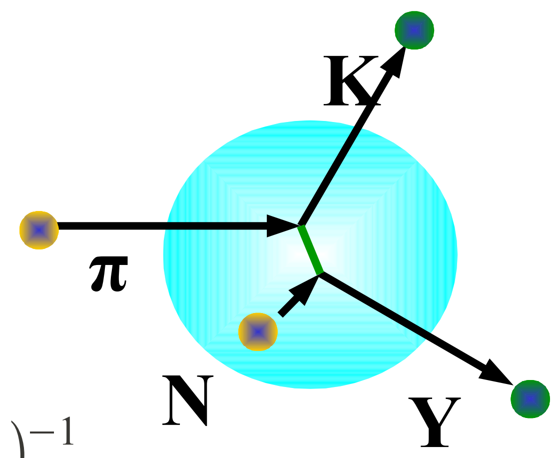
直接反応とハイペロン - 原子核ポテンシャル

Impulse Approximation (1)

- **短時間の反応であれば**
  入射粒子と核の反応 ～ Σ (入射粒子と核内核子の反応)
  → Impulse 近似
- **Lippmann-Schwinger 方程式**
  (potential 問題)



$$\Psi^{(+)} = \phi + \hat{G}_0 \hat{V} \Psi^{(+)}$$

$$\hat{H} = \hat{K} + \hat{V}, \quad \phi = \exp(i \vec{k}_i \cdot \vec{r}), \quad \hat{G}_0 = (E - \hat{K} + i\varepsilon)^{-1}$$

- **Green's function**

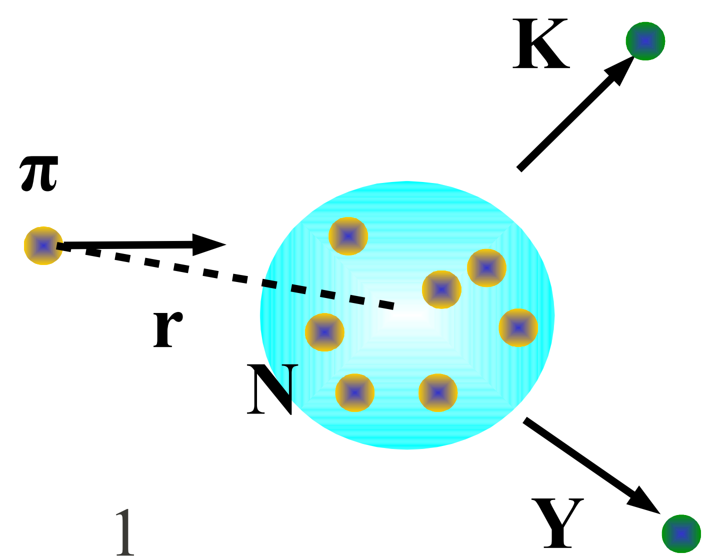
$$G_0(\vec{r}, \vec{r}\,') = -\frac{2m}{\hbar^2} \frac{1}{4\pi} \frac{e^{ikr}}{r} \quad \rightarrow \quad f(\theta) = -\frac{2m}{\hbar^2} \frac{1}{4\pi} \langle \vec{k}_f | \hat{V} | \Psi^{(+)} \rangle$$

- **T-matrix (transition matrix)**

$$\langle \vec{k}_f | \hat{T} | \vec{k}_i \rangle \equiv \langle \vec{k}_f | \hat{V} | \Psi^{(+)} \rangle \quad \rightarrow \quad \hat{T} = \hat{V} + \hat{V} \hat{G}_0 \hat{T}$$

- **ハドロン - 核反応**

$$\hat{H} = \sum_i \hat{K}_i + \frac{1}{2}\sum_{ij} v_{ij}$$
$$= \hat{K}(\vec{r}) + \hat{H}_A(\xi) + \sum_{i=1}^{A} v(\vec{r}-\vec{r}_i)$$
$$= \hat{H}_0 + \hat{V}$$



$$\hat{T} = \hat{V} + \hat{V}\hat{G}_0\hat{T} \quad , \quad \hat{G}_0 = \frac{1}{E-\hat{H}_0+i\varepsilon} = \frac{1}{E-\hat{H}_A-\hat{K}+i\varepsilon}$$

形式的にはポテンシャル問題と同じだが、多体問題なのでそのままでは解けない。

- **方針: T を核内核子との散乱振幅 τ_i で表し、最後に i と散乱した振幅 T_i の和で T を求める。**

$$\tau_i = v_i + v_i G_0 \tau_i \quad , \quad T_i = v_i + v_i G_0 T \quad , \quad T = \sum_i T_i$$

$$\rightarrow T = \sum_i T_i = \sum_i \tau_i + \sum_i \tau_i G_0 \sum_{j\neq i} T_j$$

Impulse Approximation (3)

- 近似的取扱い
  - 近似１：質量数が大きいとして、O(1/A) を無視する。

$$\sum_{j\neq i} T_j \simeq T \to T = \tilde{T} + \tilde{T} G_0 T \quad \left(\tilde{T} = \sum_i \tau_i\right)$$

  - 近似２：核子波動関数は反対称化されているので、どの T_i も同じ。
    (Kerman-McManus-Thaler の多重散乱理論)

$$\sum_{j\neq i} T_j \simeq \frac{A-1}{A} T \to T' = \tilde{T}' + \tilde{T}' G_0 T' \quad \left(\tilde{T}' = \frac{A-1}{A} \sum_i \tau_i, T' = \frac{A-1}{A} T\right)$$

いずれの場合も、$\Sigma\, \tau_i$ は光学ポテンシャルの役割を果たす

- Impulse approximation $\quad T \simeq \sum_i \tau_i \simeq \sum_i t_i$
  - 1段階反応を仮定
  - 核内２体散乱振幅を自由空間の散乱振幅と同じと仮定

断面積と有効核子数 (1)

- **Fermi's Golden Rule**

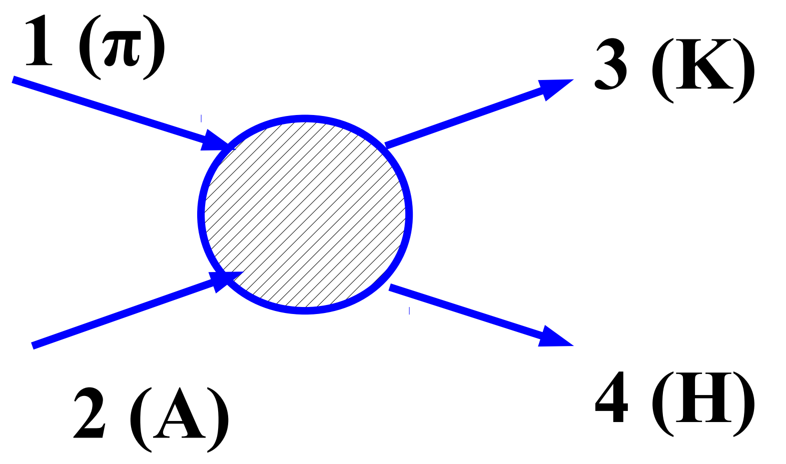
$$W = \frac{2\pi}{\hbar} |\langle f | \hat{V} | i \rangle|^2 \rho_E$$

$$\to \quad d\sigma = \frac{W}{v_i} = \frac{1}{v_i} (2\pi)^4 \delta^4 (p_1 + p_2 - p_3 - p_4) |T_{fi}|^2 \frac{d\vec{p}_3}{(2\pi)^3} \frac{d\vec{p}_4}{(2\pi)^3}$$

$$\to \quad \frac{d^2\sigma}{dE_3 d\Omega_3} = \frac{p_3 E_3}{(2\pi)^2 v_1} |T_{fi}|^2 \delta(\omega - E_1 + E_3) \quad (\omega = E_4 - E_2)$$

$$T_{fi} = \langle \chi^{(-)}(\vec{k}_f) f | \sum_i t_i | \chi^{(+)} i \rangle$$

χ: 入射･出射粒子の w.f. 、
i, f: 核の始状態、終状態



断面積と有効核子数 (2)

- 素過程散乱振幅についての近似
  - 入射・出射粒子の運動量と入射エネルギーで表せる
  - 短距離力である

$$\langle \vec{r}_2 \vec{r}_4 | t | \vec{r}_1 \vec{r}_2 \rangle \simeq t(E, \vec{k}_1, \vec{k}_3) \delta(\vec{r}_2 - \vec{r}_4) \delta(\vec{r}_1 - \vec{r}_3) \delta(\vec{r}_1 - \vec{r}_2) \hat{O}$$

$$\frac{d^2\sigma}{d\Omega_3 dE_3} = \frac{p_3 E_3}{(2\pi)^3 v_1} |t|^2 N_{\rm eff} \delta(\omega + E_3 - E_1)$$

$$\simeq \beta \left(\frac{d\sigma}{d\Omega} \right)_{\rm Lab.}^{elem.} N_{\rm eff} \delta(\omega + E_3 - E_1)$$

$$N_{\rm eff} = \sum_f \left| \int d\vec{r} \chi_3^{(-)*}(\vec{r}) \chi_1^{(+)}(\vec{r}) \langle f | \sum \hat{O}_j \delta(\vec{r} - \vec{r}_j) | i \rangle \right|^2$$

Green's Function Method

- 1 粒子過程を仮定し、終状態の原子核の状態を見ないとする。
  → 完全系を作るとすれば、δ 関数をグリーン関数に置き換え可能

$$\frac{d^2\sigma}{dE_3\,d\Omega_3}=\frac{p_3E_3}{(2\pi)^2 v_1}|T_{fi}|^2\delta(\omega-E_1+E_3)\quad(\omega=E_4-E_2)$$

$$\sum_f|\langle\chi_3 f|\hat{t}|\chi_1 i\rangle|^2\delta(E_1+E_2-E_3-E_4)=-\frac{|t|^2}{\pi}\mathrm{Im}\left[\sum_\alpha\langle F_\alpha\left|\frac{1}{E-\hat{H}_Y+i\varepsilon}\right|F_\alpha\rangle\right]$$

$$\frac{d^2\sigma}{dE_3\,d\Omega_3}=-\frac{p_3E_3}{(2\pi)^2 v_1}|t|^2\frac{1}{\pi}\mathrm{Im}\left[\sum_\alpha\langle F_\alpha|G_{\alpha\alpha}(E-E_\alpha)|F_\alpha\rangle\right]$$

