Production of doubly strange particles in statistical model

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work in progress with B.Tomasik and D.N. Voskresensky

HADES: complete measurement of particles containing strange quarks in Ar+KCl collisions @ 1.76 AGeV

Agakishiev (HADES) PRL 103, 132301 (2009);
Eur. Phys.J. A47 21 (2011)

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!

$$R_{K^-/K^+} = \frac{N_{K^-}}{N_{K^+}} = 2.5^{+1.2}_{-0.9} \times 10^{-2}$$

$$R_{\Lambda/K^+} = \frac{N_{\Lambda+\Sigma^0}}{N_{K^+}} = 1.46^{+0.49}_{-0.37}$$

$$R_{\Xi/\Lambda/K^+} = \frac{N_{\Xi^-}}{N_{\Lambda+\Sigma^0}\,N_{K^+}} = 0.20^{+0.16}_{-0.11}$$

$$R^{(\mathrm{Hades})}_{\Sigma/K^+} = \frac{1}{2}\,\frac{N_{\Sigma^+ + \Sigma^-}}{N_{K^+}} = 0.13^{+0.16}_{-0.11} \longleftarrow N^{(\mathrm{Hades})}_{\Sigma^+ + \Sigma^-} = N_{K^+} + 2\,N_{K^0_s} - N_{\Lambda+\Sigma^0} - 2\,N_{\Xi^-} - 3\,N_{K^-}$$

Isospin asymmetry coefficient for ArK and ArCl collisions is $\eta = \frac{A-Z}{Z} \simeq 1.14$

but measured ratio $\frac{2\,N_{K^0_s}}{N_{K^+}} = 0.82$

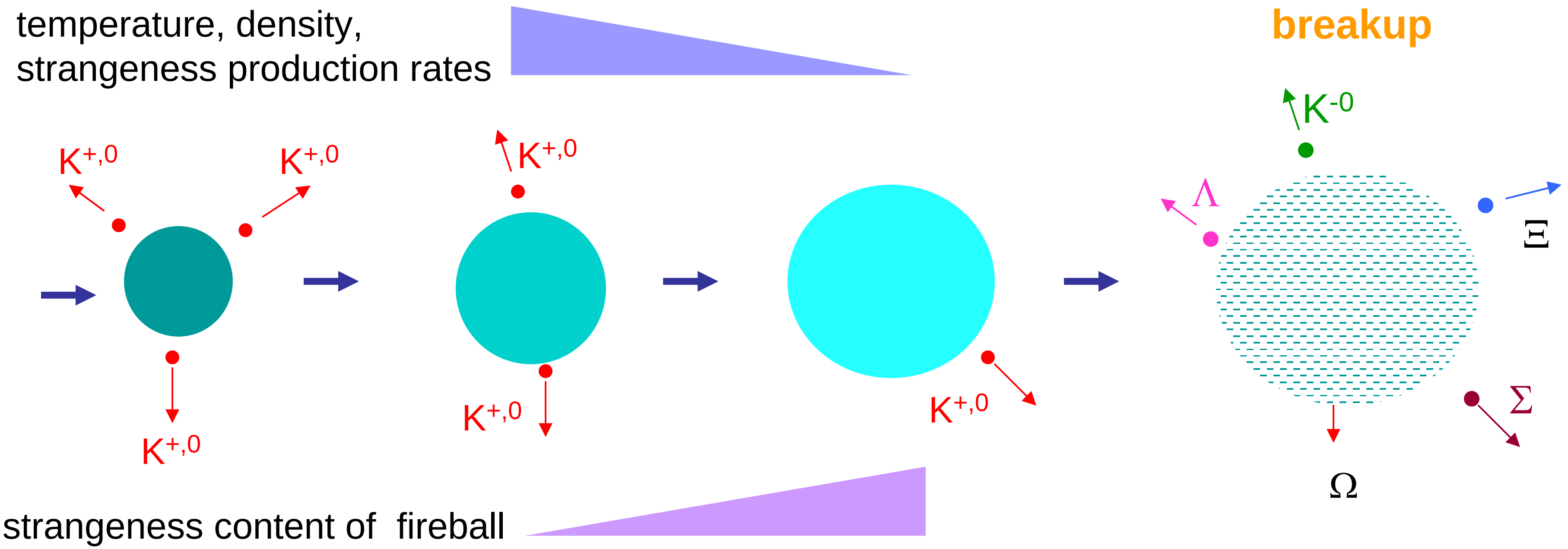
$$N^{(\mathrm{iso})}_{\Sigma^+ + \Sigma^-} = (1+\eta)\,N_{K^+} - N_{\Lambda+\Sigma^0} - (1+\tfrac{1}{\eta})\,N_{K^-} - 2\,(1+\tfrac{1}{\eta})\,N_{\Xi^-}$$

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

Statistical model for strange particles:

At SIS energies K^+ and K^0 have long mean free paths and escape the fireball right after their creation in direct reactions.

