Chiral RMF Study of Ξ hypernuclei and hyperatom

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Chiral symmetric RMF

- Relativistic Mean Field model
  - Hadronic model which is very powerful to investigate nuclear matter and finite nuclei.
  - Flavor symmetry and chiral symmetry work as constraints to B-M coupling and meson self-interaction.
- Problems in chiral symmetric RMF model
  1. Sudden chiral restoration below ρ_0
  2. Too stiff EOS
  3. Instability at large chiral condensate

[1] KT-Ohnishi, nucl-th/0607046. [2] Matsui-Serot, AP 144 (1982) 107.
[3] Ogawa et al, PTP 111 (2004) 75. [4] Boguta, PLB 120 (1983) 34.
[5] Kawamoto-Smit, NPB 192 (1981) 100.
[6] Sugahara-Toki, NPA 579 (1994) 557.

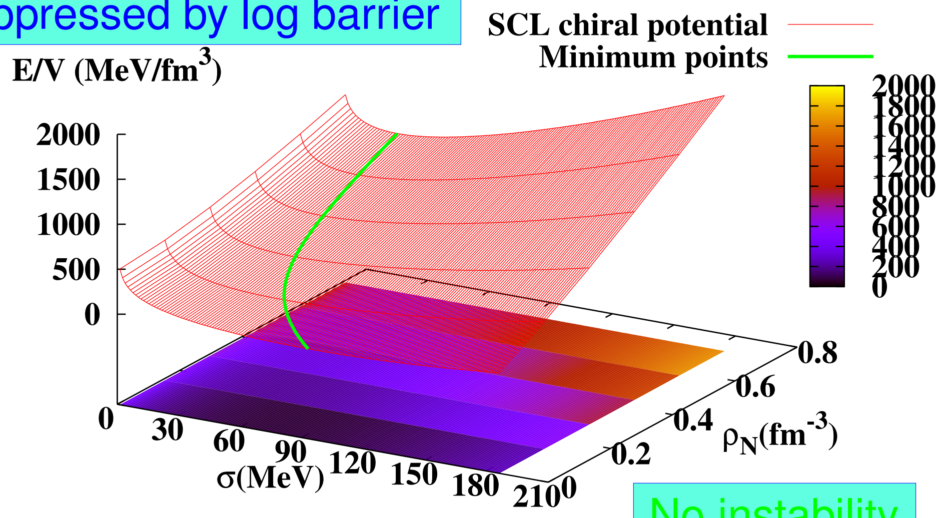
Chiral symmetric RMF

- We use scalar meson self-interaction derived from Strong Coupling Limit Lattice QCD [5]

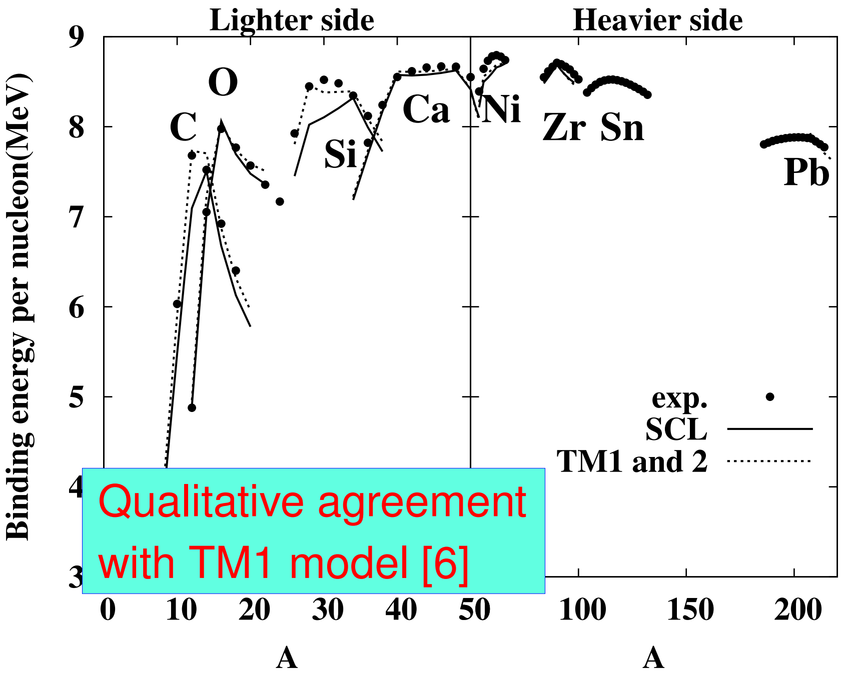
$$U_\sigma = -\,a\log(\det M_{\mathrm{SU(2)}}M^\dagger_{\mathrm{SU(2)}}) + b\,\mathrm{tr}(M_{\mathrm{SU(2)}}M^\dagger_{\mathrm{SU(2)}}) + c_\sigma\sigma$$

$$= -\,2a\left\{\log\left(1+\frac{\sigma}{f_\pi}\right)+\frac{\sigma}{f_\pi}-\frac{1}{2}\left(\frac{\sigma}{f_\pi}\right)\right\}+\frac{1}{2}m_\sigma^2\sigma^2+\frac{1}{2}m_\pi^2\pi^2$$

Sudden chiral restoration: suppressed by log barrier



No instability



Qualitative agreement with TM1 model [6]

Chiral SU(3) model

- Application to systems including hyperon
  - Needed to include ζ and ϕ_0 meson.
  - How to treat the interaction among ζ meson?
  - Our stance: simple extension from chiral SU(2) one.

$$U_{\sigma\zeta} = -\frac{a}{2}\log\det\left(M^\dagger M\right) + b\mathrm{tr}\left(M^\dagger M\right) + \overset{\text{ECSB}}{\boxed{C_\sigma\sigma + C_\zeta\zeta}} + \overset{\text{U}_A\text{(1) anomaly}}{\boxed{d\left(\det M + \det M^\dagger\right)}}$$

