Strangeness Balance in HADES Experiments: Ξ^- puzzle, etc.

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

- Can we understand HADES data within the statistical model for S<0 particles?
- Role of in-medium potentials for anti-kaons and baryons
- Where do the Ξ^{--} baryons come from?

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

[Agakishev et al arXive 1010.1675]

one experimental set-up for all particles!

S>0

$$N_{K^+} = (2.8 \pm 0.4) \times 10^{-2}$$

$$N_{K^0_s} = (1.15 \pm 0.14) \times 10^{-2}$$

$$N_{K^0_s} = \frac{1}{2}(N_{K^0} + N_{\overline{K^0}})$$

S<0

$$N_{K^-} = (7.1 \pm 1.9) \times 10^{-4}$$

$$N_{\Lambda+\Sigma^0} = (4.09 \pm 0.59) \times 10^{-2}$$

$$R_{\Xi/\Lambda} = \frac{N_{\Xi^-}}{N_{\Lambda+\Sigma^0}} = (5.6 \pm 3) \times 10^{-3}$$

[Agakishev et al, PRL 103, 132301 (2009)]

$$N_{\Sigma^+ + \Sigma^-} = N_{K^+} + 2\, N_{K^0_s} - N_{\Lambda+\Sigma^0} - 2\, N_{\Xi^-} - 3\, N_{K^-}$$
$$= (0.75 \pm 0.65) \times 10^{-2}$$

We study the relative distributions of strangeness among various hadron species

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

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

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

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

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 can be neglected).

[Kolomeitsev,Voskresensky,Kämpfer, IJMP E5, 316 (1996)] density of a hadron i with the mass m_i is $\rho_i(t) = \lambda_S^{s_i}\, n_i(t)$

λ_S strangeness fugacity

equilibrium density

$$n_i(t) = \zeta_i\, e^{q_i \frac{\mu_B(t)}{T(t)}}\, f(m_i, T(t))$$

$$f(m, T) = m^2\, T\, K_2(m/T)/2\pi^2$$

s_i # of strange quarks in the hadron

ζ_i spin-isospin degeneracy factor

q_i baryon charge of the hadron

baryon chemical potential

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

strangeness balance equation:

$$\rho_{\bar{K}}(t) + \rho_\Lambda(t) + \rho_\Sigma(t) + 2\rho_\Xi(t) = n_S(t) = 2\frac{N_{K^+}}{V(t)}$$

solution for fugacity:

$$\lambda_S = \frac{n_S}{4\, n_\Xi\, \lambda_S^{(1)}}\left[\sqrt{1 + 8\, \lambda_S^{(1)2}\, \frac{n_\Xi}{n_S}} - 1\right]$$

$$\lambda_S^{(1)} = \frac{n_S}{n_{\bar{K}} + n_\Lambda + n_\Sigma}$$

for $n_\Xi/n_S \ll 1$

$$\lambda_S \approx \lambda_S^{(1)} - 2\, \lambda_S^{(1)3}\, \frac{n_\Xi}{n_S}$$

The strangeness concentration at the freeze-out moment can be extracted from experimental data on K^+ meson production.

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

freeze-out volume:

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

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

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

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

← overlap function

↑ freeze-out density

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

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

Theoretical ratios:

small corrections ~1-2%

1. $$R_{K^-/K^+} = \frac{n_{\bar K}}{n_{\bar K} + n_\Lambda + n_\Sigma}\left[1 - \frac{2\, n_\Xi\, \lambda_S^{(1)}}{n_{\bar K} + n_\Lambda + n_\Sigma}\right]$$

2. $$R_{\Lambda/K^+} = \frac{2\, n_\Lambda + \frac{2}{3}\, n_\Sigma}{n_{\bar K} + n_\Lambda + n_\Sigma}\left[1 - \frac{2\, n_\Xi\, \lambda_S^{(1)}}{n_{\bar K} + n_\Lambda + n_\Sigma}\right]$$

3. $$R_{\Sigma/K^+} = \frac{\frac{2}{3}\, n_\Sigma}{n_{\bar K} + n_\Lambda + n_\Sigma}\left[1 - \frac{2\, n_\Xi\, \lambda_S^{(1)}}{n_{\bar K} + n_\Lambda + n_\Sigma}\right]$$

4. $$R_{\Xi/\Lambda/K^+} = \frac{n_\Xi/(n_\Lambda + \frac{1}{3}\, n_\Sigma)}{\langle V_{\rm f.o.}\rangle (n_{\bar K} + n_\Lambda + n_\Sigma)},$$

In the absence of in-medium potentials ratios 2-4 depend weakly on freeze-out density.