The fireball have some negative strangeness which is statistically distributed among K^-, anti-K^0, Λ, Σ, Ξ,Ω



temperature, density,
strangeness production rates

strangeness content of fireball

anti-strangeness released = *strangeness accumulated inside*= **strangeness released at breakup**

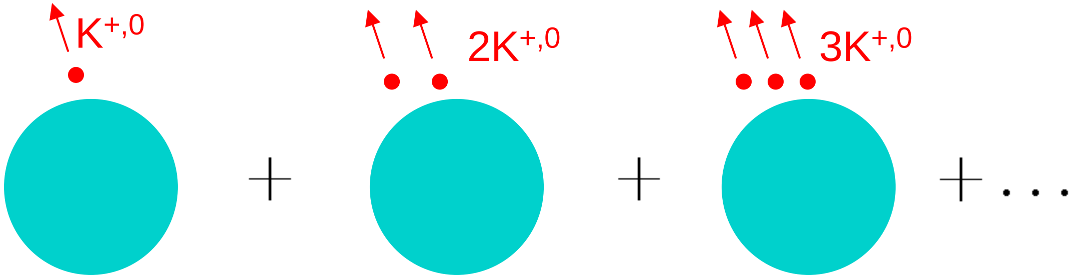
[C.-M. Ko, Phys. Lett. B 120, 294 (1983); Kolomeitsev,Voskresensky,Kämpfer, IJMP E5, 316 (1996)]

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 with K⁺ $\longrightarrow$ $N_{K+} = M_{K+} \cdot N_{tot}$ $\longleftarrow$ *total number of events*

Multi-kaon event classes:



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

$P_{s\bar{s}}^{(n)}$ probaility of creation of n $s\bar{s}$ pairs

at breakup

$\bar{K}$,Λ,Σ
no Ξ,Ω!

$\bar{K}$,Λ,Σ,Ξ
no Ω!

$\bar{K}$,Λ,Σ,Ξ,Ω

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

Λ -- integral probability of the pair production

Let W be the probability of (s bar-s) pair production in a unit of volume and a unit of time, which is a function of local temperature and density.

$$\Lambda = \int_0^{t_{\rm col}} V(t)\mathcal{W}(\rho(t),T(t))\,{\rm d}t$$

$$V(t) = f(t)\,V_{\rm fo}$$

$$t_{\rm col} = \tau V_{\rm fo}^{1/3}$$

$$\Lambda = \tau\,\overline{\mathcal{W}}\,V_{\rm fo}^{4/3} = \lambda\,V_{\rm fo}^{4/3}$$

$V_{\rm fo}$ freeze-out volume

$$P_{s\bar{s}}^{(n)} = \Lambda^n \frac{e^{-\Lambda}}{n!}$$

$$\begin{aligned}
P_{s\bar{s}}^{(1)} &= \lambda V_{\rm fo}^{4/3} - \lambda^2\,V_{\rm fo}^{8/3} + \tfrac{1}{2}\,\lambda^3\,V_{\rm fo}^{4} + O(\lambda^4)\\
P_{s\bar{s}}^{(2)} &= \tfrac{1}{2}\lambda^2\,V_{\rm fo}^{8/3} - \tfrac{1}{2}\lambda^3\,V_{\rm fo}^{4} + O(\lambda^4)\\
P_{s\bar{s}}^{(3)} &= \tfrac{1}{6}\,\lambda^3\,V_{\rm fo}^{4} + O(\lambda^4)
\end{aligned}$$

The value of λ is fixed by the total K^+ multiplicity observed in an inclusive collision.

We denote the multiplicity of K^+ mesons produced in each n-kaon events as: $M_{K^+}^{(n)} = \frac{n}{1+\eta} P_{s\bar{s}}^{(n)}$

$$\mathcal{M}_{K^+} = \sum_n \langle M_{K^+}^{(n)}\rangle = \frac{1}{1+\eta}\sum_n n\,\langle P_{s\bar{s}}^{(n)}\rangle = \frac{\langle\Lambda\rangle}{1+\eta}$$

$\langle\ldots\rangle$ -- averaging over the collision impact parameter impact parameter averaging

$$\langle \ldots \rangle = \frac{2}{b_{\mathrm{max}}^2} \int_0^{b_{\mathrm{max}}} \mathrm{d}b\, b\, (\ldots)$$

$$b_{\mathrm{max}} = 2\, r_0\, A^{1/3}$$

$$r_0 = 1.124 \text{ fm}$$

$$\langle P_{s\bar{s}}^{(1)} \rangle = (1+\eta)\, \mathcal{M}_{K^+} \Big[1 - (1+\eta)\zeta^{(2)} \mathcal{M}_{K^+} + \tfrac{1}{2}\zeta^{(3)} (1+\eta)^2 \mathcal{M}_{K^+}^2 \Big]$$

$$\langle P_{s\bar{s}}^{(2)} \rangle = \tfrac{1}{2}(1+\eta)^2 \mathcal{M}_{K^+}^2 \Big[\zeta^{(2)} - (1+\eta)\zeta^{(3)} \mathcal{M}_{K^+} \Big]$$