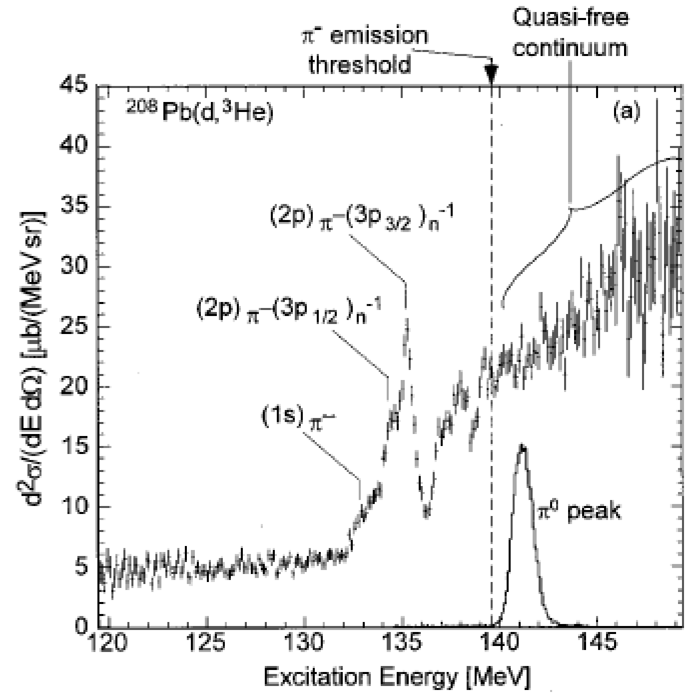
$$F_\alpha(\vec{r})=\chi_3^{(-)*}(\vec{r})\chi_1(\vec{r})\psi_\alpha$$

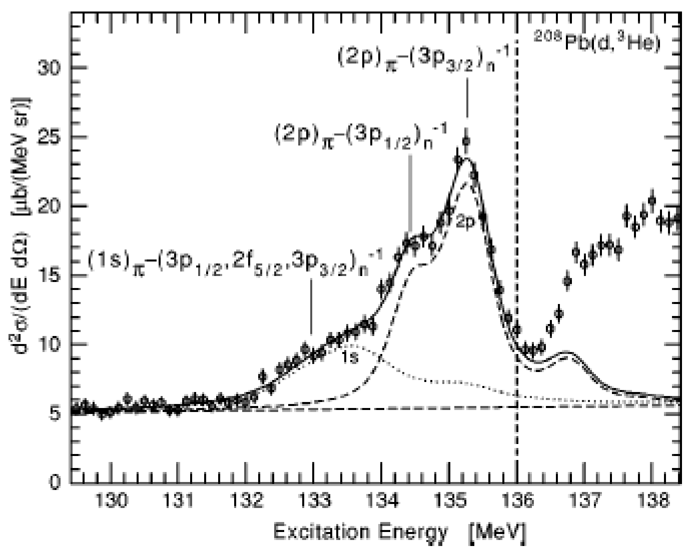
Deeply Bound pionic atom (1)

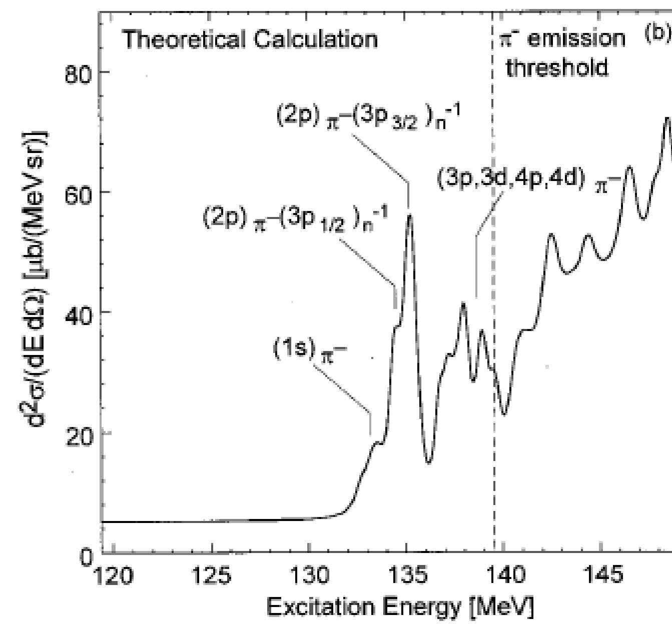
- $^{208}Pb(d, {}^3He)^{207}{}_{\pi}\, Pb$

$$\left[\frac{d\sigma}{d\Omega}\right]_{dA\to {}^3\mathrm{He}(A-1)\pi} = \left[\frac{d\sigma}{d\Omega}\right]_{dn\to {}^3\mathrm{He}\pi} \times N_{\mathrm{eff}}.$$

$$N_{\mathrm{eff}} = \sum_{M,m_s} \left| \int \chi_f^*(\mathbf{r})\xi_{1/2,m_s}^*(\sigma)[\phi_l^*(\mathbf{r}) \otimes \psi_{j'}(\mathbf{r},\sigma)]_{JM}\chi_i(\mathbf{r})d^3r d\sigma \right|^2 \times C^2S/(2j'+1)$$







K. Itahashi et al., PRC62('00)025202

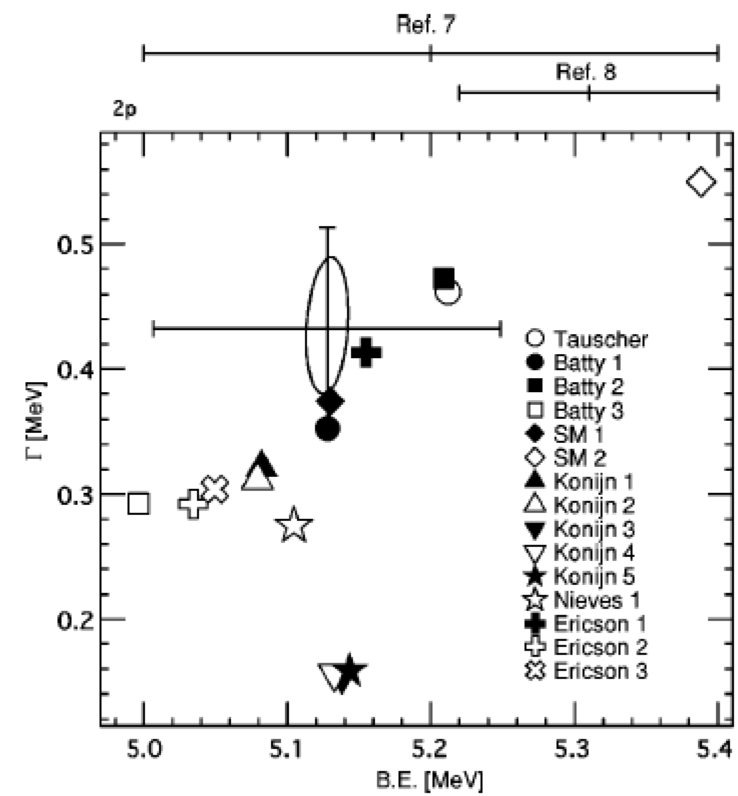
Deeply Bound pionic atom (2)

- 正確にスペクトルを再現するには、
  - 波動関数の歪曲 (Distorted Wave Impulse Approximation)
  - 始状態・終状態の波動関数の光学因子 (spectroscopic factor)

が必要

$$\chi_f^*(\mathbf{r})\chi_i(\mathbf{r}) = \exp(i\mathbf{q}\cdot\mathbf{r})D(\mathbf{b},z)$$

$$D(\mathbf{b},z) = \exp\left[-\frac{1}{2}\left(\int_{-\infty}^{z}\sigma_d\rho(\mathbf{b},z')dz' + \int_{z}^{\infty}\sigma_{^3\mathrm{He}}\rho(\mathbf{b},z')dz'\right)\right]$$



→ 束縛エネルギー・幅
→ 核内のカイラル対称性

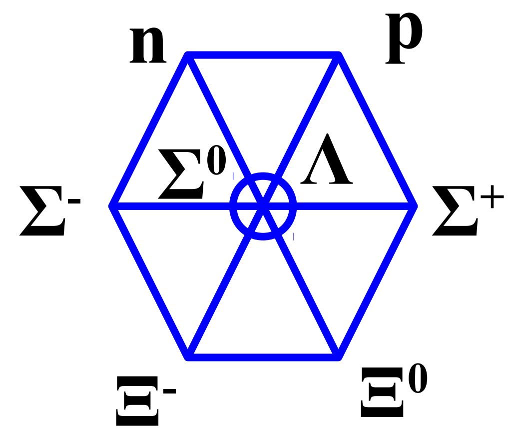
K. Itahashi et al., PRC62('00)025202

Hypernuclear Formation

Hyperons (Baryons with Strangeness)

- **Ground state baryon $SU(3)_f$ octet (J^{π}=1/2+)**

Baryon	M(Mev)	S	Comp.
n	940	0	udd
p	938	0	uud
Λ	1116	-1	$(uds-dus)/\sqrt{2}$
Σ^+	1189	-1	uus
Σ^0	1193	-1	$(uds+dus)/\sqrt{2}$
Σ^-	1197	-1	dds
Ξ^0	1315	-2	uss
Ξ^-	1321	-2	dss



$SU(3)_f$ transformation

- **Fundamental triplet $(u,d,s)^T = q \to q' = U q \; (U \in SU(3))$**
- **Diquark $D_i = \varepsilon_{ijk}\, q_j\, q_k \to D' = D\, U^+$**
- **Baryon octet $B_{ij} = D_j\, q_i \to B' = U B U^+$**

$$\begin{pmatrix} [ds]u & [su]u & [ud]u \\ [ds]d & [su]d & [ud]d \\ [ds]s & [su]s & [ud]s \end{pmatrix} = \begin{pmatrix} \frac{\Lambda}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

$SU(3)_f$ transformation

- **Fundamental triplet $(u,d,s)^T = q \to q'=U\,q\ (U \in SU(3))$**
- **Anti-quark $\bar{q} \to \bar{q}' = \bar{q}\,U^+$**
- **Meson octet $M_{ij} = \bar{q}_j\, q_i \to M'=UMU^+$**

$$\begin{pmatrix} \bar{u}u & \bar{d}u & \bar{s}u \\ \bar{u}d & \bar{d}d & \bar{s}d \\ \bar{u}s & \bar{d}s & \bar{s}s \end{pmatrix} = \begin{pmatrix} \frac{\eta}{\sqrt{6}}+\frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}}-\frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} = P$$

$$S=\begin{pmatrix} \frac{\sigma}{\sqrt{2}}+\frac{a_0}{\sqrt{2}} & a_0^+ & \kappa^+ \\ a_0^- & \frac{\sigma}{\sqrt{2}}-\frac{a_0}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & \zeta \end{pmatrix} \qquad V=\begin{pmatrix} \frac{\omega}{\sqrt{2}}+\frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega}{\sqrt{2}}-\frac{\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \varphi \end{pmatrix}$$

