Hypernuclei and MEMOs
Extending the nuclear chart

Jan Steinheimer-Froschauer
with J. Schaffner-Bielich, M. Bleicher and H. Stöcker

Goethe Universität Frankfurt
Institut für Theoretische Physik
Frankfurt Institute for Advanced Studies

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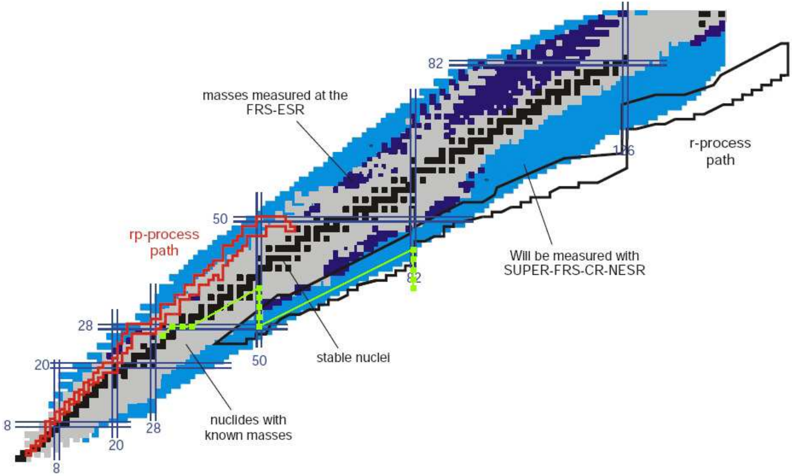
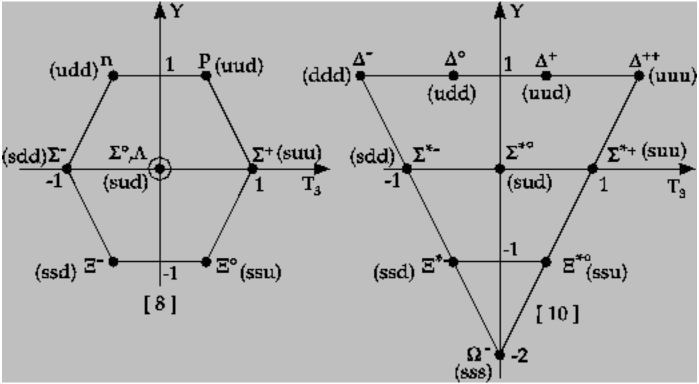
The nuclear chart



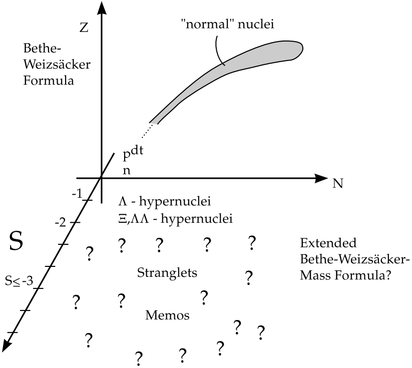
The baryon multipletts

- Lowest baryon multiplets: octet (spin 1/2) and decuplet (spin 3/2)
- For each strange quark baryon masses increases.



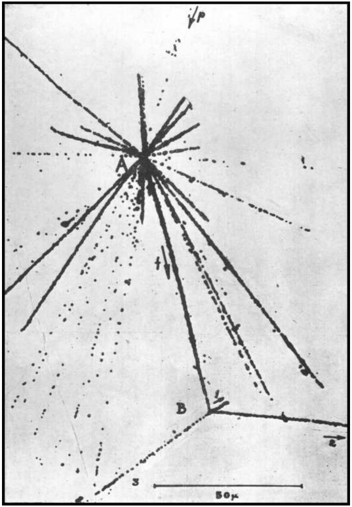
Extending the nuclear chart

- Explore Matter- Antimatter symmetry
- Extend in the third (strange) dimension [1]



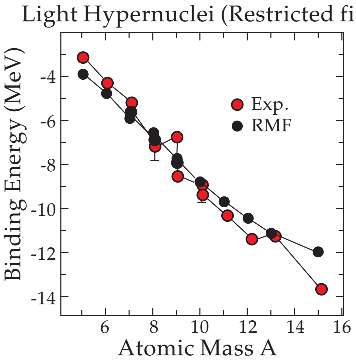
[1] W. Greiner, Int. J. Mod. Phys. E **5**, 1 (1996).

