Reference calculations for subthreshold Ξ production

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Subthreshold production of Ξ

Measured by HADES Collaboration in Ar+KCl at 1.76 *A*GeV
[G. Agakichiev *et al.*, Phys. Rev. Lett. **103** (2009) 132301]

$$\frac{\mathcal{M}_{\Xi^-}}{\mathcal{M}_{\Lambda+\Sigma^0}} = (5.6 \pm 1.2^{+1.8}_{-1.7}) \times 10^{-3}$$

whereas statistical models give $\sim 10^{-4}$

(But look also at [J. Steinheimer and M. Bleicher, arxiv:1503.07305],
M. Bleicher on Monday)

This talk: minimal statistical model reference:

- get produced amount of strangeness from data
- statistically calculate distribution of $S = -1$ hadrons
- do volume averaging (centrality averaging) of the yields

A note on isospin symmetry

We assume the isospin symmetry holds from the initial state all the time

$$\frac{K^0}{K^+} = \frac{K^-}{\bar{K}^0} = \frac{\Xi^-}{\Xi^0} = \frac{n}{p} = \eta = \frac{A-Z}{Z} = 1.14$$

this is used in extracting numbers of unseen strange particles

Kaons measure total strangeness content

- completely baryonic system $\Rightarrow$ different behaviour of strange quarks and antiquarks
- strange antiquarks leave the system in kaons $\Rightarrow$ kaon multiplicity measures produced strangeness

$$\mathcal{M}_{s\bar{s}} = \mathcal{M}_{K^+} + \mathcal{M}_{K^0} = (1+\eta)\mathcal{M}_{K^+}$$

- perturbative treatment of strangeness content:

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

- look at ratios independent on strangeness and baryon content:

$$\frac{\mathcal{M}_{\Xi^-}}{\mathcal{M}_{K^+}\mathcal{M}_{\Lambda+\Sigma^0}} = 0.20^{+0.16}_{-0.12}$$

Minimal statistical model: Total strangeness content

- probability of $s\bar{s}$ production (at fixed impact parameter):

$$W = \lambda V^{4/3}$$

$V^{4/3}$ = volume $\times$ time, λ is constant at given collision energy

- get λ from measured kaon multiplicity
(note event (volume) averaging $\langle \dots \rangle$)

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

- multiplicity distribution of $s\bar{s}$ pair

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

expand for $n = 1, 2, 3$ and insert λ (here appears volume averaging)

Statistical distribution of strange quarks

- probability to produce hadron a in event with n pairs $s\bar{s}$

$$P_a^{(n)} = \left(z_S^{(n)}\right)^{s_a} V\, p_a = \left(z_S^{(n)}\right)^{s_a} V \frac{m_a^2 T}{2\pi} K_2\left(\frac{m_a}{T}\right)$$

- normalisation $z_S^{(n)}$ differs for different numbers of $s\bar{s}$ pairs:
  $n = 1$: Λ, Σ, $\bar{K}$
  $n = 2$: Λ, Σ, Ξ, $\bar{K}$
  $n = 3$: Λ, Σ, Ξ, Ω, $\bar{K}$
- to get multiplicity: sum up contributions from all n's and (afterwards) volume (impact parameter) average

$$\mathcal{M}_a = \left\langle M_a^{(1)} + M_a^{(2)} + M_a^{(3)} \right\rangle$$

- non-trivial volume averaging due to $P_{s\bar{s}}^{(n)}$

$$M_a^{(n)} \propto P_{s\bar{s}}^{(n)}$$

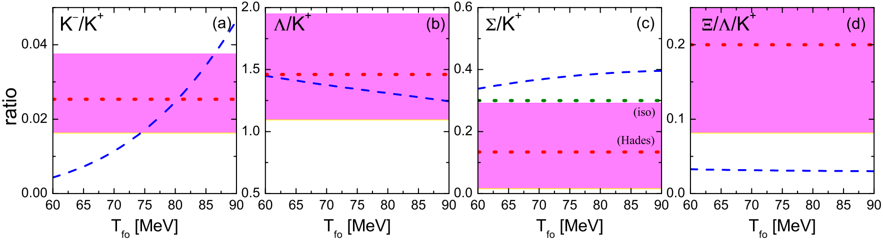
Minimal statistical model: Basic results

calculate all ratios independent of produced strangeness

result for Ξ

$$\frac{\mathcal{M}_{\Xi}}{\mathcal{M}_{\Lambda+\Sigma^0}\mathcal{M}_{K^+}} = \eta \frac{p_\Xi/(p_{\bar{K}} + p_\Lambda + p_\Sigma)}{\langle V\rangle\left(p_\Lambda + \frac{\eta p_\Sigma}{\eta^2+\eta+1}\right)} \frac{\langle V^{5/3}\rangle\langle V\rangle}{2\langle V^{4/3}\rangle^2}$$

Trigger to central collisions pushes this ratio down!
(LVL1 trigger results in suppression about 1.77)



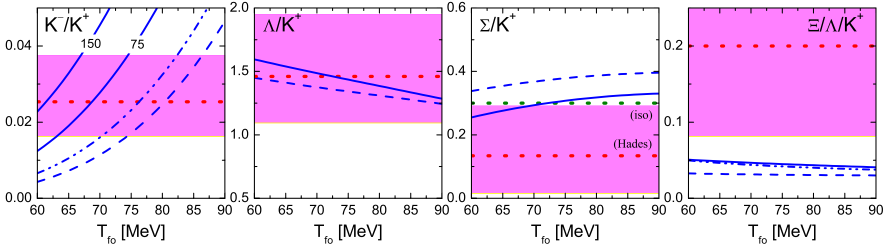
Variations of results: in-medium potentials

