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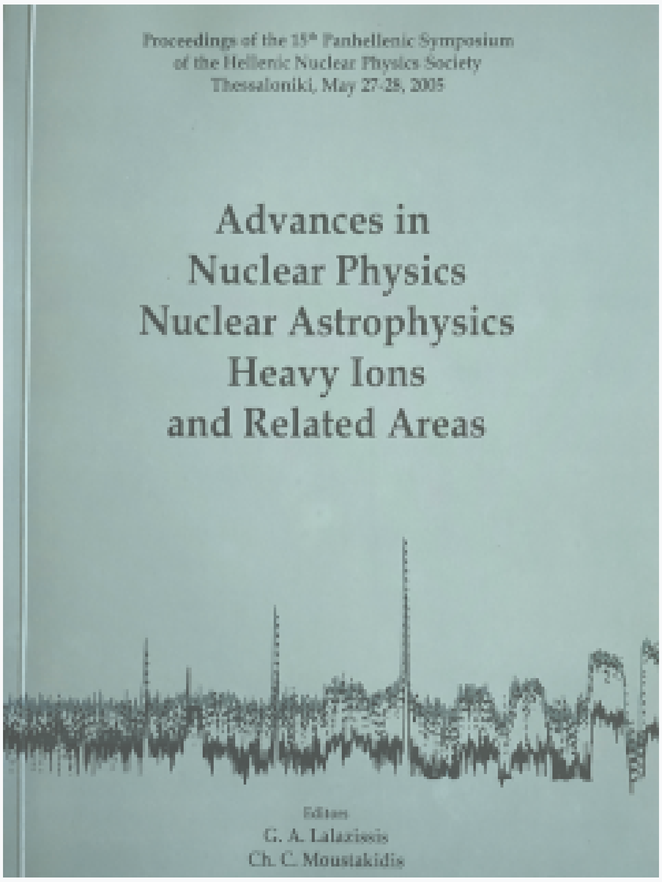

Isospin Effects on Subthreshold Particle Production

T. Gaitanos, G. Ferini, M. Colonna, M. Di Toro, H. H. Wolter

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T. Gaitanos [a,b], G. Ferini [b], M. Colonna [b], M. Di Toro [b]
H.H. Wolter [a]

[a] *Dept. für Physik, Universität München, D-85748 Garching, Germany*
[b] *Laboratori Nazionali del Sud INFN, I-95123 Catania, Italy*

Abstract

The production/absorption rate of particles in compressed and heated asymmetric matter is studied using a Relativistic Mean Field (RMF) transport model with an isospin dependent collision term. We show that the K^+/K^0 ratio reflects the isospin effects on the production rates just because of the large sensitivity around the threshold. The results are very promising with respect to the possibility of a direct link between particle production data in exotic Heavy Ion Collisions (HIC) and the isospin dependent part of the Equation of State (EoS) at high baryon densities.

Heavy Ion Collisions (HIC) at relativistic intermediate energies offer the unique possibility to study hadronic matter under extreme conditions of density, temperature and isospin in the laboratory [1,2]. This knowledge is important in understanding many astrophysical processes such as the mechanism of supernovae explosions and the neutron star structure and cooling. The study of asymmetric nuclear matter (ANM) has recently been reviewed [3]. The behavior of ANM is characterized by the a_4 parameter of the Weizsäcker mass formula at saturation density. Its value is theoretically given in the range between 28 to 36 MeV. However, at densities beyond saturation there is a lack of experimental information. Results of theoretical models of nuclear structure predict rather very different high density behaviors of the symmetry energy and have to be regarded as an extrapolation from below-normal densities [3]. Since in HIC highly compressed hadronic matter can be created for short time scales, one can attempt to set constraints on the still unknown high density dependence of the symmetry energy.