$$\langle P_{s\bar{s}}^{(3)} \rangle = (1+\eta)^3 \tfrac{1}{6} \zeta^{(3)} \mathcal{M}_{K^+}^3$$

$$\zeta^{(n)} = \frac{\left\langle V_{\mathrm{fo}}^{\frac{4}{3}\, n} \right\rangle}{\left\langle V_{\mathrm{fo}}^{4/3} \right\rangle^{n}}$$

$$V_{\mathrm{f.o.}}(b) = \frac{2\,A}{\rho_{B,\mathrm{fo}}}\, F(b/b_{\mathrm{max}})$$

overlap function

[Gosset et al, PRC 16, 629 (1977)]

freeze-out density

$$\langle V_{\mathrm{f.o.}} \rangle \approx \frac{A}{2\, \rho_{B,\mathrm{fo}}}$$

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

enhancement factors!!

total strangeness multiplicity

$$M_S^{(n)} = n\,P_{s\bar{s}}^{(n)}$$

Using the experimental kaon multiplicity $\mathcal{M}_{K^+} = (2.8 \pm 0.4) \times 10^{-2}$ we estimate

$$\langle M_S^{(1)} \rangle = 5.2 \times 10^{-2} \quad \langle M_S^{(2)} \rangle = 8.8 \times 10^{-3} \quad \langle M_S^{(3)} \rangle = 8.7 \times 10^{-4}$$

$$\frac{\langle M_S^{(2)} \rangle}{(1+\eta)\mathcal{M}_{K^+}} \simeq 15\%$$

of kaons is produced pairwise

$$\frac{\langle M_S^{(3)} \rangle}{(1+\eta)\mathcal{M}_{K^+}} \simeq 1\%$$

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

$$P_a = z_S{}^{s_a} V_{\rm fo}\, p_a = z_S{}^{s_a} V_{\rm fo}\, \nu_a\, e^{q_a \frac{\mu_B(t)}{T(t)}}\, f(m_a, T_{\rm fo})$$

s_a	# of strange quarks in the hadron
ν_a	spin-isospin degeneracy factor
q_i	baryon charge of the hadron

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

baryon chemical potential $\mu_B(t) \simeq -T(t)\,\ln\left\{4\left[f(m_N,T) + 4\,f(m_\Delta,T)\right]/\rho_B(t)\right\}$

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.

$$P_a^{(n)} = z_S^{(n)s_a}\, V_{\rm fo}\, p_a$$

single-kaon event: $n = 1$ only $\bar{\mathrm{K}}$, Λ and Σ can be in the final state

$$P^{(1)}_{\bar{K}} + P^{(1)}_{\Lambda} + P^{(1)}_{\Sigma} = 1 = z^{(1)}_{S}\, V_{\mathrm{fo}}\left(p_{\bar{K}} + p_{\Lambda} + p_{\Sigma}\right)$$

multiplicity of $\bar{K}$, Λ, Σ

$$M^{(1)}_{a} = g_a\, P^{(1)}_{s\bar{s}}\, P^{(1)}_{a} = g_a\, P^{(1)}_{s\bar{s}}\, z^{(1)}_{S}\, V_{\mathrm{fo}}\, p_a$$

isospin factor

double-kaon event: $n = 2$ $\bar{\mathrm{K}}\bar{\mathrm{K}}$, $\bar{\mathrm{K}}\Lambda$, $\bar{\mathrm{K}}\Sigma$, $\Lambda\Lambda$, $\Lambda\Sigma$, $\Sigma\Sigma$ and Ξ can be in the final state

$$\left(P^{(2)}_{\bar{K}} + P^{(2)}_{\Lambda} + P^{(2)}_{\Sigma}\right)^2 + P^{(2)}_{\Xi} = 1$$

$$z^{(2)2}_{S}\, V^2_{\mathrm{fo}}\left(p_{\bar{K}} + p_{\Lambda} + p_{\Sigma}\right)^2 + z^{(2)2}_{S}\, V_{\mathrm{fo}}\, p_{\Xi} = 1$$

multiplicity of $\bar{K}$, Λ, Σ

$$M^{(2)}_{a} = g_a\, 2\, P^{(2)}_{s\bar{s}}\, P^{(2)}_{a}\left(P^{(2)}_{\bar{K}} + P^{(2)}_{\Lambda} + P^{(2)}_{\Sigma}\right)$$

multiplicity of Ξ

$$M^{(2)}_{\Xi} = g_{\Xi}\, P^{(2)}_{s\bar{s}}\, P^{(2)}_{\Xi}$$

triple-kaon event: $n = 3$

$\overline{K}\overline{K}\overline{K}$, $\overline{K}\overline{K}\Lambda$, $\overline{K}\overline{K}\Sigma$,
$\overline{K}\Lambda\Lambda$, $\overline{K}\Lambda\Sigma$, $\overline{K}\Sigma\Sigma$,
$\Lambda\Lambda\Sigma$, $\Sigma\Sigma\Lambda$, $\Lambda\Lambda\Lambda$, $\Sigma\Sigma\Sigma$,
$\Xi\overline{K}$, $\Xi\Lambda$, $\Xi\Sigma$
and Ω