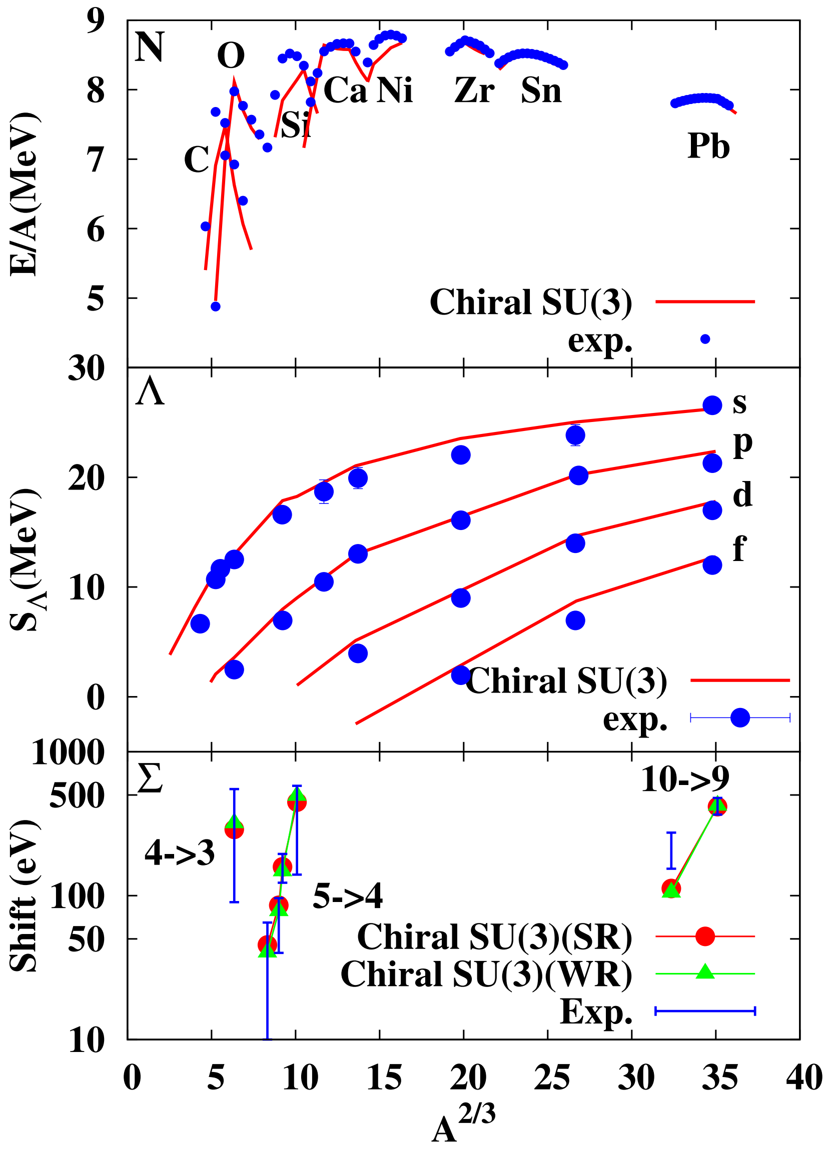
$$= \underbrace{-a\left[\left\{\log\left(1+\frac{\sigma}{f_\pi}\right) + \frac{\sigma}{f_\pi} - \frac{\sigma^2}{2f_\pi}\right\} + \frac{1}{2}\left\{\log\left(1+\frac{\sigma}{f_\zeta}\right) + \frac{\sigma}{f_\zeta} - \frac{\zeta^2}{2f_\zeta}\right\}\right]}_{V_{\sigma\zeta}}$$

$$+\frac{m_\sigma^2}{2}\sigma^2 + \frac{m_\zeta^2}{2}\zeta^2 + \xi_{\sigma\zeta}\sigma\zeta + \frac{m_\pi^2}{2}\pi^2 + \frac{m_K^2}{2}K^2$$

$$\mathcal{L}^{\text{SCL-SU(3)}} = \mathcal{L}^{\text{SU(3) baryon}} + \mathcal{L}^{\text{SU(3) meson}} + V_{\sigma\zeta} + \xi_{\sigma\zeta}\sigma\zeta + D_\omega\omega^4$$

  - B-M_v coupling constants: decided by SU$_f$(3) symmetry relation.

