ϕ and K^- meson production in subthreshold nuclear collisions in BUU

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Motivation

- Sub-threshold particle production is sensitive to
  - reaction dynamics
  - equation of state
  - microscopic creation channels, etc.
- non-equilibrium process
- $\rightarrow$ transport is the adequate tool for theory
- in BUU:
  - EOS can be influenced through potentials
  - in-medium modification of particle properties can be considered

The BUU model

- Boltzmann-Ühling-Uhlenbeck (BUU) equation:

$$\frac{\partial f_i(\mathbf{r},\mathbf{p},t)}{\partial t} + \left\{ \frac{\mathbf{p}}{E} + \frac{m_{i,\mathrm{eff}}(\mathbf{r},\mathbf{p})}{E} \nabla_{\mathbf{p}} U_i(\mathbf{r},\mathbf{p}) \right\} \nabla_{\mathbf{r}} f_i(\mathbf{r},\mathbf{p},t) - \left\{ \frac{m_{i,\mathrm{eff}}(\mathbf{r},\mathbf{p})}{E} \nabla_{\mathbf{r}} U_i(\mathbf{r},\mathbf{p}) \right\} \nabla_{\mathbf{p}} f_i(\mathbf{r},\mathbf{p},t) = I_{\mathrm{coll},i}\left[f_j(\mathbf{r},\mathbf{p},t)\right]$$

- Momentum dependent mean-field potential:

$$U_B(\mathbf{r},\mathbf{p}) = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2\frac{C}{\rho_0}\sum_i \int \frac{d^3\mathbf{p}'}{(2\pi)^3} \frac{f_i(\mathbf{r},\mathbf{p}')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2}$$

- Soft equation of state ($\kappa = 215$ MeV)
- Collision integral:

$$I_{\mathrm{coll},1}\left[f_j(\mathbf{r},\mathbf{p},t)\right] = -\frac{1}{(2\pi)^3}\int d^3\mathbf{p}_2 d^3\mathbf{p}_2' d\Omega \frac{d\sigma_{12\to1'2'}}{d\Omega} v_{12}\delta^3(\mathbf{p}_1+\mathbf{p}_2-\mathbf{p}_1'-\mathbf{p}_2') \times\left[f_1 f_2(1-f_{1'})(1-f_{2'}) - f_{1'}f_{2'}(1-f_1)(1-f_2)\right]$$

The BUU model

- Test particle ansatz:

$$f_N(\mathbf{r},\mathbf{p},t) = \frac{1}{\tilde{N}} \sum_{i=1}^{\tilde{N}\times A} \delta\left(\mathbf{r}-\mathbf{r}_i(t)\right)\delta\left(\mathbf{p}-\mathbf{p}_i(t)\right)$$

  BUU equation $\rightarrow$ equations of motion for test particles

- Parallel ensemble method:
  - $\tilde{N}$ copies of the system (ensembles)
  - only particles in the same ensemble can collide
  - the ensembles are coupled via the potential $U_i(\mathbf{r},\mathbf{p})$ and Pauli blocking
- Perturbative method for rare particles (ϕ, K^-, dileptons):
  - fictive particles are created with "probability of existance"
  - colliding particles are left untouched
  - $\rightarrow$ a tiny violation of energy-momentum conservation

Propagated particles – collision term

- Collision of baryons – resonance excitation:
  $NN \leftrightarrow NR$, $NN \leftrightarrow \Delta\Delta$
- Baryon resonances can decay via 9 channels:
  $R \leftrightarrow N\pi, N\eta, N\sigma, N\rho, N\omega, \Delta\pi, N(1440)\pi, K\Lambda, K\Sigma$
- 24 baryon resonances + Λ and Σ baryons are propagated
- $\pi, \eta, \sigma, \rho, \omega$ and K mesons
- Collisions of mesons via:
  $\pi\pi \leftrightarrow \rho$, $\pi\pi \leftrightarrow \sigma$, $\pi\rho \leftrightarrow \omega$

