The Strange Baryon-Baryon Interaction

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Chiral Group Meeting
Frankfurt, June 6, 2016
1. Hyperon-Nucleon Interaction: Hypernuclei
2. Baryon-Baryon Interactions: Dibaryons
3. Finding Strange Matter
Hyperon-Nucleon Interaction: Hypernuclei

Baryon-Baryon Interactions: Dibaryons

Finding Strange Matter
Baryon octet and decuplet

- eightfold way: baryons have three quarks
- lowest multiplets: octet (spin 1/2) and decuplet (spin 3/2)
- baryon mass increases with number of strange quarks (strangeness)
- nucleon (no s-quark): $m_N = 940$ MeV → nuclear chart
Hyperons with one s-quark: $m_\Lambda = 1116$ MeV, $m_\Sigma^+ = 1189$ MeV, $m_\Sigma^0 = 1193$ MeV, $m_\Sigma^- = 1197$ MeV

Hyperons with two s-quarks: $m_\Xi^0 = 1314$ MeV, $m_\Xi^- = 1321$ MeV

Hyperon with three s-quarks: $m_\Omega^- = 1672$ MeV (spin 3/2, Pauli principle!)

Bound system with nucleons and hyperons: hypernuclei!
First hypernuclear event

- first hypernuclear measurement: 1953 by Danysz and Pniewski from cosmic ray emulsion event
- unique double-star feature on emulsion plate: one from hypernuclear production, one from hypernuclear decay!
Danysz and Pniewski

Polish postcard commemorating Danysz and Pniewski (check out the stamp!)
Hypernuclear production mechanism

- hypernuclei produced by incoming $K^-$ beam
- nucleon transformed to a hyperon: $K^- + n \rightarrow \Lambda + \pi^-$
- measurement by outgoing $\pi^-$
- prominent feature: recoilless production, $\Lambda$ is produced at rest inside nucleus!
Light hypernuclei

- emulsion data up to mass number $A = 15$
- good measurement of $\Lambda$ binding energies
- increases linearly with mass number
Hypernuclear spectra and levels

- peak structure in pion spectra
- related to single-particle levels of hypernucleus!
- first surprise: tiny spin-orbit splitting for $^{16}_{\Lambda}O$
Hyperon-Nucleon Interaction: Hypernuclei

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Finding Strange Matter

Nuclear and hypernuclear levels in $^{17}_\Lambda$O

- hyperon potential (dotted) is shallower than nucleon potential (solid line)
- Coulomb potential: dot-dashed line
- spin-orbit splitting for hyperons is much smaller than for nucleons
Heavy hypernucleus $^{89}\Lambda Y$

- modern spectroscopy of hypernuclei via reaction: $\pi^+ + n \rightarrow \Lambda + K^+$
- several hypernuclei measured up to $^{208}\Lambda$Pb, measured shells: s, p, d, f, g and h!
- measured with pion, kaon or electron beams or in emulsion
- spin–orbit splitting smaller than experimental resolution
- fit to single particle energies: $U_\Lambda = -27$ MeV for $A \to \infty$
- note: only for the $\Lambda$ (besides nuclei) do we know its in-medium properties!
many light hypernuclei observed in emulsion experiments (up to $A=15$)

heavier systems measured spectroscopically
Hyperon-Nucleon Interaction: Hypernuclei

Baryon-Baryon Interactions: Dibaryons

Finding Strange Matter

HypHI program at GSI (Take Saito et al.)