First hypernuclear event



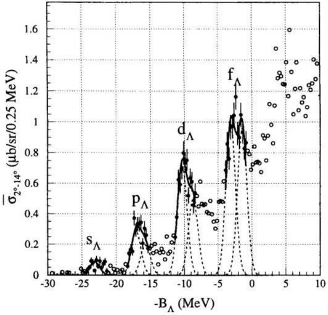
- The first hypernuclear measurement by Danysz and Pniewski from a cosmic ray emulsion event.

Light hypernuclei binding energy



- Emulsion data exists up to mass number $A = 15$
- Λ binding energies increase linearly with mass number

Heavy hypernuclei

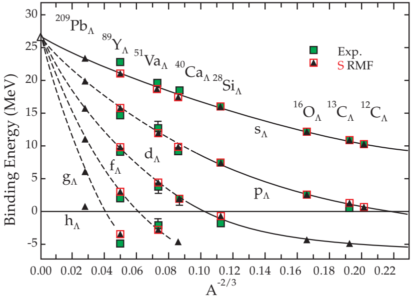


(Hotchi et al., PRC 61 (2001) 044302)

- spectroscopy of hypernuclei (e.g. $^{89}_{\Lambda}$Y via:$\pi^+ + n \rightarrow \Lambda + K^+$)
- Hypernuclei measured up to $^{208}_{\Lambda}$Pb, shells: s, p, d, f, g and h!

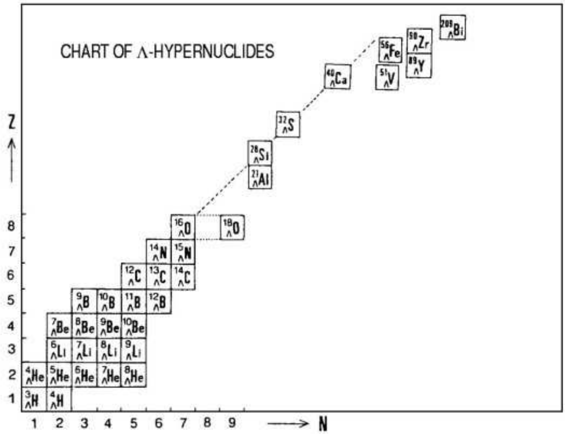
Λ single particle energies

- Spin-orbit splitting smaller than experimental resolution
- Single particle energies: $U_\Lambda = -27$ MeV for $A \to \infty$
- Λ: only baryon we know its in-medium properties!



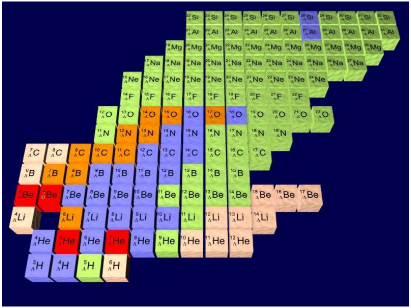
(Rufa, Schaffner, Maruhn, Stöcker, Greiner, Reinhard (1990))

The hypernuclear chart (by 1990)



(Bando (1990))

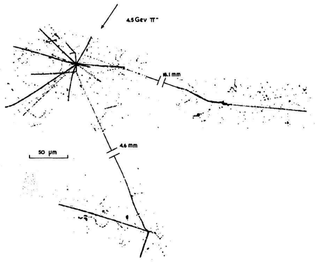
HypHI program at GSI (Take Saito et al.)



- Extending the hypernuclear chart for light systems.
- Extensive program at the planned FAIR facility.
- Note: ^{8}Be is unbound but $^{9}_{\Lambda}$Be is bound!

Ξ hypernuclei

- First bound Ξ hypernucleus seen in 1959 (Wilkinson, Lorant, Robinson, Lokanathan, PRL 3 (1959) 397)
- Two hypernuclei emitted: $\Xi + N \rightarrow \Lambda + \Lambda$
- ${}^{8}_{\Xi}$B with $B_{\Xi} = 8.1 \pm 1.2$



Hypernucleus	B_{Ξ^-} [MeV]	B_{Ξ^0} [MeV]
${}^{8}_{\Xi}$He	8.1 ± 1.2	14.2 ± 1.8
${}^{11}_{\Xi}$B	9.2 ± 2.2	0.4 ± 2.8
${}^{13}_{\Xi}$C	18.1 ± 3.2	-4.3 ± 3.8
${}^{15}_{\Xi}$C	16.0 ± 4.7	11.1 ± 5.3
${}^{17}_{\Xi}$O	16.0 ± 5.5	-4.5 ± 6.1
${}^{28}_{\Xi}$Al	23.2 ± 6.8	13.3 ± 7.4

