Production of Ξ hyperons in nuclear collisions at subthreshold energies

Boris Tomášik
Univerzita Mateja Bela, Banská Bystrica, Slovakia
FNSPE, Czech Technical University, Prague, Czech Republic

Evgeni E. Kolomeitsev
Univerzita Mateja Bela, Banská Bystrica, Slovakia

Dmitri N. Voskresensky
Moscow Physics Engineering Institute, Moscow, Russia

Zimányi School, 3.12.2012

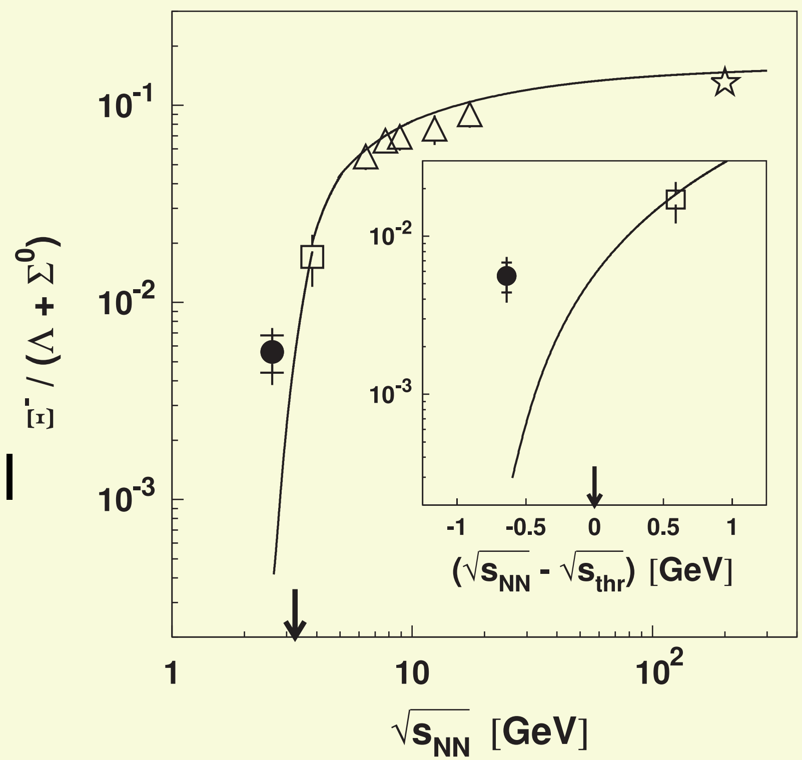
The data: Ξ production enhancemet

Ξ hyperon production at SIS energies

- HADES experiment: Ar+KCl collisions at bombarding energy 1.76*A*GeV

- data SIS:
  $\Xi^-/(\Lambda+\Sigma^0) = (5.6\pm1.2^{+1.8}_{-1.7})\times10^{-3}$
  [G. Agakishev et al. (HADES), PRL 103 (2009) 132301]

- show enhanced production as compared with statistical model (THERMUS: 2×10^{-4})
  [S. Wheaton, J. Cleymanns, M. Hauer, Comp. Phys. Commun. 180 (2009) 84]



Considerations about the system

- baryon dominated system
- strangeness produced in $\pi N \to K \Lambda(\Sigma)$
  - all strange antiquarks go into kaons
  - kaons do not interact with other particles
    - ➡ the interacting system contains net strangeness
    - ➡ net strangeness corresponds to the number of produced kaons

Strangeness as rare species

- number of kaons is very low!
  $\langle K^+ \rangle = (2.8 \pm 0.4) \times 10^{-2}$

  ➡ no kaons in most events

  ➡ one kaon in about every 50 events

  ➡ very rarely two or more kaons in one event

    ➡ cascades are produced only here, however

Take this into account when calculating the number of cascades statistically.