can be in the final state

$$\left(P^{(3)}_{\bar{K}} + P^{(3)}_{\Lambda} + P^{(3)}_{\Sigma}\right)^3 + 3\,P^{(3)}_{\Xi}\left(P^{(3)}_{\bar{K}} + P^{(3)}_{\Lambda} + P^{(3)}_{\Sigma}\right) + P^{(3)}_{\Omega} = 1$$

multiplicity of $\bar{K}$, Λ, Σ

$$M^{(3)}_{a} = g_a\, 3\, P^{(3)}_{s\bar{s}}\, P^{(3)}_{a}\left[\left(P^{(3)}_{\bar{K}} + P^{(3)}_{\Lambda} + P^{(3)}_{\Sigma}\right)^2 + P^{(3)}_{\Xi}\right]$$

multiplicity of Ξ

$$M^{(3)}_{\Xi} = g_{\Xi}\, 3\, P^{(3)}_{s\bar{s}}\, P^{(3)}_{\Xi}\left(P^{(3)}_{\bar{K}} + P^{(3)}_{\Lambda} + P^{(3)}_{\Sigma}\right)$$

multiplicity of Ω

$$M^{(3)}_{\Omega} = P^{(3)}_{s\bar{s}}\, P^{(3)}_{\Omega}$$

particle ratios:

We included leading and next-to-leading contributions

$$R_{K^-/K^+} = \eta\frac{\langle M_{\bar K}^{(1)} + M_{\bar K}^{(2)}\rangle}{(1+\eta)\,\mathcal{M}_{K^+}} = \frac{\eta\, p_{\bar K}}{p_{\bar K}+p_\Lambda+p_\Sigma}\,Y_1$$

$$R_{\Lambda/K^+} = \frac{1}{\mathcal{M}_{K^+}}\left\langle M_\Lambda^{(1)} + M_\Lambda^{(2)} + \eta\frac{M_\Sigma^{(1)}+M_\Sigma^{(2)}}{\eta^2+\eta+1}\right\rangle = (1+\eta)\frac{\left[p_\Lambda + \frac{\eta\, p_\Sigma}{\eta^2+\eta+1}\right]}{p_{\bar K}+p_\Lambda+p_\Sigma}\,Y_1$$

$$R_{\Sigma/K^+} = \frac{\eta^2+1}{2(\eta^2+\eta+1)}\,\frac{\langle M_\Sigma^{(1)}+M_\Sigma^{(2)}\rangle}{\mathcal{M}_{K^+}} = \frac{(\eta^2+1)(\eta+1)}{2(\eta^2+\eta+1)}\,\frac{p_\Sigma}{p_{\bar K}+p_\Lambda+p_\Sigma}\,Y_1$$

$$R_{\Xi/\Lambda/K^+} = \frac{\frac{\eta}{1+\eta}\langle(M_\Xi^{(2)}+M_\Xi^{(3)})\rangle}{\langle M_\Lambda^{(1)}+M_\Lambda^{(2)}+\eta\frac{M_\Sigma^{(1)}+M_\Sigma^{(2)}}{\eta^2+\eta+1}\rangle\mathcal{M}_{K^+}} = \eta\frac{p_\Xi/(p_{\bar K}+p_\Lambda+p_\Sigma)}{\langle V_{\rm fo}\rangle\left(p_\Lambda+\frac{\eta p_\Sigma}{\eta^2+\eta+1}\right)}\,Y_2$$

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

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

small correction <5%

$$Y_2 = \frac{1}{2}\tilde{\zeta}^{(2)} = \frac{1}{2}\,\frac{\langle V_{\rm fo}^{5/3}\rangle}{\langle V_{\rm fo}^{4/3}\rangle^2}\langle V_{\rm fo}\rangle \simeq 0.52$$

strong suppression!

Ξ/Λ/K ratio is sensitive to the fireball freeze-out volume

Parameters of the model

density

Analysis of pion, proton, K- yields in HICs
at SIS and Bevalac energies gives

$$\rho_{B,\mathrm{fo}} = (0.5\text{–}0.7)\,\rho_0$$

We use $\rho_{B,\mathrm{fo}} = 0.6\,\rho_0$

Voskresensky, Sov.J.Nucl.Phys. 50, 983 (1989); NPA555,293 (1993)
Kolomeitsev,Voskresensky,Kämpfer, IJMP E5, 316 (1996)
Kolomeitsev,Voskresensky nucl-th/0001062

in-medium potentials

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

$$f(m, T) \to f(m^*, T)\exp(-V/T)$$

scalar and vector potentials

nucleons:
deltas:

$$S_N \simeq S_\Delta \simeq -190\ \mathrm{MeV}\,\rho_B/\rho_0 \qquad V_N \simeq V_\Delta \simeq +130\ \mathrm{MeV}\,\rho_B/\rho_0$$