A suitable way to describe ANM is the Relativistic Mean Field (RMF) approach [4]. In RMF baryons, given by Dirac Spinors Ψ, are interacting through

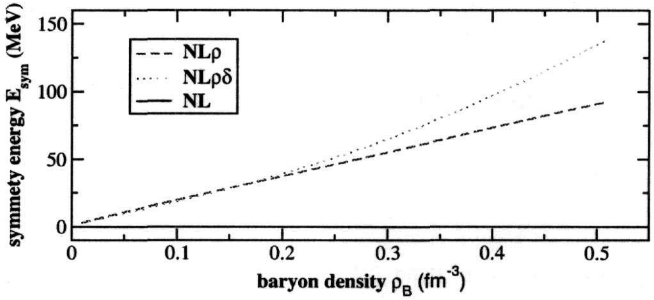

Fig. 1. Density dependence of the symmetry energy including only the ρ-meson (dashed line, $NL\rho$-model) and both, the ρ and δ mesons (dotted line, $NL\rho\delta$-model). The solid line (NL-model) does not include any isospin dependence.

classical meson fields. These have different Lorentz covariant properties; isoscalar-scalar σ, isoscalar-vector ω, isovector-scalar δ and isovector-vector ρ mesons. The first two determine symmetric matter, whereas the ρ and δ meson fields specify the isovector part of the nuclear EoS. In the following we will focus on the isovector part of the EoS in terms of the symmetry energy E_{sym} (see below) by discussing various possibilities for the description of ANM: by including only the ρ meson, or both, the ρ and δ mesons. We will call the corresponding models $NL\rho$ and $NL\rho\delta$, respectively, where NL signifies a non-linear contribution in the σ field [4]. Furthermore, we will also use the option without including isospin dependent fields (NL-model). The parameters of the models have been fixed to nuclear matter saturation properties, see [5–7].

To characterize ANM we introduce the asymmetry parameter $\alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$ which is a function of the neutron to proton fraction of nuclear matter. The symmetry energy E_{sym} is defined by the expansion of the energy per nucleon $E(\rho_B, \alpha)$ in terms of the asymmetry parameter $E(\rho, \alpha) = E(\rho) + E_{sym}(\rho)\alpha^2 + \mathcal{O}(\alpha^4) + \cdots$, i.e. $E_{sym} = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial \alpha^2}|_{\alpha=0}$. From Fig. 1 it is seen that the introduction of the isovector-scalar δ channel influences the density dependence of E_{sym}, which is understood as follows: In E_{sym} there is a strong cancellation of the ρ and δ contributions, analogous to the cancellation of the σ and ω fields in the isoscalar sector. In order to reproduce the fixed bulk asymmetry parameter $a_4 = 30.5\ MeV$ the ρ-meson coupling g_ρ has to increase [5]. However, the $\rho\delta$ cancellation in E_{sym} affects the density dependence of the symmetry energy at high densities since the δ field couples to the scalar-isovector density which is supressed at high density. This leads to a stiffer symmetry energy at supra-normal densities because of the stronger ρ-meson coupling when the δ field is taken into account, as seen in Fig. 1.

A consequence of the different Lorentz behavior of the isovector mean field is a splitting of the repulsive vector and the attractive scalar iso-vector fields between protons and neutrons [8]. This can be seen in the scalar and vector components of the baryon self energy Σ, which are described in terms of the exchange of the classical mesonic fields

$$\Sigma_s(p,n) = -(\Gamma_\sigma \sigma(\rho_s) \pm f_\delta \rho_{s3}) \ , \ \Sigma^\mu(p,n) = f_\omega j^\mu \pm f_\rho j_3^\mu \quad . \tag{1}$$

(there $\rho_s = \rho_{sp} + \rho_{sn}$, $j^\alpha = j_p^\alpha + j_n^\alpha, \rho_{s3} = \rho_{sp} - \rho_{sn}$, $j_3^\alpha = j_p^\alpha - j_n^\alpha$ are the total and isospin scalar densities and currents and Γ_σ, $f_{\omega,\rho,\delta} \equiv \frac{\Gamma^2_{\omega,\rho,\delta}}{m^2_{\omega,\rho,\delta}}$ are the coupling constants of the various mesonic fields, respectively).

We study the properties of dense and hot ANM by considering nuclear matter with a fixed asymmetry α and at given values of the temperature $T = 60$ MeV and density $\rho = 2.5\rho_{sat}$ corresponding to the values at maximal compression in a realistic HIC at about $1-2$ $AGeV$. This system is initialized according to Fermi-Dirac statistics for Fermions (neutrons and protons) in a box of fixed size (periodic boundary conditions) and its evolution is followed with a dynamical transport calculation of Boltzmann type considering only binary collisions (free propagation) [8]. Although the mean field is neglected in the propagation, it influences the dynamics due to the in-medium modifications of the threshold conditions, as discussed below.