Minimal statistical model

- respect fixed strangeness in each event
  - formulate separately for net strangeness 0,1,2,... ⇒ n–kaon classes
- distribution of net strangeness Poissonian
- distribute strange quarks according to statistical equilibrium prescription
- non–strange species distributed according to statistical equillibrium

Multiplicity of strange species

For fixed impact parameter (fixed volume):

multiplicity of species *a* with S=−1:

$$M_a = 1 P_{s\bar{s}}^{(1)} \mathcal{P}_a^{(1)} + 2 P_{s\bar{s}}^{(2)} \mathcal{P}_a^{(2)} + 3 P_{s\bar{s}}^{(3)} \mathcal{P}_a^{(3)} + \dots$$

probability to have given number of ssbar

inclusive probability of releasing species a

multiplicity of Ξ

$$M_\Xi = P_{s\bar{s}}^{(2)} \mathcal{P}_\Xi^{(2)} + 3 P_{s\bar{s}}^{(3)} \mathcal{P}_\Xi^{(3)} + \dots$$

- note the missing term for single-kaon class
- note the missing factor of 2 in the first term

Event–averaging

- for all events (or triggered events) we must average over impact parameter

$$P_{s\bar{s}}^{(i)} \to \langle P_{s\bar{s}}^{(i)} \rangle$$

- the probability to have some number of s quarks depends on volume

- kaon multiplicity is observed – gives the normalisation

Statistical distribution of s quarks

- Probability to release s quark in species a

$$P_a^{(n)} = \left(z_s^{(n)}\right)^{S_a} V\, \nu_a\, e^{B_a \mu_B / T} \frac{m_a^2 T}{2\pi^2} K_2\left(\frac{m_a}{T}\right) = \left(z_s^{(n)}\right)^{S_a} V p_a$$

normalisation | volume | degeneracy | chemical potential | integrated Boltzmann distribution

- normalisation depends on the number of strange quarks in the system

- normalisation depends on volume (non-trivial averaging over impact parameter)

Probability of n–kaon production

for fixed impact parameter:
the average number of ssbar pairs

$$W = \int_0^{t_0} V(t)\, \mathcal{W}[\rho_B(t), T(t)]\, dt = \bar{\mathcal{W}}\, \tau\, V^{4/3} \equiv \lambda\, V^{4/3}$$

multiplicities distributed Poissonian

$$\tilde{P}^{(n)}_{s\bar{s}} = W^n \frac{e^{-W}}{n!}$$

expand for different n

$$\tilde{P}^{(1)}_{s\bar{s}} = \lambda V^{4/3} - \lambda^2 V^{8/3} + \tfrac{1}{2}\lambda^3 V^4 + O(\lambda^4)\,,$$

$$\tilde{P}^{(2)}_{s\bar{s}} = \tfrac{1}{2}\lambda^2 V^{8/3} - \tfrac{1}{2}\lambda^3 V^4 + O(\lambda^4),$$

$$\tilde{P}^{(3)}_{s\bar{s}} = \tfrac{1}{6}\lambda^3 V^4 + O(\lambda^4)$$

get λ from kaon multiplicity

Normalisation from kaon multiplicity

$$\mathcal{M}_{K^+} = \frac{\langle W \rangle}{1+\eta} \qquad \eta = \frac{A-Z}{Z} = 1.14$$

average over volume (impact parameter)

$$\lambda = \frac{(1+\eta)\mathcal{M}_{K^+}}{\langle V^{4/3} \rangle}$$

we have parametrisation for V and we can do averages

Summary of the model

- total strangeness normalisation from kaon multiplicity
- assumption of isospin asymmetry
- Poissonian distribution of number of s quarks
- statistical distribution of s quarks into hadrons

