Multi-Strangeness in Heavy-ion Collisions

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- Why do we love strangeness?
- Minimal statistical model for strangeness
- Strangeness at AGS-SPS-RHIC
- Hidden strangeness (Φ-meson)
- Ξ puzzle at HADES
- Strangeness at LHC

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Strangeness is interesting because

- It is a tag on a hadron, saying that it was not in colliding nuclei but is produced in the course of collision.

- Strange quarks like baryons: $K, \Lambda, \Sigma, \Xi, \Omega, \ldots$, anti-strange quarks like mesons $K, \ldots$
  
  → strangeness/anti-strangeness separation in baryon-rich matter

- Strangeness is conserved in strong interaction
  
  → Strangeness production threshold is high,
  
  → sensitive to possible in-medium effect.
  
  QGP signal? (Rafelski-Mueller conjecture)

Strangeness is difficult because

- Strangeness production cross sections poorly known
  
  (new data from HADES on pp, COSY on pn, ANKA)

- Limited exp. information about elementary reactions among strange particles

- Strong couplings among various strange species. Complicated dynamics
Strange particles is nuclear medium

1. Hyperons

\[ E_Y(p) = \sqrt{m_Y^2 + p^2} \rightarrow \sqrt{(m + S_Y)^2 + p^2} + V_Y \]

potential model  

 scalar and vector potentials

In relativistic mean-field models S and V originates from exchanges of scalar and vector mesons

Usually one relates vector potentials to the potential for nucleons \( V_Y = \alpha_Y V_N \)

where \( \alpha_Y \) is deduced from some quark counting rule

Scalar potentials are fixed by the optical potential \( U_Y = S_Y + V_Y \), acting on hyperons in an atomic nucleus

\[
\begin{align*}
U_A &= -27 \text{ MeV} & \text{[Hashimoto, Tamura, Prog.Part.Nucl.Phys. 57, 564 (2006)]} \\
U_\Sigma &= +24 \text{ MeV} & \text{[Dabrowski, Phys.Rev.C 60, 025205 (1999)]} \\
U_\Xi &= -14 \text{ MeV} & \text{[Khaustov et al., Phys.Rev.C 61, 054603 (2000)]}
\end{align*}
\]

Caution: extrapolation of the attractive hyperon potentials in RMF models to higher densities may lead to problems with astrophysical constrains on the neutron star masses!!!
2. anti-strange mesons

Various partial wave couple in medium

$$E(p) = \sqrt{m^2 + p^2} \rightarrow \sqrt{(m + S)^2 + p^2 + V}$$

scalar and vector potentials: common prejudice $S<0; \ V>0$

3. strange mesons

Exp. $\bar{K}N$ scattering

scattering model including s-,p-,d-
partial waves

Coupled-channel scattering: Weise, Kaiser,…
Oset, Ramos,…
Lutz, EEK,…
4. K$^-$ in medium schematic spectral density

EEK, Voskresensky, Kampfer NPA588 (1995);
EEK, Voskresnensky, PRC60 (1999)

Maximum of the spectral function is shifted to higher energies

\[ \omega \sim m_\Lambda - m_N \]

“kaon” mode with attractive potential

quasi-particle branch

particle-hole modes

short-range correlations
realistic spectral densities + realistic K-N interactions + self-consistent calculations

Oset, Tolos et al; Lutz, Korpa, et al

Courageous attempts to include spectral function in transport codes by Giessen, Frankfurt, and Nantes groups [Bratkovskaya, Cassing, Aichelin et al]

\[ \Lambda(1405), \Sigma(1385) \]

\[ \Lambda(1116), \Sigma(1190) \]

How to release the in-medium kaons?

fireball break up time \( \sim 1/m_\pi \)

\[ m_K \rightarrow m_K - 75 \text{ MeV} \rho/\rho_0 \]
Minimal statistical model for strange particles:

In baryon dominated matter Kaons (anti-s-inside) interacts weaker than Anti-Kaons (s inside). There is no baryon resonances with an s-quark.

