Isospin effects in intermediate energy heavy ion collisions

T. Gaitanos¹, M. Di Toro¹, G. Ferini¹, M. Colonna¹, H. H. Wolter²
¹INFN, Laboratori Nazionali del Sud, Catania, Italy
²Sektion Physik, LMU-München, Germany

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Abstract

We investigate the density dependence of the symmetry energy in a relativistic description by decomposing the iso-vector mean field into contributions with different Lorentz properties. We find important effects of the iso-vector, scalar $\delta$ channel on the density behavior of the symmetry energy. Finite nuclei studies show only moderate effects originating from the virtual $\delta$ meson. In heavy ion collisions from Fermi to relativistic energies up to $1 - 2 \ A GeV$ one finds important contributions on the dynamics arising from the different treatment of the microscopic Lorentz structure of the symmetry energy. We discuss a variety of possible signals which could set constraints on the still unknown density dependence of the symmetry energy, when experimental data will be available. Examples of such observables are isospin collective flow, threshold production of pions and kaons, isospin equilibration and stopping in asymmetric systems like $Au + Au$, $Sn + Sn$ and $Ru(Zr) + Zr(Ru)$.

1 Introduction

Heavy ion collisions at relativistic energies from 0.1 up to $1 - 2\ A GeV$ offer the possibility to access the equation of state (EOS) of nuclear matter under extreme conditions of density and temperature [1]. Such studies are essential in understanding many astrophysical phenomena such as the physical mechanism of supernovae explosions and neutron stars. During the last three decades many attempts have been done to investigate the properties of highly excited hadronic matter [1].

So far asymmetric nuclear matter has been only poorly investigated for densities beyond saturation. Finite nuclei studies predict values for the symmetry energy at saturation in the order of $30 - 35\ MeV$, however, for supra-normal densities one has to rely on extrapolations. On the other hand, in heavy ion collisions highly compressed matter can be formed for short time scales, thus the study of such a dynamical process can provide useful information on the high density symmetry energy. Recently theoretical studies on the high density symmetry energy have been started by investigating heavy ion collisions of asymmetric systems [2,3] and they have been motivated by the planning of new experimental heavy ion facilities with neutron rich radioactive beams.

The aim of this proceedings is to explore the properties of asymmetric nuclear matter within a relativistic mean field theory in different nuclear systems, i.e. finite nuclei and heavy ion collisions, with the particular interest on understanding the high density behavior of the symmetry energy in terms of its Lorentz properties.
|      | $f_{\sigma}$ ($fm^2$) | $f_{\omega}$ ($fm^2$) | $f_{\rho}$ ($fm^2$) | $f_{\delta}$ ($fm^2$) | A     | B     |
|------|----------------------|----------------------|----------------------|----------------------|-------|-------|
| NL$\rho$ | 10.33               | 5.42                 | 0.95                 | 0.0                  | 0.033 | -0.0048 |
| NL$\rho\delta$ | 10.33              | 5.42                 | 3.15                 | 2.5                  | 0.033 | -0.0048 |
| NL3     | 15.73               | 10.53                | 1.34                 | 0.0                  | -0.01 | -0.003 |

Table 1: Nuclear matter saturation properties in terms of $f_i$ and $B \equiv \frac{E_F}{m_i^2}$ for the RMF models using the $\rho$ and both, the $\rho$ and $\delta$ mesons for the characterization of the iso vector mean field in comparison with the NL3 model.