[Kolomeitsev,Voskresensky, NPA 759,373 (2005)]

hyperons: optical potentials $U_i = [S_i + V_i(\rho_0)]\,\rho_B/\rho_0$

$U_\Lambda = -27\ \mathrm{MeV}$ [Hashimoto, Tamura, Prog.Part.Nucl.Phys. 57, 564 (2006)]

$U_\Sigma = +24\ \mathrm{MeV}$ [Dabrowski, Phys.Rev.C 60, 025205 (1999)]

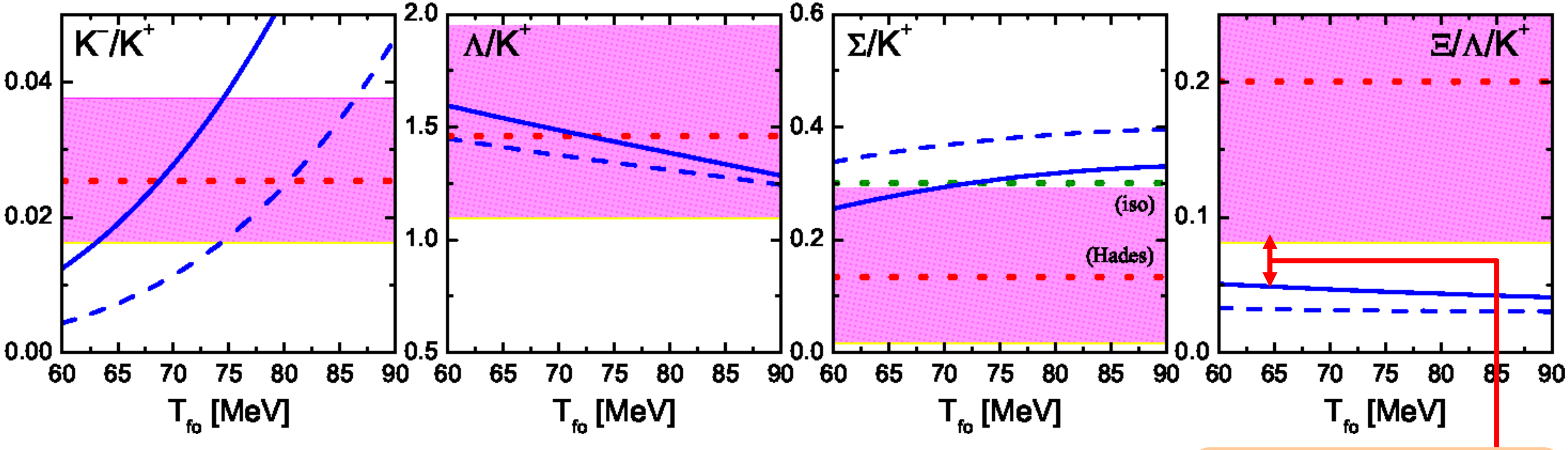
$U_\Xi = -14\ \mathrm{MeV}$ [Khaustov et al., Phys.Rev.C 61, 054603 (2000)]

kaons: $U_{\bar{K}} = -75\ \mathrm{MeV}$ used in [Schade,Wolf,Kämpfer, PRC81, 034902 (2010)]

temperature

best fit for K^{-},Λ ratios: T=69 MeV

Ratios as functions of the freeze-out temperature



— results with in-medium potentials

- - results with vacuum masses

double strangeness suppression Y_2

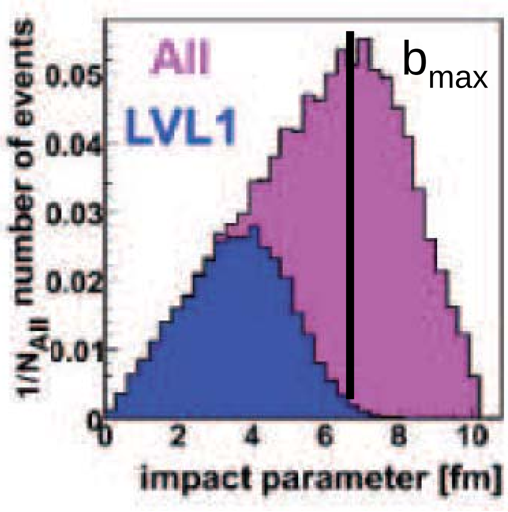
Inclusion of potentials
improves the temperature match
for K and Λ ratios,
improves Σ ratio (repulsive potential),
increases Ξ ratio (not strong enough)

ratio	exp. value	inclusive
$(K^-/K^+) \times 10^2$	$2.54^{+1.21}_{-0.91}$	2.55
Λ/K^+	$1.46^{+0.49}_{-0.37}$	1.50
Σ/K^+(Hades)	$0.13^{+0.16}_{-0.12}$	0.290
Σ/K^+(iso)	$0.30^{+0.23}_{-0.17}$	
$\Xi/\Lambda/K^+$	$0.20^{+0.16}_{-0.11}$	0.047
$(\Omega/\Lambda K^-/K^+) \times 10^2$	—	0.85
$(\Omega/\Xi/K^+) \times 10^2$	—	0.42

