News on in-medium modifications of properties of kaons measured around threshold

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- Introduction to phenomenon
- Case of $K^0_s$ from Au+Au @ 1.2A GeV
- Case of $K^+$ and $K^-$ from Ni+Ni @ 1.9A GeV
- Summary & outlook
Partial restoration of chiral symmetry

- **QCD**: vacuum is not empty $\Rightarrow \bar{q}q$ condensate
- **Gell-Mann Oakes Renner relation**:

$$m_K^* f_K^* = \frac{-m_u + m_s}{2} \langle \bar{u}u + \bar{s}s \rangle + \Theta(m^2_s)$$

Decay constant
Mass

- **A good probe**:
  - a single, easily measurable particle emitted from heavy-ion collision zone.
- **Take Kaons**:
  - Threshold $E_{\text{kin}}$ for $NN \rightarrow NK^+\Lambda$ : 1.6 GeV
  - At a few AGeV usually *single* kaon emitted

**Heavy-ion collisions: medium + probe**
Changes of Kaon properties in medium

**Approximate description:** Potential

\[
m_K(\rho) = m_{K,\text{vac}} \left(1 \pm \alpha \frac{\rho}{\rho_0}\right)
\]

**Effects induced by in-medium potential:**

- As \(m_K \neq m_{\text{Vacuum}}\), production threshold changes
- As \(K^+, K^0\) escapes the collision zone:
  \[m_K \downarrow m_{\text{Vacuum}}\] Kaon gives energy to \(E_{\text{kin}}\) (speeds up)
- As \(K^-, \bar{K}^0\) escapes the collision zone:
  \[m_K \uparrow m_{\text{Vacuum}}\] Antikaon takes energy from \(E_{\text{kin}}\) (slows down)

**Transport models – simple approaches**

Hypothesis:

Mass effectively changes proportionally to the medium density

\[
m_K(\rho) = m_{K,\text{vac}} \left(1 \pm \alpha \frac{\rho}{\rho_0}\right)
\]

**... or more advanced (eg. Chiral EFT w.CC \(\rightarrow\) HSD)**

J. Schaffner-Bielich et al., NPA 625 (1997) 325
The φ meson: a hidden player

- φ (ss): $m = 1.02$ GeV
  $T_{\text{beam,threshold}} = 2.6$ GeV

- $c t = 50$ fm (in vacuum)
  $\phi \rightarrow K^+K^-$ (BR ~ 50%)

- IQMD Simulation
  Au+Au, $T_{\text{LAB}} = 1.5A$ GeV

First attempt to gain some knowledge on $\phi \rightarrow K^+K^-$: year 2003, 23 φ events

A. Mangiarotti et al. (FOPI), NPA 714, 81 (2003)
FOPI and HADES experimental setups @ GSI, Darmstadt

**FOPI (FOur PI)**

Spectrometer for charged particles

- CDC: momentum
- Plastic Barrel & MMRPC: Time-of-flight

**HADES (High-Acceptance Di-Electron Spectrometer)**

Adjusted to measure hadrons
Operating: currently

- MDC: momentum
- TOF & RPC: Time-of-flight

FOPI and HADES: Similar acceptance for Kaon measurements
Access to $K^0_s$ via $K^0_s \rightarrow \pi^+ \pi^-$ (BR = 63%)
First tests: $K^0$ emitted from $\pi A$

$\pi$ meson hits the nucleus:
possible single-step channels:
production of kaons at $\rho \approx \rho_0$.

$\pi^- p \rightarrow K^0\Sigma^0$,  $\pi^- p \rightarrow K^0\Lambda^0$,  $\pi^- n \rightarrow K^0\Sigma^-$

Comparison of two reactions (FOPI, 2009):

$\pi^- (p=1.15 \text{ GeV/c}) + ^{208}\text{Pb} \rightarrow K^0 + ...$
$\pi^- (p=1.15 \text{ GeV/c}) + ^{12}\text{C} \rightarrow K^0 + ...$

Ratio of momentum distributions of kaons:

Distribution for $K^0$ emitted from Pb shifted to higher momenta.

Comparison to HSD transport model:

- No potential
- $U_{KON} (q_0) = 10 \text{ MeV}$
- $U_{KON} (q_0) = 20 \text{ MeV}$
- $U_{KON} (q_0) = 30 \text{ MeV}$

Data in agreement if $U_{KON} (q_0) = +20 \text{ MeV}$
In-medium effects of $K^0$ from Au+Au @ 1.23A GeV

Comparing $K^0$ and $\Lambda$ data to transport models with/without in-medium effects
(Basic production channel: $NN \rightarrow NK^0\Lambda$)

1. Multiplicity of $K^0_s$ and $\Lambda$ vs centrality:

   Transport calculations:
   - HSD $U_{KON}(q_0) = 40$ MeV
   - IQMD $U_{KON}(q_0) = 40$ MeV

   Absolute yield overstated by calculations. Large spread in yield between different models.
   - No scenario without in-medium potential reproduces the $<A_{part}>$ scaling.
   - Switching the potential on ... ... improves the description significantly!

J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)
2. Phase space distributions of $K^0_s$, 10% most central evts

Model curves were normalized to exp. data (comparison of profiles)

Again, best description with the in-medium effects.