$SU(3)_f$ invariant coupling

- **Baryon-Meson coupling**

$$\mathcal{L}_{\rm BV} = \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\,(\bar{B}B) + g_D\,{\rm tr}\,(\bar{B}\,\{M_v, B\}) + g_F\,{\rm tr}\,(\bar{B}\,[M_v, B])\}$$

$$= \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\,(\bar{B}B) + g_1\,{\rm tr}\,(\bar{B}M_vB) + g_2\,{\rm tr}\,(\bar{B}BM_v)\}$$

- **Assumption**
  - **BM coupling is SU(3) invariant**
  - **N does not couple with $s\bar{s}$ vector meson**

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

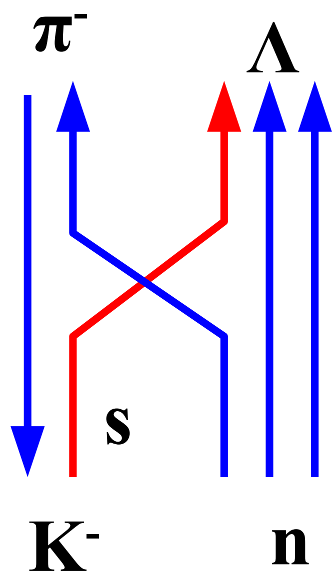
- **Further simplification: $g_{\rho N} = g_{\omega N}/3$ (quark counting)**

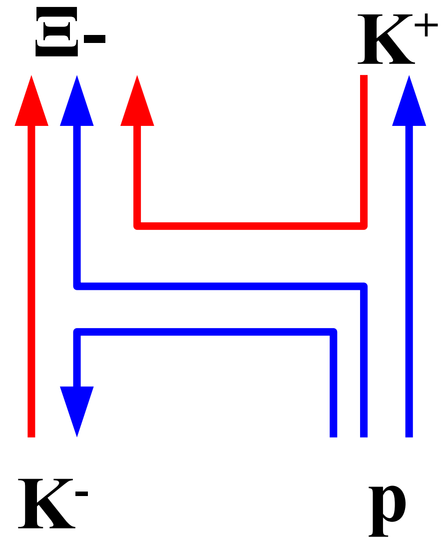
$$g_{\omega N} = g_v\,,\quad g_{\rho N} = g_v/3\,,\quad g_{\omega\Lambda} = 2g_v/3\,,\quad g_{\varphi\Lambda} = \sqrt{2}\,g_v/3$$

Hypernuclear formation

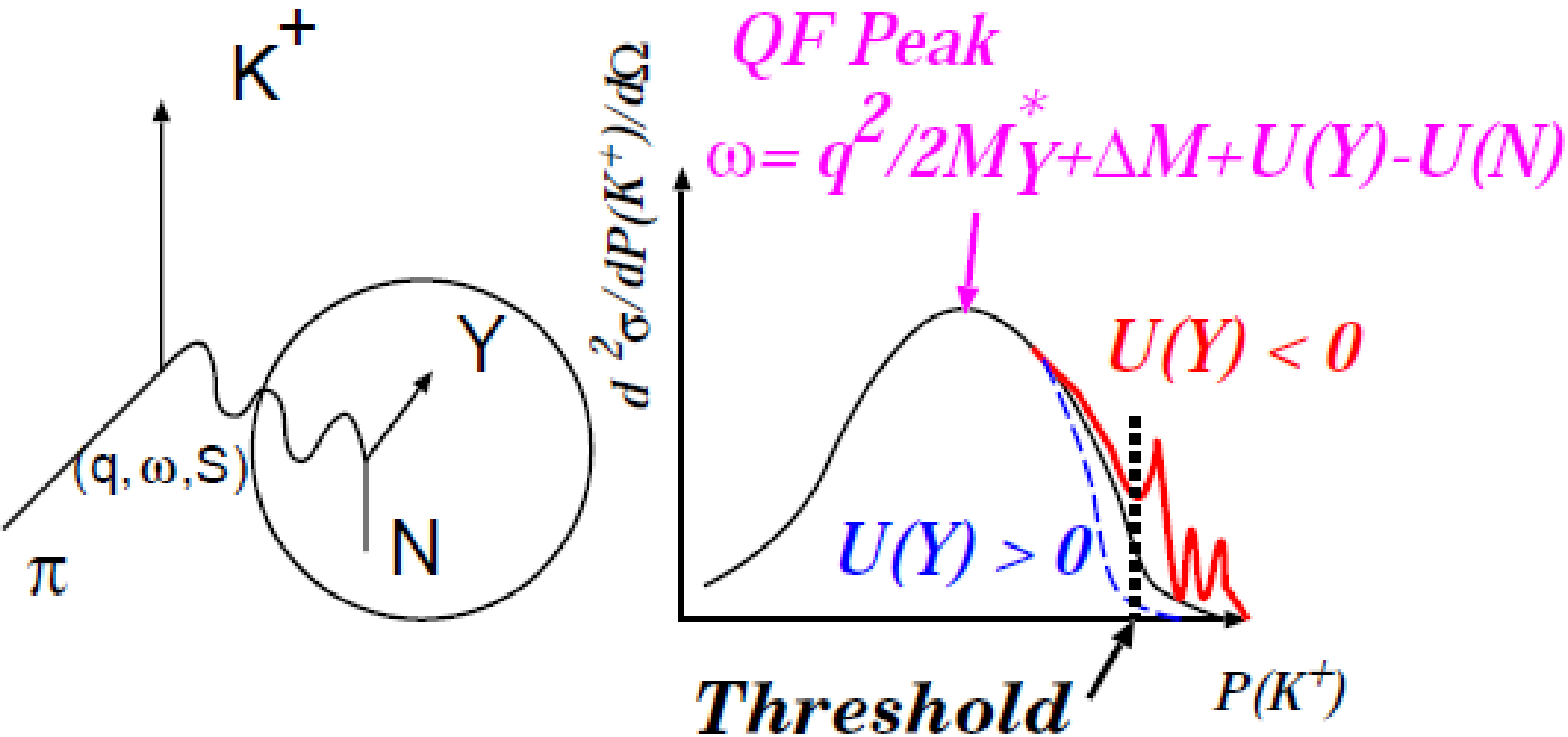
- **(K$^-$, π), (π, K$^+$), and (K$^-$,K$^+$) reactions on nuclei → Hypernuclei**

Reaction	Elementary Processes	
	Main Process	Other Processes
(K^-,π^-)	$K^-n \to \pi^-\Lambda$,	$K^-n \to \pi^-\Sigma^0$, $K^-p \to \pi^-\Sigma^+$
(K^-,π^+)	$K^-p \to \pi^+\Sigma^-$,	$K^-pp \to \pi^+\Lambda n$ (n-rich hypernuclear formation)
(π^+,K^+)	$\pi^+n \to K^+\Lambda$,	$\pi^+n \to K^+\Sigma^0$, $\pi^+p \to K^+\Sigma^+$
(π^-,K^+)	$\pi^-p \to K^+\Sigma^-$,	$\pi^-pp \to K^+\Lambda n$ (n-rich hypernuclear formation)
(K^-,K^+)	$K^-p \to K^+\Xi^-$,	$K^-pp \to K^+\Lambda\Lambda$