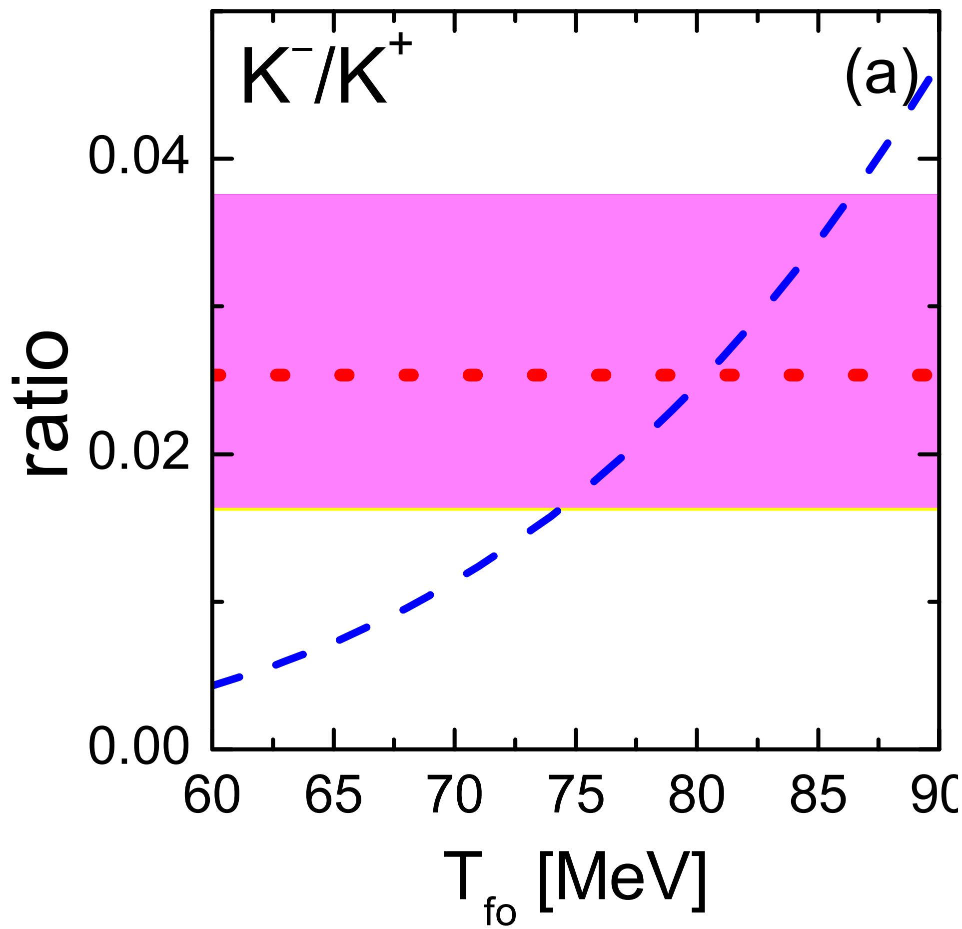
Implications:

- more K^0 estimated than in isospin symmetry
- Ξ only produced in at least 2-kaon events

Results: K⁻

$$R_{K^-/K^+} = \frac{\eta p_{\bar{K}}}{p_{\bar{K}} + p_\Lambda + p_\Sigma} \left(1 - \frac{(1-\eta)\,\mathcal{M}_{K^+}\, p_\Xi\, \zeta^{(2)}}{\langle V \rangle (p_{\bar{K}} + p_\Lambda + p_\Sigma)^2} \right)$$