J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)
In-medium effects of $K^0$ from Au+Au @ 1.23A GeV

2. Phase space distributions of $\Lambda$, 10% most central evts

Model curves were normalized to exp. data (comparison of profiles)

Legend

- UrQMD —— No potential
- IQMD —— No potential
- HSD —— No potential
- IQMD $U_{K0N}(\varrho_0) = 40$ MeV
- HSD $U_{K0N}(\varrho_0) = 40$ MeV

- Inclusion of in-medium effects for $K^0_s$ does not affect $\Lambda$
- UrQMD describes the profile best.

J. Adamczewski–Musch et al. (HADES), PLB 793, 457 (2019)
$K^-/^+$ emitted from Ni+Ni collisions (recent data)

Ratio of $K^-$ over $K^+$ from Ni+Ni @ 1.9A GeV, centrality 56%

New data (full dots)

- wide phase space coverage
- more statistics

KP et al. (FOPI), PRC 99, 014904 (2019)

... To be compared with Transport models

But ... what about $\phi$ mesons?

$\phi \rightarrow K^+K^- \ (BR \sim 50\%)$

For Al+Al @ 1.9A GeV see.:
P. Gasik et al (FOPI), EPJ A 52, 177 (2016)
**Contribution of φ decays to K⁻ (recent data)**

**φ mesons from AA collisions @ 1.9A GeV**

- Measured in K⁺K⁻ decay channel (BR = 50%) in 3 systems. Small samples (~150 events).

**Result:** φ/K⁻ = 0.36 ± 0.05

(In agreement with HADES data for Ar+KCl @ 1.76A GeV, G. Agakishiev et al., PRC 80 (2009) 025209)

Even higher φ/K⁻ ratio found by HADES for Au+Au @ 1.2A GeV, J. Adamczewski-Musch et al., PLB 778, 403 (2018)

- Since BR (φ → K⁺K⁻) ≈ 50%,

About 18% of K⁻ originates from decays of φ mesons, (different kinematics than for “direct”)

- Energy spectra of φ mesons Reconstructed and fitted in 2 cases.

K⁻ from φ decays: “colder” than these emitted directly from collision zone.

We can subtract contribution from K⁻ spectra, and obtain the K⁻/K⁺ ratio built by particles without the φ decay contribution

- Measured in K⁺+K⁻ decay channel (BR = 50%) in 3 systems. Small samples (~150 events).

**K/Petel, PRC 91, 054904 (2015)**

**KP et al., PRC 94, 014901 (2016)**
Ratio of $K^-/K^+$ (K$^-$ without $\phi$ contribution) from Ni+Ni @ 1.9A GeV, centrality 56%

$$K^{-}_{\text{Total}} = K^{-}_{\text{Direct}} + K^{-}_{\text{From } \phi}$$

$$K^{-}_{\text{Direct}} = K^{-}_{\text{Total}} - K^{-}_{\text{From } \phi}$$

Energy dependence still drops.
→ perhaps the K$^-$ modifications still non-negligible

... to be compared with Transport Models, in case if $\phi$ emission not well reproduced.

However, $\Lambda(1520) \rightarrow pK^-$ could be another player, (never measured @ $T_b < 10$A GeV)

See Dominika Wójcik’s Poster
Summary & Outlook

**Modifications of kaon properties in medium** are the result of **partial restoration of chiral symmetry**. Frequent parametrization: extra kaon-nucleus potential as function of density.

**First tests:** \( K^0_s \) emitted from \( \pi^-A \) : \( U_{KON}(q_0) \approx +20 \text{ MeV} \).

**Recent analyses:**

- **Case of** \( K^0_s \) (and \( \Lambda \)) **from Au+Au @ 1.23A GeV (HADES)**
  - Data: Yields against centrality, Pt-y spectra in wide acceptance.
  - Models: UrQMD (no in-medium), HSD & IQMD (no in-medium or \( U_{KON}(q_0) \approx 40 \text{ MeV} \))
  - Results: Yields of \( K^0_s \) and \( \Lambda \) : clear preference for in-medium scenario
    - \( K^0_s \) (\( p_t \) and rapidity profiles) : clear preference for in-medium scenario
    - \( \Lambda \) (\( p_t \) and rapidity profiles) : clear preference for UrQMD, for HSD, IQMD bad prediction in either scenario

- **Case of** \( K^- \) and \( K^+ \) **from Ni+Ni @ 1.9A GeV (FOPI)**
  - Data: Ratio of \( K^-/K^+ \) yields scanned across phase space (\( E_{\text{kin},NN} \) vs \( \cos \theta_{NN} \))
    - \( \phi \) : yields and \( \phi/K^- \) ratio against centrality, \( E_{\text{kin}} \) spectrum
    - Ratio of \( K^-/K^+ \) with \( \phi \) contribution removed
  - Ready to be compared to transport models
  - Possible new side feeding to \( K^- \) : \( \Lambda(1520) \). See Dominika Wójcik’s Poster!