HADES trigger effect

LVL1 trigger

HADES counts only the events with MUL>16



trigger function

[Schade, PhD thesis2010]

$$T_{\mathrm{LVL1}}(b) = \begin{cases} b\,, & b < 3.9\ \mathrm{fm} \\ 3.6\, e^{-0.27\left(\frac{b}{1\mathrm{fm}} - 3.75\right)^2}\,, & b \geq 3.9\ \mathrm{fm} \end{cases}$$

$$\langle V_{\mathrm{f.o.}}\rangle_{\mathrm{LVL1}} = \frac{2\,\pi \int_0^{b_{\mathrm{max}}} \mathrm{d}b\, T_{\mathrm{LVL1}}(b)\, V_{\mathrm{f.o.}}(b)}{2\,\pi \int_0^{b_{\mathrm{max}}} \mathrm{d}b\, T_{\mathrm{LVL1}}(b)} = 1.77\,\langle V_{\mathrm{f.o.}}\rangle$$

ratio	exp. value	inclusive	triggered
$(K^-/K^+) \times 10^2$	$2.54^{+1.21}_{-0.91}$	2.55	2.55
Λ/K^+	$1.46^{+0.49}_{-0.37}$	1.50	1.50
Σ/K^+(Hades)	$0.13^{+0.16}_{-0.12}$	0.290	0.290
Σ/K^+(iso)	$0.30^{+0.23}_{-0.17}$		
$\Xi/\Lambda/K^+$	$0.20^{+0.16}_{-0.11}$	0.047	0.026
$(\Omega/\Lambda K^-/K^+) \times 10^2$	—	0.85	0.26
$(\Omega/\Xi/K^+) \times 10^2$	—	0.42	0.23

$$R_{\Xi/\Lambda/K^+} \propto \frac{1}{\langle V_{\mathrm{fo}}\rangle}$$

$$R_{\Omega/(\Lambda K^-)/K^+} \propto \frac{1}{\langle V_{\mathrm{fo}}\rangle^2}$$

$$R_{\Omega/\Xi/K^+} \propto \frac{1}{\langle V_{\mathrm{fo}}\rangle}$$

Conclusion 1:

HADES data show the problems with the strangeness balance:
too few Σ baryons and too many Ξ are observed.

Isospin corrections could help to understand Σ yield.

With an inclusion of in-medium potentials yield we can describe K^-/K^+, Λ/K^+, and Σ/K^+ ratios;

$\Xi/\Lambda/K^+$ ratio cannot be described. Suppression of the ration calculated in statistical model due to explicit strangeness conservation in each collision and HADES event trigger!

What can we do?

1. in medium potential and freeze-out density

A more attractive Ξ 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.

Such a strong attraction exceeding the nucleon optical potential is unrealistic. It would imply that Ξ baryon is bound in nucleus stronglier than two Λs,

$$2(m_{\Lambda}+U_{L}) - (m_{X}+m_{N}+U_{X}+U_{N}) \sim 100\ \mathrm{MeV} > 0.$$

This would influence the description of doubly strange hypernuclei

The leading order analyzis of hyperon and nucleon mass shifts in nuclear matter using the chiral perturbation theory [Savage, Wise, PRD 53, 349 (1996)] shows that the Ξ shift is much smaller than nucleon and Λ shifts.
Recent analyses [Polinder, Haidenbauer, Meissner, PLB 653, 29 (2007),
Gasparyan, Haidenbauer, Hanhart, arXiv:1111.0513]
support the relative smallness of ΞN scattering lengths.

We can take somewhat larger freeze-out density: $\rho_{B,\mathrm{fo}} = 0.7\,\rho_0$

$$R_{\Xi/\Lambda/K^+} = 0.026 \longrightarrow 0.028$$

2. K⁺ multiplicity

We vary the K^+ multiplicity within the experimental error bars and take the maximal possible value

$$\mathcal{M}_{K^+} = 3.2 \times 10^{-2} \qquad R^{(\mathrm{exp})}_{\Xi/\Lambda/K^+} = 0.175^{+0.16}_{-0.11}$$

($0.20^{+0.16}_{-0.11}$ before)

much larger than the result of the stat model: 0.027 ± 1

Could it be that the number of produced K⁺ mesons is underestimated by HADES?

KaoS measured K⁺ @1.8 AGeV

C+C [PRL82, 1640 (1999)] $\sigma_{\mathrm{C+C}}/12^2 = (2.1 \pm 0.2) \times 10^{-2}\ \mathrm{mb}$

Ni+Ni [PRL78, 4007 (1997)] $\sigma_{\mathrm{Ni+Ni}}/58^2 = (1.7 \pm 0.45) \times 10^{-2}\ \mathrm{mb}$

Taking the median of 0.02 mb we obtain that for the Ar+KCl $\sigma_{K^+} = 31\ \mathrm{mb}$

$$\mathcal{M}_{K^+} = \frac{\sigma_{K^+}}{\sigma_{\mathrm{geom}}\,\varkappa_{\mathrm{LVL1}}}$$

← decrease of the geometrical cross section because of triggering off peripheral collisions

$$\mathcal{M}_{K^+} = 3.8 \times 10^{-2}$$

larger than Hades value!

$$\varkappa_{\mathrm{LVL1}} = \int_0^{b_{\max}} \mathrm{d}b\, T_{\mathrm{LVL1}}(b) \Big/ \int_0^{b_{\max}} \mathrm{d}b\, b \simeq 0.449$$

$$\longrightarrow \quad R^{(\mathrm{exp})}_{\Xi/\Lambda/K^+} = 0.14^{+0.10}_{-0.09}$$

3. Non-equilibrium effects

The main assumption of our model is that the strange subsystem is in thermal equilibrium with a non-strange subsystem and that strange particles are in chemical equilibrium with each other.