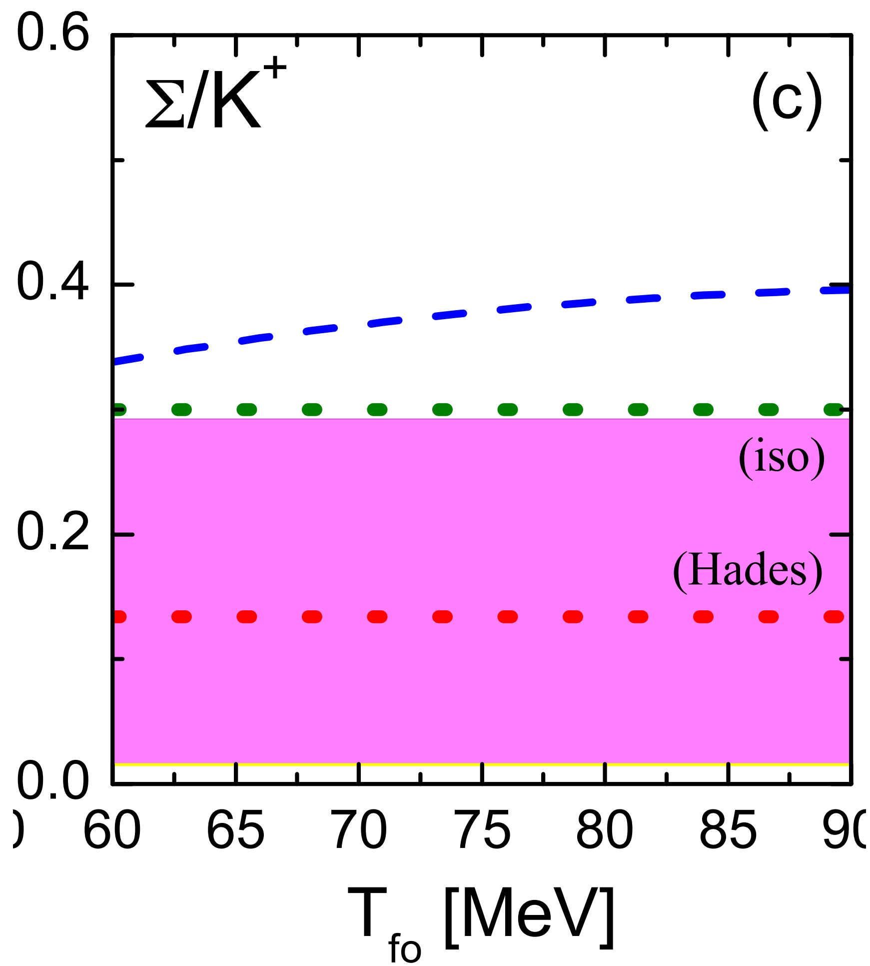
$$\zeta^{(2)} = \frac{\langle V^{5/3}\rangle \langle V \rangle}{\langle V^{4/3}\rangle^2}$$



Results: Σ

$$R_{\Sigma/K^+} = \frac{(\eta^2+1)(\eta+1)}{2(\eta^2+\eta+1)} \frac{\eta p_\Sigma}{p_{\bar{K}} + p_\Lambda + p_\Sigma} \left(1 - \frac{(1-\eta)\,\mathcal{M}_{K^+}\,p_\Xi\,\zeta^{(2)}}{\langle V\rangle (p_{\bar{K}} + p_\Lambda + p_\Sigma)^2}\right)$$

$$\zeta^{(2)} = \frac{\langle V^{5/3}\rangle\langle V\rangle}{\langle V^{4/3}\rangle^2}$$