$\Lambda\Lambda$ hypernuclei

- 1963 Danysz et al.: ${}^{10}_{\Lambda\Lambda}$Be, $\Delta B_{\Lambda\Lambda} = 4.3 \pm 0.4$ MeV
- 1966 Prowse: ${}^{6}_{\Lambda\Lambda}$He, $\Delta B_{\Lambda\Lambda} = 4.7 \pm 0.6$ MeV
- 1991 Aoki et al.: ${}^{13}_{\Lambda\Lambda}$B, $\Delta B_{\Lambda\Lambda} = 4.8 \pm 0.7$ MeV
- 2001 E373 (KEK): ${}^{6}_{\Lambda\Lambda}$He, $\Delta B_{\Lambda\Lambda} = 1.0 \pm 0.2$ MeV
- 2001 E906 (BNL): ${}^{4}_{\Lambda\Lambda}$H

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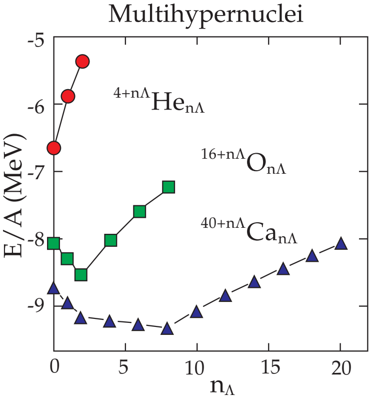
- 2001 E906 (BNL): ${}^{4}_{\Lambda\Lambda}$H
- $\Lambda\Lambda$ interaction only weakly attractive

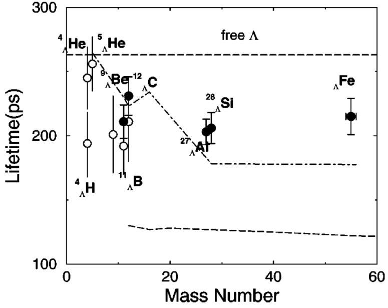
Multi-Λ hypernuclei

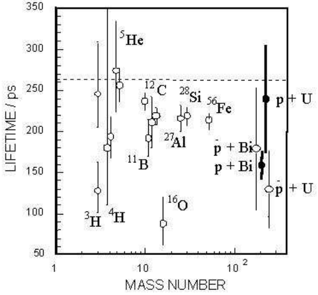
- Binding energy increases for heavy systems, some magic numbers.



Hypernuclear decays

- Hyperons decay mainly by weak interactions: e.g. $\Lambda \to p + \pi^- (64\%)$
- Hypernuclear lifetimes close to that of a free Λ, saturates around 200 ps.

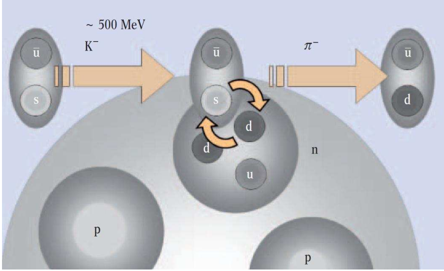


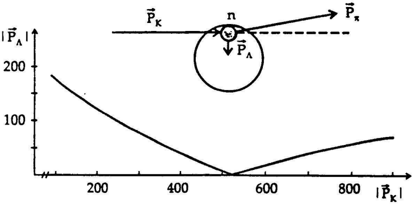


(Park et al., PRC61 (2000) 054004)

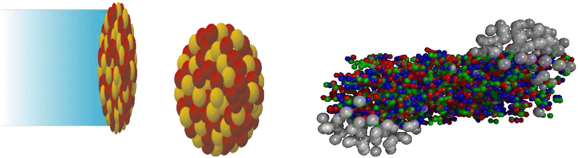
Hypernuclear production mechanisms I

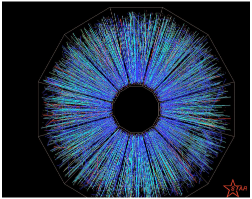
- Hypernuclei produced by incoming K^- beam
- Feature: no recoil for Λ!