- exploration of the whole hypernuclear chart for light systems!
- determination of the hypernuclear drip-line
- note: hyperons stabilize nuclei, $^8\text{Be}$ is unbound, but $^9\Lambda\text{Be}$ is bound!
- evidence for $^6\Lambda\text{H}$ by the FINUDA collaboration (2012)!
Hyperons decay mainly by weak interactions: conserves baryon number and charge but changes strangeness by one unit

- $\Lambda \rightarrow p + \pi^-(64\%), \quad n + \pi^0(36\%)$
- $\Sigma^+ \rightarrow p + \pi^0(52\%), \quad n + \pi^+(48\%)$
- $\Sigma^0 \rightarrow \Lambda + \gamma \text{ (electromagnetic)}$
- $\Sigma^- \rightarrow n + \pi^-$
- $\Xi^0 \rightarrow \Lambda + \pi^0$
- $\Xi^- \rightarrow \Lambda + \pi^-$

typical lifetime: $\tau \approx 10^{-10}$ seconds
Hyperons in the medium can also decay non-mesonically:

- $\Lambda + N \rightarrow N + N$, $\Sigma + N \rightarrow N + N$
- $\Xi + N \rightarrow \Sigma + N$ or $\Lambda + N$, $\Lambda + \Lambda \rightarrow \Sigma + N$ or $\Lambda + N$ ...

- nonmesonic decay dominates already for moderate mass number!
- hypernuclear lifetime saturates around 200 ps
Sigma-atomic states

- $\Sigma^-$ bound mainly by Coulomb forces to a nucleus
- slight shift of energy levels due to strong interactions
- $\Sigma$-potential is attractive at low densities but repulsive inside the nucleus → no bound $\Sigma$-hypernuclear states
(Mares, Friedmann, Gal, Jennings 1995)
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**Sigma hypernuclei**

![Graph showing counts/2 MeV vs. energy (MeV).](image)

(Bart et al., PRL 83 (1999) 5238)

- older data: peaks in $\Sigma$-hypernuclear spectra, bound states?
- recent data: no peaks, strongly repulsive $\Sigma$-potential needed to explain spectrum!
indirect measurement of $\Sigma$-nucleon potential by ($\pi^-, K^+$) reaction on $^{28}\text{Si}$: $U_\Sigma \approx +30$ MeV

- depends also on imaginary part of the potential (absorption)

- combining with $\Sigma$-atomic data: need density dependent potential (attractive at low densities, repulsive in the nuclear core)

(Harada and Hirabayashi 2005)
Xi hypernuclei (Dover and Gal 1983)

- first bound $\Xi$ hypernucleus seen in 1959
  (Wilkinson, Lorant, Robinson, Lokanathan, PRL 3 (1959) 397)
- incoming pion beam produces first star
- two short tracks towards south and north: two hypernuclei emitted!
- interpretation: $^8\Xi$B with $B_{\Xi} = 8.1 \pm 1.2$
  (corrected for modern value of $m_\Xi$)
- $\Xi$ reacts via $\Xi + N \rightarrow \Lambda + \Lambda$ to form two hypernuclei

<table>
<thead>
<tr>
<th>Hypernucleus</th>
<th>$B_{\Xi}$ [MeV]</th>
<th>$B_{\Xi0}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8\text{He}$</td>
<td>8.1* ± 1.2</td>
<td>14.2 ± 1.8</td>
</tr>
<tr>
<td>$^1\text{B}$</td>
<td>9.2 ± 2.2</td>
<td>0.4 ± 2.8</td>
</tr>
<tr>
<td>$^1\text{B}$</td>
<td>18.1 ± 3.2</td>
<td>−4.3 ± 3.8</td>
</tr>
<tr>
<td>$^1\text{B}$</td>
<td>16.0 ± 4.7</td>
<td>11.1 ± 5.3</td>
</tr>
<tr>
<td>$^1\text{B}$</td>
<td>16.0 ± 5.5</td>
<td>−4.5 ± 6.1</td>
</tr>
<tr>
<td>$^1\text{B}$</td>
<td>23.2 ± 6.8</td>
<td>13.3 ± 7.4</td>
</tr>
</tbody>
</table>
Xi hypernuclear potential

- double strangeness exchange reaction: \((K^{-}, K^{+})\) deposits two units of strangeness into the nucleus!
- indirect measurement of \(\Xi\)-nucleon potential by \((K^{-}, K^{+})\) reaction on \(^{12}\text{C}\): \(U_{\Xi} \approx -14\ \text{MeV}\) (Khaustov et al. (E885 collaboration) 2000)
- relativistic potential: \(U_{\Xi} \approx -18\ \text{MeV}\)
Xi-$^{14}$N Hypernucleus Event