**OUTLOOK**

- **New data on** Ag+Ag @ 1.58A GeV taken by HADES in march this year – stay tuned!
Backup slides
Relativistic heavy-ion collisions

IQMD simulation of Au+Au collision at $T_B = 1.5$A GeV

4 fm/c: onset of $\Delta$ (1232) production

8 fm/c: max. nucleon density ($2-3 \times \rho_0$)
10 fm/c: max. density of $\Delta$
12 fm/c: max. density of $\pi$

20–30 fm/c: $\pi$ multiplicity $\rightarrow$ saturates
$\Delta$ multiplicity $\rightarrow$ drops to 0

$T_{[\text{fm/c}]}$
0 10 20
0.3 1 2

Centr. dens. $Q/Q_0$

$1 \text{ fm/c} = 3.3 \cdot 10^{-23} \text{ s}$

W. Reisdorf et al., NPA 848, 366 (2010)

C. Hartnack, The nuclear equation of state is soft,
SQM 2006
ChPT Lagrangian

C. Fuchs / Progress in Particle and Nuclear Physics 56 (2006) 1–103

on this framework has been used by many other authors [8,12,29–38]. The corresponding chiral SU(3)$_c \times$ SU(3)$_F$ Lagrangian used by Kaplan and Nelson reads

\[
\mathcal{L} = \frac{1}{4} f^2 \text{Tr} \epsilon^{\mu\nu\rho\sigma} \partial_\mu A_\nu \partial_\rho A_\sigma + \frac{1}{2} f^2 A (\text{Tr} M_q (\Sigma - 1) + \text{h.c.}) + \text{Tr} \bar{B} (ig^{\mu\nu} \partial_\mu - m_B) B
\]

\[
+ \text{Tr} \bar{B} \gamma^\mu [V_\mu, B] + D \text{Tr} \bar{B} \gamma^\mu \gamma^5 (A_\mu, B) + F \text{Tr} \bar{B} \gamma^\mu \gamma^5 (A_\mu, B)
\]

\[
+ a_1 \text{Tr} B (\xi M_q \xi + \text{h.c.}) B + a_2 \text{Tr} \bar{B} B (\xi M_q \xi + \text{h.c.})
\]

\[
+ a_3 (\text{Tr} M_q \Sigma + \text{h.c.}) \text{Tr} \bar{B} B.
\]

The degrees of freedom in the Lagrangian (1) are the baryon octet $B$

\[
B = \begin{pmatrix}
\frac{A}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\
\Sigma^- & \frac{A}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\
\Xi^- & \Xi^0 & \frac{2}{\sqrt{6}} A
\end{pmatrix}
\]

(2)

with a degenerate mass $m_B$, and the pseudoscalar meson octet $\phi$

\[
\phi = \sqrt{2} \begin{pmatrix}
\frac{\eta_8}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+
\\n\pi^- & \frac{\eta_8}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0
\\K^- & K^0 & -2 \frac{2}{\sqrt{6}} \eta_8
\end{pmatrix}
\]

(3)

entering into the chiral pseudoscalar meson fields

\[
\Sigma = \exp(2i\phi/f_\pi) \quad \text{and} \quad \xi = \sqrt{\Sigma} = \exp(i\phi/f_\pi).
\]

(4)

The pseudoscalar meson decay constants are equal in the SU(3)$_V$ limit and given by the weak pion decay constant $f_\pi \simeq 93$ MeV. The current quark mass matrix which is responsible for explicit chiral symmetry breaking is given by

\[
M_q = \begin{pmatrix}
m_q & 0 & 0 \\
0 & m_q & 0 \\
0 & 0 & m_\tau
\end{pmatrix}
\]

RMF Lagrangian

2. The RMF model

It has been demonstrated by many studies that the RMF model gives a good description of nuclear matter in bulk as well as of properties of nuclei [27,28]. We start from the Lagrangian

\[
\mathcal{L} = \bar{\Psi}_N (ig^\mu \partial_\mu - m_N) \Psi_N + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - U(\sigma)
\]

\[
- \frac{1}{2} G^{\mu\nu} G_{\mu\nu} + \frac{1}{2} m_\sigma^2 V^\mu V_\mu - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + \frac{1}{4} m_R^2 R^\mu R_\mu
\]

\[-g_{\sigma N} \bar{\Psi}_N \Psi_N \sigma - g_{\omega N} \bar{\Psi}_N \gamma^\mu \omega_\mu \Psi_N - g_{\rho N} \bar{\Psi}_N \gamma^\mu \rho_\mu \Psi_N, \]

(1)

where the nucleons interact via an attractive scalar ($\sigma$) and repulsive vector ($V^\mu$, $R^\mu$) meson fields. The term $U(\sigma)$ stands for the scalar self-interaction

\[
U(\sigma) = \frac{1}{4} m_\sigma^2 \sigma^2 - \frac{b}{3} \sigma^3 + \frac{c}{4} \sigma^4
\]

(2)

The implementation of $\Lambda$ hyperons proceeds through the additional Lagrangian

\[
\mathcal{L}_\Lambda = \bar{\Psi}_\Lambda (ig^\mu \partial_\mu - m_\Lambda) \Psi_\Lambda - g_{\sigma \Lambda} \bar{\Psi}_\Lambda \Psi_\Lambda \sigma - g_{\omega \Lambda} \bar{\Psi}_\Lambda \gamma^\mu \omega_\mu \Psi_\Lambda.
\]