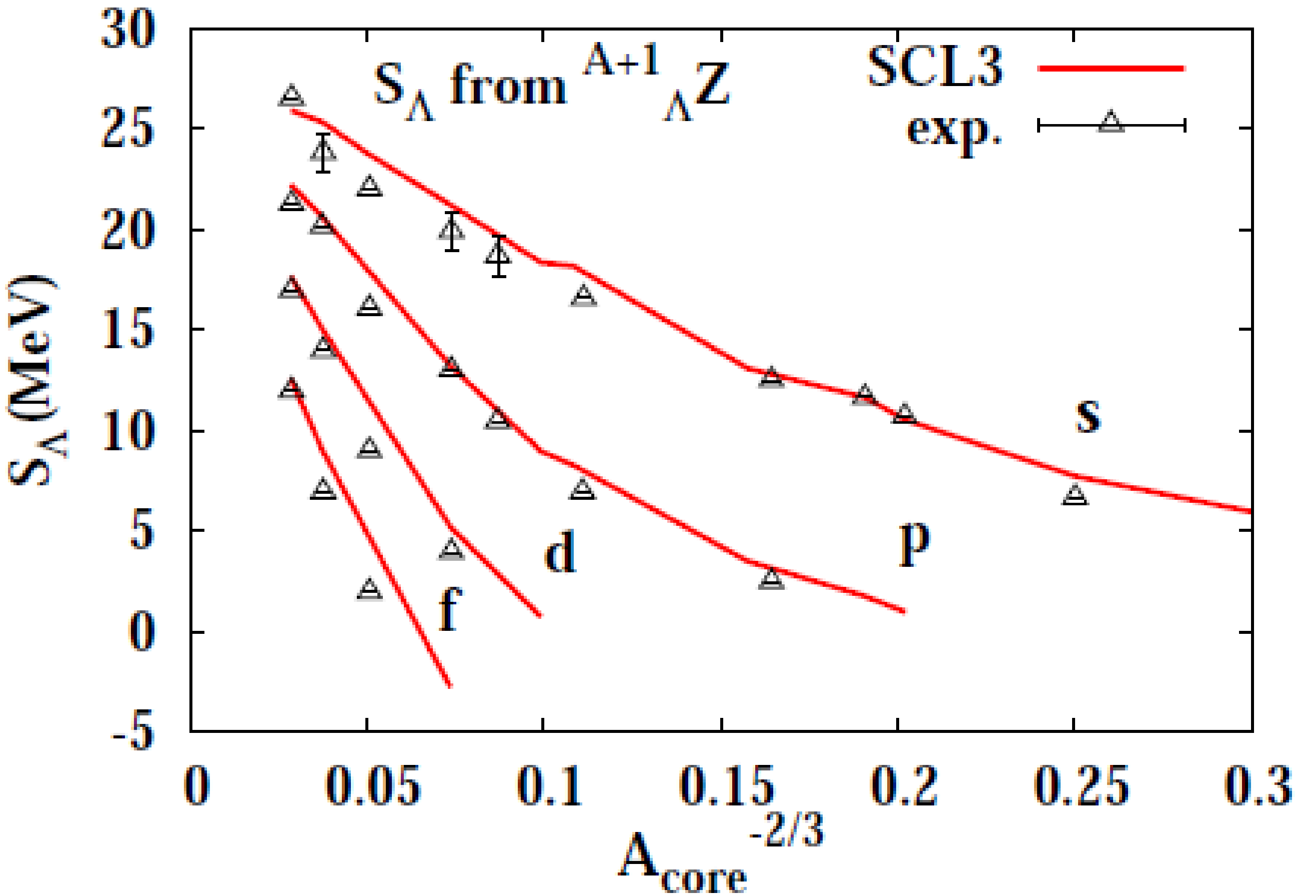


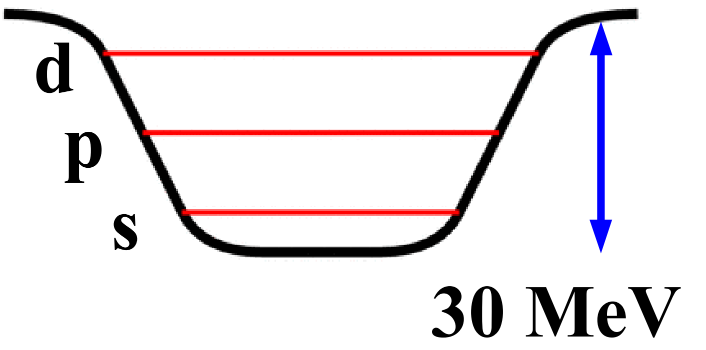
Hypernuclear formation



Single particles states of Λ in nuclei

- **Single particle potential depth of Λ is around -30 MeV**
  - **s, p, d, f, … states are clearly seen**
  - **$A_{core}^{-2/3} \propto R^{-2} \propto$ K.E. of Λ**





Hypernuclear production (discrete state)

- **Substitutional reaction**
  - **Magic momentum 近辺では q ~ 0**
    → 核子軌道にハイペロンが入る状態が有利

H. Bando, T. Motoba, J. Zofca,
Int. J. Mod. Phys. A 5 (1990), 4021-4198.

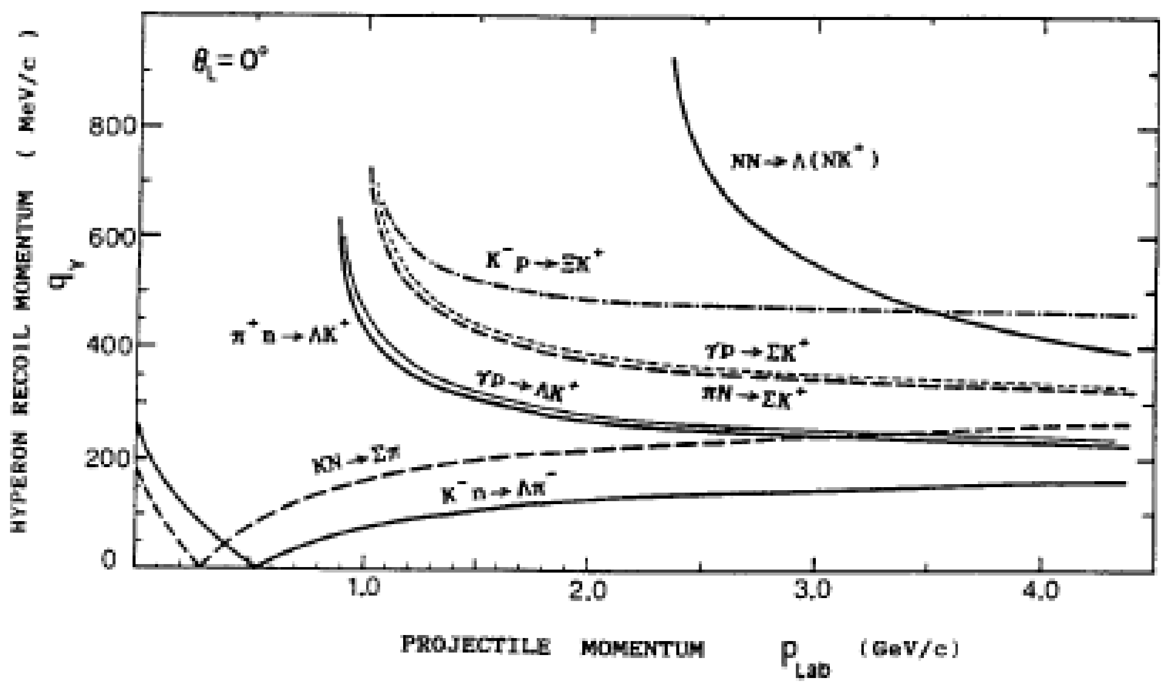
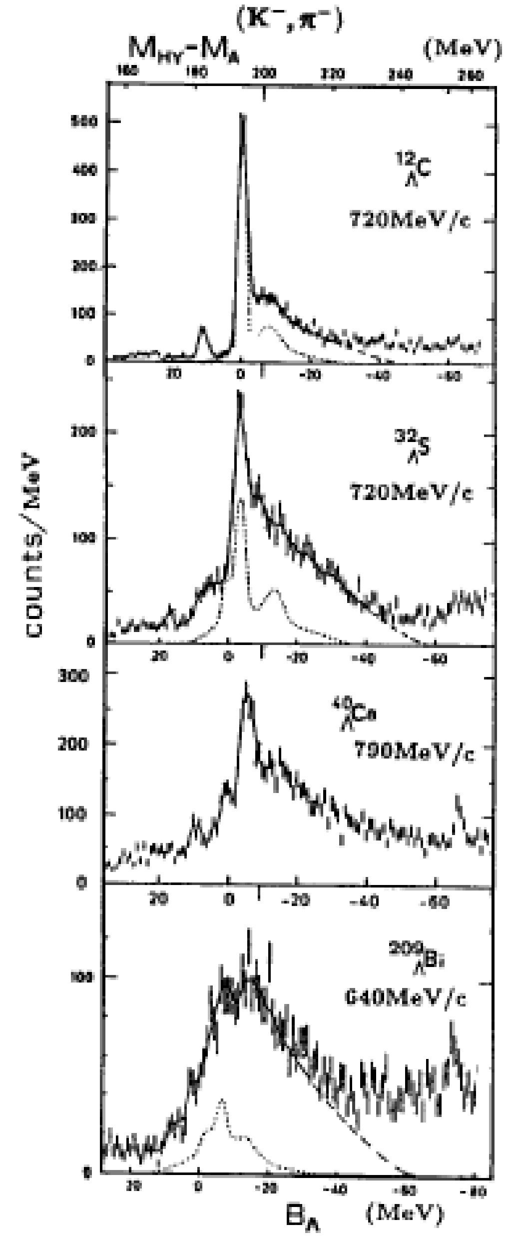
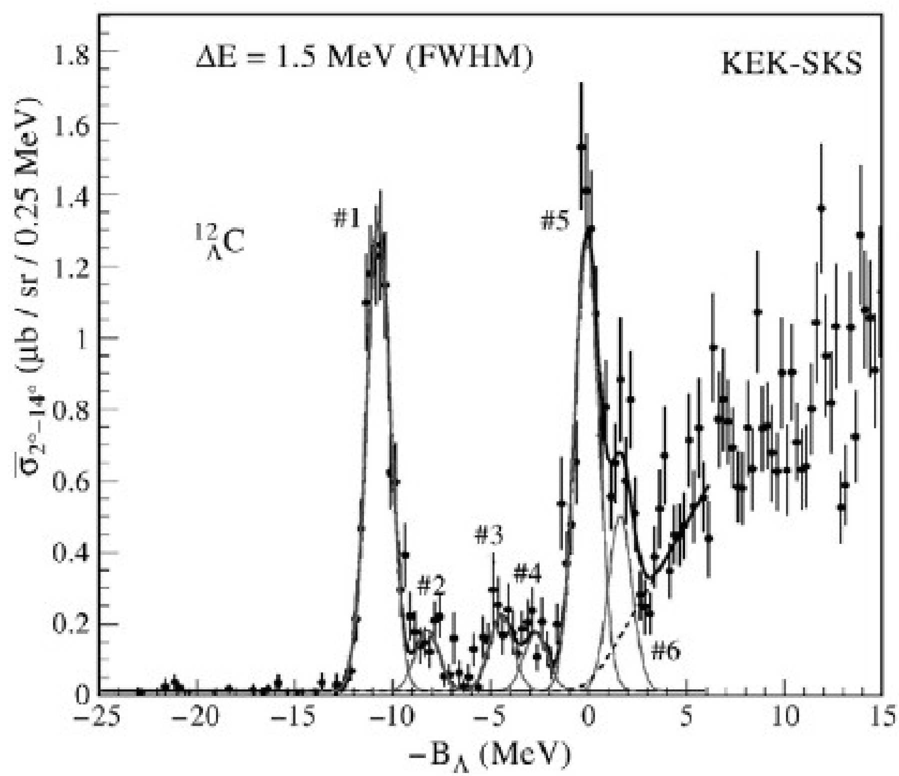


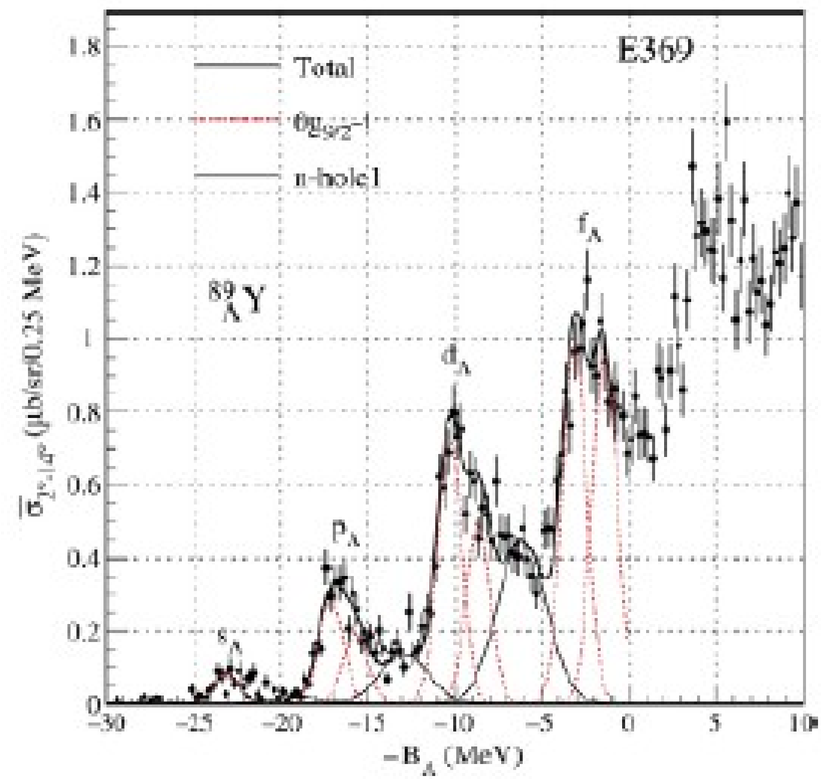
Fig. 2.3. The momentum q_Y transferred to the hyperon Y as a function of the projectile momentum $p_{proj} = p_a$ in the reaction $aN \to Yb$ at $\theta_{L.L} = 0°$.