Hypernuclear production mechanisms II

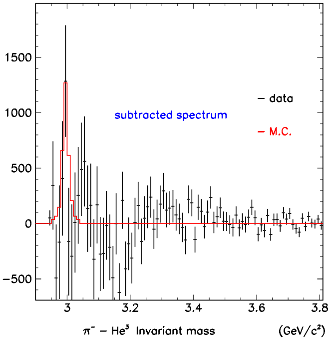




- Fireball in a HI-collision is an abundant source of strangeness
- Clusters are formed at or after the hadronic freezeout

Detecting them in a HIC

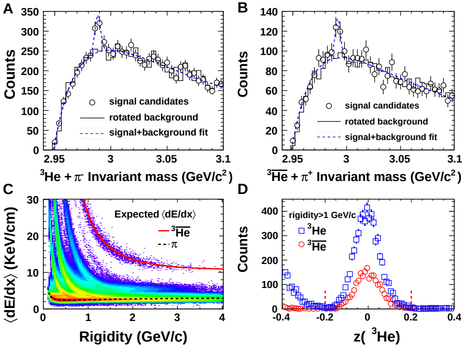
- Decay mode: ${}^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$
- Seen at the AGS (E864)



(T. A. Armstrong *et al.* [E864 Collaboration] (2004))

Recent (Anti-)Hype

- Recent results from the STAR experiment (BNL): First ANTI-Hypernucleus



(The STAR Collaboration, Science 2 April 2010: Vol. 328. no. 5974)

Summary for hypernuclear systems

- NΛ:attractive
  $U_\Lambda = -30MeV$ at $\rho = \rho_0$

Hypernuclear programs planned:
Daphne, Jlab, J-PARC, MAMI and PANDA HYPHI @ FAIR!
Possible signals also at HIC from FAIR to LHC.

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  $U_\Xi = -28 MeV$ at $\rho = \rho_0$

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- $\Lambda\Lambda$:attractive

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- ΛΛ:attractive
- YY: unknown

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Historical notes

- Exotic forms of bound objects with strangeness have been proposed long ago.[1]
- H di-baron by Jaffe.[2]
- Strangelets (Multistrange Quark bags).
- MEMO's [3]
- Purely Hyperonic states [4]

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[1] A. R. Bodmer, Phys. Rev. D **4** (1971) 1601.

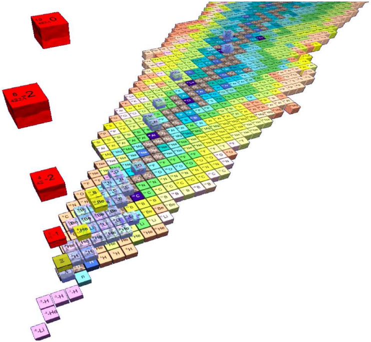
[2] R. L. Jaffe, Phys. Rev. Lett. **38** (1977) 195 [Erratum-ibid. **38** (1977) 617].

[3] J. Schaffner, H. Stoecker and C. Greiner, Phys. Rev. C **46** (1992) 322.

[4] J. Schaffner, C. B. Dover, A. Gal, C. Greiner and H. Stoecker, Phys. Rev. Lett. **71** (1993) 1328.

What's a MEMO?

- Metastable Exotic Multihypernuclear Object.
- Consist of nucleons, Λ's and Ξ's.
- Are stabilized due to Pauli blocking.
- Lifetimes: $10^{-10} - 10^{-5}s$



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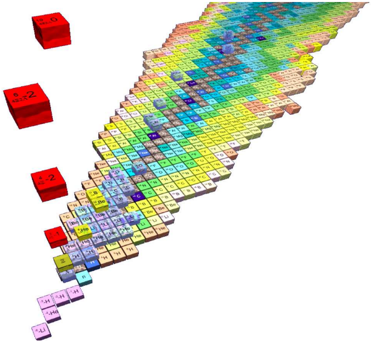
- Consist of nucleons, Λ's and Ξ's.
- Are stabilized due to Pauli blocking.
- Lifetimes: $10^{-10} - 10^{-5}s$
- First try: di-baryons



Baryon-baryon potentials from symmetry

- Couple two $\mathrm{SU}(3)_f$ baryon octets: $8 \times 8 = 1 + 8 + 8 + 10 + 10^* + 27$
- NN (deuteron) bound state in $\{10^*\}$
- $\mathrm{SU}(3)_f$ symmetry: all $\{10^*\}$ are bound states.
- Broken $\mathrm{SU}(3)_f$ symmetry: quasi-bound states become bound as hyperons are heavier than nucleons.

