ISOSPIN EFFECTS ON MESON PRODUCTION IN RELATIVISTIC HEAVY ION COLLISIONS

M. Di Toro, M. Colonna, G. Ferini, V. Greco, J. Rizzo
LNS-INFN and Physics-Astronomy Dept., Univ. of Catania, Italy
V. Baran
NIPNE-HH and Bucharest University, Romania
T. Gaitanos
Institut für Theoretische Physik, Universität Giessen, Germany
Lin Bo
IHEP, Beijing, China
G. Lalazissis, V. Prassa
Dept. of Theoretical Physics, Aristotle University, Thessaloniki, Greece
H. H. Wolter
Dept. für Physik, Universität München, Germany

Abstract

We show that the phenomenology of isospin effects on heavy ion reactions at intermediate energies (few AGeV range) is extremely rich and can allow a “direct” study of the covariant structure of the isovector interaction in a high density hadron medium. We work within a relativistic transport frame, beyond a cascade picture, consistently derived from effective Lagrangians, where isospin effects are accounted for in the mean field and collision terms. We show that rather sensitive observables are provided by the pion/kaon production ($\pi^-/\pi^+$, $K^0/K^+$ yields). Relevant non-equilibrium effects are stressed. The possibility of the transition to a mixed hadron-quark phase, at high baryon and isospin density, is finally suggested. Some signatures could come from an expected “neutron trapping” effect.
1 Introduction

Recently the development of new heavy ion facilities (radioactive beams) has driven the interest on the dynamical behaviour of asymmetric matter. Here we focus our attention on relativistic heavy ion collisions, that provide a unique terrestrial opportunity to probe the in-medium nuclear interaction in high density and high momentum regions. An effective Lagrangian approach to the hadron interacting system is extended to the isospin degree of freedom: within the same frame equilibrium properties (\(EoS\)) and transport dynamics can be consistently derived.

Within a covariant picture of the nuclear mean field, for the description of the symmetry energy at saturation (\(a_4\) parameter of the Weizsäcker mass formula) (a) only the Lorentz vector \(\rho\) mesonic field, and (b) both, the vector \(\rho\) (repulsive) and scalar \(\delta\) (attractive) effective fields can be included. In the latter case the competition between scalar and vector fields leads to a stiffer symmetry term at high density. We present here observable effects in the dynamics of heavy ion collisions. We focus our attention on the isospin content of meson production. We finally show that in the compression stage of isospin asymmetric collisions we can even enter a mixed deconfined phase.

2 Relativistic Transport

The starting point is a simple phenomenological version of the Non-Linear (with respect to the iso-scalar, Lorentz scalar \(\sigma\) field) effective nucleon-boson field theory, the Quantum-Hadro-Dynamics. According to this picture the presence of the hadronic medium leads to effective masses and momenta

\[
M^* = M + \Sigma_s, \quad k^\mu = k^\mu - \Sigma^\mu, \quad \text{with} \quad \Sigma_s, \quad \Sigma^\mu \quad \text{scalar and vector self-energies.}
\]

For asymmetric matter the self-energies are different for protons and neutrons, depending on the isovector meson contributions. We will call the corresponding models as \(NL\rho\) and \(NL\rho\delta\), respectively, and just \(NL\) the case without isovector interactions. For the more general \(NL\rho\delta\) case the self-energies of protons and neutrons read:

\[
\Sigma_s(p, n) = -f_\sigma \sigma(p_s) \pm f_\delta \rho_{s3},
\]

\[
\Sigma^\mu(p, n) = f_\omega j^\mu \mp f_{\rho j}^\mu,
\]

(1)
(upper signs for neutrons), where \( \rho_s = \rho_{sp} + \rho_{sn}, \ j^\alpha = j^\alpha_p + j^\alpha_n, \ \rho_{s3} = \rho_{sp} - \rho_{sn}, \ j^\alpha_3 = j^\alpha_p - j^\alpha_n \) are the total and isospin scalar densities and currents and \( f_{\sigma, \omega, \rho, \delta} \) are the coupling constants of the various mesonic fields. \( \sigma(\rho_s) \) is the solution of the non-linear equation for the \( \sigma \) field 8 10.