ϕ production

- Production channels: [W.S. Chung, G.Q. Li, C.M. Ko, NPA 625 ('97) 347]

$$NN, N\Delta, \Delta\Delta \rightarrow NN\phi$$
$$\pi N, \pi\Delta \rightarrow N\phi$$
$$K^+K^- \rightarrow \phi$$

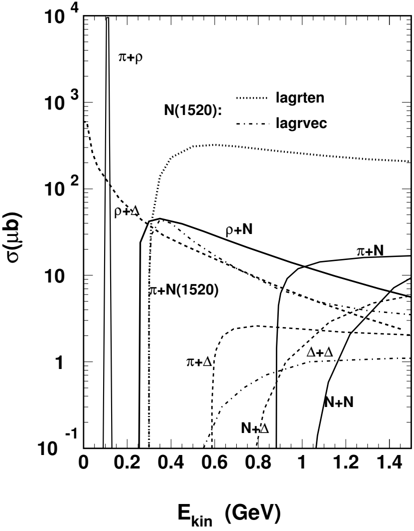
  underestimated preliminary FOPI data (Ni+Ni, 1.93A GeV; Ru+Ru 1.69A GeV)
- up to 30% of nucleons are excited to Δ and N^* resonances
- high cross section for ρ meson production
- 2-3 times normal nuclear matter density is reached, which facilitates secondary collisions
- $\rightarrow$ new production channels: [H.W. Barz, M.Z., Gy. Wolf, B. Kämpfer, NPA 705 ('02) 223]

$$\rho N, \rho\Delta \rightarrow N\phi$$
$$\pi\rho \rightarrow \phi$$
$$\pi N(1520) \rightarrow N\phi$$

- density dependent ϕ mass: $m_\phi^{\mathrm{med}} = m_\phi^{\mathrm{vac}} \left(1 - 0.025 \frac{n}{n_0}\right)$
- ϕ rescattering via $\phi B \rightarrow K\Lambda$

ϕ production – summary of cross sections

Cross sections are calculated within a one-boson exchange model



- the new channels have lower threshold ($\rho\Delta$ is above threshold for $E_{\mathrm{kin}} = 0$)
- the cross sections reach higher values at low energy
- uncertainty in the $\pi N(1520)$ channel, depending on the $N(1520)N\rho$ Lagrangian

ϕ production

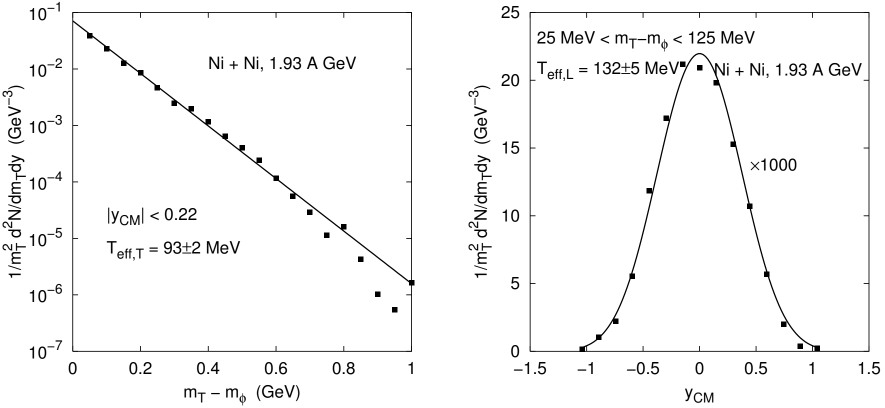
Results for Ni+Ni, 1.93 A GeV (9% central) [H.W. Barz, M.Z., Gy. Wolf, B. Kämpfer, NPA 705 ('02) 223]
in comparison with FOPI data (12% central) [A. Mangiarotti et al.(FOPI) NPA 714 ('03) 89]

B + B	3.5×10^{-4}
π + B	2.9×10^{-4}
ρ + B	8.9×10^{-4}
$\pi + \rho$	1.6×10^{-4}
π + N(1520)	0.5×10^{-4}
total yield	1.7×10^{-3}
in Central Drift Chamber (CDC)	2.7×10^{-5}
experiment, CDC	$(1.9 \pm 0.6 \pm 0.95) \times 10^{-5}$
experiment, 4π extrapolated:	
$T_{\text{source}} = 130$ MeV	$1.2 \pm 0.4 \pm 0.6 \times 10^{-3}$
$T_{\text{source}} = 70$ MeV	$4.5 \pm 1.4 \pm 2.2 \times 10^{-3}$