Λ hypernuclear formation

- **(π^+, K^+) reactions on nuclei**
  - **q ~ k_F → various s.p. states of Λ are populated**





Hasegawa et al.(1996)

Quasi-Free Λ Production (1)

- 有効核子数法 → 十分に離散的な束縛状態で成功
  → 連続状態では？
- Green's Function Method *O.Morimatsu, K. Yazaki, NPA483('88)493*
  - 束縛状態と連続状態を同時に記述可能

Harada, Hirabayashi ('04)

$$\frac{d^2\sigma}{dE_K\, d\Omega_K} = \beta \left(\frac{d\sigma}{d\Omega}\right)^{\text{elem}} S(\omega, \boldsymbol{q})$$

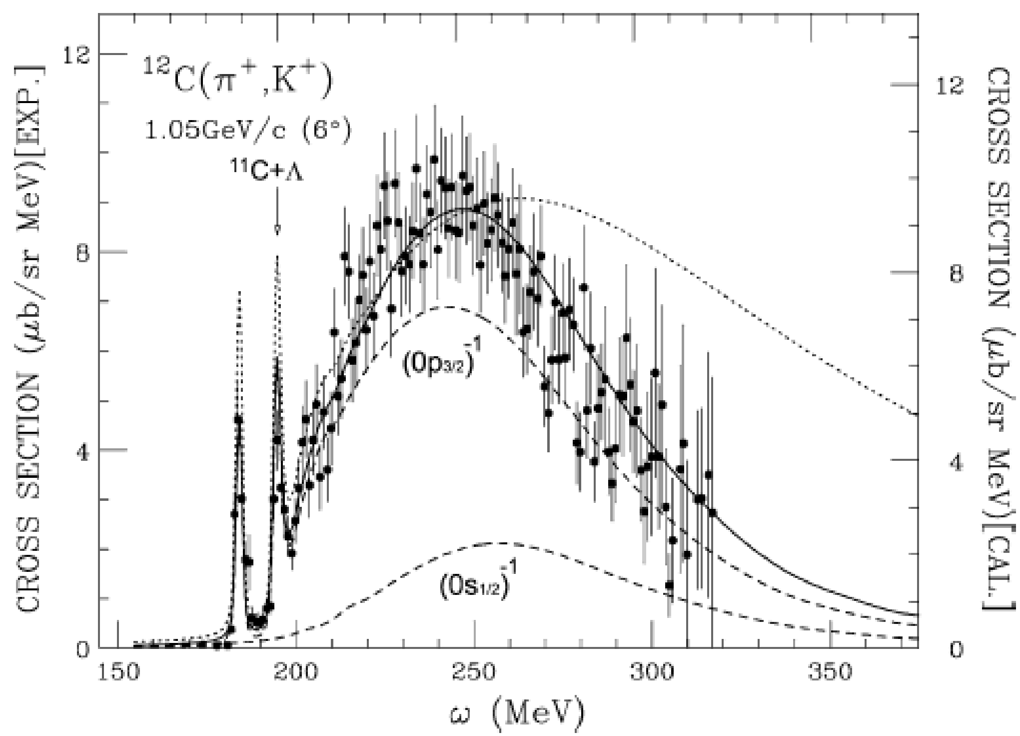
$$S(\omega,\boldsymbol{q}) = \sum_f \left|\langle f|\hat{O}|i\rangle\right|^2 \delta(\omega + E_K - E_\pi)$$

$$= (-)\frac{1}{\pi}\sum_{\alpha\alpha'}\int d\boldsymbol{r}\, d\boldsymbol{r}'\, F^\dagger_\alpha(\boldsymbol{r}) G_{\alpha\alpha'}(E_f;\boldsymbol{r},\boldsymbol{r}') F_{\alpha'}(\boldsymbol{r}')$$

$$F_\alpha(\boldsymbol{r}) = \chi_K^{(-)*}\left(\frac{M_C}{M_A}\boldsymbol{r}\right)\chi_\pi^{(+)}\left(\frac{M_C}{M_A}\boldsymbol{r}\right)\langle\alpha|\Psi_N(\boldsymbol{r})\rangle$$

$$\hat{O} = \sum_{j=1}^{A}\int d\boldsymbol{r}\, \chi_K^{(-)*}(\boldsymbol{r})\chi_\pi^{(+)}(\boldsymbol{r})\hat{U}_-(j)\delta(\boldsymbol{r}-\boldsymbol{r}_j)$$

$$\beta \equiv \left(1 + \frac{E_K^{(0)}}{E_\Lambda^{(0)}}\frac{p_K^{(0)} - p_\pi^{(0)}\cos\theta}{p_K^{(0)}}\right)\frac{p_K E_K}{p_K^{(0)} E_K^{(0)}}$$



T. Harada, Y. Hirabayashi / Nuclear Physics A 744 (2004) 323–343

Quasi-Free Λ Production

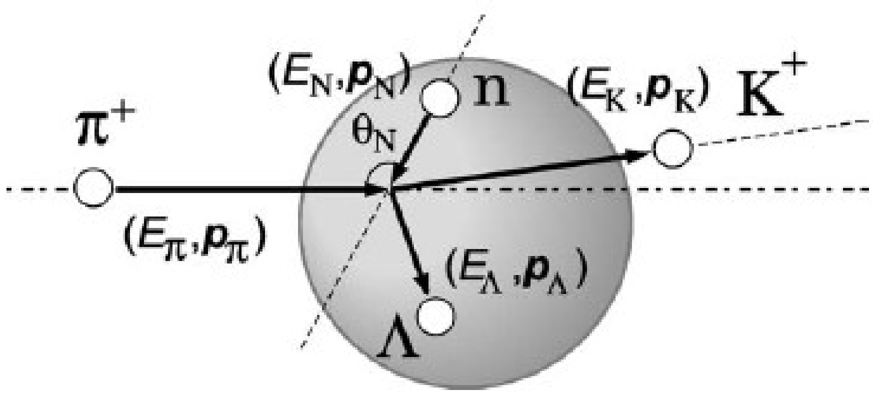
- **Kinematical factor による t-matrix の表現**
  - **狙うエネルギー領域が狭い場合には有効**

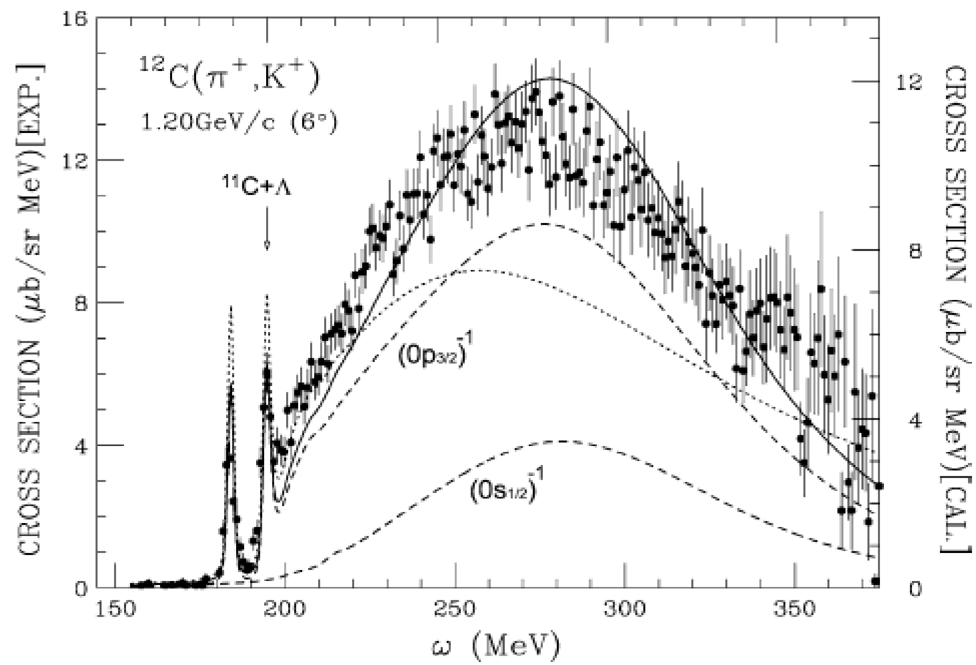
→ 広いエネルギー領域をカバーする時には最適化運動量を用いる

$$\frac{d^2\sigma}{dE_K\,d\Omega_K} = \left(\frac{d\sigma}{d\Omega}\right)^{\rm opt} S(\omega, \boldsymbol{q}),$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{\rm opt} \equiv \frac{p_K E_K}{(2\pi)^2 v_\pi} \left|t^{\rm opt}(p_\pi; \omega, \boldsymbol{q})\right|^2$$

$$t^{\rm opt}(p_\pi; \omega, \boldsymbol{q}) = \left. \frac{\int_0^\pi \sin\theta_N\, d\theta_N \int_0^\infty dp_N\, p_N^2 \rho(p_N) t(E_2; \boldsymbol{p}_\pi, \boldsymbol{p}_N)}{\int_0^\pi \sin\theta_N\, d\theta_N \int_0^\infty dp_N\, p_N^2 \rho(p_N)} \right|_{p_N = p_N^*}$$