(Nakazawa et al. 2015)

- E373 experiment at KEK
- production process: $\Xi^- + ^{14}$N $\rightarrow ^{10}$ΛBe + $^5$He
- binding energy of $B_{\Xi^-} = 4.38 \pm 0.25$ MeV
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Finding Strange Matter

### Hypernuclei

- **1963 Danysz et al.:** $^{10}_{\Lambda\Lambda}\text{Be} \rightarrow ^9_{\Lambda}\text{Be} + p + \pi^-$, $\Delta B_{\Lambda\Lambda} = 4.3 \pm 0.4$ MeV
- **1966 Prowse:** $^{6}_{\Lambda\Lambda}\text{He} \rightarrow ^5_{\Lambda}\text{He} + p + \pi^-$, $\Delta B_{\Lambda\Lambda} = 4.7 \pm 0.6$ MeV
- **1991 E176 (KEK):** $^{13}_{\Lambda\Lambda}\text{B} \rightarrow ^{13}_{\Lambda}\text{C} + \pi^-$, $\Delta B_{\Lambda\Lambda} = 4.8 \pm 0.7$ MeV
  (Dover, Millener, Gal, Davis 1991)
- **2001 E373 (KEK):** $^{6}_{\Lambda\Lambda}\text{He} \rightarrow ^5_{\Lambda}\text{He} + p + \pi^-$, $\Delta B_{\Lambda\Lambda} = 1.0 \pm 0.2$ MeV!
- **2001 E906 (BNL):** $^{4}_{\Lambda\Lambda}\text{H} \rightarrow ^4_{\Lambda}\text{He} + \pi^-$ or $^{7}_{\Lambda\Lambda}\text{Li}$ (Randeniya and Hungerford 2007)

- $\Lambda\Lambda$ interaction is weakly attractive
- total binding energy of two $\Lambda$’s: $B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}(^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}(^{A-1}_{\Lambda})$
- additional bond energy: $\Delta B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}(^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}(^{A-1}_{\Lambda})$
Updated world data on $\Lambda\Lambda$ hypernuclei (2011)

<table>
<thead>
<tr>
<th>event</th>
<th>$A^Z_{\Lambda\Lambda}$</th>
<th>$B^{exp}_{\Lambda\Lambda}$</th>
<th>$B^{CM}_{\Lambda\Lambda}$</th>
<th>$B^{SM}_{\Lambda\Lambda}$</th>
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</thead>
<tbody>
<tr>
<td>E373-Nagara</td>
<td>$^6\text{He}$</td>
<td>6.91 ± 0.16</td>
<td>6.91 ± 0.16</td>
<td>6.91 ± 0.16</td>
</tr>
<tr>
<td>E373-DemYan</td>
<td>$^{10}\text{Be}$</td>
<td>14.94 ± 0.13</td>
<td>14.74 ± 0.16</td>
<td>14.97 ± 0.22</td>
</tr>
<tr>
<td>E176-G2</td>
<td>$^{11}\text{Be}$</td>
<td>17.53 ± 0.71</td>
<td>18.23 ± 0.16</td>
<td>18.40 ± 0.28</td>
</tr>
<tr>
<td>E373-Hida</td>
<td>$^{11}\text{Be}$</td>
<td>20.83 ± 1.27</td>
<td>18.23 ± 0.16</td>
<td>18.40 ± 0.28</td>
</tr>
<tr>
<td>E373-Hida</td>
<td>$^{12}\text{Be}$</td>
<td>22.48 ± 1.21</td>
<td>−</td>
<td>20.72 ± 0.20</td>
</tr>
<tr>
<td>E176-E2</td>
<td>$^{12}\text{B}$</td>
<td>20.02 ± 0.78</td>
<td>−</td>
<td>20.85 ± 0.20</td>
</tr>
<tr>
<td>E176-E4</td>
<td>$^{13}\text{B}$</td>
<td>23.4 ± 0.7</td>
<td>−</td>
<td>23.21 ± 0.21</td>
</tr>
</tbody>
</table>