*Kaons leave fireball earlier and carry anti-strangeness away.*

The fireball have some negative strangeness which is statistically distributed among $K^-$, anti-$K^0$, $\Lambda$, $\Sigma$, $\Xi$, $\Omega$

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anti-strangeness released = strangeness accumulated inside = strangeness released at breakup
Strangeness production rate at AGS-SPS

- **strangeness production** \( K^+ \) and \( K^0 \) evolution calculated from

\[
\frac{d\rho_K}{d\tau} = \rho_K \left( -\frac{1}{V} \frac{dV}{d\tau} \right) + R^+ - R^-
\]

- **annihilation rate**
- **production rate**
- **expansion rate**

calculate from known cross-sections and evolved densities

Initial strangeness: number of \( K^+ \) from pp collisions

- **fireball expansion time vs. energy** parameterized the space-time evolution

a data/experience (HBT, spectra) driven ansatz for expansion
The K⁺ horn can be interpreted as a rise and fall of the fireball lifetime.

The time needed for a strangeness production is about 15-20 fm/c. In hydro the typical expansion time is <10 fm/c!.
**Hidden strangeness. Φ-mesons**

1985  Asher Shor [PRL 54, 1122] proposed enhancement of phi meson yield as a signal of a „colour liberation“

**AGS** [E917, PRC 69, 054901 (2004)] found enhancement factor 3-4

**SPS** [NA49, PRC 78, 044907 (2008)]

This factor can be explained by *strangeness coalescence* [Ko, Sa, PLB 258]

\[
K \bar{K} \rightarrow \phi \rho \quad K \Lambda \rightarrow \phi N \quad + \text{phi mass drop}
\]

**FOPI:** Ni +Ni @ 1.97 GeV/A [NPA 714 (2003) 89]

Large yield of phi meson which cannot be explained in theoretically


**HADIES:** Ar+KCl @ 1.76 GeV/A [Arxive: 0902.3487] phi meson enhancement

18±7 % K⁻ mesons stem from phi decays! *strangeness ballance??*
Okubo-Zweig-Iizuka suppression rule

- \( N \rightarrow N\omega \)
- \( N \rightarrow N\phi \) suppressed

I/\( N_c \) counting

\[ \frac{\sigma(\pi N \rightarrow \omega N)}{\sigma(\pi N \rightarrow \phi N)} \sim 75 \]

Phi production in reactions involving strange particles is not OZI suppressed!

- Strangeness "annihilation" \( KY \rightarrow \phi N \) strangeness hides into \( \phi \)

- Catalytic reactions \( \pi Y \rightarrow \phi Y' \) \( \bar{K}N \rightarrow \phi Y \)

If catalytic reactions are operative then some correlations among phis and strange particles could be seen in experiment:

- Centrality dependence
- Rapidity distributions
Phi production

\[
\frac{d\rho_\phi}{dt} - \rho_\phi(t) \frac{\dot{\rho}_B(t)}{\rho_B(t)} = R_{\pi N}^\phi(t) + \sum_{Y, Y' = \Lambda, \Sigma} R_{Y' Y}^\phi(t) + R_{KN}^\phi(t) + \ldots
\]

\[\pi N \rightarrow \phi N\]

Catalytic reactions

\[\pi Y \rightarrow \phi Y'\]

\[T_m = 110 \text{ MeV}, \rho_m = 4 \rho_0, \alpha = 0.2\]

\[T_m = 130 \text{ MeV}, \rho_m = 5 \rho_0, \alpha = 0.3\]

\[T_m = 150 \text{ MeV}, \rho_m = 6 \rho_0, \alpha = 0.5\]

Red lines scale with \(t_0\)!!!