# 2 Equation of state of asymmetric nuclear matter

Within a covariant description of nuclear matter one starts from a Lagrangian of an interacting many body system of baryons (protons and neutrons) and mesons which characterize the interaction between baryons in terms of baryon-meson vertices. In the spirit of a Hartree- or mean field approximation the baryons are given by quantum Dirac spinors $\Psi$ and the mesons (iso-scalar, scalar $\sigma$, iso-scalar, vector $\omega$, iso-vector, scalar $\delta$ and iso-vector, vector $\rho$) are described by classical field equations as follows [4]

\[
\begin{align*}
\left[\gamma_{\mu} i\partial^\mu - g_\omega \omega_0 \gamma^0 - g_\rho \gamma^0 \tau_3 \rho_0 - (M - g_\sigma \sigma - g_\delta \tau_3 \delta_3)\right] \Psi &= 0 \quad (1) \\
m_\sigma^2 \sigma + B\sigma^2 + C\sigma^3 &= g_\sigma <\hat{\Psi}\hat{\Psi}> = g_\sigma \rho_s \quad (2) \\
m_\omega^2 \omega^\mu &= g_\omega <\hat{\Psi}\gamma^\mu\hat{\Psi}> = g_\omega j^\mu \quad (3) \\
m_\rho^2 \rho &= g_\rho <\hat{\Psi}\gamma^0 \tau_3 \hat{\Psi}> = g_\rho \rho_{B3} \quad (4) \\
m_\delta^2 \delta &= g_\delta <\hat{\Psi}\tau_3 \hat{\Psi}> = g_\delta \rho_{3s} \quad (5)
\end{align*}
\]

In (2-5) the scalar density and the baryonic currents are given by $\rho_s$, $j^\mu = (\rho_\gamma, \rho_\gamma \beta)$, respectively. The corresponding isospin vector and scalar densities are then described by $\rho_{B3} = \rho_p - \rho_n$ and $\rho_{3s} = \rho_{sp} - \rho_{sn}$, respectively, with $\rho_{p,n}$ being the proton and neutron densities. The iso-scalar, scalar $\sigma$ field contains non-linear contributions with parameters $B$, $C$. The baryon-meson vertices are given by the different coupling functions $g_{\sigma,\omega,\rho,\delta}$. Another important quantity is the effective Dirac mass which depends on isospin in the presence of the iso-vector, scalar $\delta$ meson

\[
m_i^* = M - g_\sigma \sigma \pm g_\delta \delta \quad (- \text{proton}, + \text{neutron}) \quad (6)
\]

For the investigation of asymmetric nuclear matter the asymmetry parameter $\alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$ is defined which describes the relative ratio of the neutron to proton fraction of the nuclear matter. The symmetry energy $E_{sym}$ is defined from the expansion of the energy per nucleon $E(\rho_B, \alpha)$ in terms of the asymmetry parameter

\[
E(\rho, \alpha) = E(\rho) + E_{sym}(\rho)\alpha^2 + O(\alpha^4) + \cdots \quad (7)
\]

with the abbreviation

\[
E_{sym} = \frac{1}{2} \frac{\partial^2 E(\rho, \alpha)}{\partial \alpha^2} \bigg|_{\alpha = 0} = \frac{1}{2} \frac{\partial^2 \epsilon}{\partial \rho_{B3}^2} \bigg|_{\rho_{B3} = 0} \quad (8)
\]

From the the energy momentum tensor one obtains for the symmetry energy ($f_i \equiv (\frac{\rho_i}{m_i})^2$, $i = \sigma$, $\omega$, $\rho$, $\delta$)

\[
E_{sym} = \frac{1}{6} \frac{k_F^2}{E_F} + \frac{1}{2} \left[ f_\rho - f_\delta \left(\frac{m_i^*}{E_F}\right)^2 \right] \rho \quad (9)
\]

The calculations for symmetric and asymmetric nuclear matter can be done by solving self consistently Eqs. (1-6). The parameters of the model have been fixed to nuclear matter saturation
properties given in table 1. In the following we will focus on the iso-vector part of the equation of state in terms of the symmetry energy $E_{\text{sym}}$ given in Eq. 2.