TABLE XIII. SU(3) content of the different interaction channels. S is the total strangeness and I is the isospin. The upper half refers to the space-spin symmetric states ${}^3S_1$, ${}^1P_1$, ${}^3D$, . . . , while the lower half refers to the space-spin antisymmetric states ${}^1S_0$, ${}^3P$, ${}^1D_2$, ...

		Space-spin symmetric states	
S	I	Channels	SU(3) irreps
0	0	NN	{10*}
−1	1/2	ΛN, ΣN	{10*}, $\{8\}_a$
	3/2	ΣN	{10}
−2	0	ΞN	$\{8\}_a$
	1	ΞN, $\Sigma\Sigma$	{10}, {10*}, $\{8\}_a$
		$\Sigma\Lambda$	{10}, {10*}
−3	1/2	$\Xi\Lambda$, $\Xi\Sigma$	{10}, $\{8\}_a$
	3/2	$\Xi\Sigma$	{10*}
−4	0	$\Xi\Xi$	{10}
		Space-spin antisymmetric states	
S	I	Channels	SU(3) irreps
0	1	NN	{27}
−1	1/2	ΛN, ΣN	{27}, $\{8\}_s$
	3/2	ΣN	{27}
−2	0	$\Lambda\Lambda$, ΞN, $\Sigma\Sigma$	{27}, $\{8\}_s$, {1}
	1	ΞN, $\Sigma\Lambda$	{27}, $\{8\}_s$
	2	$\Sigma\Sigma$	{27}
−3	1/2	$\Xi\Lambda$, $\Xi\Sigma$	{27}, $\{8\}_s$
	3/2	$\Xi\Sigma$	{27}
−4	1	$\Xi\Xi$	{27}

Baryon-baryon potentials from Nijmegen soft-core models

- One-Boson exchange model for pseudoscalar, scalar, and vector mesons
- $\mathrm{SU}(3)_f$ symmetry
- Fitted to scattering data (NN and NY)
- (Stoks, Rijken 1999):

Σ^+p, Σ^-n:	quasibound
$\Sigma^+\Sigma^+$, $\Sigma^-\Sigma^-$:	$E_b = -1.5$ to -3.2 MeV
$\Xi^0\Sigma^+$, $\Xi^-\Sigma^-$:	$E_b = -2$ to -17 MeV
$\Xi^0\Xi^0$, $\Xi^0\Xi^-$:	$E_b = +1$ to -16 MeV

Baryon-baryon potentials from Quark-meson models

- Quark-meson exchange model
- $\mathrm{SU}(3)_f$ symmetry for coupling constants
- Confinement potential
- Good for light hypernuclei
- (Fujiwara, Suzuki, Nakamoto 2007):

No bound states !!

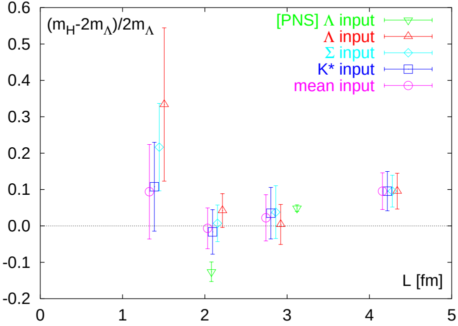
Baryon-baryon potentials from chiral effective models

- One-boson exchange of pseudoscalar mesons + contact terms
- $\mathrm{SU}(3)_f$ symmetry
- Fitted to scattering data (NN and NY)
- (Haidenbaer and Meißner 2010):

$\Xi^0\Lambda$: $E_b = -0.43$ MeV or quasibound
$\Xi^0\Sigma^+$: $E_b = -2.23$ to -6.15 MeV
$\Xi\Xi$: $E_b = -2.56$ to -7.28 MeV

Baryon-baryon potentials from lattice

- Lattice results indicate an unbound H-dibaryon



(I. Wetzorke and F. Karsch (2003))

