Ξ baryon production in sub-threshold $p + A$ collisions

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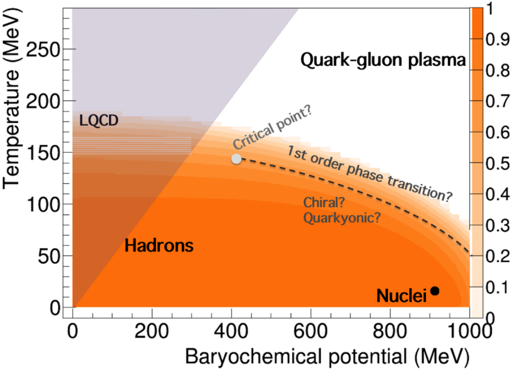
Introduction



There's life below the phase transition line: HADRONS

- there's a lot to do (look at PDG!)
- low energy (non-perturbative) QCD
- in vacuum/in the medium
- a lot of experimental activity

HADES experiment (GSI, Darmstadt): heavy-ion and hadron physics (few GeV/nucleon)

- A+A, p+A, p+p collisions
- pion beam: π+A, π+p
  (anisotropy of dilepton prod, see [E. Speranza, M.Z., B. Friman, PLB 764 (2017) 282])

For **HADES overview** see talk by Szymon Harabasz (17:50 this afternoon)!

Introduction – strangeness production

Subthreshold strangeness production is interesting, because

- sensitive to reaction dynamics
  (collision of secondaries, Fermi motion, in-medium effects, etc.)
- strangeness is conserved $\rightarrow$ high threshold
  $\rightarrow$ still subthreshold at higher energies where large baryon densities are reached

$p + A$ reactions are important, because

- intermediate step between $p + p$ and $A + A$
- cleaner than $A + A$
- less production channels
  (e.g. collision of two secondaries is unlikely)

Possible Ξ production channels:

$$\bar{K}Y \rightarrow \pi\Xi \quad (Y = \Lambda, \Sigma), \qquad YY \rightarrow \Xi N, \qquad \eta\Lambda \rightarrow \Xi K$$

Experimental results

The HADES collaboration has measured Ξ^- production in

- $Ar + KCl$ at $\sqrt{s_{NN}} = 2.61$ GeV: [Phys.Rev.Lett. 103, 132301 (2009)]

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

- $p + Nb$ at $\sqrt{s_{NN}} = 3.2$ GeV: [Phys.Rev.Lett. 114, 212301 (2015)]

  $(2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$ Ξ^-/event

  $\frac{P_{\Xi^-}}{P_{\Lambda+\Sigma^0}} = (1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$

Below the threshold of $\sqrt{s_{NN,thr}} = 3.25$ GeV

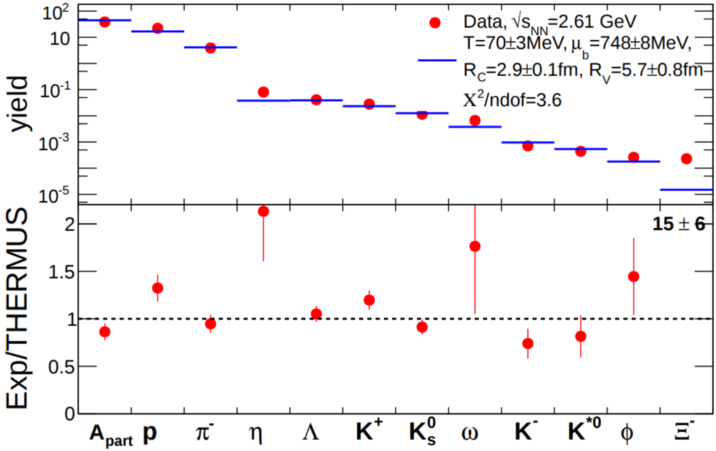
Ξ multiplicity is 8-15$\times$ the prediction of a statistical model

UrQMD can describe the data

- heavy non-strange baryon resonances decaying to ΞKK wit BR=10%
- tuned to $p + Nb \rightarrow$ describe $Ar + KCl$