At these conditions of T and ρ the following processes mainly contribute to the collision dynamics (N, R, B, Y stand for nucleons (protons, neutrons), resonances, baryons (nucleons, resonances) and hyperons, respectively, and the corresponding cross sections are taken from experimental data [8]):

(1) $NN \longleftrightarrow NR,\ RR$ (resonance production/absorption)
(2) $R \longleftrightarrow N\pi$ (pion production/absorption)
(3) $BB \longrightarrow BB$ (elastic collisions)
(4) kaon production from $BB,\ B\pi$ channels:
$NN \rightarrow BYK,\ N\Delta \rightarrow BYK,\ \Delta\Delta \rightarrow BYK,\ \pi N \rightarrow YK,\ \pi\Delta \rightarrow YK$

Finite density or in-medium effects modify the threshold conditions for inelastic binary channels. The situations is even more complicated in cases where the potential is isospin dependent. Isospin exchange processes cause a change of the isospin dependent part of the potential between ingoing and final outgoing channel in an inelastic 2-body collision. This effect should be accounted for in the calculation of the threshold energy in conserving the total energy in a binary collision.

The essential condition of two-body collisions is the energy-momentum conservation, i.e. the conservation of the total invariant collision energy s, which, in terms of ingoing (1,2) and outgoing (3,4) canonical momenta ($k^\mu_{1,2}$, $k^\mu_{3,4}$), reads:

$$s_{in} = (k_1^\mu + k_2^\mu)(k_{1\mu} + k_{2\mu}) = (k_3^\mu + k_4^\mu)(k_{3\mu} + k_{4\mu}) = s_{out} \quad . \tag{2}$$

If the isospin degree of freedom is *not* accounted for, we can simply fulfill energy-momentum conservation using effective masses and momenta

$$s^*_{in} = (k^{*\mu}_1 + k^{*\mu}_2)(k^*_{1\mu} + k^*_{2\mu}) = (k^{*\mu}_3 + k^{*\mu}_4)(k^*_{3\mu} + k^*_{4\mu}) = s^*_{out} \quad , \tag{3}$$

for a 2-body collision with ingoing (outgoing) effective 4-momenta $k^{*\mu}_{1,2}$ ($k^{*\mu}_{3,4}$). Here the relation between kinetic and canonical momenta is $k^{*\mu}_i = k^\mu_i - \Sigma^\mu_i$, $(i = 1, 2, 3, 4)$. The effective masses $m^*_i = M - \Sigma_{si}$ enter in the energy conservation via the 0-component of the 4-kinetic momentum $E^*_i = \sqrt{m^{*2}_i + k^{*2}_i}$.

The condition (3) is a constraint on the kinetic plus rest mass energy of the colliding particles. To verify Eq. (3) it is sufficient to consider symmetric ($N = Z$) matter and restricts to elastic collisions where the mean field (scalar and vector self energies) does not depend on isospin, i.e. does not distinguish between protons and neutrons, and does not change between the ingoing and the outgoing particles. In those particular cases Eq. (3) implies Eq. (2).

In the general case of asymmetric nuclear matter, however, the introduction of the isovector-scalar δ field causes a splitting in the scalar *and* in the vector fields between protons and neutrons, (see Eqs. (1)). For the other hadrons (Δ resonance) we assume that their self energies are a weighted sum of proton and neutron self energies corresponding to the quark content ($i = scalar, vector$)

$$\Sigma_i(\Delta^-) = \Sigma_i(n) \quad , \quad \Sigma_i(\Delta^0) = \frac{2}{3}\Sigma_i(n) + \frac{1}{3}\Sigma_i(p) \tag{4}$$

$$\Sigma_i(\Delta^+) = \frac{1}{3}\Sigma_i(n) + \frac{2}{3}\Sigma_i(p) \quad , \quad \Sigma_i(\Delta^{++}) = \Sigma_i(p) \quad . \tag{5}$$

Therefore, in inelastic collisions with isospin exchange, the scalar and vector self energies between the ingoing and outgoing channels may differ, such that Eq. (3) does no longer imply Eq. (2). A typical example is the inelastic process $nn \longrightarrow p\Delta^-$ from which a Δ^- resonance is formed. It is clear that, even in the presence of the ρ meson only, the vector self energy of the final channel changes. In the general case of including both ρ and δ mesons both self energies (scalar and vector) of the outgoing channel differ from those in the ingoing channel. In order to properly impose energy-momentum conservation one thus needs to replace condition (3) with (2). Then from Eq. (2) the following threshold condition for a given inelastic process follows:

$$s_{in} \geq \underbrace{(m^*_3 + \Sigma^0_3 + m^*_4 + \Sigma^0_4)^2 - (\mathbf{\Sigma}_3 + \mathbf{\Sigma}_4)^2}_{s_0} \quad . \tag{6}$$