Catalytic reactions can be competitive if \(T > 110 \text{ MeV}\) and \(t_0 > 10 \text{ fm}\)
The catalytic reaction contribution can be about 30\%-40\% for $N_{pp}=A$. 

\begin{align*}
N_\phi &\sim a_{\text{conv}} N_{pp}^{4/3} + a_{\text{cat}} N_{pp}^{5/3} \\
N_\phi &\sim a' + b' \left( \frac{N_{pp}}{A} \right)^{1/3}
\end{align*}
Rapidity distribution

The distributions can be fitted with a sum of two Gaussian functions placed symmetrically around mid-rapidity

\[ \frac{1}{\langle N \rangle} \frac{dN}{dy} = \frac{1}{\sqrt{8 \pi \sigma^2}} \left[ e^{-\frac{(y-a)^2}{2\sigma^2}} + e^{-\frac{(y+a)^2}{2\sigma^2}} \right] \]

the root mean square of the distribution \( \text{RMS}^2 = \sigma^2 + a^2 \)

Assume: \text{the rapidity distributions of particles do not change after some initial stage.}

The collision \textbf{kinematics} is restricted mainly to the \textit{exchange of transverse momenta}.

The rapidity distribution of \( \phi \)s produced in the reaction \( 1+2 \rightarrow \phi + X \) is roughly proportional to the \textbf{product of rapidity distributions} of colliding particle species 1 and 2.

\[ \text{RMS}_{12}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} + \ldots \]
Strangeness at HADES @ GSI
HADES: complete measurement of particles containing strange quarks in Ar+KCl collisions @ 1.76 AGeV

one experimental set-up for all particles!

We study the relative distributions of strangeness among various hadron species

We are not interested in how strangeness is produced!

We know the final $K^+$ multiplicity!

$$R_{K^-/K^+} = \frac{N_{K^-}}{N_{K^+}} = 2.5^{+1.2}_{-0.9} \times 10^{-2} \quad R_{\Lambda/K^+} = \frac{N_{\Lambda+\Sigma^0}}{N_{K^+}} = 1.46^{+0.49}_{-0.37}$$

$$R_{(Hades)_{\Sigma/K^+}} = \frac{1}{2} \frac{N_{\Sigma^++\Sigma^-}}{N_{K^-}} = 0.13^{+0.16}_{-0.11} \quad R_{(iso)_{\Xi/\Lambda/K^+}} = \frac{N_{\Xi^-}}{N_{\Lambda+\Sigma^0} N_{K^+}} = 0.20^{+0.16}_{-0.11}$$

if $K^+ + K^0_s$ data are used for total strangeness

$$R_{(iso)_{\Sigma/K^+}} = \frac{1}{2} \frac{N_{\Sigma^++\Sigma^-}}{N_{K^+}} = 0.30^{+0.23}_{-0.17}$$

total strangeness is $(1+\eta) K^+$

isospin asymmetry factor $\eta = \frac{A-Z}{Z}$

for ArK and ArCl collisions $\eta = 1.14$

This number is much bigger than the results of stat. models and transport codes
We know the average kaon multiplicity \( \mathcal{M}_{K^+} = (2.8 \pm 0.4) \times 10^{-2} \)

Of course kaons are produced not piecewise but as whole entities.

\[
events \text{ with } K^+ \rightarrow N_{K^+} = M_{K^+} \cdot N_{\text{tot}} \longrightarrow \text{ total number of events}
\]

**Multi-kaon event classes:**

\[
P_{s\bar{s}}^{(1)} N_{\text{tot}} + P_{s\bar{s}}^{(2)} N_{\text{tot}} + P_{s\bar{s}}^{(3)} N_{\text{tot}} + \cdots = N_{\text{tot}} (1 + \eta) \mathcal{M}_{K^+}
\]

\[
P_{s\bar{s}}^{(n)} \text{ probability of creation of } n \text{ } s\bar{s} \text{ pairs}
\]

\[
\eta = \frac{A-Z}{Z}
\]

\[
P_{s\bar{s}}^{(n)} = \Lambda^n e^{-\Lambda} / n!
\]

\( \Lambda \) -- integral probability of the pair production

\( \bar{K}, \Lambda, \Sigma \)