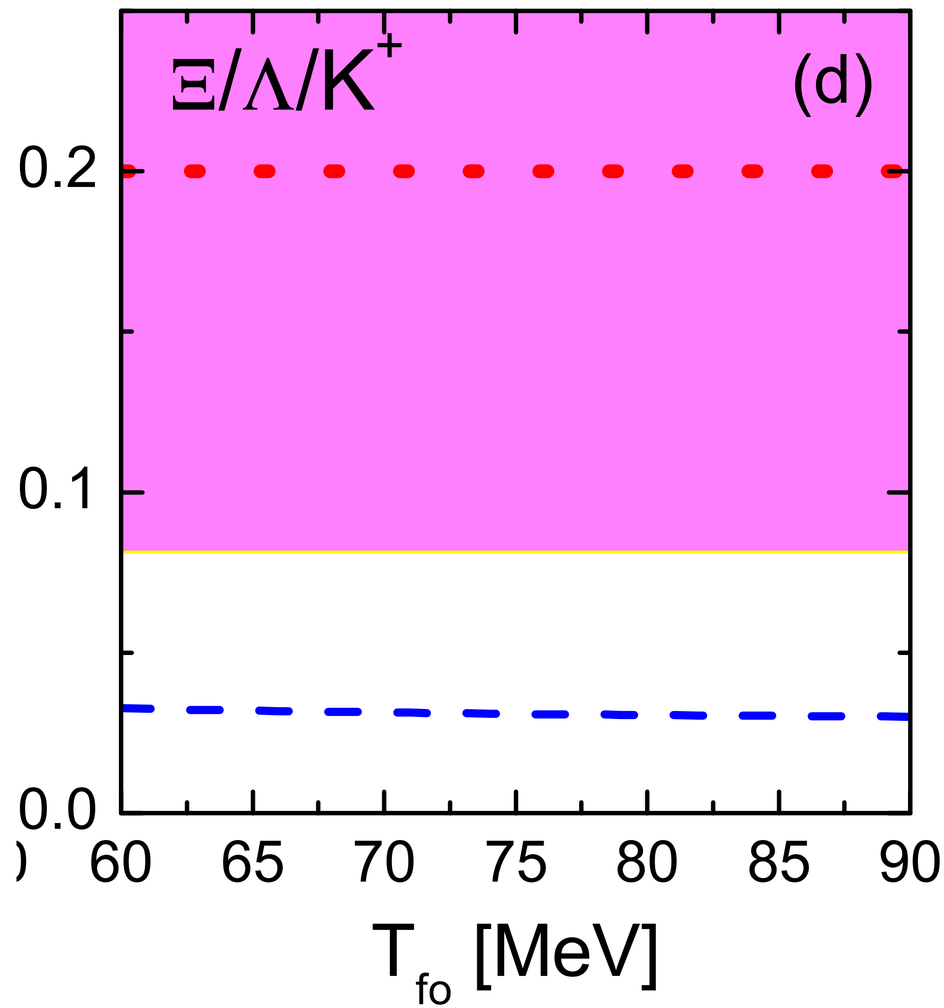


Results: Ξ

$$R_{\Xi/\Sigma/K^+} = \eta \frac{\frac{p_\Xi}{p_{\bar{K}}+p_\Lambda+p_\Sigma}}{\langle V\rangle (p_\Lambda + \frac{\eta p_\Sigma}{\eta^2+\eta+1})} \frac{1}{2} \zeta^{(2)}$$

$$\zeta^{(2)} = \frac{\langle V^{5/3}\rangle \langle V\rangle}{\langle V^{4/3}\rangle^2}$$

factor 1/2, because Ξ comes from 2-kaon events!
Difference to "normal" statistical model



In-medium potentials

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

scalar and vector potentials

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

nucleons: $S_N \simeq -190\ \mathrm{MeV}\rho_B/\rho_0$ $V_N \simeq +130\ \mathrm{MeV}\rho_B/\rho_0$

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

deltas: $S_\Delta = S_N$ $V_\Delta = V_N$

hyperons: constraint $S(\rho_0) + V(\rho_0) = U$ potential in atomic nucleus

quark counting for vector p. $V_\Lambda = V_\Sigma = 2\,V_\Xi = \frac{2}{3}V_N$

$$S_i = [U_i - V_i(\rho_0)]\,\rho_B/\rho_0$$

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

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

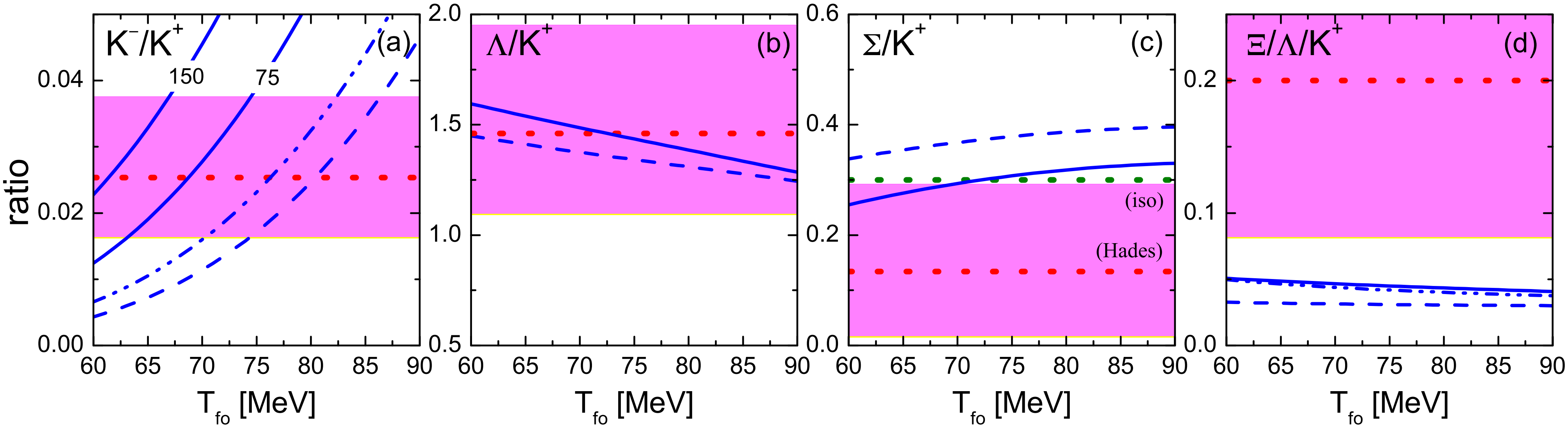
$U_\Xi = -14\ \mathrm{MeV}$ [Khaustov et al., Phys.Rev.C 61, 054603 (2000)]