For the description of heavy ion collisions we solve the covariant transport equation of the Boltzmann type within the Relativistic Landau Vlasov (RLV) method, using phase-space Gaussian test particles 5), and applying a Monte-Carlo procedure for the hard hadron collisions. The collision term includes elastic and inelastic processes involving the production/absorption of the \( \Delta(1232\,\text{MeV}) \) and \( N^*(1440\,\text{MeV}) \) resonances as well as their decays into pion channels, 6).

3 Isospin effects on pion and kaon production at intermediate energies

Kaon production has been proven to be a reliable observable for the high density EoS in the isoscalar sector 7 8). Here we show that the \( K^0+/K^0 \) production (in particular the \( K^0+/K^0 \) yield ratio) can be also used to probe the isovector part of the EoS, 9 10).

Using our RMF transport approach we analyze pion and kaon production in central \( ^{197}\text{Au} + ^{197}\text{Au} \) collisions in the 0.8 – 1.8 \( AGeV \) beam energy range, comparing models giving the same “soft” EoS for symmetric matter and with different effective field choices for \( E_{sym} \). We will use three Lagrangians with constant nucleon-meson couplings (\( NL... \) type, see before) and one with density dependent couplings (\( DDF \), see 4)), recently suggested for better nucleonic properties of neutron stars 11 12).

Fig. 1 reports the temporal evolution of \( \Delta^{\pm,0,++} \) resonances, pions (\( \pi^{\pm,0} \)) and kaons (\( K^{+,0} \)) for central \( \text{Au+Au} \) collisions at \( 1AGeV \). 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 occur within the very early (compression) stage, and the yield saturates at around \( 20\,fm/c \).

From Fig. 1 we see that the pion results are weakly dependent on the isospin part of the nuclear mean field. However, a slight increase (decrease) in the \( \pi^-/\pi^+ \) multiplicity is observed when going from the \( NL \) (or \( DDF \)) to the \( NL\rho \) and then to the \( NL\rho\delta \) model, i.e. increasing the vector contribution \( f_\rho \) in the isovector channel. This trend is more pronounced for kaons, see the right
Figure 1: Time evolution of the $\Delta^{\pm,0,++}$ resonances and pions $\pi^{\pm,0}$ (left), and kaons ($K^{+,0}$) (right) for a central ($b = 0$ fm impact parameter) Au+Au collision at 1 AGeV incident energy. Transport calculation using the NL, NLρ, NLρδ and DDF models for the iso-vector part of the nuclear EoS are shown. The inset contains the differential $K^{0}/K^{+}$ ratio as a function of the kaon emission time.

panel, due to the high density selection of the source and the proximity to the production threshold. Consistently, as shown in the inset, larger effects are expected for early emitted kaons, reflecting the early $N/Z$ of the system.

When isovector fields are included the symmetry potential energy in neutron-rich matter is repulsive for neutrons and attractive for protons. In a HIC this leads to a fast, pre-equilibrium, emission of neutrons. Such a mean field mechanism, often referred to as isospin fractionation 1), is responsible for a reduction of the neutron to proton ratio during the high density phase, with direct consequences on particle production in inelastic $NN$ collisions.