(4)

3.1. One-boson-exchange approach

In the kaon sector, we start from the following Lagrangian [13]:

\[
\mathcal{L}_{KN} = D_\mu \bar{K} D^\mu K - m_k^2 \bar{K} K - g_{\omega K} m_k \bar{K} K \sigma - g_{\delta K} m_k \bar{K} \tau \delta
\]

(15)

with the covariant derivative

\[
D_\mu = \partial_\mu + ig_{\omega K} V_\mu + ig_{\delta K} \tau R_\mu.
\]

(16)
### $K_0^s$ and $\Lambda$ production from Au+Au @ 1.23A GeV

**$\chi^2$/ndf between data and model prediction**

<table>
<thead>
<tr>
<th>Model</th>
<th>KN potential</th>
<th>$K_0^s$</th>
<th>$\Lambda$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UrQMD</td>
<td>no</td>
<td>$p_t$</td>
<td>$y$</td>
<td>Mult</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105</td>
<td>4.1</td>
<td>1619</td>
</tr>
<tr>
<td>HSD</td>
<td>yes</td>
<td>7.0</td>
<td>2.7</td>
<td>670</td>
</tr>
<tr>
<td>IQMD</td>
<td>yes</td>
<td>6.0</td>
<td>2.0</td>
<td>99</td>
</tr>
</tbody>
</table>
### Strangeness production and absorption

<table>
<thead>
<tr>
<th></th>
<th>K⁺</th>
<th>K⁻</th>
<th>φ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production (primary)</strong></td>
<td>BB → BYK⁺</td>
<td>BB → BBK⁺K⁻</td>
<td>BB → BBφ</td>
</tr>
<tr>
<td></td>
<td>( T_{pp \rightarrow p\Lambda K⁺} = 1.58 \text{ GeV} )</td>
<td>( T_{pp \rightarrow ppK⁺K⁻} = 2.5 \text{ GeV} )</td>
<td>( T_{pp \rightarrow ppK⁺K⁻} = 2.6 \text{ GeV} )</td>
</tr>
<tr>
<td><strong>Production (secondary)</strong></td>
<td>( \pi B \rightarrow Y K⁺ )</td>
<td>( \pi Y \rightarrow (\Sigma^* \rightarrow) BK⁻ )</td>
<td>( \pi B \rightarrow B φ )</td>
</tr>
<tr>
<td></td>
<td>( BY \rightarrow NK⁻Λ )</td>
<td>( \rho B \rightarrow B φ )</td>
<td>( \rho \pi \rightarrow \phi )</td>
</tr>
<tr>
<td></td>
<td>( BY \rightarrow BBK⁻ )</td>
<td>( \pi N^* \rightarrow N φ )</td>
<td>( K⁺K⁻ \rightarrow \phi ) negligible</td>
</tr>
<tr>
<td><strong>Absorption</strong></td>
<td>K⁺Y → πB</td>
<td>K⁺B → πY</td>
<td>φN → KΛ</td>
</tr>
<tr>
<td><strong>Elastic scat. (char. exch.)</strong></td>
<td>K⁺B ↔ K⁺ B</td>
<td>K⁻B ↔ K⁻B</td>
<td>φN → φN</td>
</tr>
<tr>
<td></td>
<td>K⁺n ↔ K₀ρ</td>
<td>K⁻p ↔ K₀n</td>
<td>( [B] = \rho, n, N, N^*, \Delta )</td>
</tr>
<tr>
<td></td>
<td>( [Y] = \Lambda, \Sigma )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sub- and near-threshold Production of $K^-$

- in medium: mainly strangeness exchange:
  \[ BY \rightarrow NNK^-, \quad \pi Y \rightarrow K^-B \]
  - strong reabsorption: $K^-B \rightarrow \pi Y$
  - coupled to resonances $\Sigma(1385), \quad \Lambda(1405)$

\[ \pi + Y \rightarrow \Sigma^* \rightarrow K^- + B \]

Q: Can we see them?

\[ \text{Au+Au @ 1.5A GeV (IQMD transport code)} \]

\[ \begin{align*}
  &\text{dN/dt} \times 10^{-3} \\
  t (\text{fm/c}) &
  \begin{align*}
  &\pi K^- \rightarrow \pi Y \\
  &BY \rightarrow NNK^- \\
  &\pi Y \rightarrow NK^- \\
  &\pi B \rightarrow BK^-K^- \\
  &BB \rightarrow BBK^-K^-
  \end{align*}
\end{align*} \]

\[ N(t) \\
 t (\text{fm/c}) \]

\[ \begin{align*}
  &\text{total} \\
  &\text{from BY} \\
  &\text{from } \pi Y \\
  &\text{from } \pi B \\
  &\text{from BB}
  \end{align*} \]
Observable: Ratio of $K^- / K^+$ kinetic energy spectra

First findings: FOPI, KaoS @ SIS18 accelerator, GSI Darmstadt

Effect itself appears to be confirmed…

…but probed within very narrow slice of phase space

Statistics too limited for providing uncertainties of extracted $U_{KN}$. 