Hypernuclei in Chiral SU(3) RMF



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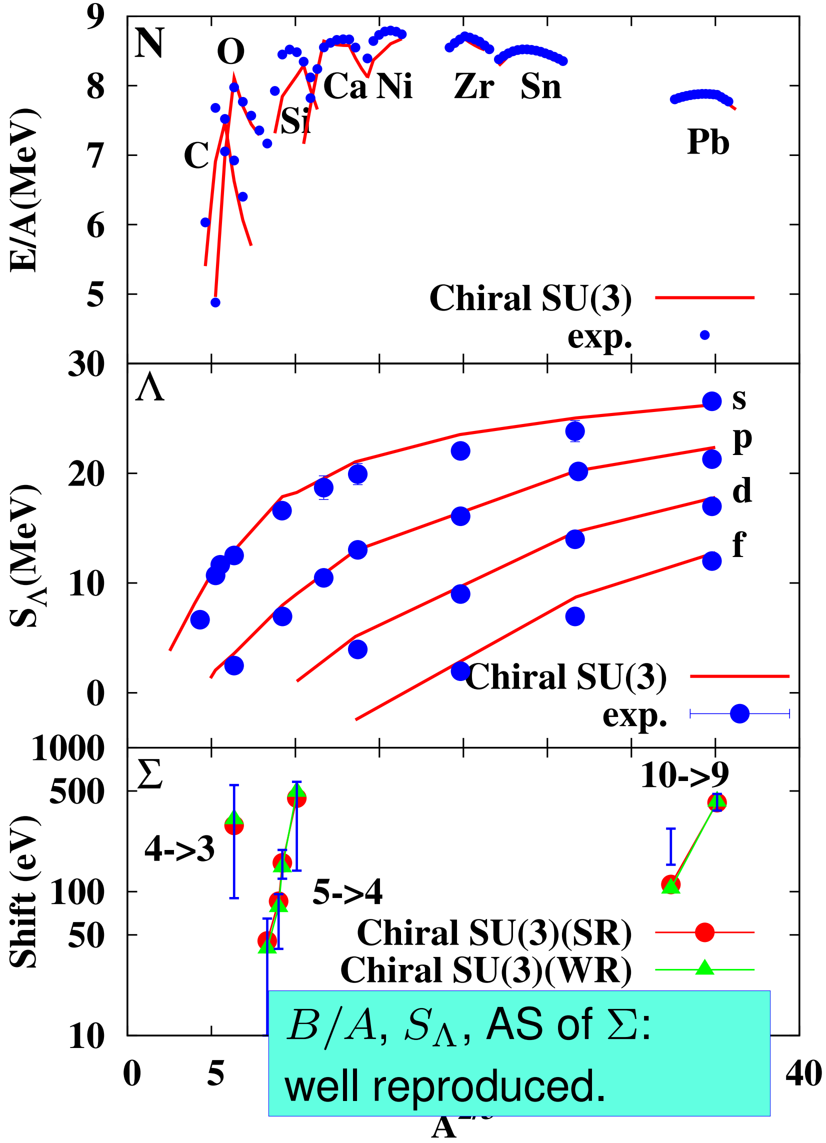
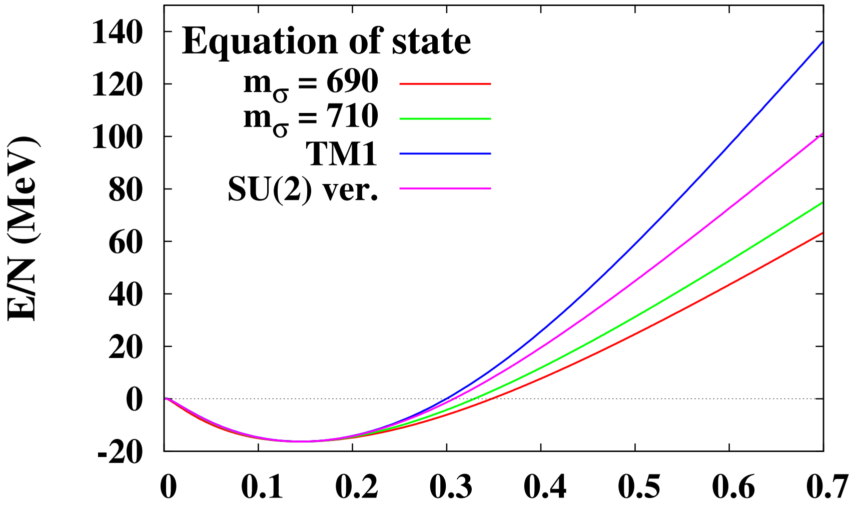
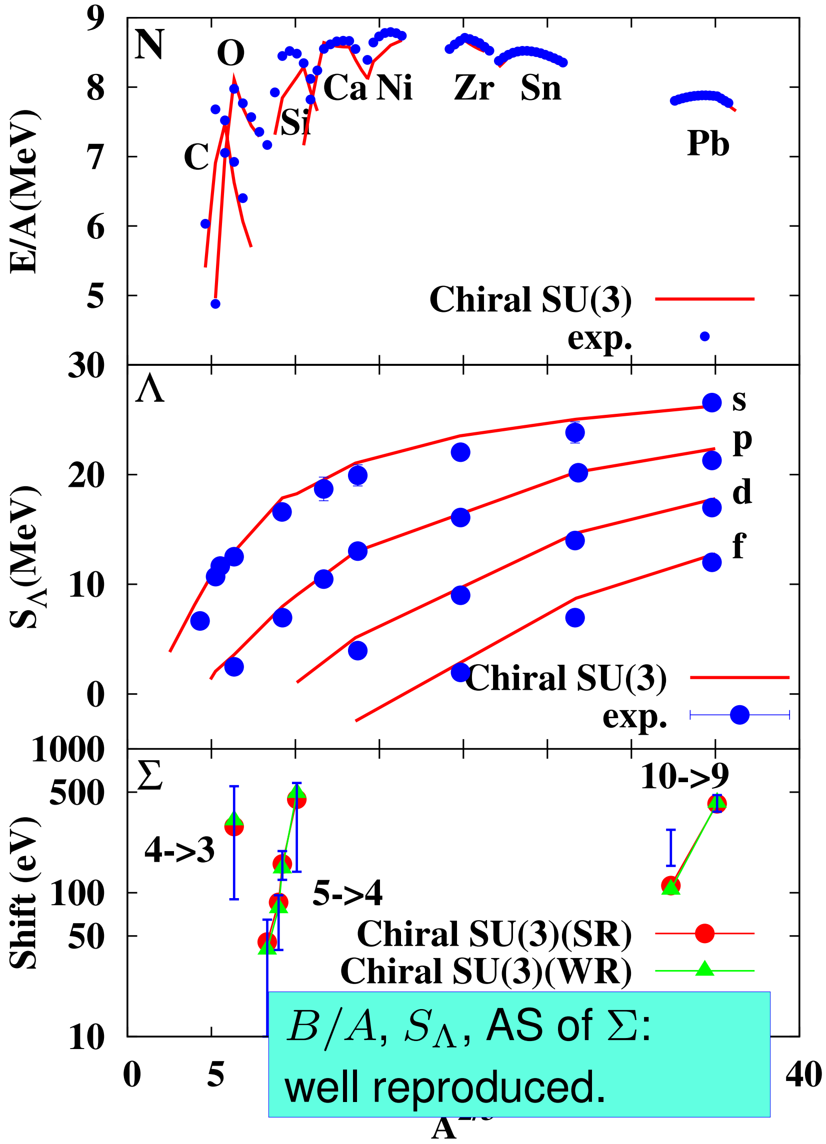


B/A, S_Λ, AS of Σ: well reproduced.

Hypernuclei in Chiral SU(3) RMF



$K \sim 0.8 K_{\text{SU(2)}} \sim 220$MeV



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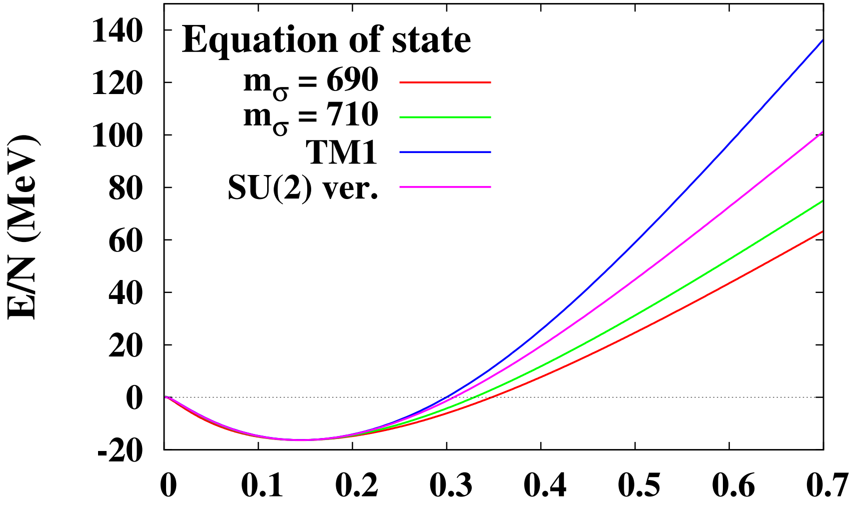
Hypernuclei in Chiral SU(3) RMF