ϕ production - effective temperature

Fitting the transverse mass and rapidity spectra (at midrapidity and small transverse momenta) with thermal distributions we get the effective temperatures:

$T_{\text{eff,T}} = 93 \pm 2$ MeV $\qquad$ $T_{\text{eff,L}} = 132 \pm 5$ MeV

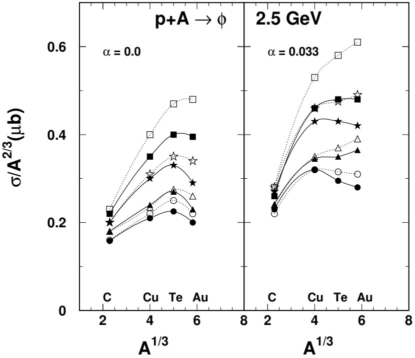


ϕ production in p+A near threshold

[H.W. Barz, M.Z., PRC 69 ('04) 024605]

- Strong attractive K^- potential $\rightarrow$ increase of $\phi \rightarrow K^+K^-$ phase-space
  $\rightarrow$ ϕ lifetime decreases (from 50 fm/c, by up to an order of magnitude)
  $\rightarrow$ the ϕ-s decay inside the nucleus
  $\rightarrow$ $K^\pm$ rescatter, and the ϕ cannot be reconstructed
- $\Gamma_{\phi \rightarrow K^+K^-}$ grows while $\Gamma_{\phi \rightarrow e^+e^-}$ is constant
  $\rightarrow$ the e^+e^- branching ratio decreases
- The effect is stronger for a larger nucleus $\rightarrow$ study the system size dependence of ϕ production via both the K^+K^- and e^+e^- channels

ϕ production in p+A near threshold



- open symbols: e^+e^-
  black symbols: K^+K^-
- Potentials:

$$U_{K^+}(n) = 25\,\mathrm{MeV}\,\frac{n}{n_0}$$

$$m_\phi^{\mathrm{med}} = m_\phi^{\mathrm{vac}}\left(1 - \alpha\,\frac{n}{n_0}\right)$$

$$U_{K^-}(n, p_K) = [a + b\exp(-c p_K)]\,\frac{n}{n_0}$$

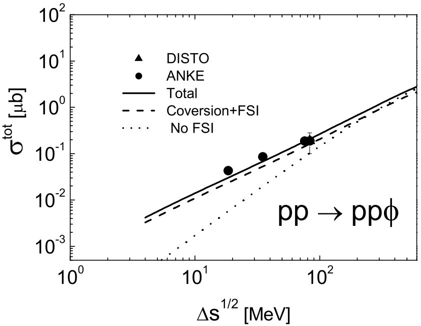
- Parameter sets for K^- potential (top to bottom):

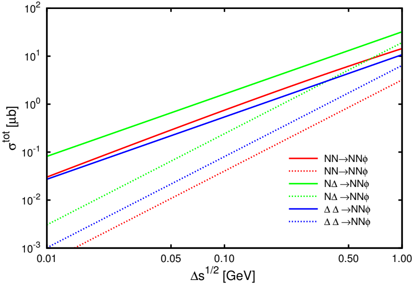
no pot.:	a=0,	b=0,	c=0;
moderate:	a=−70 MeV,	b=0,	c=0;
mom. dep.:	a=−55 MeV,	b=−130 MeV,	c=0.0025 MeV^{-1};
strong:	a=−150 MeV,	b=0,	c=0.