$\dagger B^{SM}_{\Lambda\Lambda}(^{10}\text{Be}) = 2B^0_{\Lambda}(^{9}\text{Be}) + 4[\bar{V}(^{9}\Lambda\text{Be}) - \bar{V}_{\text{average}}] + <V_{\Lambda\Lambda}>_{\text{SM}}.$

- All E176 entries refer to a single event, see NPA 828 (2009) 191.

(Gal and Millener 2011)

- three modern events, comparison to shell model and cluster model calculations
- only uniquely identified double $\Lambda$ hypernucleus: $^6\Lambda\Lambda\text{He}$ !
Summary of Hypernuclear Systems

**NΛ:** attractive $\rightarrow$ Λ-hypernuclei for $A = 3 - 209$
$U_\Lambda = -30$ MeV at $n = n_0$

**NΣ:** $^4_\Sigma$He hypernucleus bound by isospin forces
$\Sigma^-$ atoms: potential is repulsive

**NΞ:** attractive $\rightarrow$ 7 Ξ hypernuclear events
$U_\Xi = -28$ MeV at $n = n_0$
quasi-free production of Ξ: $U_\Xi = -18$ MeV

**ΛΛ:** attractive $\rightarrow$ 5 ΛΛ hypernuclear measurements

**YY:** Y = Λ, Σ, Ξ, unknown!

hypernuclear programs at:
DaΦne, JLab, J-PARC, MAMI, and PANDA, HYPHI @FAIR!
PANDA at GSI: Measurement of double Λ hypernuclei

1. Hyperon-antihyperon production at threshold

2. Slowing down and capture of Λ- in secondary target nucleus

3. γ-spectroscopy with Ge-detectors

- production of Ξ via antiproton beam on nuclei
- capture of Ξ in another nucleus
- γ-spectroscopy of produced double-Λ hypernucleus
Content

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Multi-Quark States: Some History (incomplete)

- multi-quark states already mentioned by Gell-Mann in 1964
- strange four-quark states ($qsq̄s$): Jaffe 1977
- heavy tetraquarks ($QQq̄q̄$): Ader, Richard, Taxil 1982
- pentaquarks with charm ($qqqs̄c$): Lipkin 1987 and Gignoux, Silvestre-Brac, Richard 1987
- ... light pentaquark ($qqqq̄s$) in chiral soliton model: Diakonov, Petrov, Polyakov 1997
- light pentaquark in diquark model: Jaffe and Wilczek 2003
### Classification of Strange Dibaryons

<table>
<thead>
<tr>
<th>$-S \backslash Z$</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>+1</th>
<th>+2</th>
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<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>nn</td>
<td>np</td>
<td>pp</td>
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<td>$\Sigma^-n$</td>
<td>$\Lambda n$</td>
<td>$\Lambda p$</td>
<td>$\Sigma^+p$</td>
</tr>
<tr>
<td>2</td>
<td>$\Sigma^-\Sigma^-$</td>
<td>$\Xi^-n$</td>
<td>$\Lambda\Lambda$</td>
<td>$\Xi^0p$</td>
<td>$\Sigma^+\Sigma^+$</td>
</tr>
<tr>
<td>3</td>
<td>$\Xi^-\Sigma^-$</td>
<td>$\Xi^-\Lambda$</td>
<td>$\Xi^0\Lambda$</td>
<td>$\Xi^0\Sigma^+$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$\Xi^-\Xi^-$</td>
<td>$\Xi^0\Xi^-$</td>
<td>$\Xi^0\Xi^0$</td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>$\Xi^-\Omega^-$</td>
<td>$\Xi^0\Omega^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$\Omega^-\Omega^-$</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