kaons: $V_{\bar{K}} = 0$ $S_{\bar{K}} = U_{\bar{K}}\rho/\rho_0$

$U_{\bar{K}} = -(70\text{–}150)\ \mathrm{MeV}$ optical potential from kaonic atoms

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

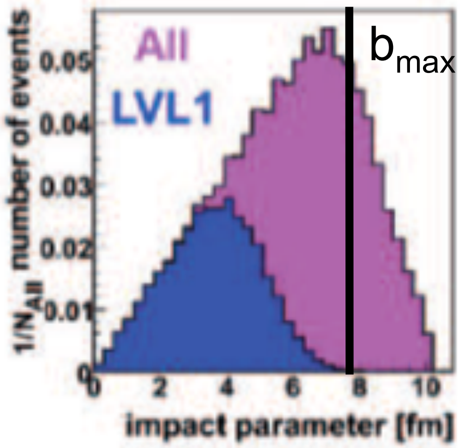
Results with in-medium potentials



Trigger effect

LVL1 trigger

HADES counts only the events with MUL>16



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

trigger function

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

ratio	exp. values	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	another factor of 2 decrease!!!
$(\Omega/\Lambda/K^-/K^+) \times 10^2$	—	0.85	0.26	
$(\Omega/\Xi/K^+) \times 10^2$	—	0.42	0.23	

Conclusions

- Statistical model underestimates Ξ production even more than thought previously
- There must be some non-equilibrium process of Ξ production - once they are produced, they leave the system

Ξ production, distribution of strangeness

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 has some negative strangeness which is statistically distributed among K^-, anti-K^0, Λ, Σ, Ξ (Ω can be neglected).

The following ratios do not depend on strangeness suppression factors (the γ_s) and the fugacity

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

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

$$R_{\Sigma/K^+} = \frac{1}{2}\frac{N_{\Sigma^-+\Sigma^+}}{N_{K^+}} = 0.13^{+0.16}_{-0.11}$$

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

Strangeness concentration

can be extracted from K^+ multiplicity and the freeze-out volume

$$n_{S,\mathrm{fo}} = n_S(t_{\mathrm{fo}}) \approx \frac{2\langle N_{K^+}\rangle}{\langle V_{\mathrm{fo}}\rangle}$$

(mean) freeze-out volume: $$\langle V_{\mathrm{fo}}\rangle = \frac{2\pi \int_0^{b_{\mathrm{max}}} \mathrm{d}b\, b\, V_{\mathrm{fo}}(b)}{2\pi \int_0^{b_{\mathrm{max}}} \mathrm{d}b\, b}$$