K\textasciitilde K^+: experiment vs transport

• K^+: $U_{K^N}$ repulsive
K^-: $U_{K^N} \sim$attractive
K^-/K^+: promising observable

• IQMD transport code
  \[ m_{K^\pm}(\rho) = m_{K^\pm}(\rho_0) \cdot \left(1 + \alpha_{\pm} \cdot \frac{\rho}{\rho_0}\right) \]
  at $\rho = \rho_0$
  $\Delta m_{K^+} = 40$ MeV, $\Delta m_{K^-} = -100$ MeV

• HSD transport code
  \( K^+ \) as in IQMD
  \( K^- \): off-shell G-matrix approach

\[ m_{K^\pm}(\rho_0) = m_{K^\pm}(\rho_0) \cdot \left(1 + \alpha_{\pm} \cdot \frac{\rho}{\rho_0}\right) \]

Clear preference for $U_{K^N} \neq 0$ option
"$U_{K^+}$ only" scenario: insufficient
IQMD: potentials used probably too strong

Al+Al @ 1.93A GeV, 9% most central events

(P. Gasik)

HSD, $U_{K^+} = 40$ MeV, $K^-$ Not Modified
HSD, $U_{K^+} = 40$ MeV, $U_{K^-} = G$-Matrix
IQMD, $U_{K^+} = 40$ MeV, $U_{K^-} = -100$ MeV
In-medium effects of $K^0$ from Ar+KCl @ 1.76A GeV

Transverse momentum distributions of $K^0_s$

\[ \times 10^6 \]

\[ \begin{align*}
-0.07 < y_{\text{c.m.}} < 0.07 & \quad \text{data} \\
0.07 < y_{\text{c.m.}} < 0.20 & \quad \text{with pot} \\
0.20 < y_{\text{c.m.}} < 0.33 & \quad \text{w/o pot} \\
0.33 < y_{\text{c.m.}} < 0.47 & \quad \text{data} \\
0.47 < y_{\text{c.m.}} < 0.60 & \quad \text{with pot} \\
\end{align*} \]

\[ p_t \text{ [MeV/c]} \]

\[ \begin{align*}
0 < 200 < 400 < 600 < 800 & \quad \text{data} \\
0 < 200 < 400 < 600 < 800 & \quad \text{with pot} \\
\end{align*} \]

- Densities reached: $2 \rho_0$
- $K_S^0 \quad c\tau = 2.7 \text{ cm}$
- $K_L^0 \quad c\tau = 15.3 \text{ m}$

- IQMD transport calc.:
  - No potential
  - $U_{KON}(\rho_0) = 46 \text{ MeV}$

Obtained $U_{KON}(\rho_0)$ for Ar+KCl seems to be stronger than in case of $U_{KON}(\rho_0)$ for $\pi^- A \rightarrow K^0 + ...$

(1) Non-linear dependency of $U_{KON}(\rho)$? (2) Momentum-dependent potential?
$K^0$ emitted from nucleus (new data)

$K^0_s$ mesons from $p$ ($T_B = 3.5$ GeV) + Nb. Phase space distributions ($p_T - y$):

Comparison to GiBUU transport model. The ChPT potential was used; for first time $U = f(p)$
Effect of $\phi$ decays on $K^-$ slopes

Previously:
Difference of $K^+,K^-$ slopes explained by $U_{KN}$ potentials

Present studies:
About 50% can be explained by $\phi \to K^+K^-$ decays
**Observable: azimutal angle distribution ("Flow")**

**Azimuthal angle distribution wrt Reaction Plane**  
After $(p_T - y)$, $\phi$ is a 3$^{rd}$ phase space dimension.

**Directed Flow $v_1$**  
**Elliptic Flow $v_2$**  

**Azimuthal distribution** is decomposed into Fourier series:

$$\frac{dN}{d\phi} \sim 1 + 2v_1\cos\phi + 2v_2\cos(2\phi) + \ldots$$

$v_1, v_2, \ldots = \text{Coefficients of Fourier expansion ("flow coefficients")}$

**Mass change effect:** wrt. flow of matter (usually protons), $K^-$ should flow more like protons do, $K^+$ should flow more against.

---

C. Pinkenburg et al., PRL 83, 1295 (1999)
**Observable:** azimutal angle distribution (Flow)

**First findings: FOPI & KaoS**

- **KaoS analysis:**
  - Fit to $dN/d\phi (K^+)$ for 2 systems at 1 – 2A GeV
  - Preference for $U_{K^+N}$
  - No information on $U_{K^-N}$

- **FOPI analysis:**
  - $n_1 (K^+)$ as function of $p_T$ for 2 systems at 1.5 – 2A GeV
  - Preference for $U_{K^+N} \approx 20$ MeV
  - No information on $U_{K^-N}$

**Fragmentary insight, coarse results**
In-medium $K^+/-$ modifications via Flow: current status

Flow of $K^+$ and $K^-$ emitted from Ni+Ni @ 1.9A GeV

Centrality 56%

**IQMD**

$U_{K^+N} = +20$ MeV
$U_{K^-N} = -45$ MeV

0 MeV

**HSD**

$U_{K^+N} = +20$ MeV
$U_{K^-N} = -50$ MeV

0 MeV

$v_1$: Rather weak $U_{K^+N}$ potential.
Preference for $U_{K^-N} \approx -25..50$ MeV
Production of Kaons in AA: Primary or secondary?