(ordering according to lowest sum of vacuum masses for given strangeness $S$ and charge $Z$)

(JS, C.Greiner, Stöcker 1992, JSB, Dover, Gal, Millener, C.Greiner, Stöcker 1993, 1994)
Hyperon-Nucleon scattering data

(Nagels, Rijken, Yamamoto 2015)

- total $\Lambda p$ cross sections (left), elastic $\Sigma^\pm p$ cross section (middle), inelastic $\Sigma^\pm p$ cross section (right)
- model fits for different Nijmegen models
  (NSC: Nijmegen soft core, ESC: Extended soft core)
- ingredients: one boson exchange of meson nonets, pomeron and odderon exchange, two pseudoscalar exchange, meson pair exchange
Baryon-baryon potentials: SU(3) symmetry

- classify states according to SU(3)
- coupling of two octets:
  \[ 8 \times 8 = 1 + 8 + 8 + 10 + 10^* + 27 \]
- NN has bound state in \(^3S_1 - ^3D_1\) (deuteron) \(\rightarrow \{10^*\}\)
- NN has quasi-bound state in \(^1S_0\) \((E = +90 \text{ keV}) \rightarrow \{27\}\)
- SU(3) symmetry: bound states in all pure \(\{10^*\}\)
- broken SU(3): 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 \(^3S_1, ^1P_1, ^3D_1, \ldots\), while the lower half refers to the space-spin antisymmetric states \(^1S_0, ^3P_1, ^1D_2, \ldots\).

<table>
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<th>(S)</th>
<th>(I)</th>
<th>Channels</th>
<th>SU(3) irreps</th>
</tr>
</thead>
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<td>0</td>
<td>0</td>
<td>(NN)</td>
<td>{10*}</td>
</tr>
<tr>
<td>-1</td>
<td>1/2</td>
<td>(\Lambda N, \Sigma N)</td>
<td>{10*}, {8}_a</td>
</tr>
<tr>
<td></td>
<td>3/2</td>
<td>(\Sigma N)</td>
<td>{10}</td>
</tr>
<tr>
<td>-2</td>
<td>0</td>
<td>(\Xi N)</td>
<td>{8}_a</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>(\Xi N, \Sigma \Sigma)</td>
<td>{10}, {10*}, {8}_a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Sigma \Lambda)</td>
<td>{10}, {10*}</td>
</tr>
<tr>
<td>-3</td>
<td>1/2</td>
<td>(\Xi \Lambda, \Xi \Sigma)</td>
<td>{10}, {10*}</td>
</tr>
<tr>
<td></td>
<td>3/2</td>
<td>(\Xi \Sigma)</td>
<td>{8}_a</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>(\Xi \Xi)</td>
<td>{10}</td>
</tr>
</tbody>
</table>

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<td></td>
<td>3/2</td>
<td>(\Sigma N)</td>
<td>{27}</td>
</tr>
<tr>
<td>-2</td>
<td>0</td>
<td>(\Lambda \Lambda, \Xi N, \Sigma \Sigma)</td>
<td>{27}, {8}_a, {1}</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>(\Xi N, \Sigma \Lambda)</td>
<td>{27}, {8}_a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(\Sigma \Sigma)</td>
<td>{27}</td>
</tr>
<tr>
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<td>1/2</td>
<td>(\Xi \Lambda, \Xi \Sigma)</td>
<td>{27}, {8}_a</td>
</tr>
<tr>
<td></td>
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<td>(\Xi \Sigma)</td>
<td>{27}</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>(\Xi \Xi)</td>
<td>{27}</td>
</tr>
</tbody>
</table>

