submitted to Phys. Lett. B), 2014.

[12] D. T. Khoa, N. Ohtsuka et al., *Nucl. Phys. A*, **548** (1992) 102.

[13] M. D. Cozma et al., *Phys. Rev. C*, **88** (2013) 044912.

[14] C. B. Das, S. D. Gupta, C. Gale et al., *Phys. Rev. C*, **67** (2003) 034611.

[15] B. A. Li, *Nucl. Phys. A*, **708** (2002) 365.

[16] C. Hartnack and J. Aichelin, *Phys. Rev. C*, **49** (1994) 2801.

[17] W. Reisdorf et al. [FOPI Collab.], *Nucl. Phys. A*, **848** (2010) 366.