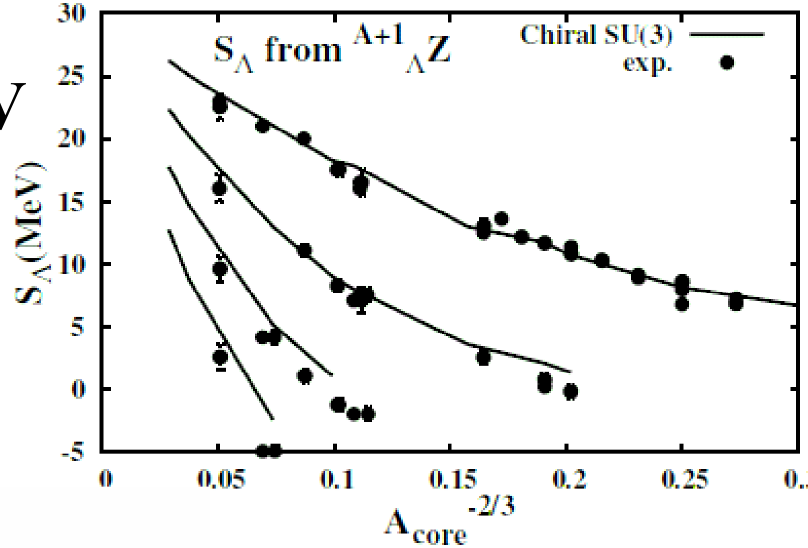
T. Harada, Y. Hirabayashi / Nuclear Physics A 744 (2004) 323–343

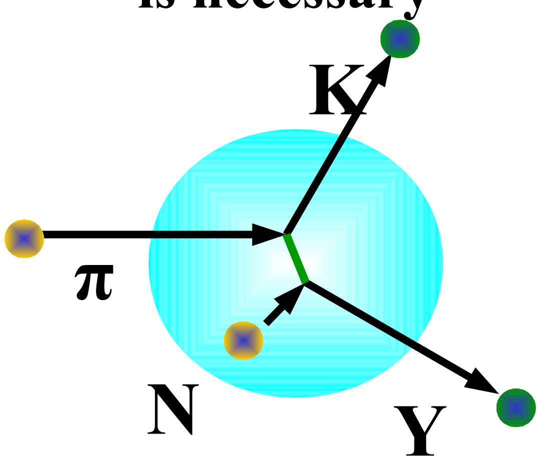
Σ Potential in Nuclear Matter

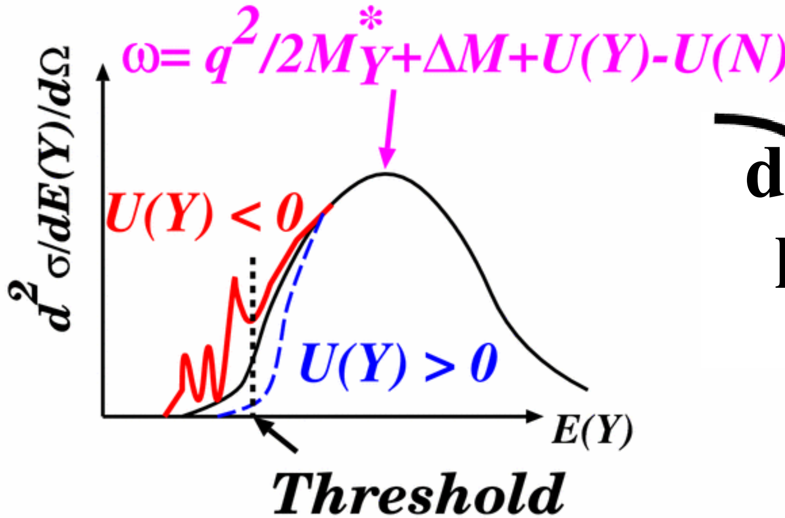
- $U_\Lambda(\rho_0) \sim -30$ MeV: Well known from single particle energies
- Naïve expectation
  = Quark Number (ud number) Scaling
  $U_\Lambda \sim 2/3\, U_N \rightarrow U_\Sigma \sim 2/3\, U_N \sim -30$ MeV
- Problems with Σ
  - Only one bound state $^4_\Sigma$He (Too light !)

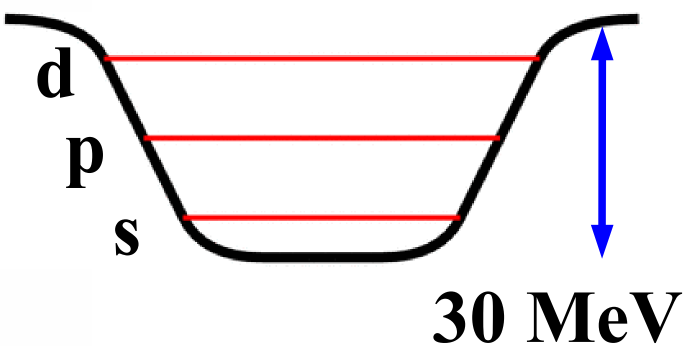
  → Continuum (Quasi-Free) Spectroscopy is necessary

Tsubakihara, Maekawa, AO, EPJA33('07),295.









Quasi-Free Σ Production

- **KEK data of Σ- production on nuclear target**

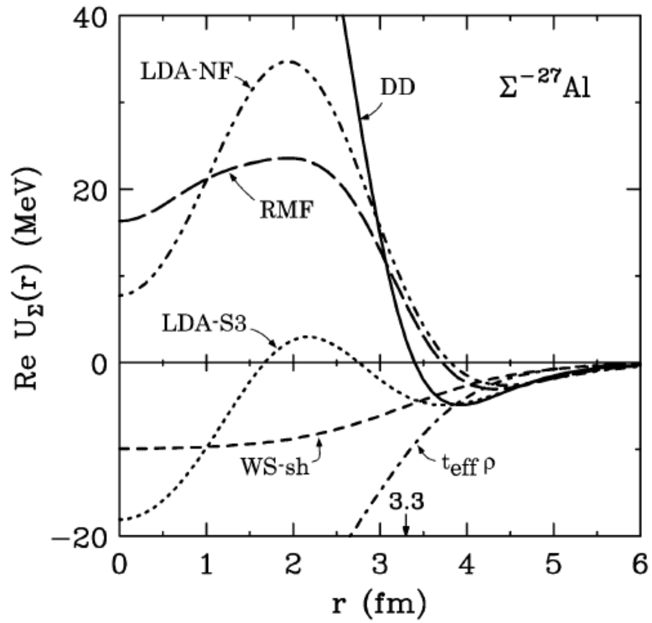
  H. Noumi, et al., Phys. Rev. Lett. 89 (2002) 072301;
  H. Noumi, et al., Phys. Rev. Lett. 90 (2003) 049902, Erratum.

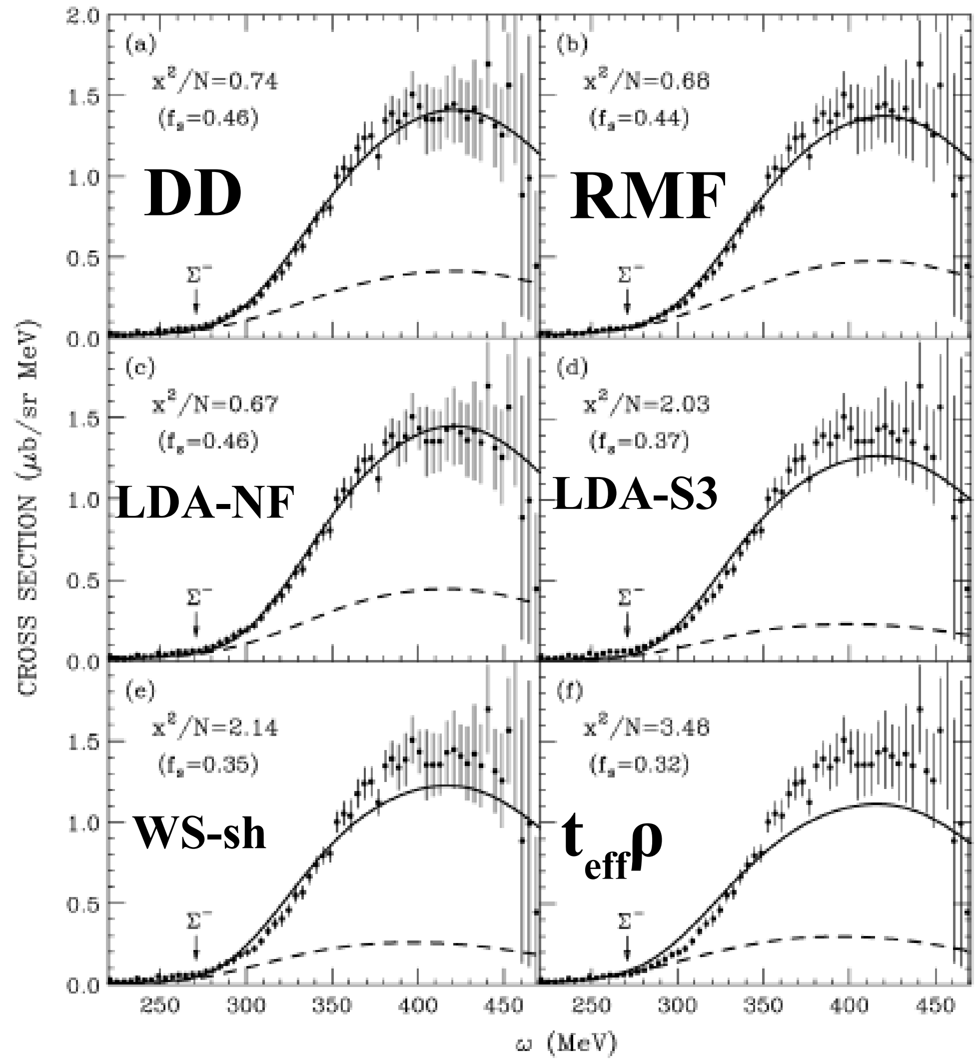
  - **Naïve analysis suggest**
    Re U ~ 90 MeV

- **Green's Function Method +OFA t-matrix (DWIA)**

  - **QF data is consistent with Atom data, but sensitivity is small.**

Harada, Hirabayashi ('05)