(Stoks and Rijken 1999)
Baryon-baryon potentials: Nijmegen soft-core models

- Nijmegen soft core model NSC97a-f (newer versions of extended soft-core model: ESC04-08)
- one-boson exchange model for pseudoscalar, scalar, and vector mesons
- uses SU(3) flavour symmetry
- fitted to NN and NY scattering data
- predictions for dibaryons (Stoks, Rijken 1999):

  \[\Sigma^+ p, \Sigma^- n: \text{quasibound state}\]
  \[\Sigma^+ \Sigma^+, \Sigma^- \Sigma^-: E_b = -1.5 \text{ to } -3.2 \text{ MeV}\]
  \[\Xi^0 \Sigma^+, \Xi^- \Sigma^-: E_b = -2 \text{ to } -17 \text{ MeV}\]
  \[\Xi^0 \Xi^0, \Xi^0 \Xi^-: E_b = +1 \text{ to } -16 \text{ MeV}\]
  \[\Xi^- \Xi^-: \text{less bound by } \approx 1 \text{ MeV}\]

update: N\Xi(3S_1, I = 1) with \(E_b = 1.56 \text{ MeV}\)
(ESC08, Nagels, Rijken, Yamamoto 2015)
Baryon-baryon potentials: Quark-meson models

- quark-meson exchange model
- uses confinement potential for quarks
- SU(3) symmetry for quark-meson coupling constants
- describes light hypernuclei
- predictions for dibaryons
  (Fujiwara, Suzuki, Nakamoto 2007):

  no bound states
Baryon-baryon potentials: chiral effective models

- one-boson exchange of pseudoscalar mesons plus contact terms
- uses SU(3) symmetry, low-energy constants
- fixed to NN and NY scattering data
- predictions for dibaryons
  (Haidenbauer and Meißner 2010):

\[
\begin{align*}
\Xi^0 \Lambda: & \quad E_b = -0.43 \text{ MeV or quasibound} \\
\Xi^0 \Sigma^+: & \quad E_b = -2.23 \text{ to } -6.15 \text{ MeV} \\
\Xi \Xi: & \quad E_b = -2.56 \text{ to } -7.28 \text{ MeV}
\end{align*}
\]

results depend on cutoff
News from Lattice Data on Dibaryons

- HALQCD collaboration (Inoue et al. 2010, 2011): bound H-dibaryon with $B_H = 26$ MeV (for $m_{ps} = 469$ MeV, $N_f = 3$)

- NPLQCD collaboration (Beane et al. 2010, 2011): bound H-dibaryon with $B_H = 13.2(1.8)(4.0)$ MeV and bound ($\Xi^-\Xi^-)_b$ state with $B_{\Xi\Xi} = 14.0(1.4)(6.7)$ MeV (for $m_{\pi} = 390$ MeV, $N_f = 2 + 1$)

- Haidenbauer and Meißner 2011: either \Lambda\Lambda is unbound (HALQCD) or a resonant state 5 MeV below $\Xi N$ threshold (NPLQCD)

- Shanahan, Thomas, Young 2011, 2013: H dibaryon unbound by $26 \pm 11$ MeV at physical pion mass
**nΣ^- state on the Lattice**

- scattering length for singlet and triplet $nΣ^-$ (left plots)
- repulsive potential at nonvanishing density (right plot)
- at unphysical pion mass of $m_\pi \sim 390$ MeV
- comparison to Nijmegen model, Jülich model and effective field theory

(See Beane et al. 2012)
Hypernuclei on the Lattice

(Beane et al. 2013)

- Light nuclei and hypernuclei on the lattice
- at unphysical pion mass of $m_\pi \sim 800$ MeV and in SU(3) flavor symmetry
Dibaryon on the Lattice

- bound $\Xi^-\Xi^-_b$ state with $B_{\Xi\Xi} = 14.0(1.4)(6.7)$ MeV (for $m_\pi = 390$ MeV)
- extrapolation to physical pion mass: $\Xi\Xi$ dibaryon bound by $-2.56 \cdots - 7.27$ MeV!
- NSC97a-f: Nijmegen OBE model, HM: Haidenbauer and Meißner chiral EFT, Miller: SU(3) flavor symmetry arguments
Dibaryons close to physical point