\( \bar{K}, \Lambda, \Sigma, \Xi \)

\( \bar{K}, \Lambda, \Sigma, \Xi, \Omega \)

no \( \Xi, \Omega \!

no \( \Omega \!

\[ \Lambda = \lambda V_{fo}^{4/3} \]

We denote the multiplicity of \( K^+ \) mesons produced in each \( n \)-kaon events as:

\[ M_{K^+}^{(n)} = \frac{n}{1 + \eta} P_{ss}^{(n)} \]

\[ \mathcal{M}_{K^+} = \sum_n \langle M_{K^+}^{(n)} \rangle = \frac{1}{1 + \eta} \sum_n n \langle P_{ss}^{(n)} \rangle = \frac{\langle \Lambda \rangle}{1 + \eta} \]

\[ \langle P_{ss}^{(1)} \rangle = (1 + \eta) \mathcal{M}_{K^+} \left[ 1 - (1 + \eta) \zeta^{(2)} \mathcal{M}_{K^+} + \frac{1}{2} \zeta^{(3)} (1 + \eta)^2 \mathcal{M}_{K^+}^2 \right] \]

\[ \langle P_{ss}^{(2)} \rangle = \frac{1}{2} (1 + \eta)^2 \mathcal{M}_{K^+}^2 \left[ \zeta^{(2)} - (1 + \eta) \zeta^{(3)} \mathcal{M}_{K^+} \right] \]

\[ \langle P_{ss}^{(3)} \rangle = (1 + \eta)^3 \frac{1}{6} \zeta^{(3)} \mathcal{M}_{K^+}^3 \]

\[ \zeta^{(1)} = 1, \quad \zeta^{(2)} = 2.51, \quad \zeta^{(3)} = 8.11 \]

15% of kaons is produced pairwise \quad 1% of kaons is produced triplewise
The **statistical probability** that strangeness will be released at freeze-out in a hadron of type \(a\) with the mass \(m_a\) is

\[
P_a = z_S^{S_a} V_{fo} p_a = z_S^{S_a} V_{fo} \nu_a e^{q_a \frac{\mu_B(t)}{T(t)}} f(m_a, T_{fo})
\]

- \(S_a\): \# of strange quarks in the hadron
- \(\nu_a\): spin-isospin degeneracy factor
- \(Q_i\): baryon charge of the hadron

\[
f(m, T) = \frac{m^2 T}{2\pi^2} K_2\left(\frac{m}{T}\right)
\]

\(z_S\) is a **normalization factor** which could be related to a probability of one \(s\)-quark to find itself in a hadron \(a\).

This factor follows from the requirement that the sum of probabilities of production of different strange species and their combinations, which are allowed in the finale state, is equal to one.

This factor depends on how many strange quarks are produced. Hence, it is different in single-, double- and triple-kaon events.
**single-kaon event:** \( n = 1 \)

only \( \bar{K}, \Lambda \) and \( \Sigma \) can be in the final state

\[
P^{(1)}_{\bar{K}} + P^{(1)}_{\Lambda} + P^{(1)}_{\Sigma} = 1 = z^{(1)}_S V_{fo} (p_{\bar{K}} + p_{\Lambda} + p_{\Sigma})
\]

multiplicity of \( \bar{K}, \Lambda, \Sigma \)

\[
M^{(1)}_a = g_a P^{(1)}_{ss} P^{(1)}_a = g_a P^{(1)}_{ss} z^{(1)}_S V_{fo} p_a
\]

isospin factor

**double-kaon event:** \( n = 2 \)

\( \bar{KK}, \bar{K}\Lambda, \bar{K}\Sigma, \Lambda\Lambda, \Lambda\Sigma, \Sigma\Sigma \) and \( \Xi \) can be in the final state

\[
(P^{(2)}_{\bar{K}} + P^{(2)}_{\Lambda} + P^{(2)}_{\Sigma})^2 + P^{(2)}_{\Xi} = 1
\]