Model for weak decays

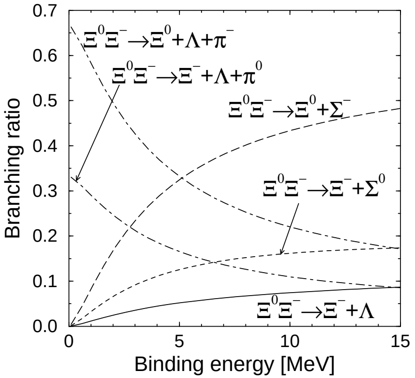
Mesonic decay

- $\mathrm{SU}(3)_f$ symmetry for weak interaction vertex of two baryons and one pseudoscalar meson
- Fitted to hyperon decay amplitudes (Schaffner-Bielich, Mattiello, Sorge 2000)

Non-mesonic decay

- Meson exchange model:strong vertex from one-boson exchange
- Use parameterized deuteron-like wavefunction

Weak decays of the $\Xi^0\Xi^-$ dibaryon



- Can be seen in $\Xi^-\Lambda$ invariant mass plots
- Small branching ratio: needs larger production rate

Decay characteristics

Track them down by:

- Exotic tracks in TPC
- Invariant mass spectra for bound clusters
- Correlations: resonances and interaction potential

Coalescence

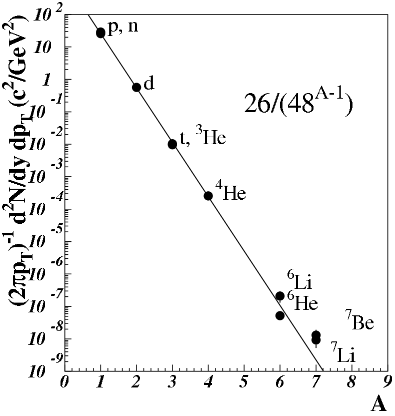
- Take transport model of choice and calculate phase space distributions of baryons.
- A cluster is formed whenever the correct combination of baryons occupies a certain phase space „point“

$$\begin{aligned} dN/d\vec{P} &= g\int f_A(\vec{x}_1,\vec{p}_1) f_B(\vec{x}_2,\vec{p}_2)\rho_{AB}(\Delta\vec{x},\Delta\vec{p}) \\ &\quad \delta(\vec{P}-\vec{p}_1-\vec{p}_2)d^3x_1\ d^3x_2\ d^3p_1\ d^3p_2 \end{aligned}$$

Results depend on parameters!

The penalty factor

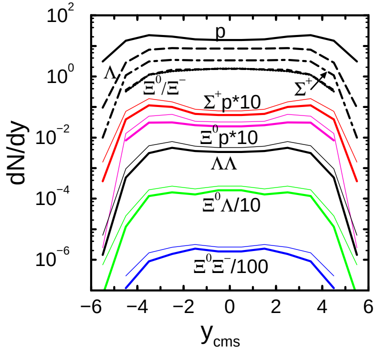
Usually cluster production is characterized by a penalty factor for introducing a baryon to a cluster:



The penalty factor can be understood in therms of a Boltzmann factor: $\exp -(m-\mu)/T$

Coalescence estimates

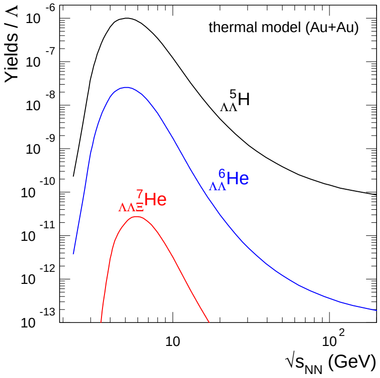
- Coalescence model predictions at RHIC energies $\sqrt{s} = 200A$ GeV (multiplicity of $\Xi^0\Xi^- \approx 10^{-3}$).



(Schaffner-Bielich, Mattiello, Sorge (2010))

Thermal production rates

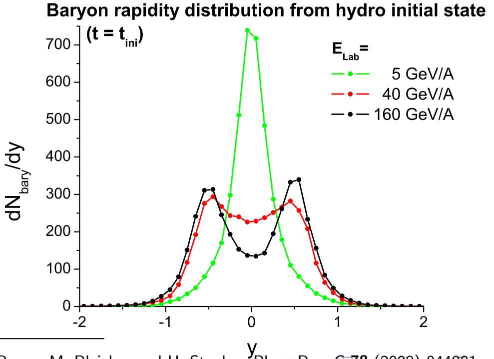
- Thermal models give a reasonable description of hadron yields in HIC
- Parameters are usually temperature and the baryo-chemical potential
- Can also be used to estimate cluster production



(A. Andronic et al.)