- preliminary $N_f = 2 + 1$ lattice calculation at $(m_\pi, m_K) \simeq (146, 525)$ almost at physical masses
- phase shifts (left) and potential (right) for $\Xi\Xi$
- $\Xi\Xi$ interaction with strong attraction but not enough for a bound state
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Timeline for strange matter detection

**Timescales**

**Heavy-ion collision and strange matter:**
- MEMO's
- Strangelets
- Short-lived
- Long-lived
- $E_{96}(H)$
- $E_{64}$, NASA

**Hot & dense matter**
- Reaction
- Separation
- Distillation

**Strong interactions**

**Weak interactions**

$$10^{-23} \quad 10^{-22} \quad 10^{-21}$$

$$10^{-10} \quad \Lambda \rightarrow N + \pi \quad 10^{-7} \quad 10^{-5} \quad 10^{-4} \quad t/s$$

$$Q \rightarrow Q' + \pi, N, Y$$

$$Q \rightarrow Q' + e + \nu_e$$

$$10^{-10} \quad 10^{-7}$$
Sensitivity range for detecting strange matter

(Dover, talk given at PANIC meeting 1991, preprint BNL-46322)

- rough coalescence estimate:
  production $\propto q^A \cdot \lambda^{\mid S\mid}$, $q = N_d/N_p$, $\lambda = N_Y/N_N$
- for a sensitivity of the experiment of $10^{-n}$: $\mid S\mid + A \leq n + 3$
- includes (stable) dibaryon states!
Production of hypernuclei in heavy-ion collisions

- Production of $^3\Lambda\text{H}$ and $^4\Lambda\text{H}$ seen!
- Decay modes: $^3\Lambda\text{H} \rightarrow ^3\text{He} + \pi^-$, $^4\Lambda\text{H} \rightarrow ^4\text{He} + \pi^-$
- Historical note: last paper of Carl Dover (posthumous)!
Fishing hypernuclei out of the QGP at RHIC

- production of $^3\Lambda$H and its antiparticle seen
- measurement of invariant mass spectrum of $\pi^-$ and $^3$He
- initiated follow-up experiments at GSI (FOPI) and LHC (ALICE)!
H-Dibaryon Production Rates at the LHC

Pb-Pb | $s_{NN} = 2.76$ TeV
13.8 million events (0-80% central)

- data
- syst. error
- injected signal ($m_H = 2.21$ GeV/$c^2$)
- syst. error ($m_H = 2.21$ GeV/$c^2$)
- injected signal ($m_H = 2.23$ GeV/$c^2$)
- syst. error ($m_H = 2.23$ GeV/$c^2$)

(Benjamin Doenigus for the ALICE collaboration, QM2012)

- production limit for H-Dibaryons from $Λpπ^−$ mass spectrum
- limit is about a factor 10 below prediction from statistical model!
Hypernuclear production at the LHC

(ALICE collaboration 2015)

- invariant mass distribution for $^3\text{He},\pi^-$
- $dN/dy \times B.R.(^3\Lambda\rightarrow ^3\text{He},\pi^-) = (3.86 \pm 0.77(\text{stat.}) \pm 0.68(\text{syst.})) \times 10^{-5}$
ΛΛ correlation function

ΛΛ correlation function measured by STAR (Au+Au at 200 AGeV)
fit with hydro expansion and correction from feed down from Σ^0 and other hyperons
residual suppression at high values of Q \sim 0.4 (?)
**ΛΛ scattering parameters**

(Ohnishi, Morita, Furumoto, 2016)

- Scattering parameters for ΛΛ for different interactions
- STAR data without feed down corrections
- Feed down corrections: yellow area (offset $\lambda = 0.67$)
- LL: Lednicky & Lyuboshits model
How to detect strange matter?

- unique opportunity to produce and study them in heavy-ion collisions
- tracking down strange dibaryons by:
  - (A) a direct look: exotic decay tracks in TPC
  - (B) backtracking: invariant mass spectra for bound dibaryons
  - (C) correlations: resonances seen in correlation functions, reveals interaction potential
- poised for discoveries!