Strangeness production in nuclear collisions around the threshold

Boris Tomášik[a,b], Evgeni Kolomeitsev[a], Dmitri Voskresensky[c]

[a]Univerzita Mateja Bela, Banská Bystrica, Slovakia

[b]Fakulta jaderná a fyzikálně inženýrská, České vysoké učení technické, Praha, Czech Republic

[c]National Research Nuclear University, MEPhI, Moscow, Russia

Support:
APVV 0050-11, VEGA 1/0457/12

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

one experimental set-up for all particles!

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

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!

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

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

if K⁺+K⁰ₛ data are used for total strangeness

This number is much bigger than the results of statistical models and transport codes

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

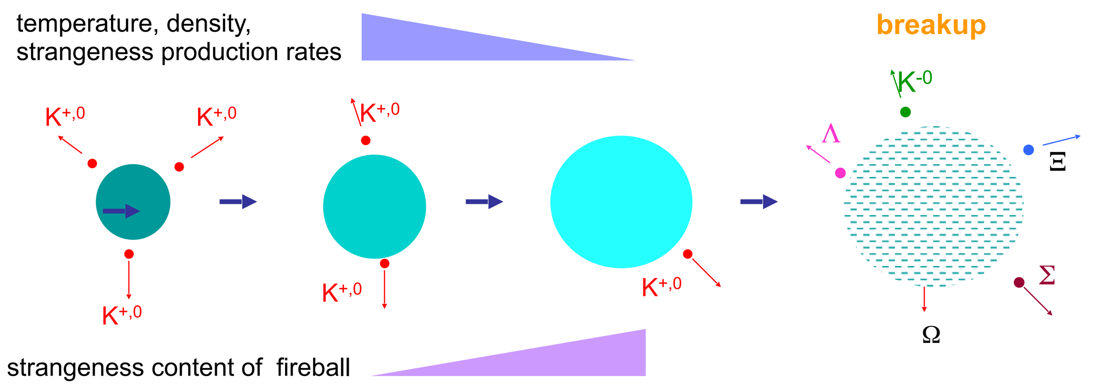
total strangeness is (1+η) K⁺

isospin asymmetry factor $\eta = \frac{A-Z}{Z}$ for ArK and ArCl collisions η=1.14

2. Minimal statistical model for strange particles:

At SIS energies K⁺ and K⁰ 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-K⁰, Λ, Σ, Ξ,Ω



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

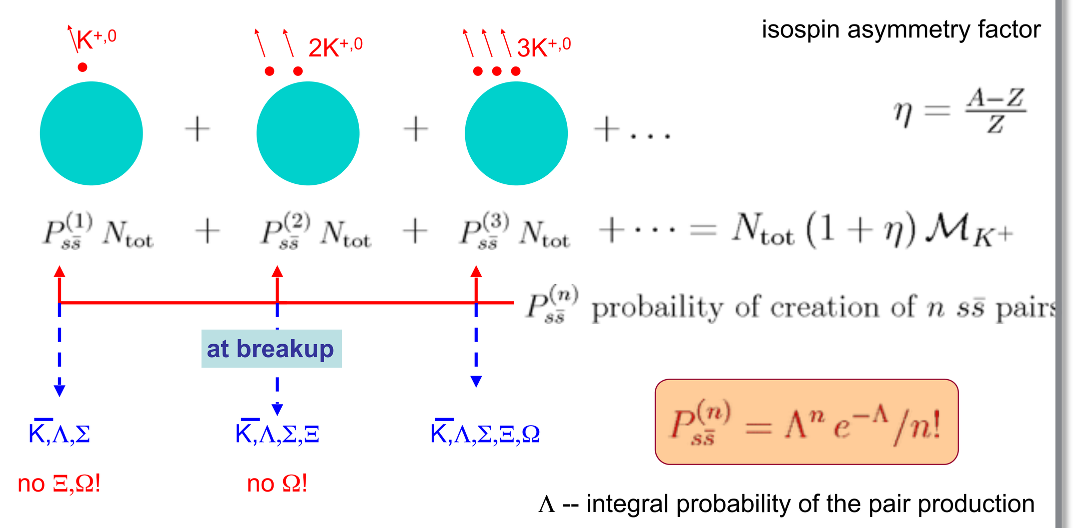
[C.-M. Ko, Phys. Lett. B 120, 294 (1983); Kolomeitsev,Voskresensky,Kämpfer, IJMP E5, 316 (1996)]