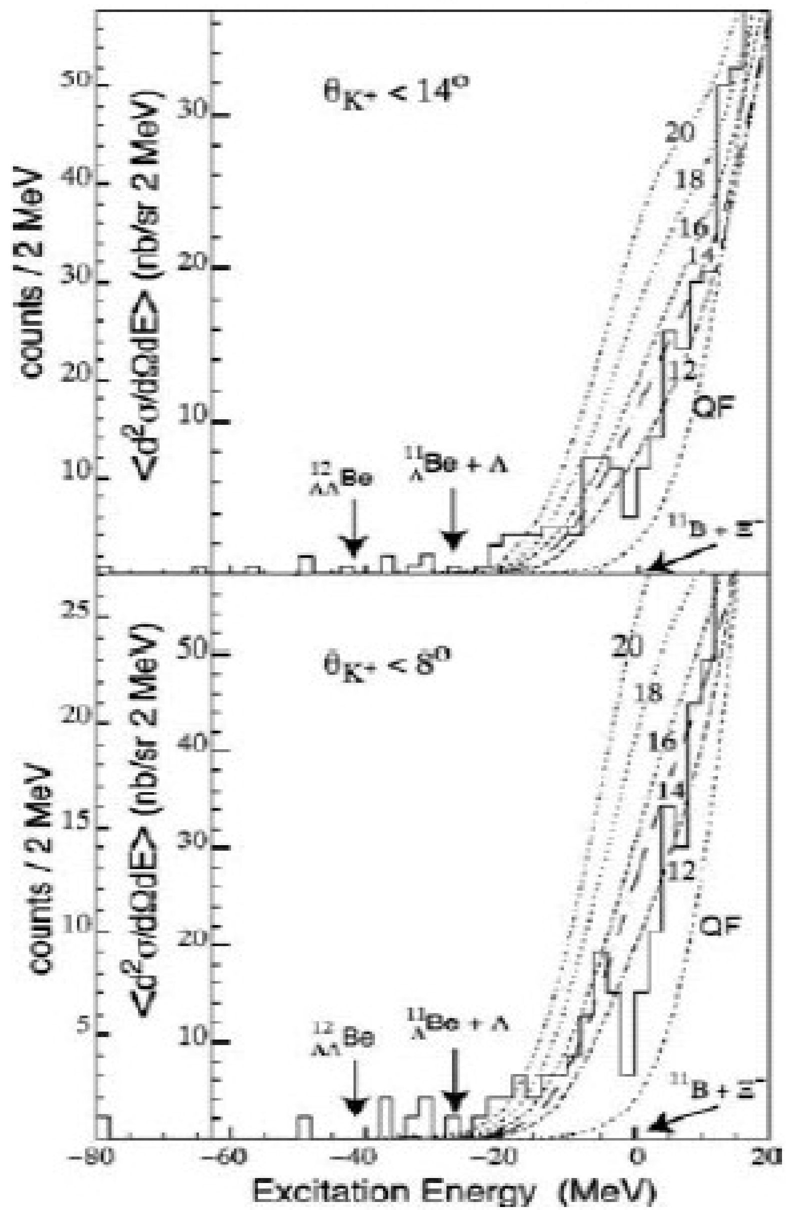


T. Harada, Y. Hirabayashi / Nuclear Physics A 759 (2005) 143–169

Ξ hypernuclear formation

- **Missing mass spectroscopy BNL E885 $^{12}C(K^-,K^+)$**
  Fukuda et al. PRC58('98),1306; Khaustov et al. PRC61('00), 054603.
  - **No clear bound states found**
- **Twin hypernuclear formation**
  Aoki et al. PLB355('95),45.
- **Potential depth**
  $U_\Xi \sim -14$ MeV

E885 (BNL)



"Stars" of Hyperon Potentials (A la Michelin)

- **$U_\Lambda(\rho_0) \sim -30$ MeV**
  - ***Bound State Spectroscopy + Continuum Spectroscopy***
- **$U_\Sigma(\rho_0) > +15$ MeV**
  - **Continuum (Quasi-Free) spectroscopy with *Optimal Fermi Averaging t-matrix***
  - **Atomic shift data (attractive at surface) should be respected.**
  - **First example of quark Pauli blocking effects in potential ?**
- **$U_\Xi(\rho_0) \sim -14$ MeV**
  - **No confirmed bound state, No atomic data, High mom. transf., ... → Small Potential Deps.**
  - **Continuum low-res. spectrum shape → – 14 MeV**
  - **Spin-Isospin deps. (π exch.) → Deformation → Spectrum shape may be modified.**

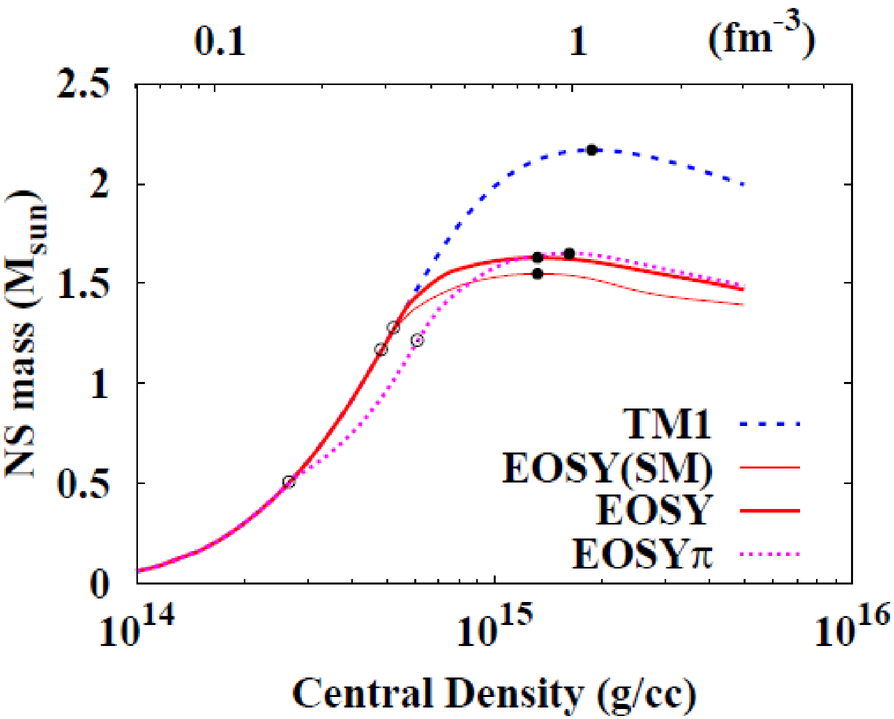
Strangeness Nuclear Physics

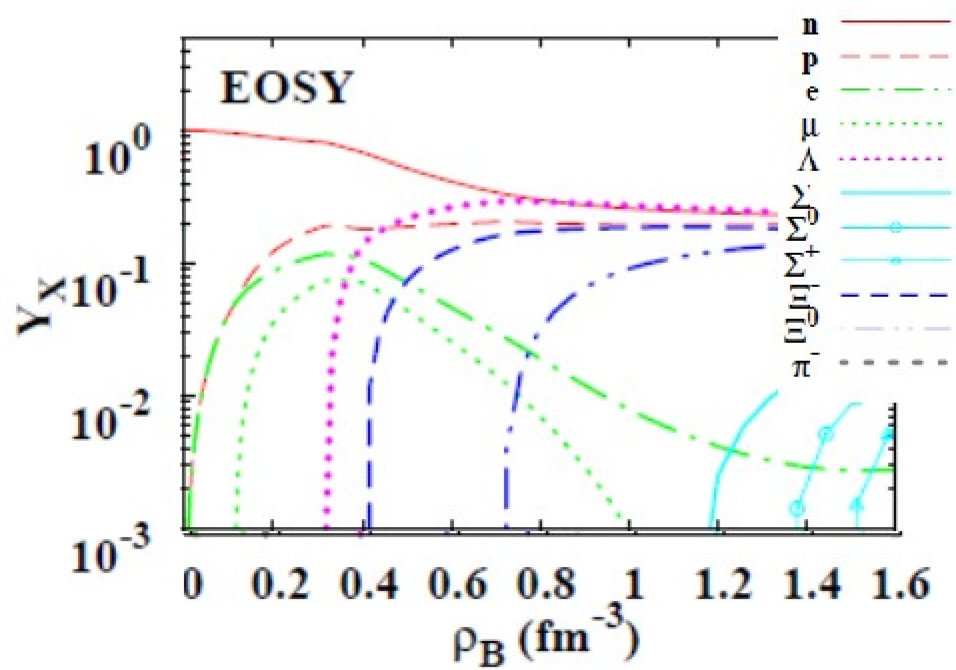
- **Before Oct.2010,**

  $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV

  Harada, Hirabayashi ('05), Noumi et al. ('02),
  Fukuda et al. PRC58('98),1306; Khaustov et al. PRC61('00), 054603;
  Aoki et al. PLB355('95),45.