ϕ production

$BB \to NN\phi$:

- new data from ANKE [M. Hartmann et al.(ANKE), PRL 96 ('06) 242301]
- new calculation with FSI [L.P. Kaptari, B. Kämpfer EPJA 23 ('05) 291; and arXiv:0810.4512]





ϕ production

New BUU calculation: [H. Schade, Gy. Wolf, B. Kämpfer, PRC 81 ('10) 034902]

B + B	11.2×10^{-4}
π + B	2.4×10^{-4}
ρ + B	8.6×10^{-4}
$\pi + \rho$	1.5×10^{-4}
π + N(1440)	0.6×10^{-4}
π + N(1520)	0.5×10^{-4}
total yield	2.5×10^{-3}
experiment, CDC	$(1.9 \pm 0.6 \pm 0.95) \times 10^{-5}$
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$T_{\text{source}} = 130$ MeV	$1.2 \pm 0.4 \pm 0.6 \times 10^{-3}$
$T_{\text{source}} = 70$ MeV	$4.5 \pm 1.4 \pm 2.2 \times 10^{-3}$

Role of ϕ in K^- production

- HADES results for Ar(1.756A GeV)+KCl
  [G. Agakishiev et al. (HADES), PRC 80 ('09) 025209]

- BUU calculation with the above model
  - soft EOS ($\kappa = 215$ MeV)
  - in-medium masses of K^+, K^- and ϕ via $m^* = m[1 + C(n/n_0)]$:

$$\Delta m_{K^+}(n_0) = +23\text{MeV}$$
$$\Delta m_{K^-}(n_0) = -75\text{MeV}$$
$$\Delta m_{\phi}(n_0) = -22\text{MeV}$$

Role of ϕ in K^- production

K^+ and K^- production channels:

- baryon - baryon

$$NN \rightarrow \begin{cases} NNK^+K^- \\ NYK^+ \\ \Delta YK^+ \end{cases} \qquad N\Delta \rightarrow \begin{cases} NNK^+K^- \\ N\Delta K^+K^- \\ NYK^+ \\ \Delta YK^+ \end{cases} \qquad \Delta\Delta \rightarrow \begin{cases} NNK^+K^- \\ \Delta\Delta K^+K^- \\ NYK^+ \\ \Delta YK^+ \end{cases}$$

- pion - baryon

$$\pi N \rightarrow \begin{cases} NK^+K^- \\ YK^+ \end{cases} \qquad \pi\Delta \rightarrow \begin{cases} NK^+K^- \\ YK^+ \end{cases}$$

- ϕ decay

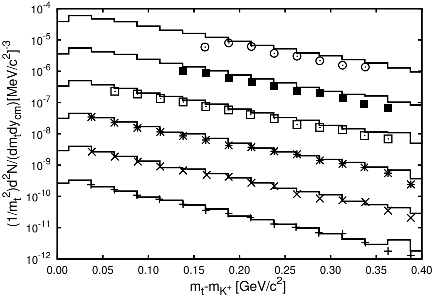
$$\phi \rightarrow K^+K^-$$

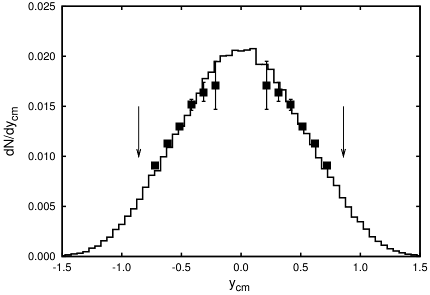
- baryon - hyperon and pion - hyperon

$$\left.\begin{array}{l} NY \\ \Delta Y \end{array}\right\} \leftrightarrow NNK^- \qquad \pi Y \leftrightarrow K^-N$$

$K^{\pm}$ and ϕ in Ar+KCl

K^+ spectra, impact parameter $b = 3.9$ fm (experiment: $\langle b \rangle \approx 3.6$ fm)





Transverse mass spectra of K^+ rapidity bins:

$0.1 < y_{\text{lab}} < 0.2$

$\vdots$

$0.6 < y_{\text{lab}} < 0.7$ (scaled by 10^5)

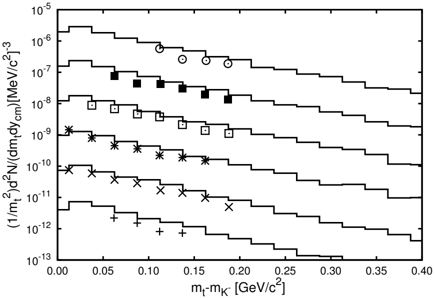
Rapidity distribution of K^+ in C.M.