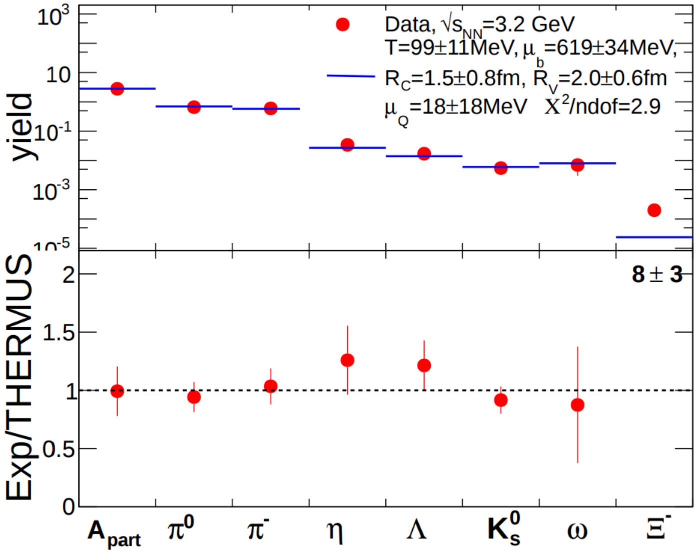
Statistical model

$Ar + KCl$ at $\sqrt{s_{NN}} = 2.61$ GeV:



Statistical model

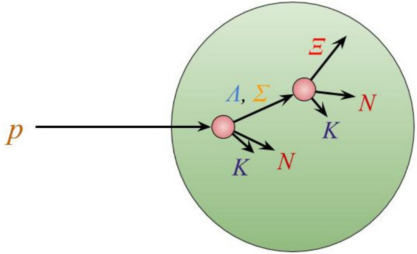
$p + Nb$ at $\sqrt{s_{NN}} = 3.2$ GeV:



Ξ production in $\Lambda/\Sigma + N$

New production mechanism:

[M.Z., Gy. Wolf, PLB 785 (2018) 226]



$p + N \to N + K + \Lambda/\Sigma$: $\sqrt{s_{NN}} = 3.2$ GeV c.f. $\sqrt{s_{thr}} = 2.55$ GeV for Λ
$\sqrt{s_{thr}} = 2.62$ GeV for Σ

$\Lambda/\Sigma + N \to N + \Xi + K$: $\sqrt{s_{\Lambda N}}_{max} = 3.05$ GeV c.f. $\sqrt{s_{thr}} = 2.75$ GeV

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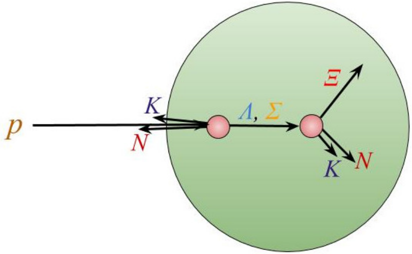

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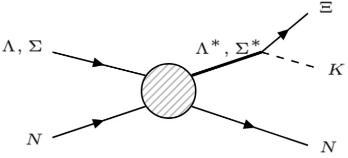
Cross section for $\Lambda/\Sigma + N \rightarrow N\Xi K$

Assume that Ξ production proceeds via an intermediate Λ^*/Σ^*

If everything else is also created via Λ^*/Σ^* resonances, then $\sigma_{YN,tot}$ = resonance production cross section

Ξ production: $\sigma_{YN\rightarrow\Xi} \approx BR_{Y^*\rightarrow\Xi K} \times \sigma_{YN,tot}$

$\sigma_{YN,tot} \approx 10$ mb (similar to $p+p$ total cross section)



$\Lambda(2100)\ 7/2^-$ $\quad I(J^P) = 0(\frac{7}{2}^-)$

Mass m = 2090 to 2110 ($\approx$ 2100) MeV
Full width Γ = 100 to 250 ($\approx$ 200) MeV

Λ(2100) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–35 %	751
$\Sigma\pi$	$\sim$ 5 %	705
$\Lambda\eta$	<3 %	617
ΞK	<3 %	491
$\Lambda\omega$	<8 %	443
$N\overline{K}^*(892)$	10–20 %	515

$BR_{Y^*\rightarrow\Xi K} \approx 3\%$

$\rightarrow \sigma_{YN\rightarrow\Xi} \approx 0.3$ mb

BUU

Version of BUU developed by Gy. Wolf

24 baryon resonances are propagated

Elementary cross sections for (non-strange) particle production are described by resonance production and decays

Resonance properties and creation cross sections are determined by a fit to πN and NN data

Successfully applied to strangeness production near and below threshold

[H.W. Barz, M.Z., Gy. Wolf, B. Kämpfer, NPA 705 ('02) 223]

[H. Schade, Gy. Wolf, B. Kämpfer, PRC 81 ('10) 034902]

Ξ^- production in BUU ($p + Nb$ at $\sqrt{s_{NN}} = 3.2$ GeV)

With the "naive" cross section, $\sigma_{YN \to \Xi} \approx 0.3$ mb:

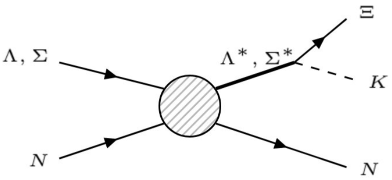
10×10^{-4} Ξ^-/event too much!