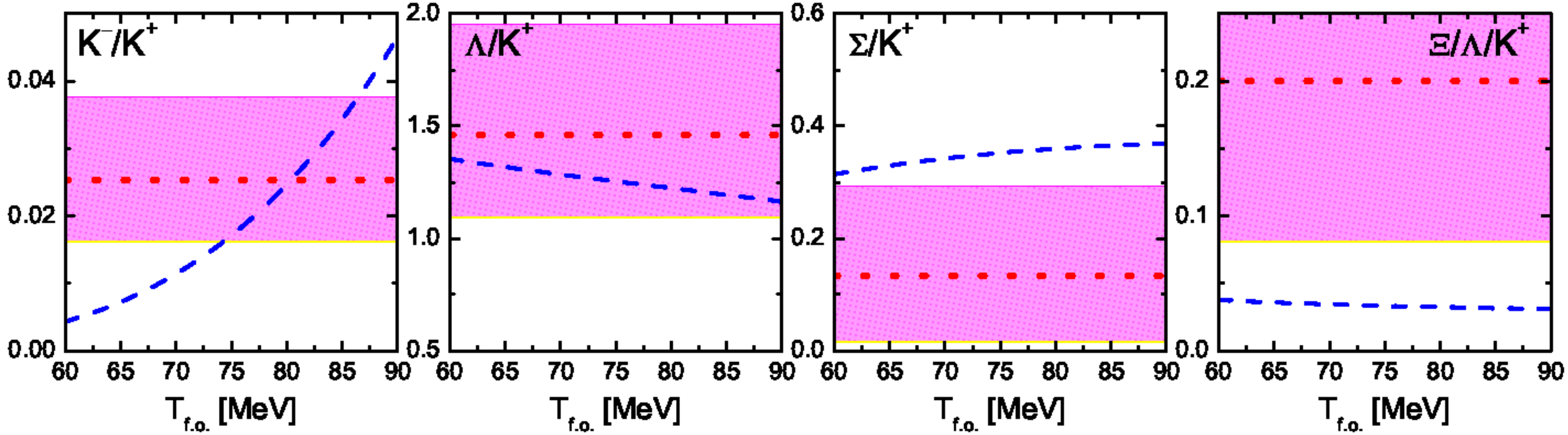
Analysis of pion, proton, K^- yields in HICs at SIS and Bevalac energies gives $\rho_{B,\rm fo} = (0.5\text{–}0.7)\, \rho_0$

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

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

Ratios as functions of the freeze-out temperature

vacuum masses



← T mismatch →

too high!?

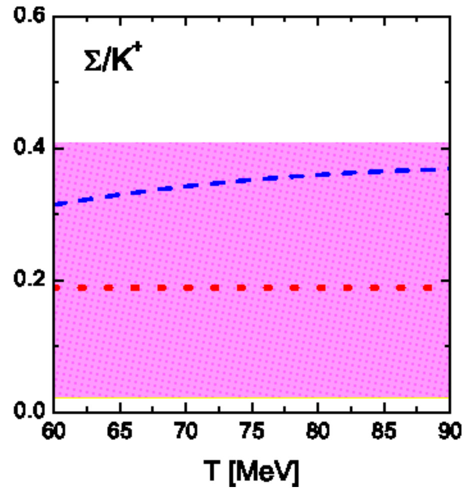
too low!?

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 $\frac{N_{K^+}}{2\,N_{K_s^0}} = 1.22$