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⁺ ⟶ $N_{K^+} = M_{K^+} N_{tot}$ ⟵ *total number of events*

Multi-kaon event classes:



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

$$P^{(1)}_{s\bar s} N_{\rm tot} + P^{(2)}_{s\bar s} N_{\rm tot} + P^{(3)}_{s\bar s} N_{\rm tot} + \dots = N_{\rm tot}(1+\eta)\mathcal{M}_{K^+}$$

$P^{(n)}_{s\bar s}$ probability of creation of n $s\bar s$ pairs

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

Λ -- integral probability of the pair production

Let $\mathcal{W}$ 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.

$$\Lambda = \int_0^{t_{\rm col}} V(t)\mathcal{W}(\rho(t),T(t))\,{\rm d}t \qquad V(t)=f(t)V_{\rm fo} \qquad t_{\rm col} = \tau V_{\rm fo}^{1/3} \qquad \Lambda = \tau\overline{\mathcal{W}}V_{\rm fo}^{4/3} = \lambda V_{\rm fo}^{4/3}$$

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

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:

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

$$\langle\dots\rangle = \frac{2}{b^2_{\rm max}}\int_0^{b_{\rm max}}{\rm d}b\, b(\dots)$$ -- averaging over the collision impact parameter

$$r_0 = 1.124\ {\rm fm} \qquad b_{\rm max} = 2r_0 A^{1/3}$$

$$V_{\rm f.o.}(b) = \frac{2A}{\rho_{B,\rm fo}}F(b/b_{\rm max})$$ overlap function [Gosset et al, PRC 16, 629 (1977)]

freeze-out density

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

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

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

$$\langle P^{(3)}_{s\bar s}\rangle = (1+\eta)^3\tfrac{1}{6}\zeta^{(3)}\mathcal{M}^3_{K^+} \qquad \zeta^{(n)} = \frac{\langle V_{\rm fo}^{\frac{4}{3}n}\rangle}{\langle V_{\rm fo}^{4/3}\rangle^n}$$

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

total strangeness multiplicity $M^{(n)}_S = n P^{(n)}_{s\bar s}$

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

$$\frac{\langle M^{(2)}_S\rangle}{(1+\eta)\mathcal{M}_{K^+}} \simeq 15\%$$ **of kaons is produced pairwise**

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

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

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

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.

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

single-kaon event: $n=1$ only K̄, Λ and Σ can be in the final state

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

multiplicity of $\bar K$, Λ, Σ $\quad M^{(1)}_a = g_a P^{(1)}_{s\bar s}P^{(1)}_a = g_a P^{(1)}_{s\bar s} z^{(1)}_S V_{\rm fo} p_a$

isospin factor

double-kaon event: $n=2$ K̄K̄, K̄Λ, K̄Σ, ΛΛ, ΛΣ, ΣΣ and Ξ can be in the final state

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

$$z^{(2)2}_S V^2_{\rm fo}(p_{\bar K}+p_\Lambda+p_\Sigma)^2 + z^{(2)2}_S V_{\rm fo}\, p_\Xi = 1$$

multiplicity of $\bar K$, Λ, Σ $\quad M^{(2)}_a = g_a\, 2P^{(2)}_{s\bar s}P^{(2)}_a\big(P^{(2)}_{\bar K} + P^{(2)}_\Lambda + P^{(2)}_\Sigma\big)$