For L and Σ

$$\Lambda N \leftrightarrow \Lambda N \qquad \Sigma N \leftrightarrow \Sigma N \qquad \Lambda N \leftrightarrow \Sigma N$$

$$\sigma \sim 80 - 25 \text{ mb}$$

for relative moments p_T to $2p_T$

p_T~300 MeV is the thermal momentum for T=70 MeV

For $\bar{K}$

$$K^- N \leftrightarrow \pi\Lambda(\Sigma) \qquad \pi\Lambda(\Sigma) \leftrightarrow \pi\Lambda(\Sigma)$$

resonance reactions

For Ξ

ΞN interaction is expected to be smaller than ΛN and ΣN interactions

$$\sigma(\Xi^- p \to \Xi^- p) \sim 15 \text{ mb} \qquad \sigma(\Xi^- p \to \Lambda\Lambda) \lesssim 10 \text{ mb} \qquad \sigma(\Xi^0 p \to \Xi^0 p) \lesssim 15 \text{ mb}$$

[Polinder, Haidenbauer, Meissner, PLB 653, 29 (2007)]

Scattering of Ξs on pions for nearly isospin symmetrical matter is considerably weaker than the πN scattering (vey narrow Ξ*(1532) resonance, not broad Δ(1232))

Ξ baryons are presumably weaklier coupled to the non-strange system

Earlier freezeout!

$$R_{\Xi/\Lambda/K^+} \sim \frac{p_\Xi[\widetilde{T}_{\rm fo}]}{(p_\Lambda + \frac{1}{3}p_\Sigma)\,(p_{\bar{K}} + p_\Lambda + p_\Sigma)[T_{\rm fo}]}\, Y_2 \qquad \widetilde{T}_{\rm fo} > T_{\rm fo}$$

increase of the ratio

Where do Ξ baryons come from?

strangeness creation reactions: $\bar{K}N \rightarrow K\Xi - 380\ \mathrm{MeV}$

$\pi\Sigma \rightarrow K\Xi - 480\ \mathrm{MeV}$

$\pi\Lambda \rightarrow K\Xi - 560\ \mathrm{MeV}$

$N_{K^-} \ll N_{\Lambda,\Sigma}$

very exothermic,
very inefficient

ss quarks are strongly bound in Ξ!

strangeness recombination reactions:

anti-kaon induced reactions

$\overline{K}\Lambda \rightarrow \Xi\pi + 154\ \mathrm{MeV}$ $\sigma \sim 10\ \mathrm{mb}$

$\overline{K}\Sigma \rightarrow \Xi\pi + 232\ \mathrm{MeV}$ [Li,Ko NPA712, 110 (2002)]

double-hyperon processes

$\Lambda\,\Lambda \rightarrow \Xi N - 26\ \mathrm{MeV}$

$\Lambda\,\Sigma \rightarrow \Xi N + 52\ \mathrm{MeV}$

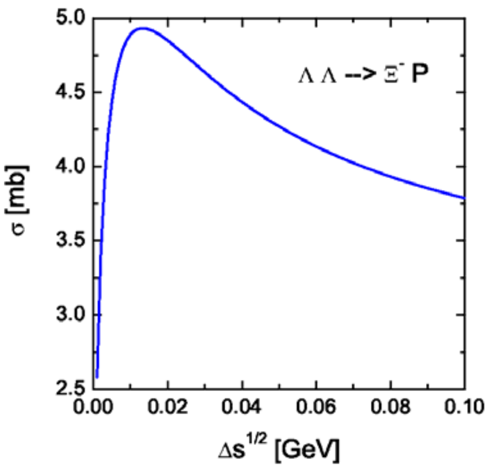
$\Sigma\,\Sigma \rightarrow \Xi N + 130\ \mathrm{MeV}$

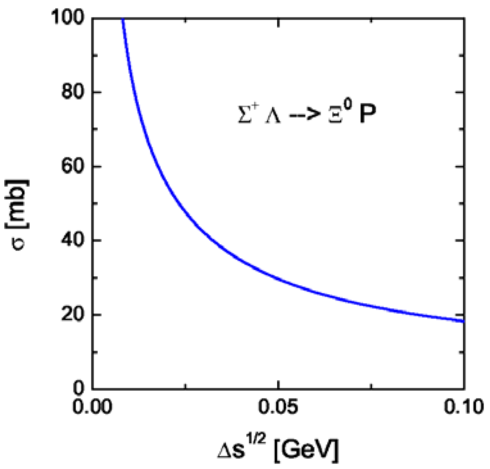
can be more efficient since

$N_{K^-} \ll N_{\Lambda,\Sigma}$

[Tomasik, E.K., arXiv:**1112.1437**]

