Strangeness as a probe of equilibration mechanism in Heavy-ion collisions in FOPI

Krzysztof Piasecki for the FOPI Collaboration

- Production of strangeness @ 1..2 A GeV
- Model approaches to equilibration mechanism
- Particle ratios from FOPI
- Summary & Outlook
Strangeness production near threshold

- Production thresholds:
  - $NN \rightarrow NK^+\Lambda$, $E_{lab} = 1.6$ GeV
  - $NN \rightarrow K^+K^-NN$, $E_{lab} = 2.5$ GeV

- At SIS energies, resonance production ($\Delta$, $N^*$) reaches maximum

**Production processes (dominant)**

- $K^+0$ and $Y$ via **multi-step** processes
  
  $N + N \rightarrow \Delta + N \rightarrow K^{+,0} + Y + B$

- $K^-$ production more complex:
  
  - via **strangeness exchange** reactions:
    
    $\pi + Y \leftrightarrow K^- + B$
  
  - coupled to resonances e.g. $\Sigma(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$
  
  - $K^-N$ potential strongly attractive (-70 MeV at $\rho = \rho_0$)
Equilibration in Transport models

- BUU with resonances and string d.o.f
- 'Infinite' hadronic matter, initial $\varepsilon=\varepsilon_0$, $\rho_B=\rho_0$, $\rho_S=0$
- $\tau_{eq}$: typical time of yield stabilization: $\tau_{eq} @ 2/3$ of $N_{equil}$

Thermal equilibrium

Quadrupole moment

$\langle Q_{zz} \rangle = \langle 2p_z^2 - p_T^2 \rangle$

$\langle Q_{zz} \rangle \begin{cases} > 0 & p_z > p_T \\ < 0 & p_z < p_T \\ = 0 & isotropy \end{cases}$

C. Hartnack nucl-th/0507002

Chemical equilibrium

- $K^+$ produced during earlier stages of the collision (high $\rho$ !)

No Equilibrium @ 1..2 A GeV

particle yields sensitive to initial conditions
Assumption: equilibrium @ chemical freeze-out

Density of species $i$ (in grandcanonical ensemble):

$$n_i(\mu, T) = \frac{N_i}{V} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp\left(\frac{E_i - \mu_B B_i - \mu_S S_i - \mu_I I_{3i}}{T}\right) \pm 1}$$

Free parameters: chemical potential $\mu_B$
temperature $T$

For particle ratios: $V$ cancels out
Fixed by conservation laws: $\mu_S, \mu_{I3}$

...but

No equilibration of strangeness!

Extension:

$$\exp\left(\frac{\mu_B B_i + \ldots}{T}\right) \to \exp\left(\frac{\mu_B B_i + \ldots}{T}\right) \cdot (\gamma_S)^{n_S}$$

$\gamma_S$ “suppression factor”
$n_S$ number of strange quarks

Yield ratios @ SPS


Looking very successful!
**FOPI experimental setup**

- **Nearly 4π coverage**
  
- **Identification of p, d, t, \(^3\)He, \(\pi^\pm\), K\(\pm\)**
  
- **Reconstruction of short lived particles (\(\phi\), \(K^0(*)\), \(\Lambda/\Sigma^0\), \(\Sigma^*\), ..)**

- **Colliding systems**: \(^{27}\)Al+\(^{27}\)Al and \(^{56}\)Ni+\(^{58}\)Ni
- **Beam energy**: 1.91A GeV
- **ca. \(3 \cdot 10^8\) evts, 10 TB of data**

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M. Merschmeyer, X. Lopez *et al.* (FOPI), PRC 76, 024906 (2007)
Strange resonances: \( \Sigma^* \) and \( K^* \)

**\( \Sigma^\pm (1385) \to \Lambda + \pi^\pm \) (88 ± 2%)**

\[ \mathsf{dN}/\mathsf{dM} \text{ (counts)} \]

- \( P(\Sigma^{*-} + \Sigma^{*+}) = 0.125 \pm 0.026 \pm 0.033 \)
- \( X. \) Lopez et al. (FOPI), PRC 76, 052203(R) (2007)

**\( \Sigma^0 (1385) \to p + \pi^- \) (short lived)**

- \( E_{\text{th}} = 2.33 \text{ GeV} \) (subthreshold)
- \( \Gamma = 39.4 \text{ MeV}, \ c\tau = 5 \text{ fm} \)
- Dominant channel in UrQMD: \( \Lambda + \pi \to \Sigma^* \) (76%)

**\( K^0 (892) \to K^\pm + \pi^\mp \) (~100%)**

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- \( E_{\text{th}} = 2.75 \text{ GeV} \) (subthreshold)
- \( \Gamma = 50.7 \text{ MeV}, \ c\tau = 4 \text{ fm} \) (short lived)
- Dominant channel in UrQMD: \( K + \pi \to K^* \) (70%)

**\( P(K^0) \) \( P(K^0) \)**

- \( P(K^0) = 0.032 \pm 0.003 \pm 0.012 \)
**φ (s̅s̅) meson**

- $\phi \rightarrow K^+ + K^-$ (49.1%)
- $m = 1019$ MeV
- $E_{th} = 2.6$ GeV (subthreshold)
- $\Gamma = 4.3$ MeV, $c\tau = 50$ fm

**Preliminary Result**

$N_{\phi} = 189 \pm 17 \pm 5$

S/B = 1.9

Signif = 11.1

Mean = 1019 MeV/c

$\Gamma = 4 \pm 2$ MeV/c

$$\frac{P(\phi)}{P(K^{0*})} = 0.040 \pm 0.020$$
Particle yields at freeze-out

6 independent ratios with 5 strange particles:
\( p, \pi^-, K^0, (\Lambda + \Sigma^0), \phi, K^*(892) \) and \( \Sigma^*(1385) \)


- Canonical ensemble
- \( T, \mu \) from fit to 4 ratios
- \( K^0/K^0 \) and \( \phi/K^*0 \) are predictions

Equilibrium picture \( (\gamma_s=1) \) works surprisingly well, even for \( \phi/K^*0 \)

Freeze-out on Phase diagram
No equilibration assumed

Cascade model – no mean field
  – no in-medium effects

$\Sigma^{*\pm}$ and $K^*$ reconstructable in experiment:

*Excluded decay products undergoing inelastic rescattering with medium*

$\phi/K^0$ channel – potential to resolve scenario

| FOPI Data | 0.24±0.13 |
| SM | 0.245 |
| UrQMD | 0.037 |
Summary & Outlook

- At 1..2A GeV theoretical models suggest no equilibration of strangeness

- **FOPI** measured particle yields for Al+Al @ 1.91A GeV, involving
  \[ \rightarrow \ p, \ \pi^-, \ K^0, \ (\Lambda+\Sigma^0), \ K^*(892), \ \Sigma^{*\pm}(1385) \]  and \( \phi \)

- **Statistical Model** agrees with **Yield Ratios**, despite assuming thermal and chemical equilibration

- **UrQMD** agrees too, despite no equilibration assumption

- **SM** and **UrQMD** differ in predicting \( \phi/K^0 \)
  \[ \rightarrow \ ]  Potential to sort out predictions

- More \( \phi \)'s to come from **FOPI** experiments
  \[ \rightarrow \ Ni +Ni @ 1.91A GeV \]  (analysed)
  \[ \rightarrow \ Ni +Pb @ 1.91A GeV \]  (started today!)
  \[ \rightarrow \ Ru+Ru @ 1.69A GeV \]  (March 2009)

- **FOPI** upgrade: **MMRPC** - wider acceptance for \( K^\pm \)