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

$$r_0 = 1.124\,\mathrm{fm}$$

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

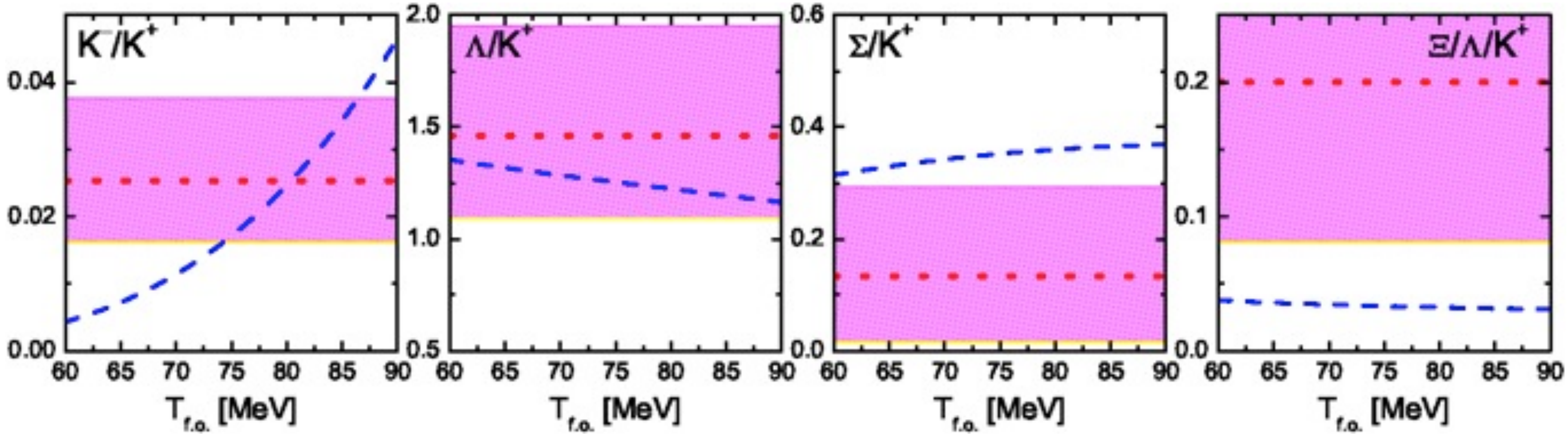
← overlap function

↑ freeze-out density

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

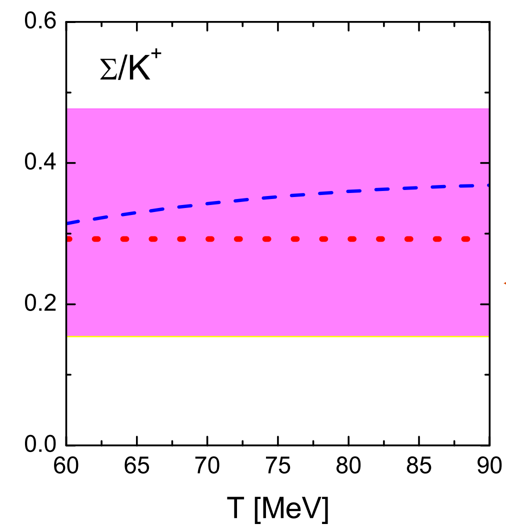
$$\langle V_{\mathrm{fo}}\rangle \approx \frac{A}{2\,\rho_{B,\mathrm{fo}}}$$

Ratios as functions of FO temperature



too high!? too low!?

Maybe we estimate the number of Σ incorrectly?



Isospin asymmetry coefficient for ArK and ArCl collisions is

$$\eta = \frac{A-Z}{Z} \simeq 1.11$$

but $\frac{2N_{K_S^0}}{N_{K^+}} = 0.82$

$$N^{\rm iso}_{(\Sigma^+ + \Sigma^-)} = (1+\eta)N_{K^+} - N_{\Lambda+\Sigma_0} - 2N_{\Xi^-} - (1+1/\eta)N_{K^-}$$

Backup: where do Ξ baryons come from?

strangeness creation reactions:

$\bar{K}N \to K\Xi - 380$ MeV

$\pi\Sigma \to K\Xi - 480$ MeV

$\pi\Lambda \to K\Xi - 560$ MeV

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

very endothermic, very inefficient

strangeness recombination reactions:

ss quarks are strongly bound in Ξ!

anti-kaon induced reactions

$\overline{K}\Lambda \to \Xi\pi + 154$ MeV

$\overline{K}\Sigma \to \Xi\pi + 232$ MeV

$\sigma \sim 10$ mb

[Li,Ko NPA712, 110 (2002)]

double-hyperon processes

$\Lambda\Lambda \to \Xi N - 26$ MeV

$\Lambda\Sigma \to \Xi N + 52$ MeV

$\Sigma\Sigma \to \Xi N + 130$ MeV

can be more efficient since

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

$|A|^2 \simeq 5$ mb