(data by HADES)

- K^+ yield: 2.7×10^{-2} [experiment: $(2.8 \pm 0.4) \times 10^{-2}$]

$K^{\pm}$ and ϕ in Ar+KCl

K^{-} spectra, impact parameter $b = 3.9$ fm

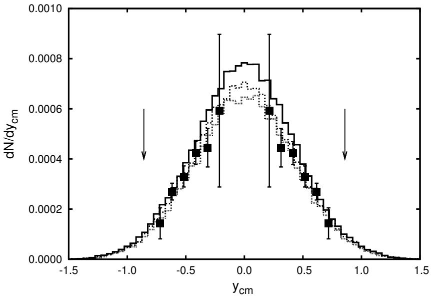


Transverse mass spectra of K^{-}
rapidity bins:

$0.1 < y_{\text{lab}} < 0.2$

$\vdots$

$0.6 < y_{\text{lab}} < 0.7$ (scaled by 10^5)



Rapidity distribution of K^{-} in C.M.

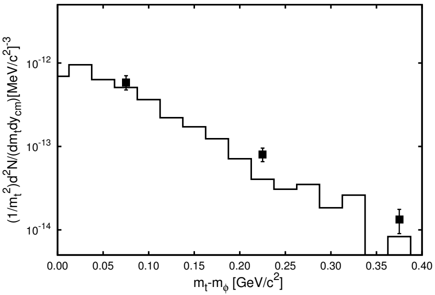
$\kappa = 215$ MeV, 290 MeV, 380 MeV
(solid, dashed, dotted)

(data by HADES)

- K^{-} yield: 7.8×10^{-4} [experiment: $(7.1 \pm 1.9) \times 10^{-4}$]

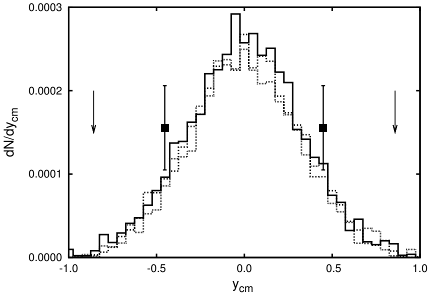
$K^{\pm}$ and ϕ in Ar+KCl

ϕ spectra, impact parameter $b = 3.9$ fm



Transverse mass spectrum of ϕ

$0.2 < y_{\text{lab}} < 0.6$



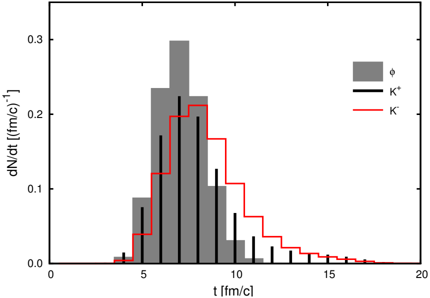
Rapidity distribution of ϕ in C.M.

$\kappa = 215$ MeV, 290 MeV, 380 MeV
(solid, dashed, dotted)

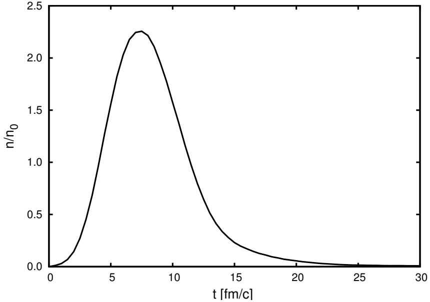
- ϕ yield: 2.2×10^{-4} [experiment: $(2.6 \pm 0.8) \times 10^{-4}$]
- ϕ/K^{-} ratio $= 0.28$ [experiment: 0.37 ± 0.13]
- Switching off $K^{\pm}$ and ϕ potentials $\to$ K^{-}: 40% increase; K^{+}: 15% decrease