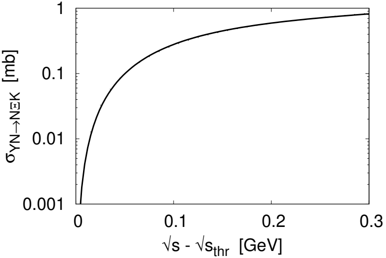
HADES experiment:

$(2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$ Ξ^-/event

BUT: $\sqrt{s}$ dependence of $\sigma_{YN \to \Xi}$ was neglected

"Model" for $YN \to \Xi$ cross section





Include the (better) known Λ^*-s and Σ^*-s from PDG

Assume (universal) constant Y^* production matrix elements
tuned to experimental Ξ multiplicity
$\sigma_{YN\to Y^*} \sim 30$ mb, cf. $\sigma_{pp} \sim 40 - 50$ mb

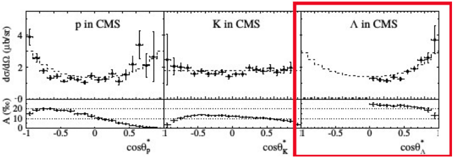
Assume universal $BR_{Y^*\to\Xi K} = 3$ %

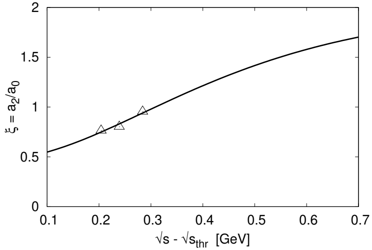
Include mass dependence of Γ_{Y^*}

Add contributions incoherently

Effect of anisotropic Λ/Σ creation

[COSY-TOF, EPJ A46 (2010) 27]

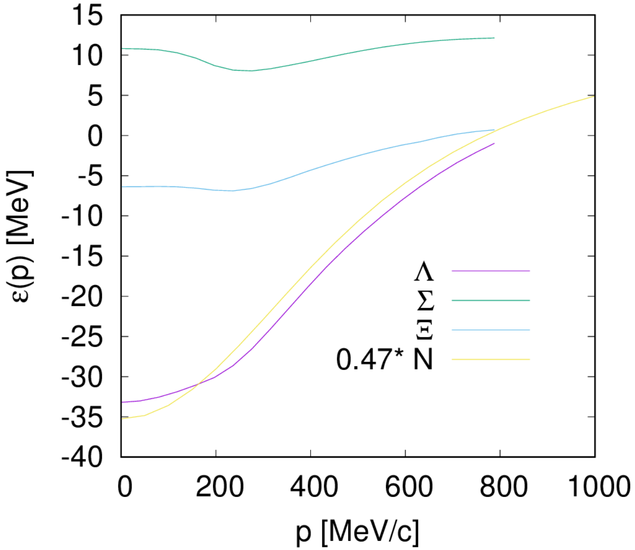




- Angular distribution measured at three energies
- Expanded in Legendre-polinomials: $\frac{d\sigma}{d\Omega_\Lambda} = \sum_l a_l P_l(\cos\theta_\Lambda)$
- $\xi = a_2/a_0$: measure of anisotropy
- extrapolate ξ to higher energy

HADES: $\sqrt{s} - \sqrt{s}_{\rm thr} = 0.63$ GeV

In-medium hyperon potentials



[T. Inoue, PoS INPC 2016 (2017) 277.]

Results

	hyperon multiplicity/10^{-2}			Ξ multiplicity/10^{-4}			
	Λ	Σ^0	$\Lambda+\Sigma^0$	$N\Lambda$	$N\Sigma$	total	$\Xi/(\Lambda+\Sigma^0)$
full model	1.296	0.673	1.969	0.317	1.682	**1.999**	1.015×10^{-2}
no aniso.	1.307	0.682	1.989	0.129	0.655	**0.785**	0.395×10^{-2}
no hyp. pot.	1.311	0.694	2.005	0.248	1.465	**1.713**	0.854×10^{-2}
no hyp. abs.	1.302	0.685	1.987	0.363	2.787	**3.150**	1.585×10^{-2}

HADES results:

$P_{\Lambda+\Sigma^0} = 0.017 \pm 0.003$

$P_{\Xi^-} = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$

$\frac{P_{\Xi^-}}{P_{\Lambda+\Sigma^0}} = (1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$

Conclusions

The high Ξ^- multiplicity found by HADES in subthreshold $p + Nb$ can be explained via the reaction

$$Y + N \to \Xi K N$$

Both the energy, and the two units of strangeness are accumulated in two steps

Clearly non-thermal production mechanism

The angular distribution of hyperon production is relevant! (factor of 2.5)

Λ^* and Σ^* states play an important role in multi-strange particle production $\to$ better knowledge of their properties is needed