If primary:

For pA → KX: \[ MUL_K = \frac{\sigma_K}{\sigma_{inelastic}} = \text{const} \]

AA → KX: Glauber: \[ AA = A \otimes NA \]

\[ \Rightarrow MUL_K^{AA} = A \times MUL_K^{pA} \propto A \]

KaoS

\[ K^+, 1.5 \text{ AGeV} \times 10^{-4} \]
\[ K^+, 1.0 \text{ AGeV} \times 10^{-5} \]
\[ K^+, 0.8 \text{ AGeV} \times 10^{-6} \]
\[ K^+, 1.5 \text{ AGeV} \times 10^{-1} \]

C+C \quad Ni+Ni \quad Au+Au

secondary processes are involved

K^0 near-threshold production processes:

- \( N_{\text{beam}} + N_{\text{target}} \), \( N_{\text{target}} \) has Fermi motion
- predominantly via \( \Delta N, \Delta \Delta \rightarrow K^{+,0} Y B \)
- \( \pi N, \pi \Delta \rightarrow K^{+,0} Y \), \( Y = [\Lambda, \Sigma] \)
- \( U_{KN} \) involved (increases K mass → lower yields)
Search for in-medium modifications of $K^-$

$K^+, K^-$ and $\phi$ emitted from Ar + KCl @ 1.76A GeV: phase space distributions

\[ m_T = \sqrt{p_T^2 + m^2} \]

**Boltzmann Fit to phase space distributions**

inverse slope ("temperature")

\[ \frac{1}{m_T^2} \frac{d^2 N}{dm_T dy} = C(y) \exp \left[ -\frac{(m_T - m_0) \ ch y}{T} \right] \]

Inverse slope for $K^+$ is higher than that for $K^-$.  

( $\leftrightarrow$ ratio of kinetic energy distributions of $K^-$ to $K^+$ drops with energy) :

\[ T_{\text{eff}} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>Multiplicity/LVL1</th>
<th>$T_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-$</td>
<td>$(7.1 \pm 1.5 \pm 0.3 \pm 0.1) \cdot 10^{-4}$</td>
<td>$69 \pm 2 \pm 4$</td>
</tr>
<tr>
<td>$K^+$</td>
<td>$(2.8 \pm 0.2 \pm 0.1 \pm 0.1) \cdot 10^{-2}$</td>
<td>$89 \pm 1 \pm 2$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$(2.6 \pm 0.7 \pm 0.1^{+0.0}_{-0.3}) \cdot 10^{-4}$</td>
<td>$84 \pm 8$</td>
</tr>
</tbody>
</table>

Q: Is it due to in-medium effects or $\phi \rightarrow K^-$ feeddown?
**Two-source model of $K^-$ emission**

**Assumptions:**

1. Observed $K^-$ originate from two sources:
   - directly from collision zone ("direct")
   - feeddown from $\phi$ meson decays, $\phi \rightarrow K^+ K^-$ (BR $\approx 50\%$) in a proportion as measured experimentally.

2. "Direct" $K^-$ have the same "temperature" as $K^+$.

3. $\phi$ mesons are emitted with "temperature" as measured.
   Next, $\phi$ decay into $K^+$ and $K^-$ (PLUTO simulation).

4. We combine $K^-$ distributions from both sources – and check the "temperature" of total.

**Result:** $T(K^-, \text{total}) = 74 \text{ MeV}$

Let’s compare to experimental $T(K^-)$:

<table>
<thead>
<tr>
<th>Particle</th>
<th>$T_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-$</td>
<td>$69 \pm 2 \pm 4$</td>
</tr>
<tr>
<td>$K^+$</td>
<td>$89 \pm 1 \pm 2$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$84 \pm 8$</td>
</tr>
</tbody>
</table>

$\phi$ admixture strongly "cools down" the $K^-$ spectrum.

It contributes to generating a drop of ratio of $K^-/K^+$ kinetic energy distribution with energy.

We cannot reject that $\phi$ (and not in-medium) Could be the only responsible for $K^-/K^+ \downarrow E_{\text{kin}}$...
2-source model of $\phi$ emission

- Al+Al @ 1.9A GeV (FOPI)

Experiment:

<table>
<thead>
<tr>
<th>Particle</th>
<th>$T_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>82 ± 7 ± 11</td>
</tr>
<tr>
<td></td>
<td>109 ± 2 ± 9</td>
</tr>
<tr>
<td></td>
<td>93 ± 14 ± 16</td>
</tr>
</tbody>
</table>

$T (K^- \text{ from } \phi) = 58 \text{ MeV}$

$T (K^- \text{ direct}) = 92 \pm 16 \text{ MeV}$

$\phi$ contribution to $K^-$: indication that $T_{\text{direct}} @ \sim 10 \text{ MeV above } T_{\text{inclusive}}$
Ni+Ni @ 1.9A GeV (FOPI, KaoS)

Experiment:

<table>
<thead>
<tr>
<th>Particle</th>
<th>$T_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>84 ± 4</td>
</tr>
<tr>
<td></td>
<td>108 ± 5</td>
</tr>
<tr>
<td></td>
<td>106 ± 18 ± 16</td>
</tr>
</tbody>
</table>

$\phi$ contribution to $K^-$: indication that $T_{\text{direct}}$ @ ~10 MeV above $T_{\text{inclusive}}$
**φ yield – BUU predictions**

- **BUU** calculations for Ni+Ni @ 1.93A GeV, 9% most central collisions

- **φ** production channels:
  
  \[
  \begin{align*}
  &BB \rightarrow \phi, \quad B = \{N, \Delta\} \\
  &\mu B \rightarrow \phi, \quad \mu = \{\pi, \rho\} \\
  &\pi \rho \rightarrow \phi \\
  &K^+K^- \rightarrow \phi \quad \text{negligible}
  \end{align*}
\]

**Table:**

<table>
<thead>
<tr>
<th>Yields from Ni + Ni (1.93 GeV)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B + B</td>
<td>3.5 x 10^{-4}</td>
</tr>
<tr>
<td>π + B</td>
<td>2.9 x 10^{-4}</td>
</tr>
<tr>
<td>ρ + B</td>
<td>8.9 x 10^{-4}</td>
</tr>
<tr>
<td>π + ρ</td>
<td>1.6 x 10^{-4}</td>
</tr>
<tr>
<td>π + N(1520)</td>
<td>0.5 x 10^{-4}</td>
</tr>
<tr>
<td>Total yield</td>
<td>1.7 x 10^{-3}</td>
</tr>
</tbody>
</table>

**φ yield compared to K⁻**

- $\tau = 50$ fm
- $\phi \rightarrow K^+K^-$ (BR ~ 50%)
- $\frac{\phi}{K^-} \approx \frac{1}{3}$
- ~ 15 .. 20% K⁻ originates from $\phi$ decays

**UrQMD model**

Resonance states in medium:

- $N^* \rightarrow N + \phi$

---

**Graphs:**

- HADES preliminary
- UrQMD, Au+Au central, $|y|<0.5$
- Data

**Preliminary**

- Production threshold
- in elementary p+p
$\phi/K^-$ within the statistical model approach

\[ \frac{\phi}{K^-} \]

\[ \sqrt{S_{NN}} \text{ (GeV)} \]

G. Agakishiev et al., PRC 80, 025209 (2009)
Excitation function of $\phi$ inverse slopes
**Particle yields vs Statistical Model and UrQMD**

- **Al+Al**: 8 independent ratios involving $p$, $d$, $\pi^-$, $K^+$, $K^-$, $K^0_s$, $\phi$, $K^{*0}$, $\Sigma^*$, $\Lambda$

- **Ni+Ni**: 8 independent ratios involving $p$, $d$, $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0_s$, $\phi$, $\Lambda$

**Statistical Model**
- Grand Canonical ensemble;
- For $S \neq 0$, Canonical ensemble
- calc: THERMUS code
  
  
  SM fitting quite well

**UrQMD v 2.3**
- No equilibration assumed
- Cascade model – no mean field
  - no in-medium effects
  
  UrQMD fits quite well too

---

**Al+Al**

- $\chi^2/\nu = 5.0/5$
- $T = 72 \pm 3$ MeV
- $\mu_B = 738 \pm 10$ MeV

**Ni+Ni**

- $\chi^2/\nu = 7.9 / 6$
- $T = 68.5 \pm 11.8$ MeV
- $\mu_B = 758 \pm 10$ MeV
Λ(1520) baryon: another player?

**Λ(1520)**: BR (Λ → pK⁻) = 22.5%.
Emission of this particle at \( T_B < 10A \) GeV never observed!

**Thermal model**: estimation of yield
For Ni+Ni @ 1.9A GeV (THERMUS code, canonical ensemble for strangeness production),

**Step 1**: Fit of thermal parameters (\( T, \mu_B \)) to the experimental data.

\[
\chi^2/\nu = 7.3 / 4
\]

\[
T = 76.1 \pm 0.5 \text{ MeV}
\]

\[
\mu_B = 821 \pm 1 \text{ MeV}
\]

\[
R_c = 2.1 \pm 0.1 \text{ fm}
\]

**Step 2**: estimation of Λ(1520) yield compared to K⁻:

\[
\frac{P(\Lambda^*)}{P(K^-)} = 0.46
\]

\[
\frac{P(\Lambda^* \rightarrow K^-)}{P(K^-)} = 10\%
\]

Contribution of \( \Lambda^* \) to \( K^- \) seems to be non-negligible...
Strange meson excitation functions near threshold

![Graph showing strange meson excitation functions near threshold.](image)


In-medium KN potential: Quest for kaonic clusters

- KN interaction is strongly attractive!
  \( \Lambda(1405) \) is \((K^- p)\) bound state.