Threshold effects represent a more subtle point. The energy conservation in a hadron collision in general has to be formulated in terms of the canonical momenta, i.e. for a reaction $1 + 2 \rightarrow 3 + 4$ as $s_{1n} = (k_1^\mu + k_2^\mu)^2 = (k_3^\mu + k_4^\mu)^2 = s_{out}$. Since hadrons are propagating with effective (kinetic) momenta and masses, an equivalent relation should be formulated starting from the effective in-medium quantities $k^*^\mu = k^\mu - \Sigma^\mu$ and $m^* = m + \Sigma_s$, where $\Sigma_s$ and $\Sigma^\mu$ are the scalar and vector self-energies, Eqs.(1). The self-energy contributions will influence the particle production at the level of thresh-
olds as well as of the phase space available in the final channel. In fact the threshold effect is dominant and consequently the results are nicely sensitive to the covariant structure of the isovector fields. At each beam energy we see an increase of the $\pi^-/\pi^+$ and $K^0/K^+$ yield ratios with the models $NL \rightarrow DDF \rightarrow NL\rho \rightarrow NL\rho\delta$. The effect is larger for the $K^0/K^+$ compared to the $\pi^-/\pi^+$ ratio. This is due to the subthreshold production and to the fact that the isospin effect enters twice in the two-step production of kaons, see [9]. Interestingly the Iso-EoS effect for pions is increasing at lower energies, when approaching the production threshold.

We have to note that in a previous study of kaon production in excited nuclear matter the dependence of the $K^0/K^+$ yield ratio on the effective isovector interaction appears much larger (see Fig.8 of ref.[13]). The point is that in the non-equilibrium case of a heavy ion collision the asymmetry of the source where kaons are produced is in fact reduced by the $n \rightarrow p$ “transformation”, due to the favored $nn \rightarrow p\Delta^-$ processes. This effect is almost absent at equilibrium due to the inverse transitions, see Fig.3 of ref.[6]. Moreover in infinite nuclear matter even the fast neutron emission is not present. This result clearly shows that chemical equilibrium models can lead to uncorrect results when used for transient states of an open system.

4 Testing Deconfinement at High Isospin Density

The hadronic matter is expected to undergo a phase transition to a deconfined phase of quarks and gluons at large densities and/or high temperatures. On very general grounds, the transition’s critical densities are expected to depend on the isospin of the system, but no experimental tests of this dependence have been performed so far. In order to check the possibility of observing some precursor signals of a new physics even in collisions of stable nuclei at intermediate energies we have performed some event simulations for the collision of very heavy, neutron-rich, elements. We have chosen the reaction $^{238}U + ^{238}U$ (average proton fraction $Z/A = 0.39$) at 1 AGeV and semicentral impact parameter $b = 7 \text{ fm}$ just to increase the neutron excess in the interacting region. In Fig.2 we report the evolution of momentum distribution and baryon density in a space cell located in the c.m. of the system. We see that after about 10 fm/c a local equilibration is achieved. We have a unique Fermi distribution and from a simple fit we can evaluate the local temperature (black numbers
Figure 2: $^{238}U + ^{238}U$, 1 AGeV, semicentral. Correlation between density, temperature, momentum thermalization inside a cubic cell, 2.5 fm wide, in the center of mass of the system.

in MeV). We note that a rather exotic nuclear matter is formed in a transient time of the order of 10 fm/c, with baryon density around $3 - 4 \rho_0$, temperature 50–60 MeV, energy density 500 MeV fm$^{-3}$ and proton fraction between 0.35 and 0.40, likely inside the estimated mixed phase region.

In fact we can study the isospin dependence of the transition densities [13]. The structure of the mixed phase is obtained by imposing the Gibbs conditions [15] for chemical potentials and pressure and by requiring the conservation of the total baryon and isospin densities

$$
\begin{align*}
\mu_B^{(H)} &= \mu_B^{(Q)} , \\
\mu_3^{(H)} &= \mu_3^{(Q)} , \\
P^{(H)}(T, \mu_B^{(H)}, \mu_3^{(H)}) &= P^{(Q)}(T, \mu_B^{(Q)}, \mu_3^{(Q)}) , \\
\rho_B &= (1 - \chi)\rho_B^H + \chi \rho_B^Q , \\
\rho_3 &= (1 - \chi)\rho_3^H + \chi \rho_3^Q ,
\end{align*}
$$