The hybrid Model

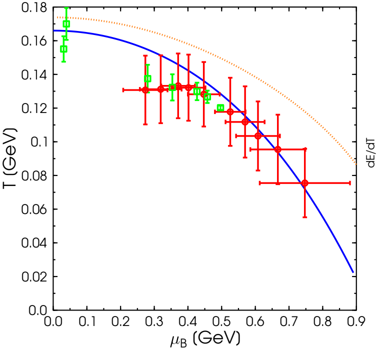
- We investigate production of MEMO's in a micro+macro hybrid approach [1] to heavy ion collisions.
- Initial state from UrQMD mapped on 3+1 d Hydro grid.
- Accounts for fluctuations, baryon density phase-space separation (transparency).

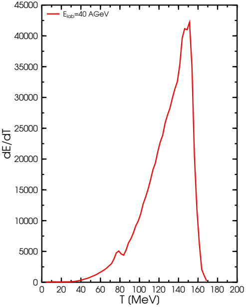


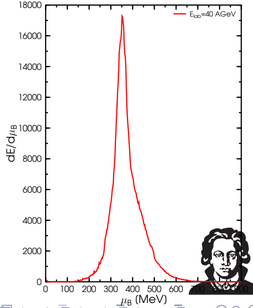
[1] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C **78** (2008) 044901.

The hybrid Model

- Transition from hydro to transport when $\epsilon < 600 MeV/fm^3$ ($\approx 4\epsilon_0$) in all cells of one transverse slice (**Gradual freeze-out**, GF)
- Cooper Frye Prescription $E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$
- For MEMO production the final state interactions are neglected.
- T and μ_B have a distribution at freezeout (still f_s is locally 0):

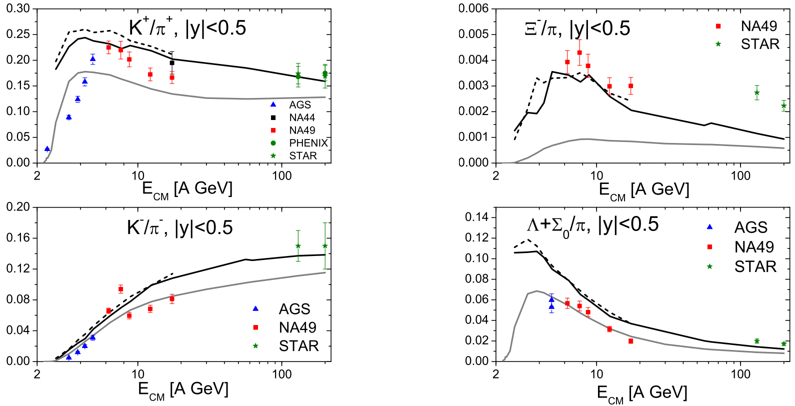






Particle ratios from the hybrid model

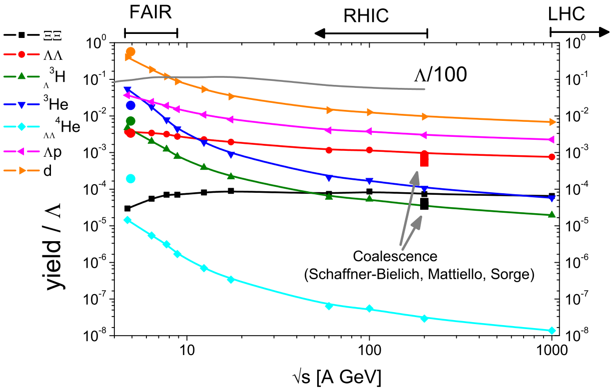
- Central Pb+Pb/Au+Au collisions from AGS to RHIC.



solid line: $4\epsilon_0$ GF, dashed line: $5\epsilon_0$ GF, grey line: UrQMD 2.3

Multiplicities for various energies

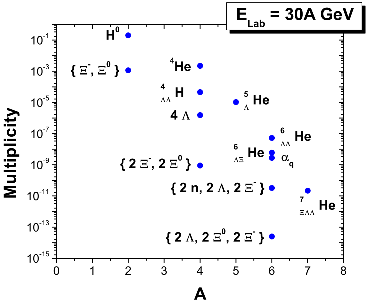
Midrapidity results from the hybrid model for various energies.

