Symmetry Energy Effects in Particle Production

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Symmetry Energy: Importance at different density ranges

\[ E(\rho_B, I)/A = E(\rho_B) + E_{\text{sym}}(\rho_B)I^2 + O(I^4) + \ldots \]

\[ I = \frac{N - Z}{N + Z} \]

Finite symmetry energy at zero energy due to clustering effects (G. Röpke, S. Typel)

High density: HIC at relativistic energies:

Differences in proton/neutron or light isobaric cluster flow

Ratio of isospin partners of produced particles:

\[ \rightarrow \text{pions } \pi^+ \text{ vs. } \pi^- \]
\[ \rightarrow \text{strangeness } K^+ \text{ vs. } K^0 \]
The Nuclear Symmetry Energy in different Models

microscopic asym-EOS's soft at low densities but stiff at high densities


Treatment of symmetry energy in RMF: $\rho$ and $\delta$ meson

<table>
<thead>
<tr>
<th>isoscalar</th>
<th>isovector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>$\delta$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$\rho$</td>
</tr>
</tbody>
</table>

A cancellation between scalar and the isovector sector, similarly as for the isoscalar vector parts in potential.

$$E_{\text{sym}} = \frac{1}{6} \frac{k_F^2}{E_F^*} + \frac{1}{2} \left[ f_\rho - f_\delta \left( \frac{M^*_\rho}{E^*} \right)^2 \right] \rho_B$$

No $\delta$

$$f_\delta \approx 1.5 f_\rho^{\text{FREE}}$$

$\rho$ and $\delta$ meson

$$f_\rho \approx 5 f_\rho^{\text{FREE}}$$

Liu, Greco, et al., PRC65(02)045201
Sensitivity to Symmetry Energy in Heavy Ion Collisions

Difference in neutron and proton potentials

1. „direct effects“: difference in proton and neutron (or light cluster) emission and momentum distribution → M. Di Toro

2. „secondary effects“: production of particles, isospin partners

\[ \text{NN} \rightarrow \text{N}\Delta \]

\[ \text{N}_\pi \quad \text{N}\Lambda \quad \text{K} \]

1. Mean field effect: \( U_{\text{sym}} \) more repulsive for neutrons, and more for asystiff

   \( \rightarrow \) pre-equilibrium emission of neutron, reduction of asymmetry of residue

2. Threshold effect, in medium effective masses:

   \( \rightarrow m^*_N, m^*_\Lambda, \) contribution of symmetry energy; \( m^*_K, \) models for K-potentials
Pion and Kaon production in “open” system (HIC)...

time dependence of $\Delta$, $\pi$, and $K$ production

- direct early production: high density phase
- isovector channel effects

G. Ferini et al., PRL 97 (2006) 202301

Au+Au@1AGeV

Pions: high and low density phase
Kaons: high and low density phase

Au+Au, 0.6AMeV, central
**PION PRODUCTION**

Main mechanism \(NN \Rightarrow N\Delta \Rightarrow \pi N\)

\[
\begin{align*}
nn & \quad \text{pp} \\
\quad p\Delta^- & \quad n\Delta^0 & \quad p\Delta^+ & \quad n\Delta^{++} \\
n\pi^- & \quad p\pi^- & \quad n\pi^+ & \quad p\pi^+ \\
\end{align*}
\]

1. Fast neutron emission: “mean field effect”

\[
\begin{align*}
\frac{n}{p} \downarrow & \Rightarrow Y(\Delta^{0,-}) \downarrow \Rightarrow \pi^- \downarrow \\
\text{decrease: } NL & \to NL\rho \to NL\rho\delta
\end{align*}
\]

\[\text{This should depend also on momentum dependence}\]