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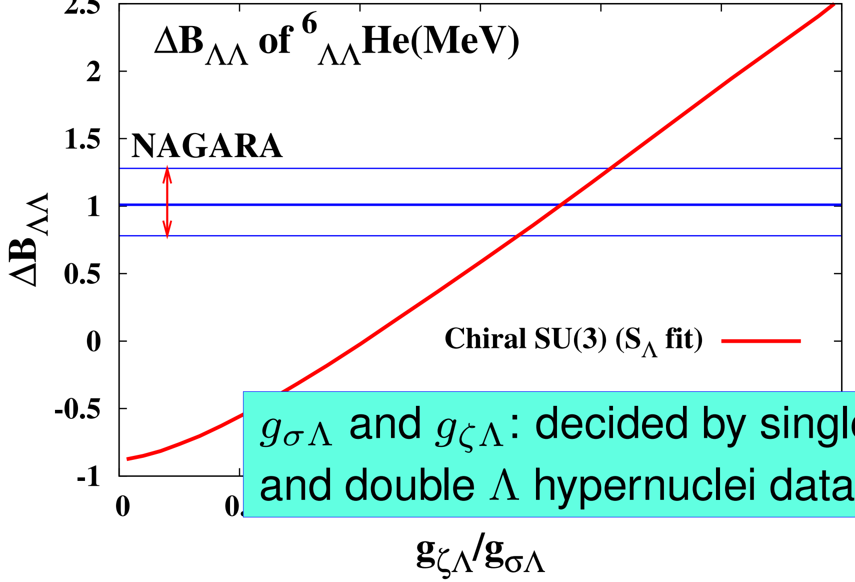
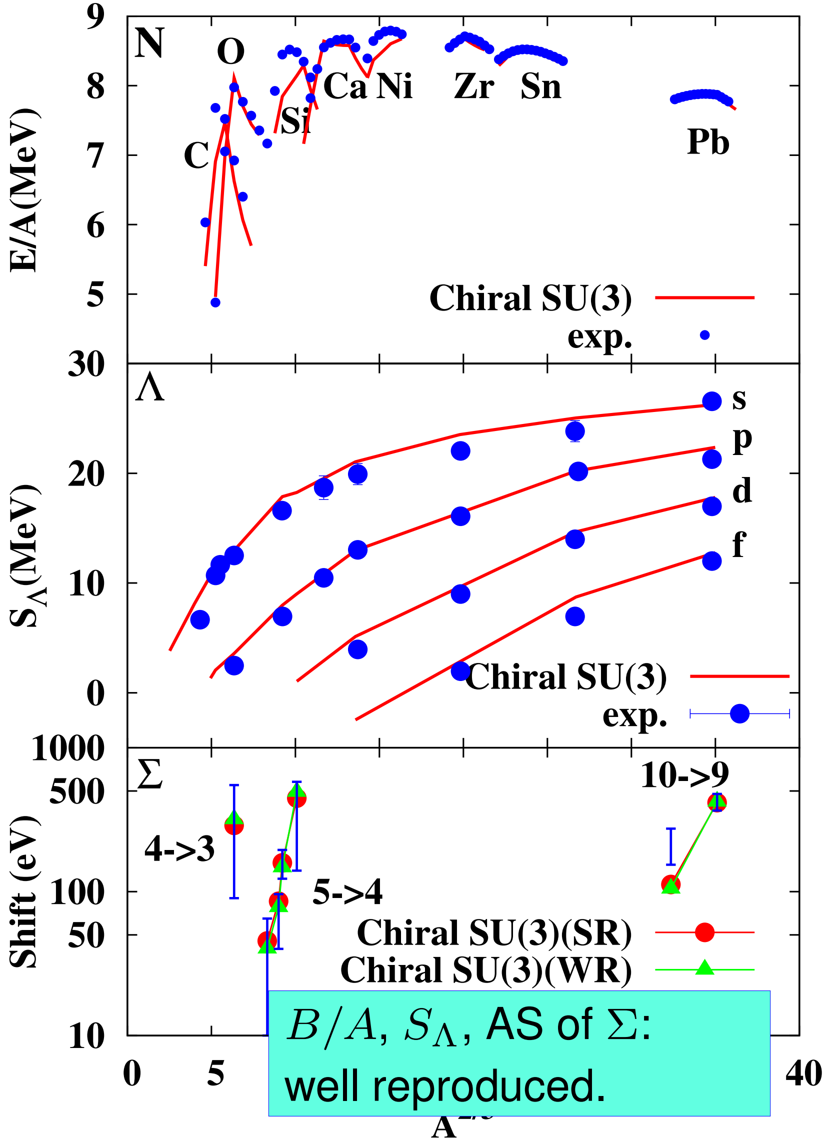


$g_{\sigma\Lambda}$ and $g_{\zeta\Lambda}$: decided by single and double Λ hypernuclei data.



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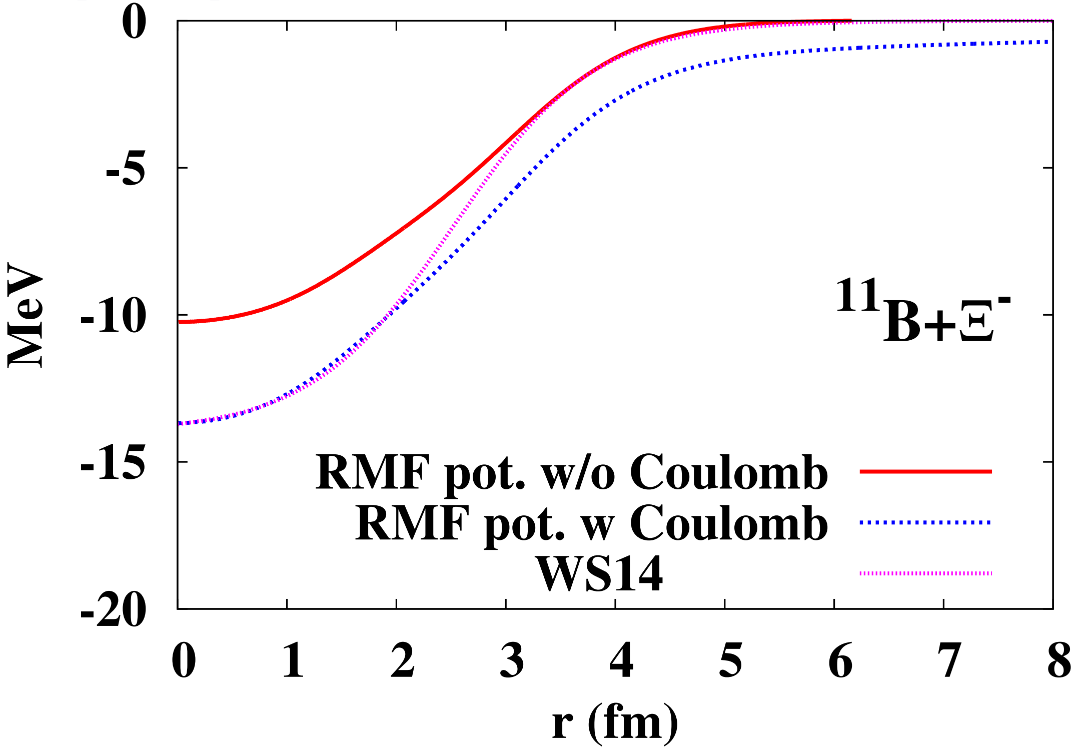
ΞN potential