\[
z^{(2)}_S V_{fo}^2 (p_{\bar{K}} + p_{\Lambda} + p_{\Sigma})^2 + z^{(2)}_S V_{fo} p_{\Xi} = 1
\]

multiplicity of \( \bar{K}, \Lambda, \Sigma \)

\[
M^{(2)}_a = g_a 2 P^{(2)}_{ss} P^{(2)}_a (P^{(2)}_{\bar{K}} + P^{(2)}_{\Lambda} + P^{(2)}_{\Sigma})
\]

multiplicity of \( \Xi \)

\[
M^{(2)}_{\Xi} = g_{\Xi} P^{(2)}_{ss} P^{(2)}_{\Xi}
\]
particle ratios:  

\[ R_{K^-/K^+} = \eta \frac{\langle M^{(1)}_K + M^{(2)}_K \rangle}{(1 + \eta) \mathcal{M}_{K^+}} \]

\[ R_{\Lambda/K^+} = \frac{1}{\mathcal{M}_{K^+}} \left\langle M^{(1)}_\Lambda + M^{(2)}_\Lambda + \eta \frac{M^{(1)}_\Sigma + M^{(2)}_\Sigma}{\eta^2 + \eta + 1} \right\rangle \]

\[ R_{\Sigma/K^+} = \frac{\eta^2 + 1}{2(\eta^2 + \eta + 1)} \frac{\langle M^{(1)}_\Sigma + M^{(2)}_\Sigma \rangle}{\mathcal{M}_{K^+}} \]

\[ R_{\Xi/\Lambda/K^+} = \frac{\frac{\eta}{1+\eta} \langle (M^{(2)}_\Xi + M^{(3)}_\Xi) \rangle}{\langle M^{(1)}_\Lambda + M^{(2)}_\Lambda + \eta \frac{M^{(1)}_\Sigma + M^{(2)}_\Sigma}{\eta^2 + \eta + 1} \rangle \mathcal{M}_{K^+}} \]

We included leading and next-to-leading contributions

\[ \frac{\eta p_K}{p_K + p_\Lambda + p_\Sigma} Y_1 \]

\[ (1 + \eta) \frac{p_\Lambda + \frac{\eta p_\Sigma}{\eta^2 + \eta + 1}}{p_K + p_\Lambda + p_\Sigma} Y_1 \]

\[ \frac{(\eta^2 + 1)(\eta + 1)}{2(\eta^2 + \eta + 1)} \frac{p_\Sigma}{p_K + p_\Lambda + p_\Sigma} Y_1 \]

\[ \frac{p_\Xi}{(p_K + p_\Lambda + p_\Sigma)} \left( \frac{p_\Xi}{p_K + p_\Lambda + p_\Sigma} \right) \frac{\eta}{\langle V_{fo} \rangle} \left( \frac{V_{fo}^{5/3}}{V_{fo}^{4/3}} \right) Y_2 \]

in **blue** the standard results; in **red** corrections

\[ Y_1 = 1 - \frac{(1 + \eta) \mathcal{M}_{K^+} p_\Xi}{(p_K + p_\Lambda + p_\Sigma)^2} \frac{\langle V_{fo}^{5/3} \rangle}{\langle V_{fo}^{4/3} \rangle^2} \]

small correction <5%  

\[ Y_2 = \frac{1}{2} \tilde{\zeta}^{(2)} = \frac{1}{2} \left( \frac{\langle V_{fo}^{5/3} \rangle}{\langle V_{fo}^{4/3} \rangle^2} \right) \langle V_{fo} \rangle \simeq 0.52 \]

strong suppression!

\[ \Xi/\Lambda/K \text{ ratio is sensitive to the fireball freeze-out volume} \]
Ratios as functions of the freeze-out temperature

parameters of the model: \( \rho_{B,fo} = 0.6 \rho_0 \)

potential models for strange particles in medium

potentials for nucleons \( \Delta s \):

\[
S_N \approx S_\Delta \approx -190 \text{ MeV} \frac{\rho_B}{\rho_0} \\
V_N \approx V_\Delta \approx +130 \text{ MeV} \frac{\rho_B}{\rho_0}
\]