Scalar and vector potentials: $f(m_a, T) \to f(m_a + S_a, T)\exp(-V_a/T)$

$$V_N = V_\Delta = \frac{3}{2}V_\Lambda = \frac{3}{2}V_\Sigma = 3V_\Xi = 130\,\mathrm{MeV}\frac{\rho_B}{\rho_0} \qquad S_N = -190\,\mathrm{MeV}\frac{\rho_B}{\rho_0}$$

$$S_a = (U_a - V_a(\rho_0))\frac{\rho_B}{\rho_0} \quad U_\Lambda = -27\,\mathrm{MeV} \quad U_\Sigma = 24\,\mathrm{MeV} \quad U_\Xi = -14\,\mathrm{MeV}$$

$$U_{\bar{K}} = 75\;\mathrm{or}\;150\,\mathrm{MeV}$$



Statistical model prediction for Au+Au @ 1.23 AGeV

The ratio $\mathcal{M}_\Xi/\mathcal{M}_{\Lambda+\Sigma^0}/\mathcal{M}_{K^+}$ is independent of the produced amount of strangeness!

Move from Ar+KCl ($A \sim 40$) to Au+Au ($A \sim 200$):
increase of volume by factor $197/40 \sim 5$.

$$\frac{\mathcal{M}_\Xi}{\mathcal{M}_{\Lambda+\Sigma^0}\mathcal{M}_{K^+}} = \eta \frac{p_\Xi/(p_{\bar{K}} + p_\Lambda + p_\Sigma)}{\left(p_\Lambda + \frac{\eta p_\Sigma}{\eta^2+\eta+1}\right)} \frac{\left\langle V^{5/3}\right\rangle}{2\left\langle V^{4/3}\right\rangle^2} \propto \frac{1}{V}$$

Decrease of the ratio by a factor of 5 in Au+Au collision
(independent of collision energy, at subthreshold energies)

A note on comparison with canonical statistical model

Minimal statistical model

- exact strangeness conservation
- amount of produced strangeness parametrised through coefficient λ
- amount of strangeness proportional to $V^{4/3}$
- averaging over different volumes

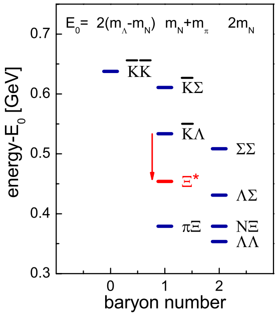
Canonical statistical model

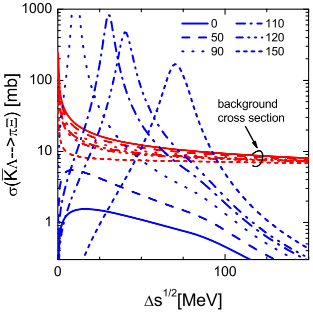
- exact strangeness conservation
- amount of produced strangeness parametrised through canonical volume
- amount of strangeness proportional to V_{can}
- single effective volume for all events in the sample

Production of Ξ: speculations

- once produced, Ξ must decouple from the system
- most viable are strangeness recombination reactions
- with lowering $\bar{K}$ mass the Ξ^* resonance in $\bar{K}N$ channel can be reached
- cross sections parametrised in

  B. Tomášik, E.E. Kolomeitsev, Acta Phys. Pol. B Proc. Suppl. **2** (2012) 201





Conclusions

- minimal statistical model (these issues are there in Nature):
  - exact strangeness conservation
  - statistical distribution of s quarks
  - $V^{4/3}$-dependence of produced strangeness
  - averaging over impact parameter
- even stronger underestimation of Ξ production
  - take into account trigger effects
  - medium modification of masses is not enough to explain data
  - prediction for Au+Au: $\mathcal{M}_{\Xi}/\mathcal{M}_{\Lambda+\Sigma^0}/\mathcal{M}_{K^+}$ 5 times smaller than Ar+KCl
- there must be non-equilibrium Ξ production

E.E. Kolomeitsev, B. Tomášik, D.N. Voskresensky, Phys. Rev. C **86** (2012) 054909

B. Tomášik and E.E. Kolomeitsev, Acta Phys. Pol. B Proc. Suppl. **5** (2012) 201

E.E. Kolomeitsev *et al.*, PoS(Baldin ISHEPP XXII)071 (arXiv:1502.05437)

Backup: volume factors in probabilities

Expanded probabilities to have n pairs $s\bar{s}$:

$$
\begin{aligned}
P_{s\bar{s}}^{(1)} &= \lambda V^{4/3} - \lambda^2 V^{8/3} + \frac{1}{2}\lambda^3 V^4 + O(\lambda^4)\,, \\
P_{s\bar{s}}^{(2)} &= \frac{1}{2}\lambda^2 V^{8/3} - \frac{1}{2}\lambda^3 V^4 + O(\lambda^4), \\
P_{s\bar{s}}^{(3)} &= \frac{1}{6}\lambda^3 V^4 + O(\lambda^4).
\end{aligned}
$$