From Eq. 2 it is seen that the introduction of the iso-vector, scalar $\delta$ channel influences the density dependence of the symmetry energy: in order to reproduce the fixed bulk asymmetry parameter $a_4 = 30.5$ MeV one also has to increase the $\rho$-meson coupling $g_\rho$, see table 1. On the other hand, the Lorentz decomposition of the potential part of $E_{\text{sym}}$ in terms of a vector $\rho$ and a scalar $\delta$ field affects the density dependence of the symmetry energy at high densities due to the suppression of the scalar density ($\rho_s \approx m_\pi^2 E_F^\rho$). This will lead to a stiffer symmetry energy at supra-normal densities because of the stronger $\rho$-meson coupling when the $\delta$ field is taken into account in this description.

However, in general the situation can be more complicated, i.e. by studying asymmetric nuclear matter within more microscopic models such as the Density Dependent Hadronic (DDH) field theory [5]. In the DDH model the baryon-meson vertices are explicitly density dependent with a general decrease of the iso-scalar coupling functions ($g_{\sigma,\omega}(\rho)$) with respect to the baryon density $\rho$. Such a behavior is consistent with realistic Dirac-Brueckner-Hartree-Fock (DBHF) calculations of symmetric nuclear matter where no parameters need to be adjusted [6]. Asymmetric nuclear matter is only poorly investigated within the DBHF theory. In Ref. [6] it was shown that the $\rho$ meson coupling strongly decreases with baryon density, but the $\delta$ meson coupling, on the other hand, increases for densities above saturation.

The whole picture is summarized in Fig. 1 where the density dependence of the symmetry energy in the spirit of relativistic mean field theory (upper curves) is displayed. The bottom panels show separately the kinetic and potential contributions to the total symmetry energy. We used the non-linear Walecka model (NL) in two different treatments for the iso-vector channel: (a) only with the iso-vector, vector $\rho$ meson (NL$\rho$) and (b) with both, the iso-vector, vector $\rho$ and iso-vector, scalar $\delta$ mesons (NL$\rho\delta$). The same procedure was applied within the DDH theory by fixing the parameters of the iso-vector channel ($DDH\rho$ and $DDH3\rho\delta$) to the density dependence of the iso-vector coupling functions of the parameter free Dirac-Breuckner model [6]. Finally, in the $DDH\rho$ model, which contains

Figure 1: Density dependence of the symmetry energy, Eq. (9), for different models: (NL$\rho$, NL$\rho\delta$) non-linear Walecka model including only the $\rho$-meson and both, the $\rho$ and $\delta$ mesons for the iso-vector EOS, respectively. ($DDH\rho$, $DDH3\rho$, $DDH\rho\delta$) Same as in the NL cases for the iso-vector EOS, but within the Density Dependent Hadronic (DDH) mean field theory where all the baryon-meson couplings are explicitly density dependent (taken from [7]).
Figure 2: (Top) transverse flow $F^{pn}$ as function of the rapidity $y_{cm} = \frac{1+\beta_z}{2(1-\beta_z)}$ ($\beta_z$ being the component of the velocity along the beam direction) and (bottom) elliptic flow $v_2^{pn} = \frac{p_x^2-p_y^2}{p_t}$ as function of the normalized transverse momentum $p_t^{(0)} = \frac{p_t}{(p_t^2+m^2/A)}$. These quantities are calculated from the difference between the proton and neutron flows (indicated with the abbreviation pn). Calculations with the $NL\rho$ (circles), $NL\rho\delta$ (squares) and $DDH\rho$ (diamonds) models for a semi-central ($b = 6$ fm) $Sn + Sn$ are shown (taken from [3]).

only the $\rho$ meson for the description of the iso-vector EOS, the parameters were fixed to finite nuclei properties [7].

We see that the iso-vector, scalar $\delta$ channel has important contributions to the symmetry energy for baryon densities above saturation due to the relativistic effects as discussed above. However, in the framework of the DDH theory the contribution of the $\delta$ meson to the high density symmetry energy is different. Only the comparison between $DDH\rho$ and $DDH3\rho\delta$ leads to the same contribution on $E_{sym}$ as the corresponding one between $NL\rho$ and $NL\rho\delta$. This is due to the fact that in the DDH models the iso-vector couplings has an additional density dependence which also contributes to the density behavior of $E_{sym}$, apart from the relativistic effects which are always present.