(2)

where $\chi$ is the fraction of quark matter in the mixed phase. In this way we get the binodal surface which gives the phase coexistence region in the $(T, \rho_B, \rho_3)$ space. For a fixed value of the conserved charge $\rho_3$ we will study the boundaries of the mixed phase region in the $(T, \rho_B)$ plane. In the hadronic phase the charge chemical potential is given by $\mu_3 = 2E_{sym}(\rho_B) \frac{\rho_3}{\rho_B}$. Thus, we expect critical densities rather sensitive to the isovector channel in the hadronic EoS.
Figure 3: Variation of the transition density with proton fraction for various hadronic $EoS$ parameterizations. Dotted line: $GM3$ $RMF$-model [11]; dashed line: $NL\rho$; solid line: $NL\rho\delta$. For the quark $EoS$: MIT bag model with $B^{1/4}=150$ MeV. The points represent the path followed in the interaction zone during a semi-central $^{132}\text{Sn}+^{132}\text{Sn}$ collision at 1 AGeV (circles) and at 300 AMeV (crosses).

In Fig. 3 we show the crossing density $\rho_c$, separating nuclear matter from the quark-nucleon mixed phase, as a function of the proton fraction $Z/A$. We can see the effect of the $\delta$-coupling towards an earlier crossing due to the larger symmetry repulsion at high baryon densities. In the same figure we report the paths in the $(\rho, Z/A)$ plane followed in the c.m. region during the collision of the n-rich $^{132}\text{Sn}+^{132}\text{Sn}$ system, at different energies. At 300 AMeV we are just reaching the border of the mixed phase, and we are well inside it at 1 AGeV. We expect a neutron trapping effect, supported by statistical fluctuations as well as by a symmetry energy difference in the two phases. In fact while in the hadron phase we have a large neutron potential repulsion (in particular in the $NL\rho\delta$ case), in the quark phase we only have the much smaller kinetic contribution. Observables related to such neutron “trapping” could be an inversion in the trend of the formation of neutron rich fragments and/or of the $\pi^-/\pi^+$, $K^0/K^+$ yield ratios for reaction products coming from high density regions, i.e. with large transverse momenta.

5 Perspectives

We have shown that meson production in n-rich heavy ions collisions at intermediate energies can bring new information on the isovector part of the in-medium interaction at high baryon densities. Important non-equilibrium effects for particle production are stressed. Finally the possibility of observing
precursor signals of the phase transition to a mixed hadron-quark matter at high baryon density is suggested.

Acknowledgements. We warmly thanks A.Drago and A.Lavagno for the intense collaboration on the mixed hadron-quark phase transition at high baryon and isospin density.

References

1. V.Baran, M.Colonna, V.Greco, M.Di Toro, Phys. Rep. **410** (2005) 335.
2. B. D. Serot, J. D. Walecka, Advances in Nuclear Physics, **16**, 1, eds. J. W. Negele, E. Vogt, (Plenum, N.Y., 1986).
3. B. Liu, V. Greco, V. Baran, M. Colonna, M. Di Toro, Phys. Rev. **C65** (2002) 045201.
4. T. Gaitanos, et al., Nucl. Phys. **A732** (2004) 24.
5. C. Fuchs. H.H. Wolter, Nucl. Phys. **A589** (1995) 732.
6. G. Ferini, M. Colonna, T. Gaitanos, M. Di Toro, Nucl. Phys. **A762** (2005) 147.
7. C. Fuchs, Prog.Part.Nucl.Phys. **56** 1-103 (2006).
8. C.Hartnack, H.Oeschler, J.Aichelin, Phys. Rev. Lett. **96** (2006) 012302.
9. G.Ferini et al., Phys. Rev. Lett. **97** (2006) 202301.
10. V.Prassa et al., Nucl.Phys. **A789** (2007) 311.
11. T.Klähn et al., Phys. Rev. **C74** (2006) 035802.
12. B.Liu et al., Phys. Rev. **C75** (2007) 048801.
13. M. Di Toro, A. Drago, T. Gaitanos, V. Greco, A. Lavagno, Nucl. Phys. **A775** (2006) 102.
14. N.K.Glendenning, S.A.Moszkowski, Phys. Rev. Lett. **67** (1991) 2414.
15. L.D.Landau, L.Lifshitz, Statistical Physics, Pergamon Press, Oxford 1969.