multiplicity of Ξ $\quad M^{(2)}_\Xi = g_\Xi P^{(2)}_{s\bar s}P^{(2)}_\Xi$

3. First results for Xi

particle ratios: We included leading and next-to-leading contributions

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

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

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

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

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%

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

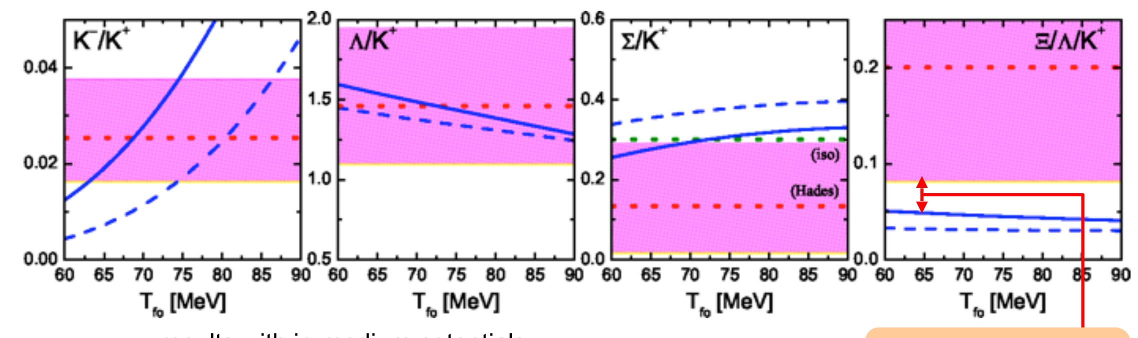
Ξ/Λ/K ratio is sensitive to the fireball freeze-out volume

Ratios as functions of the freeze-out temperature

parameters of the model: $\rho_{B,\rm fo} = 0.6\,\rho_0$

potential models for strange particles in medium

potentials for nucleons Δs:
$S_N \simeq S_\Delta \simeq -190\ {\rm MeV}\rho_B/\rho_0$
$V_N \simeq V_\Delta \simeq +130\ {\rm MeV}\rho_B/\rho_0$



results with in-medium potentials
results with vacuum masses

double strangeness suppression Y₂

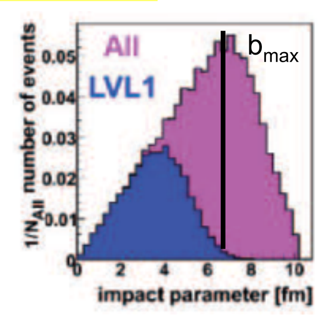
best fit for K^-,Λ ratios: $T_{\rm f.o}$=69 MeV

Inclusion of potentials improves the temperature match for K and Λ ratios,

improves Σ ratio (repulsive potential), increases Ξ ratio (not strong enough)

4. HADES trigger effect

LVL1 trigger HADES counts only the events with MUL>16



trigger function [Schade, PhD thesis2010]

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

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

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

ratio	exp. value	inclusive	triggered
$\Xi/\Lambda/K^+$	$0.20^{+0.16}_{-0.11}$	0.047	0.026

Triggering can effect the ratios with multi strange particles

5. Strange particles is nuclear medium

Hyperons $\quad E_Y(p) = \sqrt{m_Y^2+p^2} \longrightarrow \sqrt{(m+S_Y)^2+p^2}+V_Y$

scalar and vector potentials

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

Usually one relates vector potentials to the potential for nucleons $V_Y = \alpha_Y V_N$ where α_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

$U_\Lambda = -27$ MeV [Hashimoto, Tamura, Prog.Part.Nucl.Phys. 57, 564 (2006)]
$U_\Sigma = +24$ MeV [Dabrowski, Phys.Rev.C 60, 025205 (1999)]
$U_\Xi = -14$ MeV [Khaustov et al., Phys.Rev.C 61, 054603 (2000)]

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!!!

6. Possible ways of explaining the enhanced Xi production

A. in medium potential and freeze-out density

A more attractive Ξ in-medium potential? We would need U_Ξ< - 120 MeV to increase the ratio Ξ⁻/Λ/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,

$$2(m_\Lambda+U_L) - (m_\Xi+m_N+U_\Xi+U_N) \sim 100\ {\rm MeV}>0.$$

This would influence the description of doubly strange hypernuclei

The leading order analysis 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: $\rho_{B,\rm fo} = 0.7\,\rho_0$

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

Further reading:

E.E.Kolomeitsev, B. Tomášik, D.N.Voskresensky, Phys.Rev.C **86** (2012) 054909
B. Tomášik, E.E.Kolomeitsev, Acta Phys. Pol. B Suppl. **5** (2012) 201
E.E.Kolomeitsev, B. Tomášik, Phys. Atom. Nucl. **75** (2012) 685

B. 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 Λ and Σ: $\Lambda N\leftrightarrow\Lambda N \quad \Sigma N\leftrightarrow\Sigma N \quad \Lambda N\leftrightarrow\Sigma N$