It is important to realize that the relativistic effects, i.e. the suppression of the iso-vector, scalar $\delta$ channel for high densities and the effective mass splitting between protons and neutrons, lead to a natural momentum dependence of the iso-vector EOS even if the baryon-meson vertices do not explicitly depend on energy. This important feature is not included in phenomenological non-relativistic studies [2], where a momentum dependence can be introduced in addition, however, with more parameters to be fixed.

We have applied our models of Fig. 1 both to the static case of finite nuclei and the dynamical one of heavy ion collisions [7]. In finite nuclei only moderate effects arising from the $\delta$ meson were found due to the fact that the symmetry energy shows a similar density dependence for all the models considered for densities at and below saturation. In the next section we thus study the more interesting dynamical case where highly compressed asymmetric baryonic matter can be formed for short time scales.
3 Heavy ion collisions at SIS energies: The key observables

In heavy ion collisions (HIC) at SIS energies (0.1 – 2 AGeV) the highly compressed matter mainly consists of protons, neutrons and intermediate mass fragments. By choosing collisions of asymmetric nucleus like $^{197}$Au or $^{132,124,112}$Sn one can hope to see dense asymmetric nuclear matter at least for some short time scales from which one could select sensitive signals related to the symmetry energy at supra-normal densities, before expansion and fragmentation sets in. The analysis of HIC’s with the models discussed in the previous section was performed within the relativistic transport equation of a Boltzmann-type (RBUU equation) which describes the dynamical evolution of a 1-particle phase space distribution function under the influence of a mean field (depending on the EOS) and binary collisions. For a detailed review of the transport theory we refer to Ref. [8]. In the following we discuss some of the most important observables which could set constraints on the symmetry energy at high densities.

(1) Collective isospin flows

An important observable in HIC’s is the collective flow due to its high sensitivity on the pressure gradients, i.e. on the degree of the stiffness of the EOS at high densities. Strong collective flow is related to a more repulsive mean field, i.e. to a stiffer EOS with high pressure gradients. There are different components of collective flow: (a) directed in-plane flow which describes the dynamics into the reaction plane and can be described by the mean transverse in-plane flow $F = < p_x(y) >$ as function of the rapidity $y$ and (b) elliptic flow which describes the dynamics perpendicularly to the reaction plane. The later observable is the most important one due to its earlier formation during the high density phase. It can be extracted from a Fourier analysis of azimuthal distributions as the second Fourier coefficient $v_2$.

Fig. 2 shows the rapidity dependence of the isospin transverse flow (defined as the difference in the flow between protons and neutrons) as function of the normalized rapidity $y^{(0)}$ and the transverse momentum dependence of the isospin elliptic flow. A stronger collective flow is seen with the calculations including the $\delta$ meson in the iso-vector channel. This effect becomes very pronounced for the elliptic flow $v_2$ of high energetic ($p_t^{(0)} \geq 0.4$) particles due to the fact that those particles are emitted earlier during the formation of the high density asymmetric matter.

We can understand the observed effects by referring to Eq. (9). The $\rho$ meson has a repulsive vector character, whereas the $\delta$ meson exhibits an attractive scalar one. This Lorentz decomposition is more dominant in the dynamical situation due to relativistic effects: the $\rho$ meson linearly increases with the Lorentz $\gamma$ factor, whereas the $\delta$ meson is not affected by such dynamical effects since the scalar density is a Lorentz scalar quantity. Thus, the stiffness of the symmetry energy is effectively enhanced when including the $\delta$ meson in these descriptions which yields more repulsion for neutrons than for protons with the net effect of a stronger collective dynamics in the $NL\rho\delta$ case.