This condition reduces to $s^*_{in} \geq (m^*_3 + m^*_4)$ whenever we have either no isospin dependence, i.e. for symmetric nuclear matter and in general for the NL model,

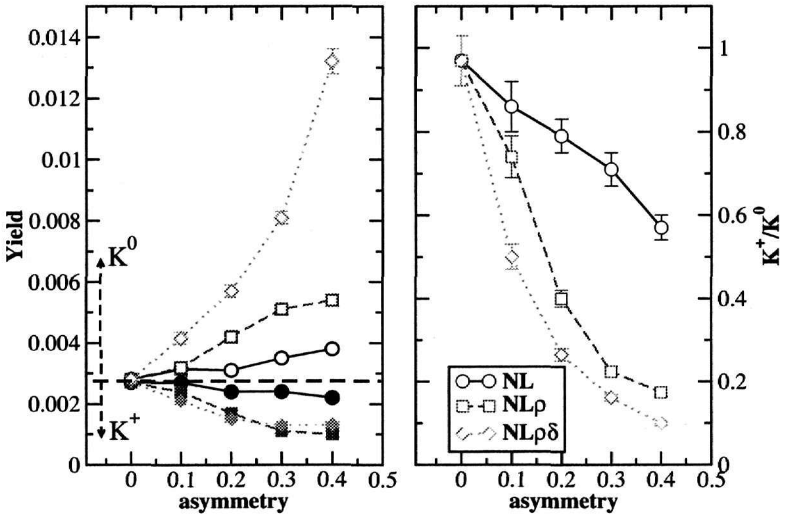

Fig. 2. Asymmetry dependence of the $K^{+,0}$ yields (left) and of the K^+/K^0 ratio (right) for the different iso-vector models as in Fig. 1.

or for elastic collisions. Thus, the multiplicity of particle produced in the inelastic processes allowed by Eq.(6) depends on the available energy above the threshold, i.e. on the difference $\Delta s = s_{in} - s_0$, which is affected by the isovector channel through both the effective masses and the vector self-energies and therefore changes when considering the NL, $NL\rho$ and $NL\rho\delta$ models.

A detailed discussion [8] shows that a gradual increasing (decreasing) multiplicity of Δ^- (Δ^{++}) states follows when going from the NL to the $NL\rho$ and then to the $NL\rho\delta$ model. This affects the relative populations of different isospin states for kaons, as can be seen in Fig. 2 (similar effects have been found also for the pions, see [8] for more details). The yield for the different isovector models is seen to increase with α for the K^0 yield, but decreases for K^+ production and decreases strongly for the K^+/K^0 ratio.

Generally the isospin effects on kaon yields originate from at least two different mechanisms: the isospin dependencies of the $\pi^\pm$ yields, a moderate effect, and the isospin dependent threshold conditions. The isospin effect on the kaon production threshold is complicated, due to the many channels that are affected by the threshold conditions (and hence the yields) differently. However, changes in opposite directions originating from different channels do not exactly cancel each other. A detailed study (see [8]) has shown that for collisions involving neutrons (protons) s_{in} increases (decreases) when going from NL to $NL\rho$ and then to $NL\rho\delta$ model. Therefore, the available energy for K^0 production increases as the symmetry energy becomes stiffer, leading to an enhanced

K^0 yield. On the other hand, the trend for the isospin behavior of the K^+ yield is found to be opposite.

In conclusion, we have investigated the high density behavior of the iso-vector part of the nuclear EoS, which is still poorly known experimentally, controversially predicted by theory, but of great interest in extreme nuclear systems. Here we discuss its behavior for an idealized system of infinite asymmetric hadronic matter. We have analyzed the production of kaons at extreme conditions of baryon density and temperature that temporarily occur in intermediate energy HIC. The relativistic effects arising from the different treatment of the iso-vector EoS turned out to affect particle production. In particular, in asymmetric matter a given isospin state of produced particles is differently populated depending on the high density behavior of the symmetry energy. As an important result the K^0 and K^+ yields were affected in opposite ways leading to a sensitive isospin dependence of the K^+/K^0 ratio, which one would expect to observe in heavy ion collisions at subthreshold energies [9].

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