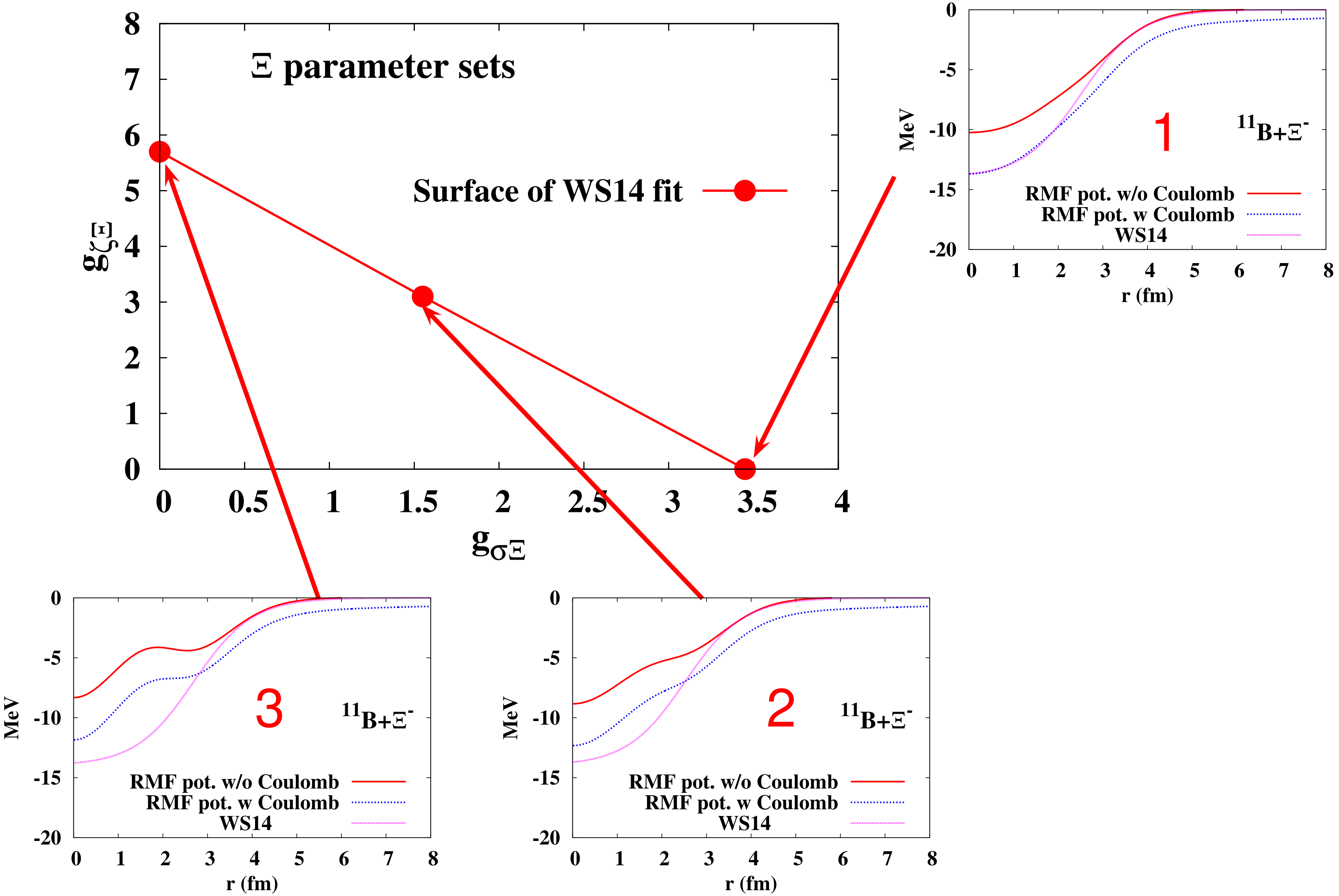
- How to resolve couplings about Ξ: agreement between RMF potential and Woods-Saxon -14MeV [7, 8] around surface.



[7] Fukuda et al., PRC 58 (1998) 1306.

[8] Khaustov et al., PRC 61 (2000) 054603.