(2) Particle production

Particle production at these high energies is also directly related to the dynamics of the earlier high density stage of a heavy ion collision. At SIS energies the most dominant inelastic channels are the production of the lowest mass resonances $\Delta(1232)$ and $N^*(1440)$. The resonances are mainly produced during the first nucleon-nucleon collisions and during the high density phase and they decay into pions ($\pi^+\pi^-$). Furthermore, strange particles like kaons are created together with hyperons ($Y = \Lambda, \Sigma$) due to strangeness conservation through baryon-baryon ($BB \rightarrow BYK^+$ with $B = p, n, \Delta$) and $\pi$-baryon ($\pi B \rightarrow YK^+$) collisions.

Fig. 3 shows the energy, rapidity and transverse momentum dependence of the ($\pi^-/\pi^+$)-ratio. This ratio is reduced on the average in the models which contain the $\delta$ meson in the iso-vector EOS, only for high energetic pions ($p_t^{(0)} \geq 0.35$) the trend turn out to be opposite. The observed isospin effects here mainly originate from (a) the different density dependence of the symmetry energy and (b) the effective mass splitting ($m_n^* < m_p^*$).

(a) Due to the more stiffer character of $E_{sym}$ neutrons are emitted earlier than protons making the
Figure 3: Left: energy dependence of the $(\pi^-/\pi^+)$-ratio for central $(b < 2 \text{ fm}) \text{Au} + \text{Au}$ reactions. Calculations with $NL(\rho, \rho\delta)$ and $DDH(\rho, \rho\delta)$ are shown as indicated. Right: rapidity ($y^0$) and transverse momentum ($p_t^{(0)}$) dependence of the $(\pi^-/\pi^+)$-ratio for central $(b < 1.5 \text{ fm}) \text{Ru} + \text{Ru}$ reactions with $NL\rho$ and $NL\rho\delta$ ($y^0$ and $p_t^{(0)}$ are normalized to the corresponding quantities of the projectile per nucleon). The open diamonds shown in all the figures are FOPI data taken from [9, 10] (the figure is taken from [7]).

High density phase more proton rich. On the other hand, $\pi^-$ particles are essentially produced via negative charged resonances $\Delta^-$, for example through the process $nn \rightarrow p\Delta^-$, which then decay into $\pi^-$. Thus due to the earlier neutron emission one observes a reduction of the $(\pi^-/\pi^+)$-ratio. This interpretation is also valid for the more complicated cases of the $DDH(\rho, \rho\delta)$ models.

(b) The effective mass splitting leads additionally to threshold effects since in the $(NL, DDH)\rho\delta$ cases less kinetic energy $\sqrt{s^*} = m^*_n + p^2$ is available for resonance production due to the decrease of $m^*_n$.

However, the comparison with very preliminary FOPI data does not yet support any definitive conclusion. One reason could be that pions interact strongly with the hadronic environment due to absorption effects in secondary collisions and the Coulomb interaction. Furthermore, with increasing beam energy these secondary effects increase (more energy available).

We note that pion production takes place over all the collision after compression, and thus the differences arising from the high density symmetry energy are not very pronounced, however, one want to mention that the density dependence of the symmetry energy are not so different between the models used here by comparing with other studies, see e.g. [2]. It might be also more useful to select particles directly emitted from the high density region. This can be done by choosing pions with high transverse momenta $p_t$, since in other studies [12] it was found that baryons are emitted the earlier, the higher their energy or transverse momentum is. This is seen in Fig. 3 where the differences between $NL\rho$ and $NL\rho\delta$ turn out to be more important for high transverse momenta $p_t^{(0)}$. In particular, for low $p_t^{(0)} < 0.35$ the $(\pi^-/\pi^+)$-ratio is reduced with the $NL\rho\delta$ model, in consistency with the previous discussion. Since the multiplicity is maximal at this $p_t^{(0)}$ region, on average one obtains a reduction of the $(\pi^-/\pi^+)$-ratio with the $NL\rho\delta$ model. However, for high energetic particles the situation is different. The reason for the increase of the $(\pi^-/\pi^+)$-ratio for $p_t^{(0)} > 0.35$ arises from a combination of isospin and Coulomb effects: in the earlier stage of the collision the isospin diffusion takes place which populates the central shell of the collision with more protons and other positive charged particles. Thus, there are two competing
Figure 4: Time evolution of $\Delta$ resonances ($\Delta$), pions ($\pi$) and kaons ($K^+$) for central ($b = 0 \text{ fm}$) $Au+Au$ reactions at 1 $AGeV$ beam energy. Calculations with a soft ($NL2$ with a compressibility of 200 $MeV$) and stiff ($NL3$ with a compressibility of 380 $MeV$) EOS within the non-linear Walecka model are shown (taken from [14]).