$K^{\pm}$ and ϕ in Ar+KCl

Time dependence



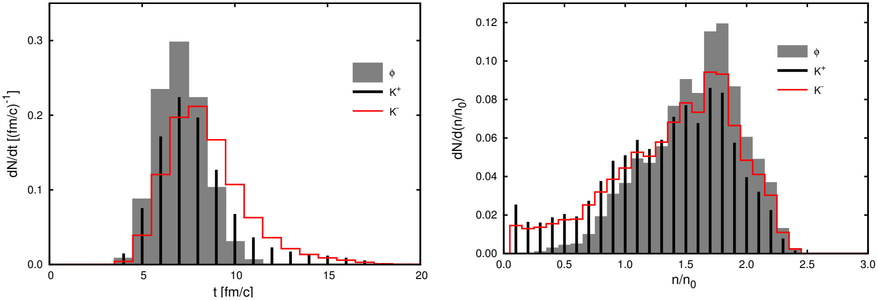
Creation rate (normalized)



Density in the center

$K^{\pm}$ and ϕ in Ar+KCl

Creation rate (normalized)



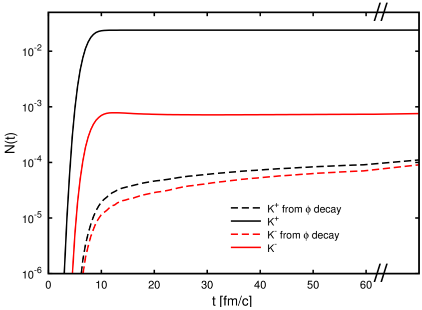
Time dependence

Density dependence

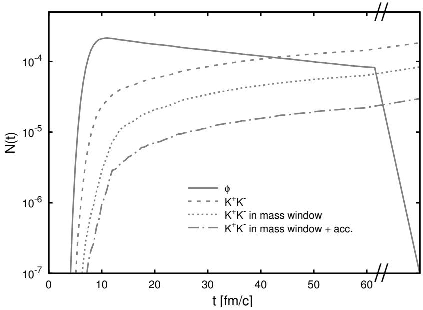
- Some of the K^- (and K^+) are created later, and at lower density
- Are they from (relatively slow) ϕ decays?

$K^{\pm}$ and ϕ in Ar+KCl

Time dependence of particle number



kaons

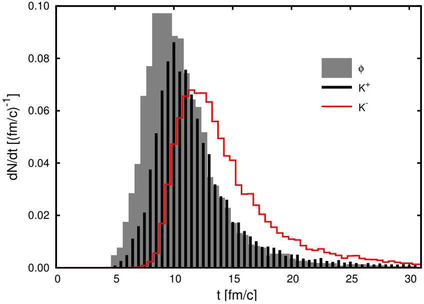


ϕ mesons

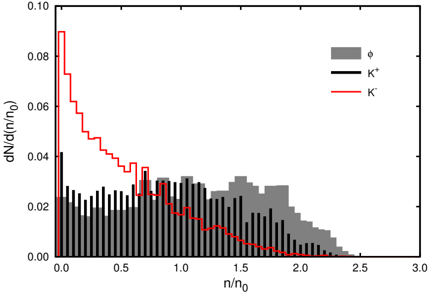
- Kaons from ϕ decay come later
- 14% of K^- from ϕ
- Invariant mass of kaon pairs destroyed by rescattering
- K^- absorption $\rightarrow$ less K^- from ϕ than K^+

$K^{\pm}$ and ϕ in Ar+KCl

Freeze-out



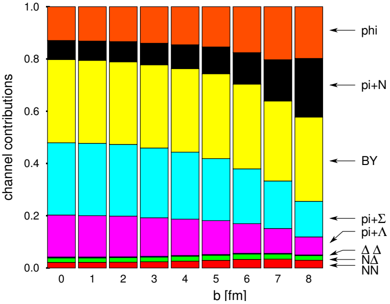
last interaction time



last interaction density

- K^- decouple significantly later and at lower density
- Large cross section of K^- rescattering

K^- production channels - impact parameter dependence



- dominant sources:
  - strangeness transfer, $\pi Y \to K^- N$
  - $BY \to NNK^-$
- large impact parameter:
  ϕ decay and $\pi N \to NK^+K^-$ becomes important