ΞN potential



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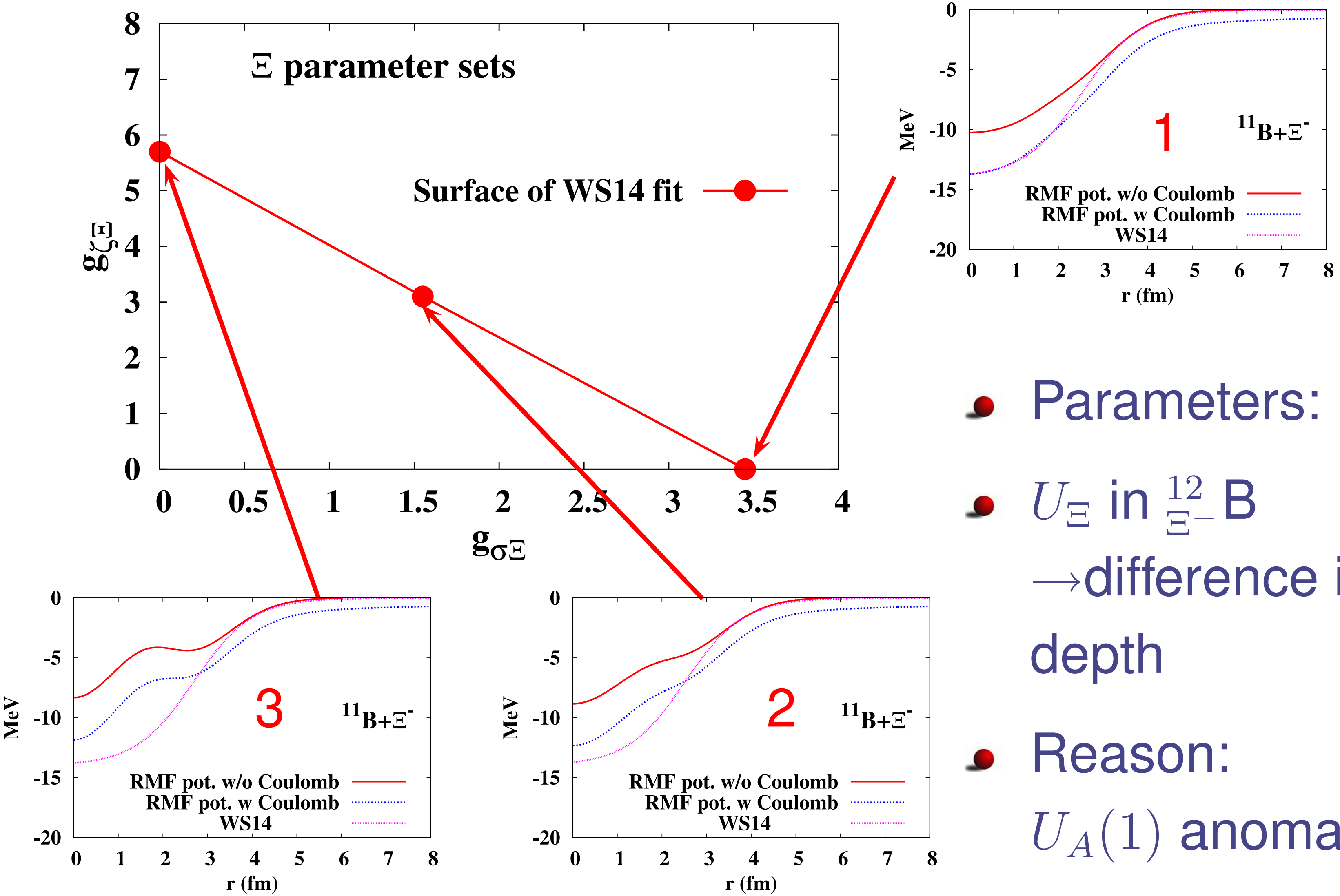
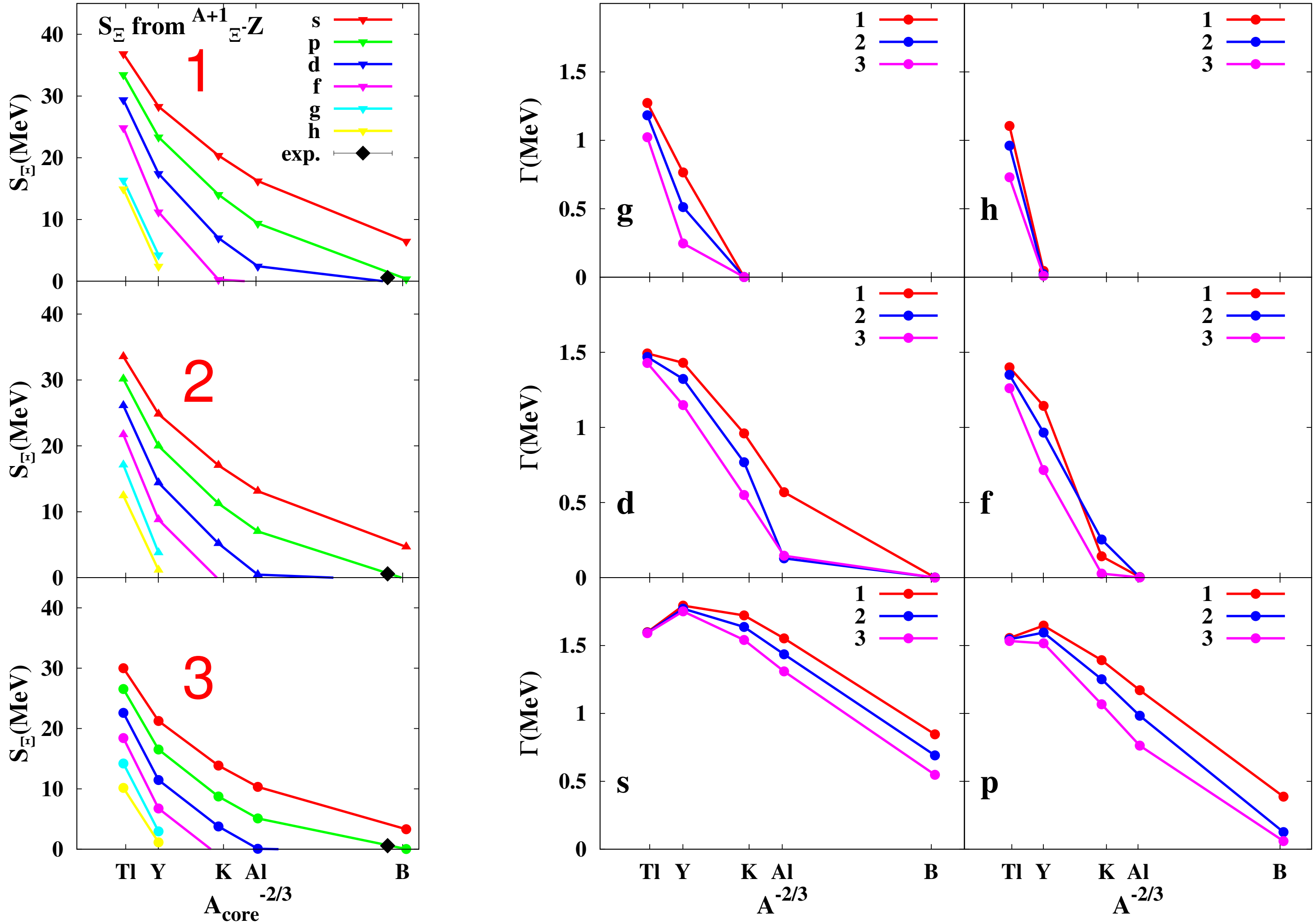


- Parameters: linear.
- U_Ξ in ${}^{12}_{\Xi^-}$B →difference in their depth
- Reason: $U_A(1)$ anomaly

Ξ hypernuclei

$$(\mathrm{Im}U_\Xi = \frac{\rho_p}{\rho_0/2} \times 1\mathrm{MeV})$$



[9] Aoki et al., PTP 89 (1993) 493.

[10] Aoki et al., PLB 355 (1995) 45.

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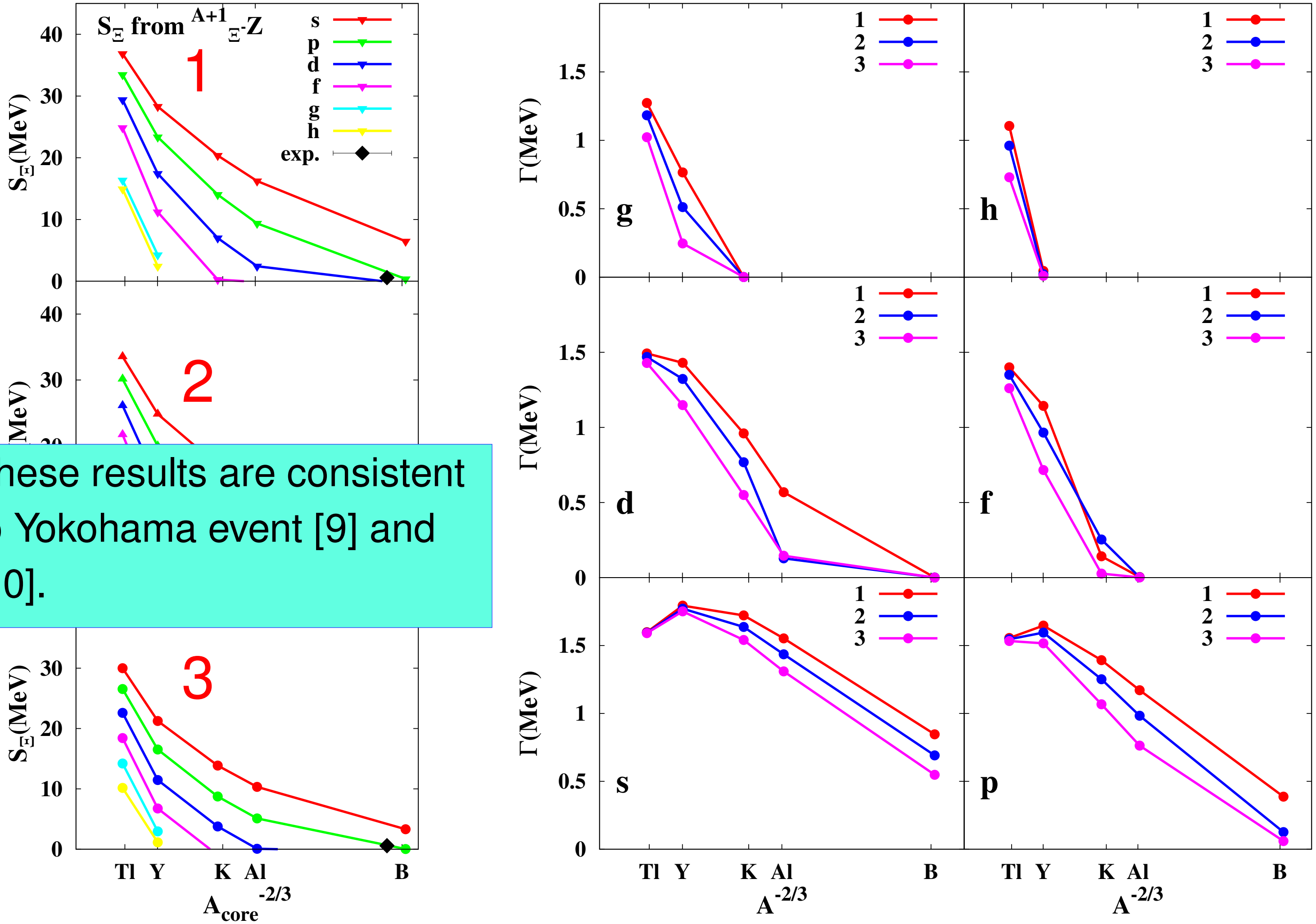