2. C.M. energy available: “threshold effect”

\[
\begin{align*}
\epsilon_{n,p} &= E_{n,p}^* + f_o\rho_B \mp f_\rho\rho_{B3} \\
s_{nn}(NL) &< s_{nn}(NL\rho) < s_{nn}(NL\rho\delta) \\
s_{pp}(NL) &> s_{pp}(NL\rho) > s_{pp}(NL\rho\delta)
\end{align*}
\]

\[\sigma = \sigma(s_{in} - s_{th}) \quad \frac{\pi^-}{\pi^+} \uparrow \text{increase } NL \to NL\rho\delta\]

\[\text{Vector self energy } + \text{ for } n \text{ and } - \text{ for } p\]
The Threshold Effect: $nn \rightarrow p\Delta^-$ vs $pp \rightarrow n\Delta^{++}$

\[
\begin{align*}
\text{nn} & \rightarrow \text{pD}^- \\
 s_{in} &= 4\left(E_n^* + \Sigma_n^0\right)^2 = 4\left(p_n^0\right)^2 \\
 s_{th} &= \left[m_p - \Sigma_s(p) + \Sigma^0(p) + m_{\Delta^-} - \Sigma_s(\Delta^-) + \Sigma^0(\Delta^-)\right]^2 \\
\sigma = \sigma(s_{in} - s_{th}) &\uparrow \text{Increasing with momentum}
\end{align*}
\]

\[
\begin{align*}
\text{pp} & \rightarrow \text{nD}^{++} \\
 s_{in} &= 4\left(E_p^* + \Sigma_p^0\right)^2 = 4\left(p_p^0\right)^2 \\
 s_{th} &= \left[m_n - \Sigma_s(n) + \Sigma^0(n) + m_{\Delta^{++}} - \Sigma_s(\Delta^{++}) + \Sigma^0(\Delta^{++})\right]^2 \\
\text{Compensation of Isospin Effects in } s_{th} &\downarrow \text{due to simple assumption for S(D)}
\end{align*}
\]

\[
\begin{align*}
\Sigma_i(\Delta^-) &= \Sigma_i(n) \\
\Sigma_i(\Delta^0) &= \frac{2}{3}\Sigma_i(n) + \frac{1}{3}\Sigma_i(p) \\
\Sigma_i(\Delta^+) &= \frac{1}{3}\Sigma_i(n) + \frac{2}{3}\Sigma_i(p) \\
\Sigma_i(\Delta^{++}) &= \Sigma_i(p),
\end{align*}
\]

- Same thresholds $\rightarrow$ the $s_{in}(NN)$ rules the relative yields $\rightarrow$ very important at low energies

$\Rightarrow \frac{\pi^-}{\pi^+} \uparrow \text{with } E_{\text{sym}}$

What is conserved is not the effective $E^*,p^*$ momentum-energy but the canonical one.
Pion production

Equilibrium production (box results)

\[ \frac{\pi^-}{\pi^+} = \frac{\sigma_{\pi^-}^{abs}}{\sigma_{\pi^+}^{abs}} \exp \left[ 2(\mu_\pi - \mu_\mu) / T \right] \]

~ 5 (NLρ) to 10 (NLρδ) at \( \alpha \approx 0.2 \)

Finite nucleus simulation:
Au+Au, semicentral

much below thermodynamic limit, non-equilibration

Ferini, NPA762(2005) 147
Pion ratios in comparison to FOPI data

W. Reisdorf et al.
NPA781 (2007) 459

Ferini, NPA762 (2005) 147

Zhigang Xiao et al.
PRL 102, 062502 (2009)

Agreement in the sense, that symmetry energy is small

Threshold effects very important!
Transverse Pion Flows

W. Reisdorf et al. NPA781 (2007) 459

Simulations: V. Prassa, PhD thesis 09

Antiflow: Decoupling of the Pion/Nucleon flows

OK general trend.
but:
- smaller flow for both
  \( \pi^- \) and \( \pi^+ \)
- not much dependent on iso-EoS
Directed and Elliptic Flow:

Au+Au, 0.8 AGeV, midrapidity, as function of centrality
Kaon Production:
A good way to determine the symmetric EOS (C. Fuchs et al., PRL 86(01)1974)

Main production mechanism:
NN→BYK
πN→YK

Also useful for Isovector EoS?
- charge dependent thresholds
- in-medium effective masses
- Mean field effects
Strangeness ratio: Infinite Nuclear Matter vs. HIC

\[ \alpha_{\text{Au}} \approx 0.2 \]

\[ \text{Au+Au@1AGeV (HIC)} \]