effects leading to the observed effect. In one hand, one has a population of protons from low to high density regions, but this effect is not as strong as compared with the fast neutron emission due to the $\delta$ meson. On the other hand, the neutron emission makes the central shell more proton-rich and, especially, reduces the production of other negative charged resonances. Therefore, the coulomb field acting to high energetic pions, which is important at this stage due to high densities, is more repulsive leading the enhancement of the pion ratio for pions emitted directly from high density phase space. Thus, with the help of coulomb effects one is able to understand the influence of the $\delta$ meson on the dynamics of high energetic charged pions and their corresponding ratios.

The kaon production turns out to be a better candidate for our studies, see Fig. 4 since they are produced directly during the high density phase without any secondary effects like the pions. The kaon yield strongly depends on the EOS, in contrary to the pions, as it can be seen from Fig. 4. Thus, one will expect to set more stringent constraints on the high density symmetry energy from kaon production since there are a lot of experimental studies. Such a progress is under investigation.

(2) Isospin transparency in the mixed $Ru(Zr) + Zr(Ru)$ systems

Another interesting aspect in HIC’s is the isospin transparency which has been extensively studied by experiments of the FOPI collaboration [13]. The idea is to use collisions between equal mass nuclei $A = 96$, but different isotope ($Ru$ and $Zr$) which can be taken as projectile and target by making use of all four combinations $Ru(Zr)+Ru(Zr)$ and $Ru(Zr)+Zr(Ru)$. The following imbalance ratio of differential rapidity distributions for the mixed reactions $Ru(Zr) + Zr(Ru)$, $R(y^{(0)}) = N_{RuZr}(y^{(0)})/N_{ZrRu}(y^{(0)})$, was considered, where $N^i(y^{(0)})$ is the particle yield inside the detector acceptance at a given rapidity for $Ru + Zr$, $Zr + Ru$ with $i = RuZr$, $ZrRu$. The observable $R$ can be particularly determined for different particle species, like protons, neutrons, light fragments such as $t$ and $^3He$ and produced particles such as pions ($\pi^{0,\pm}$), etc. The observable $R$ characterizes different stopping scenarios. E.g. in the proton case $R(p)$ rises (positive slope) for partial transparency, falls (negative slope) for full local stopping and is flat when total isospin mixing is achieved in the collision. Therefore, $R(p)$ can be regarded as a sensitive
observable with respect to isospin diffusion, i.e. to properties of the symmetry term.

Fig. 5 shows the rapidity dependence of $R$ for different particles and energies. With the $NL\rho\delta$ model $R$ decreases for protons and increases for neutrons at rapidities near target one. At mid rapidity $R \approx 1$ means full isospin mixing, as expected. In an ideal case of full transparency $R$ should approach the initial value of $R(p) = Z_{Zr}/Z_{Ru} = 40/44 = 0.91$ and $R(n) = N_{Zr}/N_{Ru} = 56/52 = 1.077$ for protons and neutrons at target rapidity, respectively. In the calculations one can see that this is approximately the case when the $\delta$ meson is taken in the iso-vector channel of the EOS into account. This effect is obvious since in the $NL\rho\delta$ model the neutrons experience a more repulsive iso-vector mean field at high densities than the protons and it leads to a less degree of stopping. This isospin effect is moderate at low, but more essential at higher beam energy due to the higher compression in the later case.