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

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

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

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

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

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

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

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

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

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

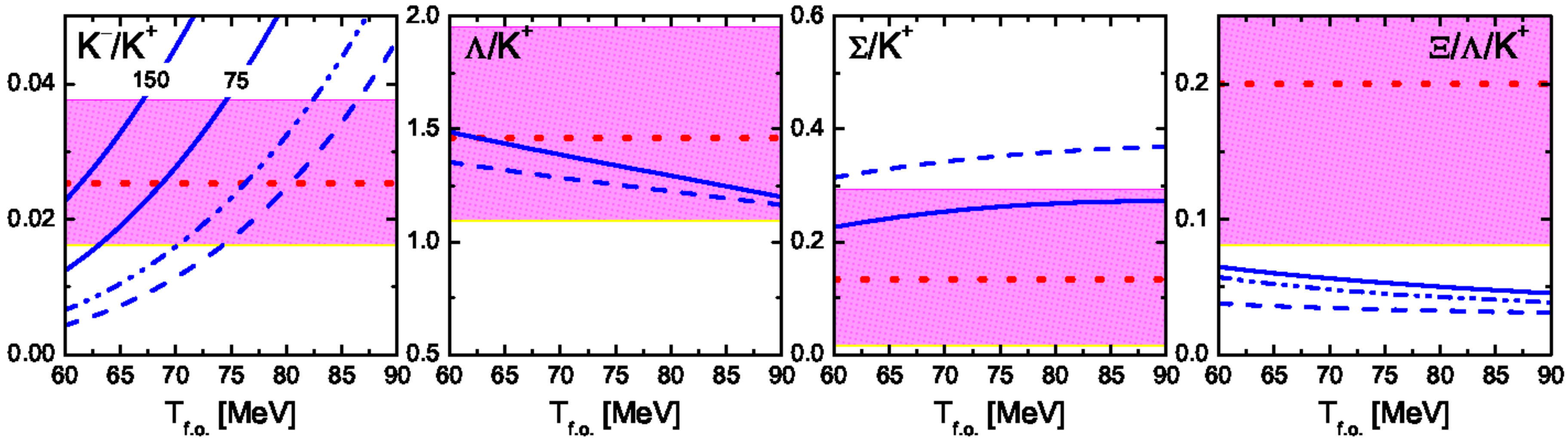
kaons: $V_{\bar{K}} = 0 \qquad S_{\bar{K}} = U_{\bar{K}} \rho/\rho_0$

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

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

Ratios as functions of the freeze-out temperature

in-medium potentials



results with in-medium potentials

Hyperon ratios depend weakly on U_K (U_K=-75 MeV used)

only nucleon potentials are included

Kaon and Ξ ratios are sensitive to the nucleon potentials

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

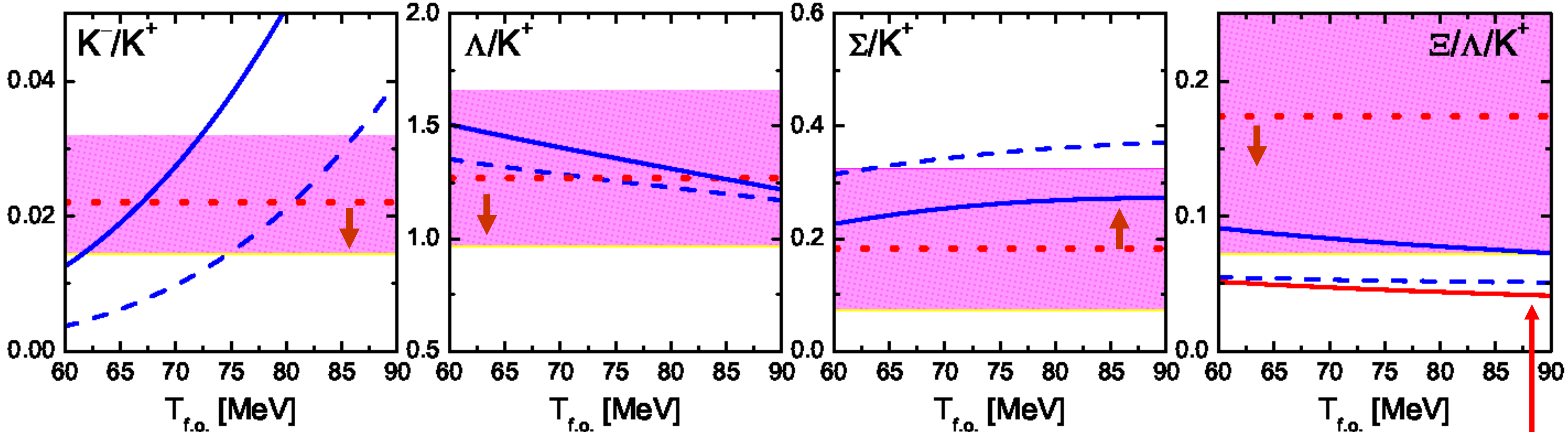
improves Σ ratio (repulsive potential),

improves Ξ (but not enough; we would need U_Ξ=-60 MeV!)