These results are consistent to Yokohama event [9] and [10].

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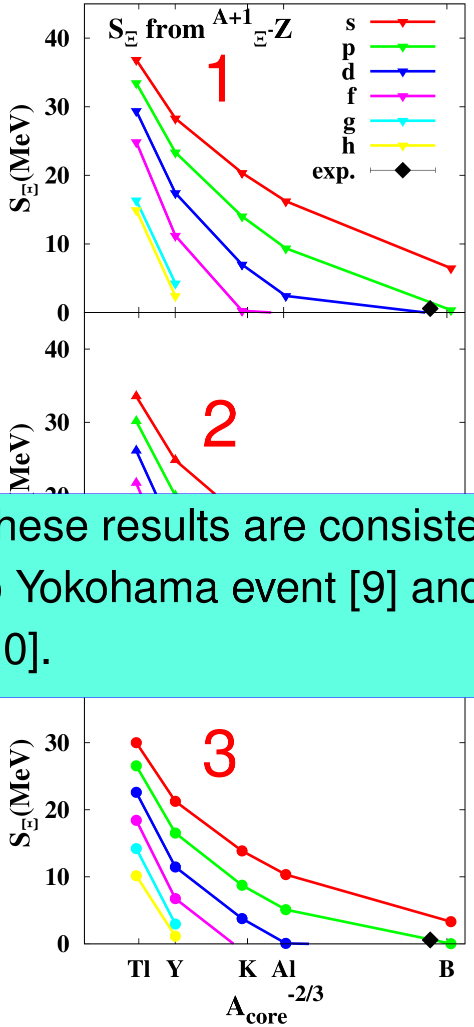

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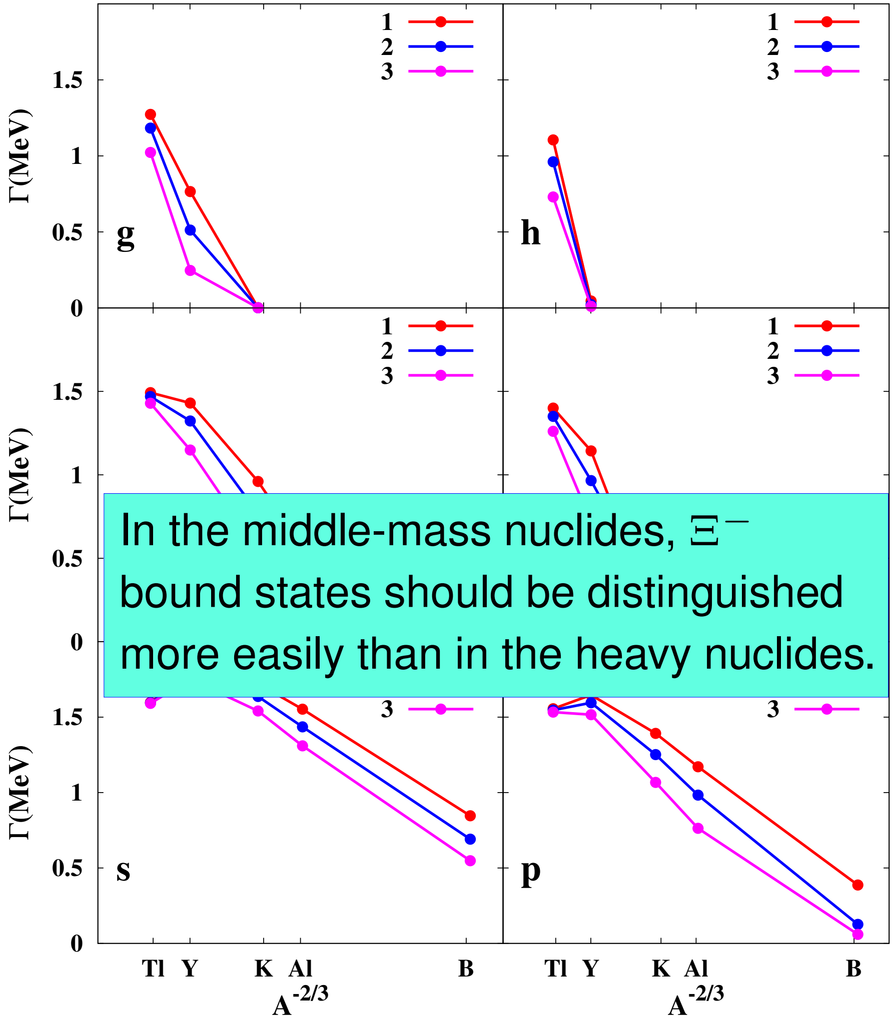

In the middle-mass nuclides, Ξ^- bound states should be distinguished more easily than in the heavy nuclides.