$\sigma\sim 80-25$ mb for relative moments p_T to $2p_T$

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

For $\bar K$: $K^-N\leftrightarrow\pi\Lambda(\Sigma) \quad \pi\Lambda(\Sigma)\leftrightarrow\pi\Lambda(\Sigma)$ resonance reactions

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

$\sigma(\Xi^-p\to\Xi^-p)\sim 15$ mb $\quad \sigma(\Xi^-p\to\Lambda\Lambda)\lesssim 10$ mb $\quad \sigma(\Xi^0p\to\Xi^0p)\lesssim 15$ mb

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

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

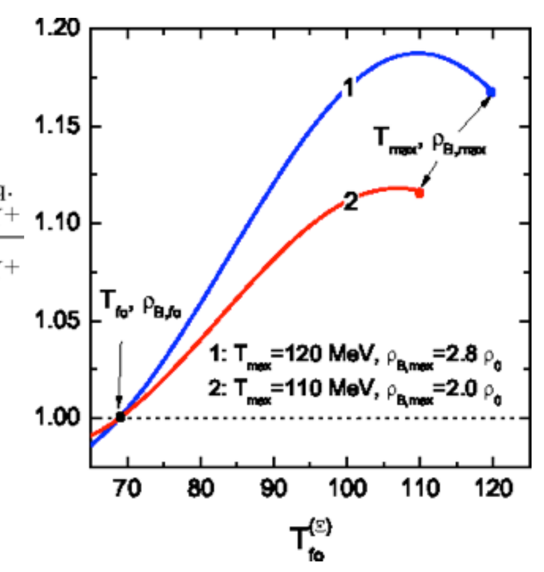
Ξ baryons are presumably weakly coupled to the non-strange system

Earlier freezeout!

$$R^{\rm non-eq.}_{\Xi/\Lambda/K^+}\sim\frac{p_\Xi[\widetilde T_{\rm fo}]}{(p_\Lambda+\frac{1}{3}p_\Sigma)(p_K+p_\Lambda+p_\Sigma)[T_{\rm fo}]}Y_2 \qquad \widetilde T_{\rm fo} > T_{\rm fo}$$

increase of the ratio

$$h_\Xi = \frac{R^{\rm non-eq.}_{\Xi/\Lambda/K^+}}{R_{\Xi/\Lambda/K^+}}$$



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

C. Direct reactions

To get any substantial increase in the number of Ξ'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 Ξ baryons and enough time t?

Where do Ξ baryons come from?

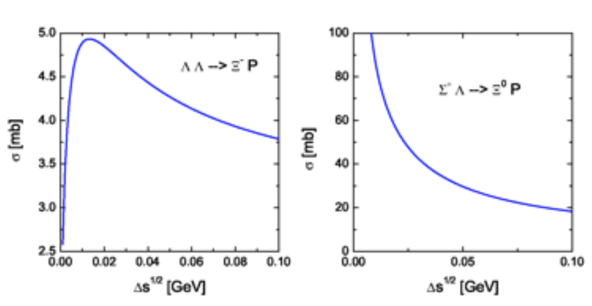
strangeness creation reactions: $\bar K N\to K\Xi - 380$ MeV $\quad N_{K^-}\ll N_{\Lambda\Sigma}$
$\pi\Sigma\to K\Xi - 480$ MeV *very exothermic,*
$\pi\Lambda\to K\Xi - 560$ MeV *very inefficient*

strangeness recombination reactions: ss quarks are strongly bound in Ξ!

anti-kaon induced reactions $\bar K\Lambda\to\Xi\pi + 154$ MeV $\quad\sigma\sim 10$ mb
$\bar K\Sigma\to\Xi\pi + 232$ MeV [Li,Ko NPA712, 110 (2002)]

double-hyperon processes $\Lambda\Lambda\to\Xi N - 26$ MeV can be more efficient since
$\Lambda\Sigma\to\Xi N + 52$ MeV $\quad N_{K^-}\ll N_{\Lambda\Sigma}$
$\Sigma\Sigma\to\Xi N + 130$ MeV [Tomasik, Kolomeitsev, arXiv:**1112.1437** Acta Phys. Pol. Proc. Supp **5** (2012) 201]

[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