It is very important to stress the opposite behavior of $R$ as function of rapidity between protons and neutrons which will result to an essential difference between $NL\rho$ and $NL\rho\delta$ models for the same observable $R$, in particular, of the ratio of $t$ to $^3He$ fragments. Indeed, it can be seen that $R(t/^3He)$ strongly depends on the consideration of the $\delta$ meson in the iso-vector channel, although the corresponding differences for $R(p)$ and $R(n)$ are rather moderate for 0.4 AGeV. Our finding for the imbalance ratio $R$ of $R(t/^3He)$ is in full agreement with a transparency scenario which, in particular, becomes more pronounced if the $\delta$ meson is taken in these descriptions into account. Finally, the comparison with FOPI data seems to support a stiffer symmetry energy for high densities, i.e. the importance of the $\delta$ meson in the description of asymmetric nuclear matter. Corresponding experimental data for $R(t/^3He)$ would give a more precise conclusion.

4 Final remarks

We analyze the relativistic features of the iso-vector part of the equation of state by means of a covariant description of symmetric and asymmetric nuclear matter. Nuclear matter studies indicate that the stiffness of the symmetry energy is mainly dominated by the introduction of a iso-vector, scalar $\delta$ meson which significantly changes the Lorentz structure of the iso-vector part of the mean field potential at high densities.

In dynamical situations of heavy ion collisions the high density part of the symmetry energy has been studied in terms of different observables which may be directly linked to the density dependence of the symmetry energy. Observables which are related to the earlier high density phase of the process show the strongest effects arising from the different treatment of the iso-vector EOS. The collective isospin flow, the transverse momentum dependence of the $(\pi^-/\pi^+)$-ratio and the imbalance ratio of clusters seem to be very good candidates for studying isospin effects. Also the kaon production might be the best observable for such investigations.

The relativistic decomposition of the iso-vector potential into a vector (repulsive $\rho$ field) and a scalar (attractive $\delta$ field) turns out to be essential in understanding the high density behavior of the symmetry energy. Furthermore, in dynamical situations of heavy ion collisions the density dependence of $E_{sym}$ appears to be effectively stronger affected by the different treatment of the iso-vector mean field due to the enhancement of relativistic effects. Other important features of a relativistic description are (a) the mean field is naturally momentum dependent, important for heavy ion collisions for energies above the Fermi one and (b) the effective mass splitting, without introducing any additional parameters. In this context one should note that in non-relativistic studies the momentum dependence of the iso-vector mean field and the splitting in the effective masses between protons and neutrons have to be included in addition. Finally, the advantage of such relativistic descriptions is a direct comparison with more realistic microscopic Dirac-Brueckner-Hartree-Fock theories.

At this level of investigation we conclude that the symmetry energy should exhibit a stiff behavior at supra-normal densities which can be achieved by the introduction of an additional degree of freedom.
Figure 5: Left: rapidity ($y^{(0)}$) dependence of the imbalance ratio for protons $R(p)$ (top and bottom on the left) and neutrons $R(n)$ (top and bottom on the right) for central ($b = 1.5$ fm) mixed reactions $Ru(Zr) + Zr(Ru)$ at 0.4 AGeV (top) and 1.528 AGeV (bottom) beam energy. Right: The same but for the ratio of tritons ($t$) to $^3$He at 0.4 AGeV beam energy. Calculations with $NL\rho$ (squares) and $NL\rho\delta$ (circles) are shown and compared with FOPI data [10] as indicated (the figure is taken from [15]).

(iso-vector, scalar $\delta$ channel). The comparison with microscopic DBHF models supports our findings, however, more heavy ion data with radioactive beams are needed to make a final definite statement.

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