Best fit for K^{-},Λ and Σ ratios: T=68 MeV with $\chi^2=1.3$

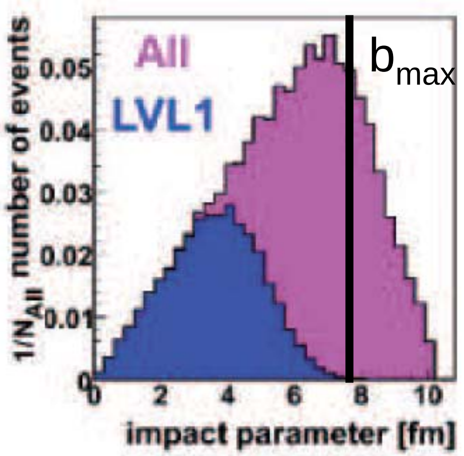
Blasphemous thought: Maybe too few K^+ were measured in the experiment?

increase N_{K^+} by 15% (within the experimental error bars) and $\rho_{B,\mathrm{fo}} = 0.7\,\rho_0$



U_K=-75 MeV best global fit: T=67 MeV with χ^2=2.4

LVL1 trigger HADES counts only the events with MUL>16



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

trigger function

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

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 and a small increase of the observed K^+ yield we can describe K^-/K^+, Λ/K^+, and Σ/K^+ ratios;

$\Xi/\Lambda/K^+$ ratio cannot be described if we take into account HADES event trigger!

Dynamical effects of Ξ production could be important

$$\frac{dN_\Xi}{dt} = \mathrm{Gain(t)} - \mathrm{Loss(t)}$$

In an expanding system the Loss term can decrease faster than the Gain term.

Where do Ξ baryons come from?

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

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

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

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

very exothermic, very inefficient

strangeness recombination reactions:

ss quarks are strongly bound in Ξ!

anti-kaon induced reactions

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

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

$\sigma \sim 10\ \mathrm{mb}$

[Li,Ko NPA712, 110 (2002)]

double-hyperon processes

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

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

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

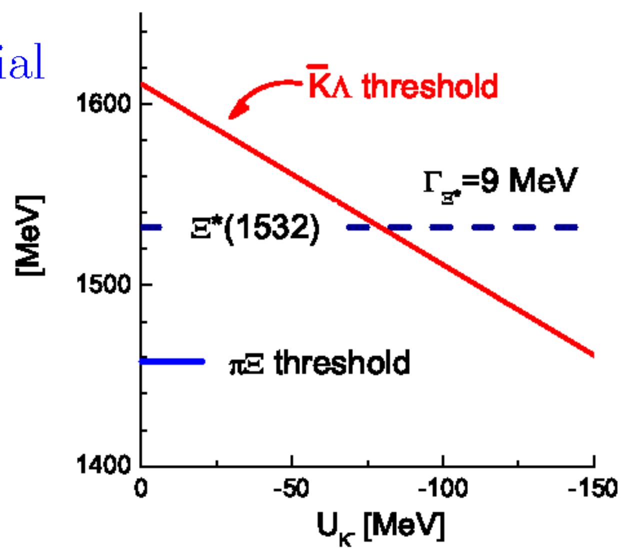
can be more efficient since

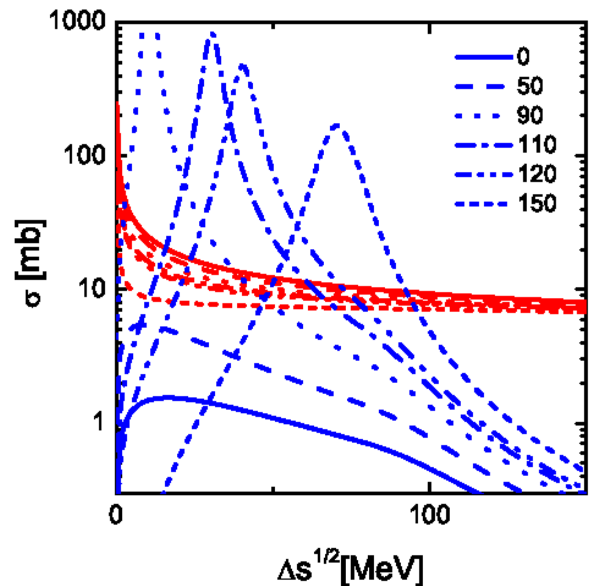
$N_{K^-} \ll N_{\Lambda,\Sigma}$

$|A|^2 \simeq 5\ \mathrm{mb}$

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

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





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

(slide from NICA Round table meeting 2009)

What to measure?

just K^+ mesons – deadly boring

K^+ and K^{--} mesons – boring

kaons and Λ – check for strangeness conservation

kaons mesons and Λ and Σ – check for strangeness conservation
isospin

kaons mesons and hyperons and ϕ – interesting

kaons mesons and hyperons and ϕ and Ξ – very interesting
strangeness dynamics

kaons mesons and S=1,2 hyperons and ϕ and hyperon resonances –
exciting