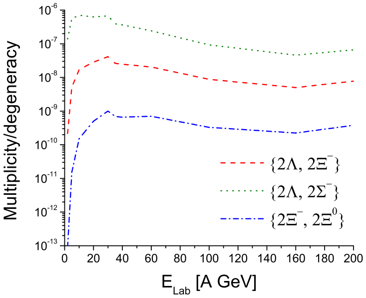


Reasonable agreement with coalescence predictions.

Multiplicities for FAIR

- FAIR will be ideal place to look for baryon-rich clusters.
- Multiplicities for various MEMOs (per degeneracy factor).

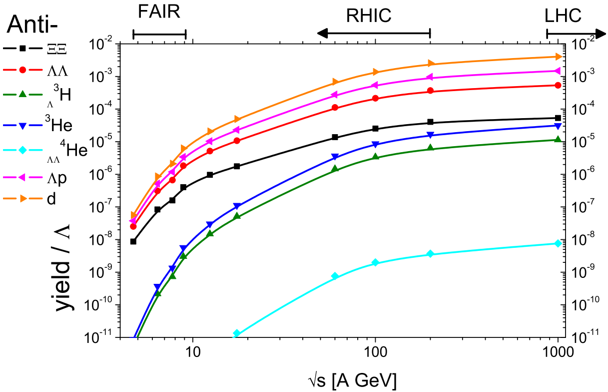




(Steinheimer, Mitrovski, Schuster, Petersen, Bleicher, Stöcker 2009)

Anti-multiplicities for various energies

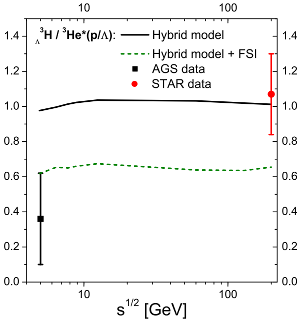
Midrapidity results from the hybrid model for various energies.



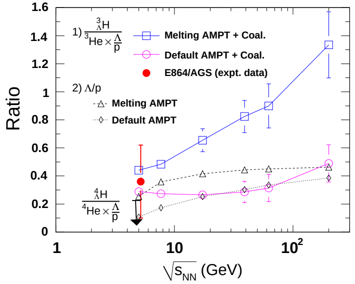
Highest RHIC and LHC energies will open up Anti-Hypermatter opportunities.

A strange ratio

- Consider the following ratio $R_H = {}^3_\Lambda H / {}^3He \cdot p/\Lambda$.
- All fugacities cancel as well as should simple canonical corrections!



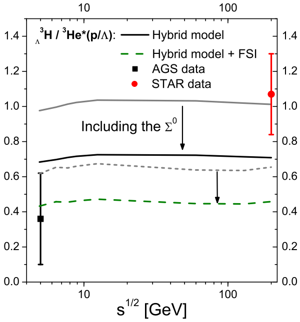
(Hybrid-model results)



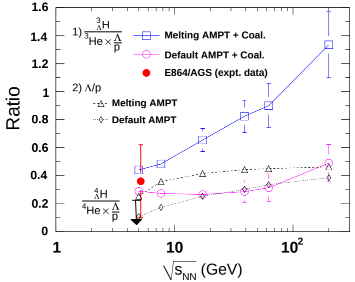
Coalescence (Zhang, Chen, Crawford, Keane, Ma, Xu)

A strange ratio

- Consider the following ratio $R_H = ^3_\Lambda H/^3He \cdot p/\Lambda$.
- All fugacities cancel as well as should simple canonical corrections!
- But what about Σ^0 (30% of all Λ's come from the Σ^0)



(Hybrid-model results)



Coalescence (Zhang, Chen, Crawford, Keane, Ma, Xu)

Conclusion

- Bound states of hyperons might exist, $\Xi^-\Xi^0$ is a candidate.
- CBM experiment at FAIR is ideally placed for for the search of exotic multihypernuclear Objects.
- For exploring the anti-hyper world RHIC and especially the LHC are promising

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- Bound states of hyperons might exist, $\Xi^-\Xi^0$ is a candidate.
- CBM experiment at FAIR is ideally placed for for the search of exotic multihypernuclear Objects.
- For exploring the anti-hyper world RHIC and especially the LHC are promising
- Can we learn about strangeness equilibration and correlations from hyperclusters?

Backup

- Way to enhance cluster production is by destillation
- We use a model that has a phase coexistence of hadrons and quarks (crossover like lattice)