Inclusion of potentials improves the temperature match for \( K \) and \( \Lambda \) ratios,

best fit for \( K^-/K^+ \), \( \Lambda/K^+ \) ratios: \( T_{fo} = 69 \text{ MeV} \)

improves \( \Sigma \) ratio (repulsive potential),

increases \( \Xi \) ratio (not strong enough)
1. in medium potential and freeze-out density

A more attractive $\Xi$ in-medium potential? We would need $U_{\Xi} < -120$ MeV to increase the ratio $\Xi^-/\Lambda/K^+$ up to the lowest end of the empirical error bar.

2. Earlier freeze-out

The enhancement is too small! We need at least factor 5!

3. Direct reactions

To get any substantial increase in the number of $\Xi$'s we have to assume that these baryons are not absorbed after being produced and their number is determined by the rate of direct production reactions, as, for example, for dileptons.

However, this raises a new question: whether there are sufficiently strong sources of $\Xi$ baryons and enough time $t$?
Where do $\Xi$ baryons come from?

strangeness creation reactions:  
$\bar{K}N \rightarrow K\Xi - 380$ MeV \hspace{1cm} $N_{K^-} \ll N_{\Lambda,\Sigma}$
$\pi\Sigma \rightarrow K\Xi - 480$ MeV \hspace{1cm} very exothermic, very inefficient
$\pi\Lambda \rightarrow K\Xi - 560$ MeV

strangeness recombination reactions:  
anti-kaon induced reactions
$\bar{K}\Lambda \rightarrow \Xi\pi + 154$ MeV \hspace{1cm} $\sigma \sim 10$ mb
$\bar{K}\Sigma \rightarrow \Xi\pi + 232$ MeV \hspace{1cm} [Li,Ko NPA712, 110 (2002)]

double-hyperon processes
$\Lambda\Lambda \rightarrow \Xi N - 26$ MeV \hspace{1cm} can be more efficient since $N_{K^-} \ll N_{\Lambda,\Sigma}$
$\Lambda\Sigma \rightarrow \Xi N + 52$ MeV
$\Sigma\Sigma \rightarrow \Xi N + 130$ MeV \hspace{1cm} [Tomasik, E.K., arXiv:1112.1437]

[Polinder, Haidenbauer, Meissner, PLB 653, 29 (2007)]
Influence of $U_K$ potential on $\bar{K} \Lambda \to \Xi \pi$ reaction

Reaction threshold drops below the p-wave $\Xi^*(1532)$ resonance

$\Xi^*$ resonance contribution for different values of $K$-potential (in MeV)

background

[Li,Ko NPA712, 110 (2002)]
**Strangeness at LHC**

Freeze-out state from analysis of transverse momentum

[Melo and Tomasik]

**Used:** *DRAGON is MC code based on Blast Wave model*

+ decays of unstable resonances, 277 hadrons included
+ possible fragmentation of fireball is included (not used here)

Pb+Pb @ 2.76 TeV

*Spectra of multiply strange baryons do not agree with data, particularly at higher pt. This might be due to earlier freeze-out. Separate fit to these spectra yields higher temperature and weaker transverse expansion.*
Strangeness is interesting and complicated!
We need “complete strangeness measurement not only kaons, hyperons but also multi-strange baryons and phi’s!

**Shopping list for NICA**

just $K^+$ mesons – time scale for strangeness production

$K^+$ and $K^-$ mesons – in-medium effects for $K^-$

kaons and $\Lambda$ – strangeness balance

kaons mesons and $\Lambda$ and $\Sigma$ – check for strangeness conservation isospin

kaons mesons and hyperons and $\phi$ – interesting

kaons mesons and hyperons and $\phi$ and $\Xi$ – very interesting strangeness dynamics

kaons mesons and S=1,2 hyperons and $\phi$ and hyperon resonances – exciting