Consequence of strong attraction: Shrinking!

\[
K^- p \rightarrow \Lambda(1405)
\]

but:

\[
\Lambda(1405) \rightarrow \Sigma + \pi
\]
\[
\Sigma \rightarrow p + \pi^0, n + \pi^\pm
\]

Not seen in FOPI.

\[
K^- pp \rightarrow \Lambda + p
\]
\[
ppnK^- \rightarrow \Lambda + d
\]

A.Dote et al., PRC70,044313(2004)

Excess observed in Ni+Ni and Al+Al with statistical significance of ~ 5.
Yield located in spectator/fireball interface region (like non-strange clusters).
Peak position in variance with FINUDA result.
Interpretation unclear: \( \Sigma N \rightarrow \text{FSI} \),
bound state (H1\(^+\)),
partial inv. mass of heavier state (e.g. \( ^4_\Lambda \text{He} \)).

**FINUDA @ DaΦne:**

\[ e^+e^- \rightarrow \Phi \rightarrow K^+K^- \]
\[ K^- + A \rightarrow (ppK) + X \rightarrow \Lambda + p + X \]

M. Agnello et al., PRL 94, 212303 (2005)

---

**FINUDA**

\[ \Lambda p : \text{invariant mass} \]

\[ M. \text{Reithner, HK 12.3} \]

\[ \Lambda p : \text{Al+Al} \]

\( S = 1735 \pm 480 \)
\( S/B = 0.015 \pm 0.005 \)
\( \text{SIGNIF} = 5 \pm 1.4 \)
\( \text{MEAN} = 2.121 \pm 0.01 \text{ MeV/c}^2 \)
\( \sigma = 25 \pm 6 \text{ MeV/c}^2 \)

\[ \Lambda p : \text{Ni+Ni} \]

\( S = 1342 \pm 350 \)
\( S/B = 0.022 \pm 0.006 \)
\( \text{SIGNIF} = 5.4 \pm 1.4 \)
\( \text{MEAN} = 2.14 \pm 0.01 \text{ MeV/c}^2 \)
\( \sigma = 25 \pm 8 \text{ MeV/c}^2 \)
Chiral effective field theory w/ coupled-channels

- \( K^- \) production in medium \((\pi Y \rightarrow K^- N)\) coupled to strange resonances e.g. \( \Sigma^*(1385) \), \( \Lambda^*(1405) \):
  \[
  (\pi \Lambda \rightarrow \Sigma^* \rightarrow K^- N)
  \]

- \( \Sigma^* \) resonance found in HI collisions
  Input to fix \( \pi + \Lambda \rightarrow K^- + N \) in medium

**Al+Al @ 1.9A GeV**

\[
\Sigma^{\pm*}(1385) \rightarrow \Lambda + \pi^\pm \quad (88 \pm 2\%)
\]

\[
\rightarrow p + \pi^-
\]

\[
\Lambda \pi^- + \Lambda \pi^+
\]

\[
\frac{Y(\Sigma^{*\pm} + \Sigma^{**})}{Y(\Lambda + \Sigma^0)}
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>FOPI</th>
<th>Statist. Model</th>
<th>UrQMD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.125 ± 0.042</td>
<td>0.097</td>
<td>0.177</td>
</tr>
</tbody>
</table>

\[ S = 3115 \pm 480 \]
\[ S/B = 0.03 \pm 0.01 \]
\[ \text{SIGNIF} = 9.1 \pm 1.4 \]
\[ \text{MEAN} = 1387 \pm 5 \text{MeV/c}^2 \]
\[ \Gamma = 51 \pm 13 \text{MeV/c}^2 \]

\[ X. \text{Lopez et al. (FOPI)}, \text{PRC 76, 052203(R)} (2007) \]
In-Medium $\Sigma^*(1385)$

**Chiral unitary theory**

$\Sigma^*(1385) \rightarrow \Lambda(\Sigma) + \pi$ at $\rho=\rho_0$

$c\tau = 5$ fm

$\Gamma = -2\text{Im}[\Sigma]\Sigma^*(1385) = 76$ MeV

Mass:

$V_{\Sigma^*N} \approx -45$ MeV (attractive)

---

$\Sigma^*(1385) \rightarrow \Lambda(\Sigma) + \pi$ at $\rho=\rho_0$

$\Gamma = -2\text{Im}[\Sigma]\Sigma^*(1385) = 76$ MeV

**Mass:**

$V_{\Sigma^*N} \approx -45$ MeV (attractive)

---

FOPI expt. data

PDG mass ($\rho = 0$)

short lifetime $\rightarrow$ $\Sigma^*$ should probe finite density!

$\Gamma$ broadening not yet observed (more statistics...)

Need to measure with heavier system

Need to include spectral function in transport codes

---

X. Lopez et al., PRC 76, 052203(R) (2007)
HADES: FAIR Phase 0 Experiment

HADES monitoring
Ag+Ag 1.58A GeV

Date: 01 April 2019
Event rate: 16-18 kHz
Collected events: 15268.68 \times 10^6
Collected data: 359.23 TB
Last update: 6:00

Event Display
Run statistics

PID: Velocity vs Momentum - TOF
\( \beta = \frac{v}{c} \)

\( p \times q \) (MeV/c)

\( e^+ / e^- \) Cherenkov Rings

Online Hyperons: \( \Lambda \rightarrow p + \pi^- \)

https://web-docs.gsi.de/~webhades/onlineMon/mar19/hades-online.html