[Polinder, Haidenbauer, Meissner, PLB 653, 29 (2007)]



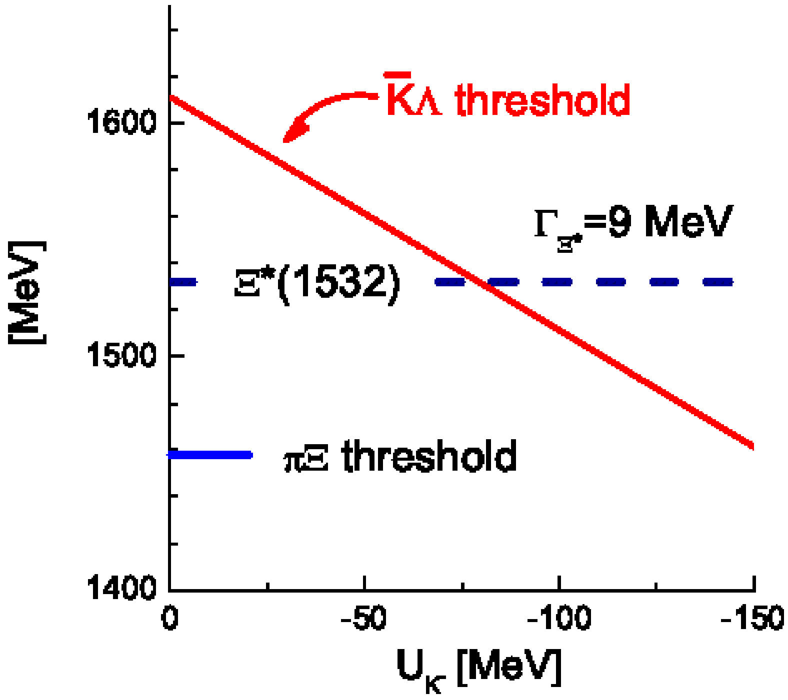


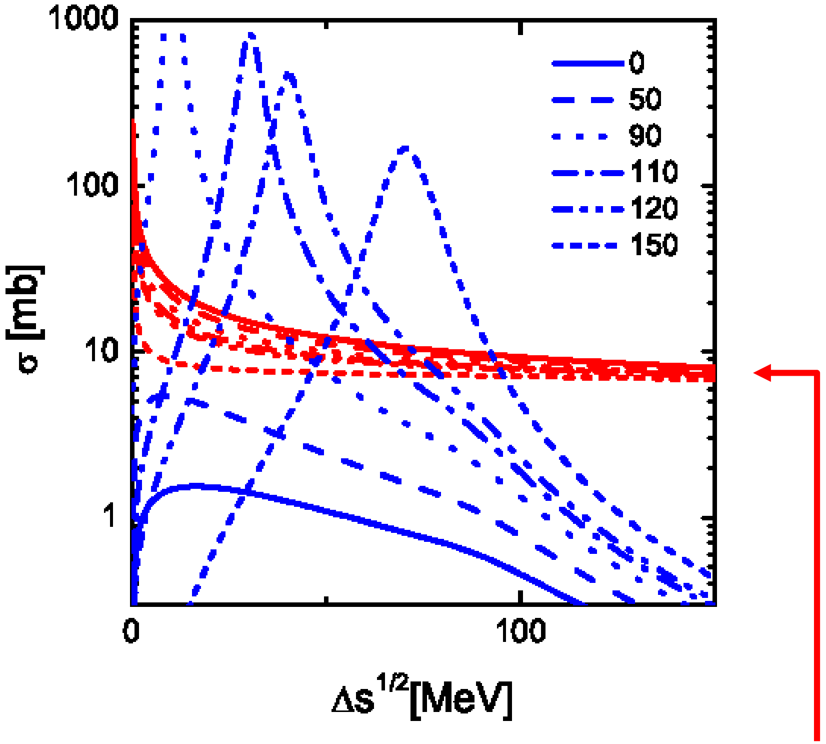
[Li,Chen,Ko,Lee 1204.1327] calculated the same cross sections in Born approximation [much larger σ] and implemented in transport code.

→ increased Ξ production

Influence of $U_{\overline{K}}$ potential on $\overline{K}\Lambda \to \Xi\pi$ reaction

Reaction threshold drops below the p-wave Ξ*(1532) resonance





—— Ξ* resonance contribution
for differnt values of
K- potential (in MeV)

background
[Li,Ko NPA712, 110 (2002)]

[Tomasik, E.K., SQM2011 proceedings, arXiv:1112.1437]

Conclusion 2:

The main source of Ξ is strangeness recombination reactions.

Double-hyperon processes can be very important.

Anti-kaon induced reactions can be strongly enhanced if
the attractive kaon potential is included