Density & asymmetry of the K-source

\[ \frac{N}{Z_{\text{Au}}} \approx 1.5 \]

\[ \text{NL} \rightarrow \text{DDF} \rightarrow \text{NL}_1 \rightarrow \text{NL}_2 \delta : \]
more neutron escape and more \( n \rightarrow p \) transformation (less asymmetry in the source)

Pre-equilibrium emission (mainly of neutrons) reduced asymmetry of source for kaon production \( \rightarrow \) reduces sensitivity relative to equilibrium (box) calculation

G. Ferini, et al., NPA762(2005) 147
**Au+Au central: Pi and K yield ratios vs. beam energy**

**Kaons:**
- \( g_{\rho} \) decreasing with density

**Inclusive multiplicities**

**Pions:** less sensitivity \( \sim 10\% \), but larger yields

G. Ferini et al., PRL 97 (2006) 202301
Kaon ratios: comparison with experiment


Compared to FOPI data

- (Ru+Ru)/(Zr+Zr)
- Equilibrium (box) calculations
- Finite nucleus calculations

Data (FOPI)
X. Lopez, et al. (FOPI), PRC 75 (2007)

- Sensitivity reduced in collisions of finite nuclei
- Single ratios more sensitive
- Enhanced in larger systems
**Effect of kaon potentials**

In-medium Klein-Gordon eq. for Kaon propagation:

\[
\left( \partial_\mu + iV_\mu \right)^2 + m_{K}^* \phi_K(x) = 0
\]

Two models for medium effects tested:

**Chiral perturbation (Kaplan, Nelson et al.)**

\[
m_K^* = \sqrt{m_K^2 + \frac{\Sigma_{KN}}{f_\pi^2} \rho_s + C f_\pi^2 \rho_{s3} + V_\mu V_\mu} \quad \text{(upper sign, } K^+)\]

\[
V_\mu = \frac{3}{8f_\pi^2} j_\mu \pm \frac{1}{8f_\pi^2} j_{\mu3}
\]

**One-Boson Exchange (Schaffner-Bielich et al.)**

\[
m_K^* = \sqrt{m_K^2 + \frac{m_K}{3} \left( g_{\sigma N} \sigma + f_\delta \rho_{s3} \right)}
\]

\[
V_\mu = \frac{1}{3} \left( f_{\omega} j_\mu \pm f_{\rho} j_{\mu3} \right)
\]

**Ion-Medium K energy (k=0)**

\[
E_K(k) = k_0 = \sqrt{k^2 + m_{K}^*} + V_0
\]

Splitting for \( K^0,^+ \) for NL\( \rho \) and NL\( \rho \delta \)

Isospin-dependence

ChPT

OBE
Kaon production and data (Kaos and FOPI)

Ni+Ni system

Au+Au system

Ni+Ni, 1.93 AGeV, central

Au+Au, 1 AGeV, central
Test of kaon potentials models

Two models for medium effects tested:
1. Chiral perturbation (Kaplan, Nelson, et al.) (ChPT)
2. One-boson-exch. (Schaffner-Bielich, et al.) (OBE)

→ density and isospin dependent

\[ E_K(k) = k_0 = \sqrt{k^2 + m_K^2} + V_0 \]

Ratios to minimize influence of \( \sigma_{\text{eff}} \) kaon potentials

→ robust relative to K-potential, but dep. on isospin-dep part
Summary:

- Particle production is an interesting alternative to the determination of the high density symmetry energy in heavy ion collisions.
- The production is sensitive to mean field and threshold effects, which depend on the symmetry energy, but also on the modelling of other input, as e.g. the Δ-sector.
- Thus, the question for the pion ratio must still be considered open.
- The strangeness sector is promising since the reaction mechanism is more transparent.
analysis of $\pi^-/\pi^+$ ratios in Au+Au
Zhigang Xiao, Bao-An Li et al. PRL 102, 062502 (2009)
FOPI data, W. Reisdorf et al.
NPA 781 (2007)