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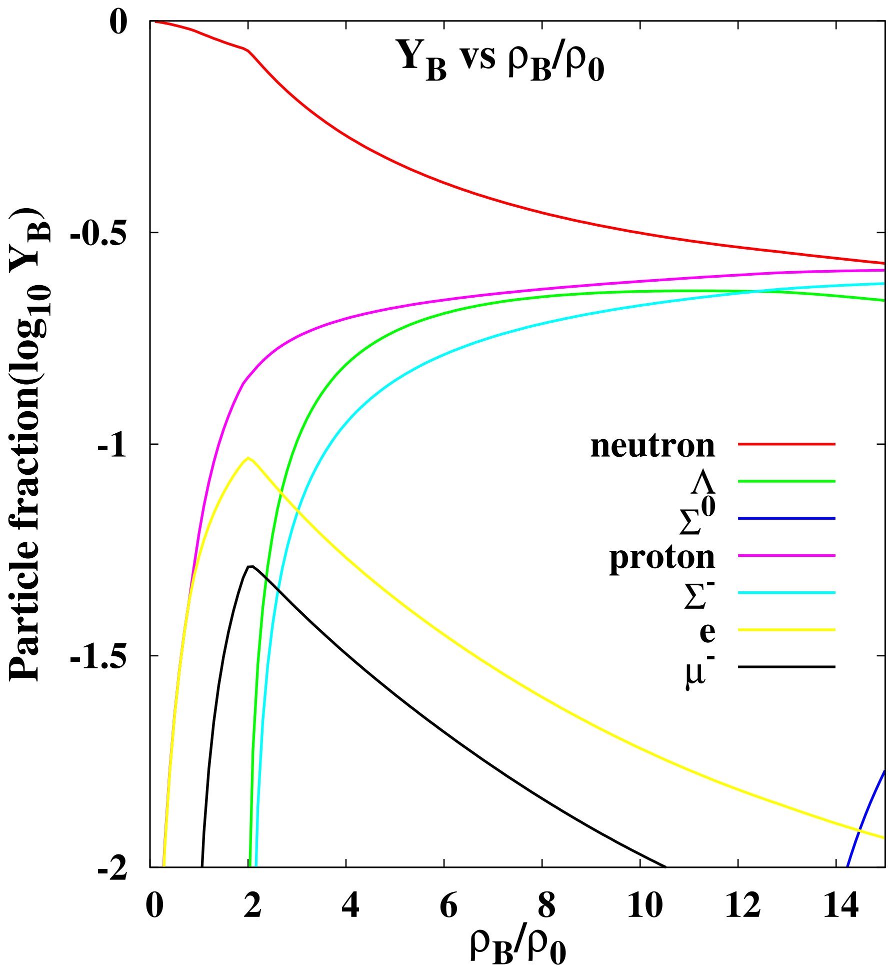
T=0 dense matter(preliminary)



- $T = 0$ EOS including charge neutrality and β-equilibrium without ν
- Σ^+, Ξ^0 and Ξ^- can't appear even if ρ_B rises and rises.
- $g_{\phi\Xi}$ given by SU$_f$(3) coupling: biggest value in couplings about Ξ ↔ small effect in determining attractive potential in Ξ hypernuclei.

Summary

- Ξ hypernuclei in a RMF model with Chiral SU(3) symmetric interaction + SU$_f$(3) coupling rule
  - $\sigma\zeta$ mixing derived from $U_A(1)$ anomaly leads wide variety in S_Ξ
  - Conversion width on $\Xi^- p \to nn$: In middle-mass nuclides, there may be hope that Ξ^- bound states will be detected more easily than in heavy nuclides.
- $g_{\phi\Xi}$ given by SU$_f$(3) coupling suppresses existences of Ξ^0 and $\Xi^- \leftrightarrow \Xi$ potential may be repulsive in strangeness-rich environment.

Future works

- Check a consistency between quasi-free spectrum.
  - We have investigated Σ^- and Ξ^- quasi-free spectrum with DWIA+Local Optimized Fermi Average [11].
- Including a_0 meson to chiral RMF model
  - a_0:chiral partner of ρ and needed to be included when we apply RMF model for neutron-rich nuclei.
  - That may cure large SU$_f$(3) symmetry breaking in B-M_v coupling constants.
  - Larger $g_{\rho B}$ will be a key about supporting the maximum neutron star mass $2.1m_\odot$ if EOS includes hyperon.

That’s all.

Thank you for your attention!

B-M_v coupling constants

- SU$_v$(3) coupling relation

$$\mathcal{L}_{\text{B-M}} = \sqrt{2}\left(g_s \mathrm{tr}(M)\mathrm{tr}(\bar{B}B) + g_1 \mathrm{tr}(\bar{B}MB) + g_2 \mathrm{tr}(\bar{B}BM)\right)$$

$$g_{\omega\Lambda} = \frac{5}{6}g_{\omega N} - \frac{1}{2}g_{\rho N}, \quad g_{\phi\Lambda} = \frac{\sqrt{2}}{3}\left(g_{\omega N} + 3g_{\rho N}\right)$$

$$g_{\omega\Sigma} = g_{\rho\Sigma} = \frac{g_{\phi\Xi}}{\sqrt{2}} = \frac{1}{2}(g_{\omega N} + g_{\rho N})$$

$$g_{\omega\Xi} = g_{\rho\Xi} = \frac{g_{\phi\Sigma}}{\sqrt{2}} = \frac{1}{2}(g_{\omega N} - g_{\rho N})$$

$$g_{\sigma\Xi} = \frac{2}{3}g_{\sigma N} - \frac{\sqrt{2}}{2}g_{\zeta\Lambda}, \quad g_{\zeta\Xi} = \frac{1}{3}g_{\sigma N} + \frac{\sqrt{2}}{2}g_{\zeta\Lambda}$$

  - Coupling constants between vector mesons and hyperons: given by fixing couplings between vector mesons and nucleons.

B-M_v coupling constants

- SU$_v$(3) coupling relation

$$\mathcal{L}_{\text{B-M}} = \sqrt{2}\left(g_s \mathrm{tr}(M)\mathrm{tr}(\bar{B}B) + g_1 \mathrm{tr}(\bar{B}MB) + g_2 \mathrm{tr}(\bar{B}BM)\right)$$

$$g_{\omega\Lambda} = \frac{5}{\;} g_{\omega N} - \frac{1}{\;} g_{\rho N}, \quad g_{\phi\Lambda} = \frac{\sqrt{2}}{\;}\left(g_{\omega N} + 3 g_{\rho N}\right)$$

$$g_{\sigma\Xi} \quad \frac{\;}{3} g_{\sigma N} \quad \frac{\;}{2} g_{\zeta\Lambda}, \quad g_{\zeta\Xi} \quad \frac{\;}{3} g_{\sigma N} + \frac{\;}{2} g_{\zeta\Lambda}$$

- Parameters: $g_{\omega N}$, $g_{\rho N}$, $g_{\sigma Y}$, $g_{\zeta Y}$, D_ω and m_σ → decided so as to reproduce symmetric nuclear matter, normal nuclei, and hypernuclear data.
- ○: Λ hypernucleus, △: Atomic Shift in Σ^-

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References

[1] KT-AO, nucl-th:0607046.

[2] Matsui-Serot, AP 144 (1982) 107.

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[10] Aoki et al., PLB 355 (1995) 45.

[11] Maekawa-KT-Ohnishi, arXiv:0704.3929.