  → Maximum mass of NS ~ 1.6 $M_\odot$

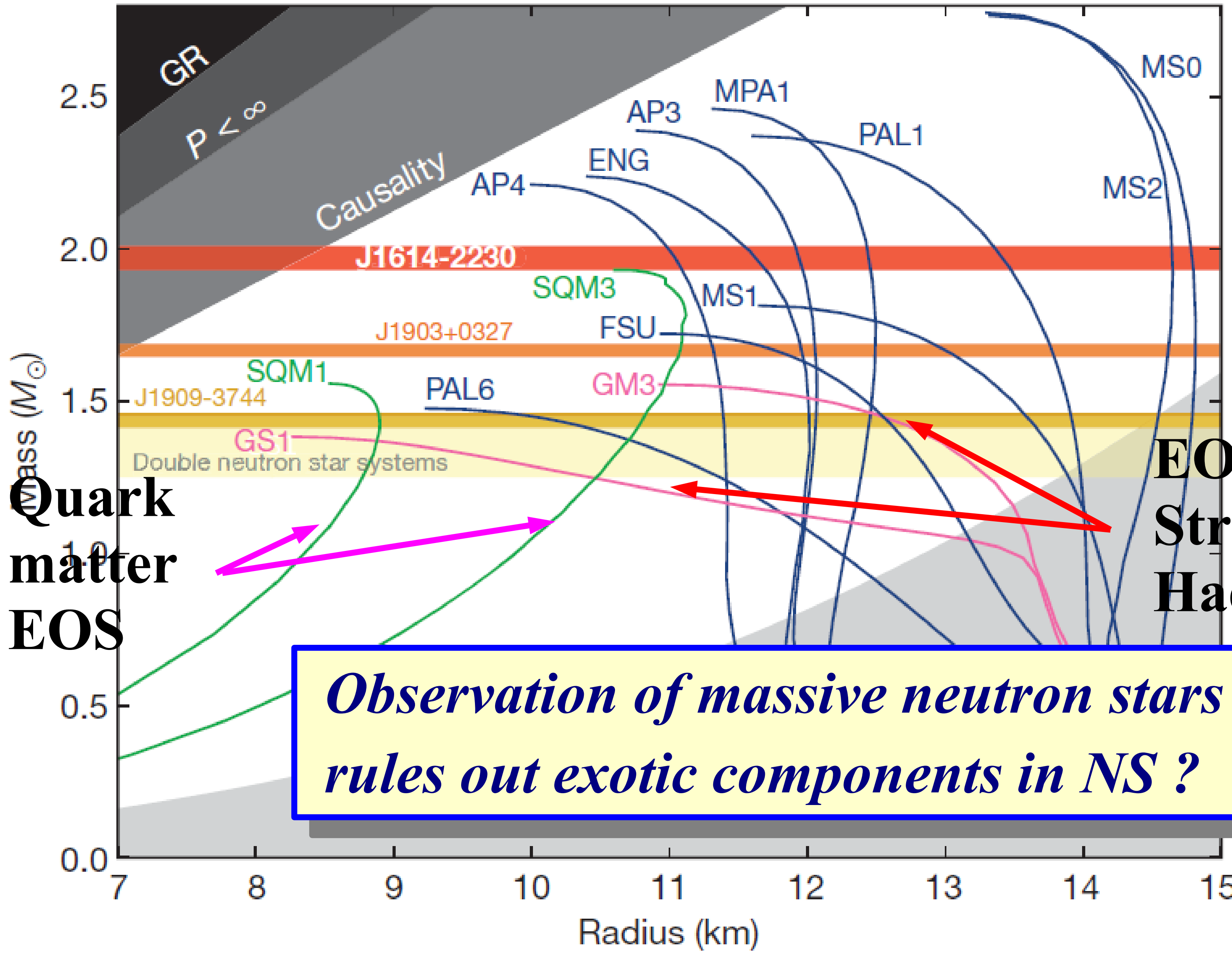




Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada ('08)

Hyperon Puzzle

Hyperon Puzzle



Quark matter EOS

EOS w/ Strange Hadrons

Observation of massive neutron stars ($M \sim 2\ M_\odot$) rules out exotic components in NS ?

PSR J1614-2230: 1.97 ± 0.04 $M_\odot$ *Demorest et al., Nature 467('10)1081 (Oct.28, 2010).*

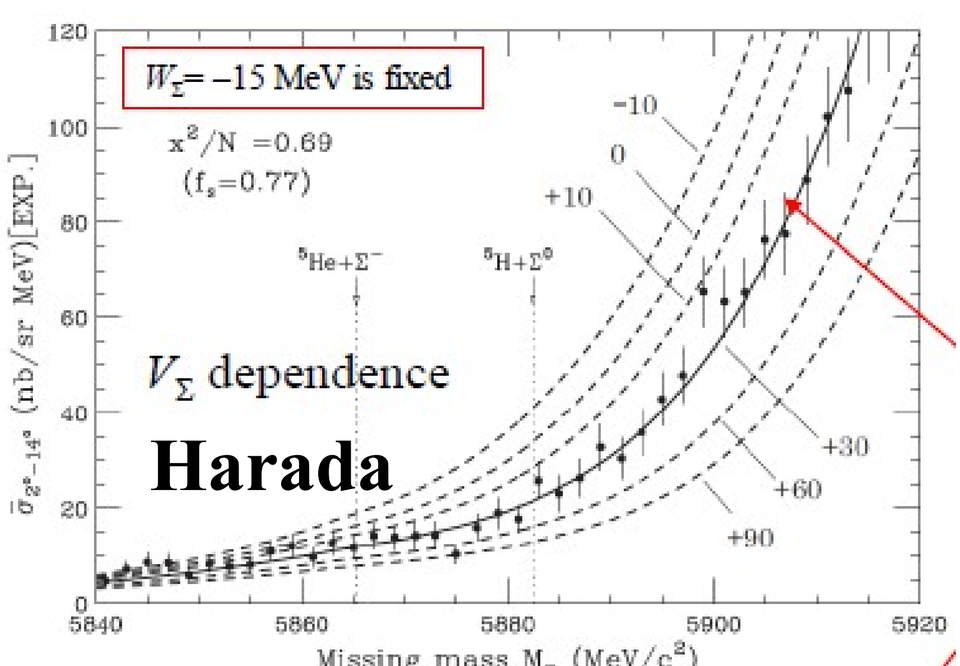
PSR J0348+0432: 2.01 ± 0.04 $M_\odot$ *Antoniadis et al., Science 340('13)1233232.*

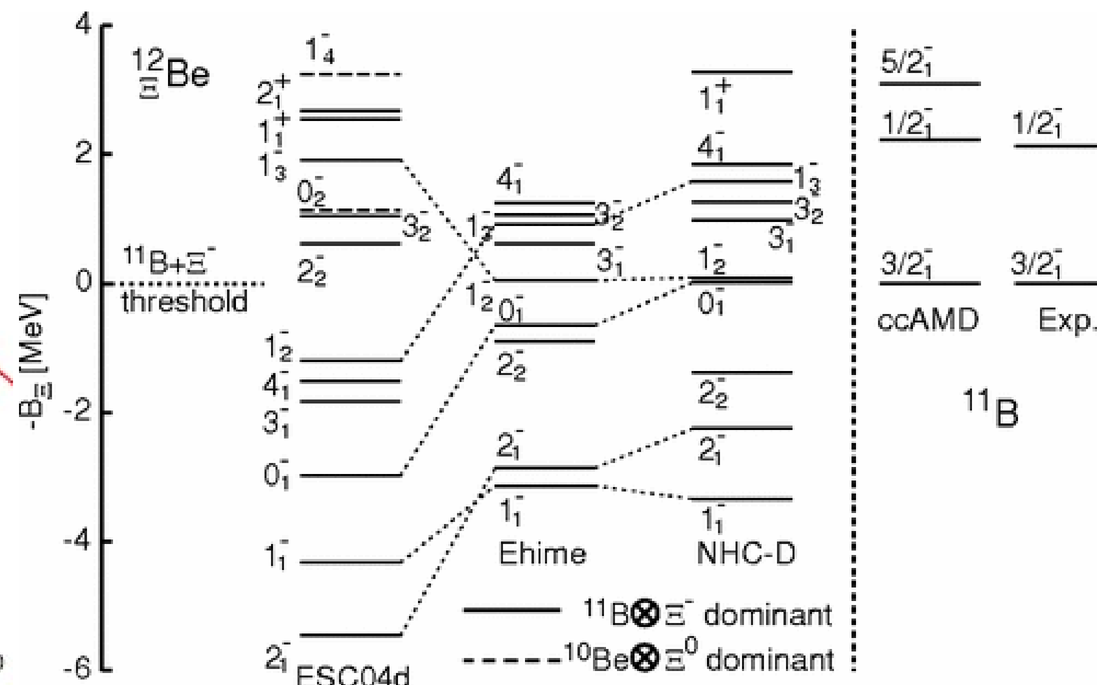
What did we miss ?

- Hyperon potential in nuclear matter ?
  - $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV
- Hyperon-Hyperon potential ?
  - If vacuum ΛΛ potential is much more attractive than Nagara event implies, ΛΛN potential must be very repulsive.
- Kaon potential in nuclear matter ?
- Three-baryon (3B) interaction ?
- Quark matter core ?
- Modified gravity ?

Σ or Ξ potential in nuclei ?

- **New analysis of Σ production reaction: ^{6}Li (π^{-}, K^{+}) Σ^{-} ^{5}He (Honda, Harada)**
  → U_{Σ} ~ +30 MeV (consistent)
- **New Ξ hypernuclei → B.E. = 9 MeV & 1 MeV (Takahashi (A01), Nakazawa, Kanatsuki, Yamamoto)**
  → Deeper than previous estimate !





Matsumiya, Tsubakihara, Kimura, Dote, AO ('11)

T. Harada

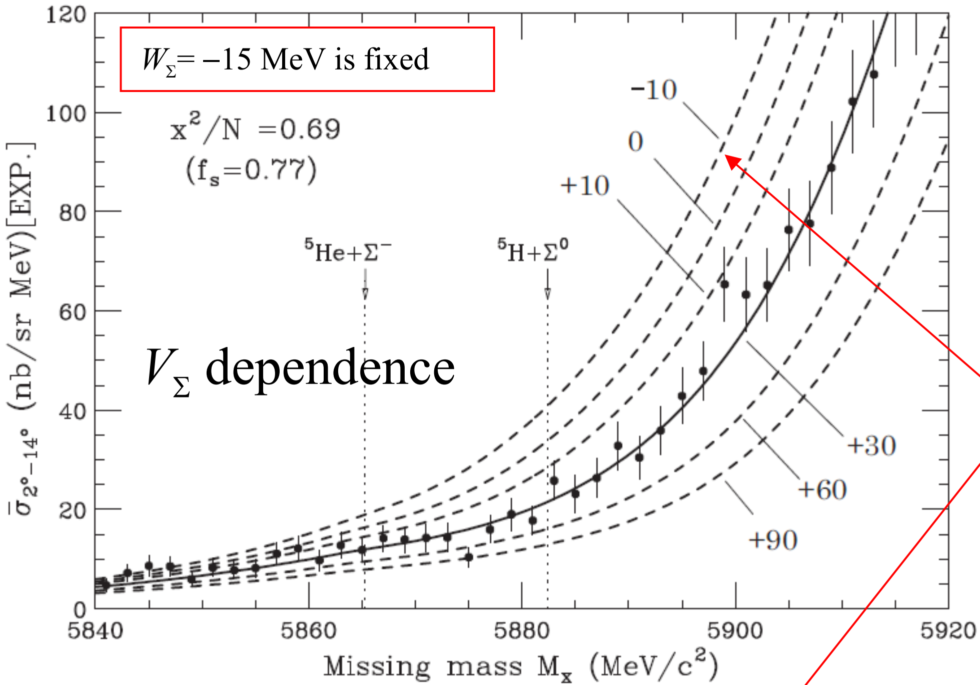
Repulsion and absorption of the Σ-nucleus potential in the $^{6}Li(\pi^{-},K^{\pm})$ reactions

Σ^{-}-^{5}He

Dependence of the calculated average spectra for the ^{6}Li(π^-,K^+) reaction

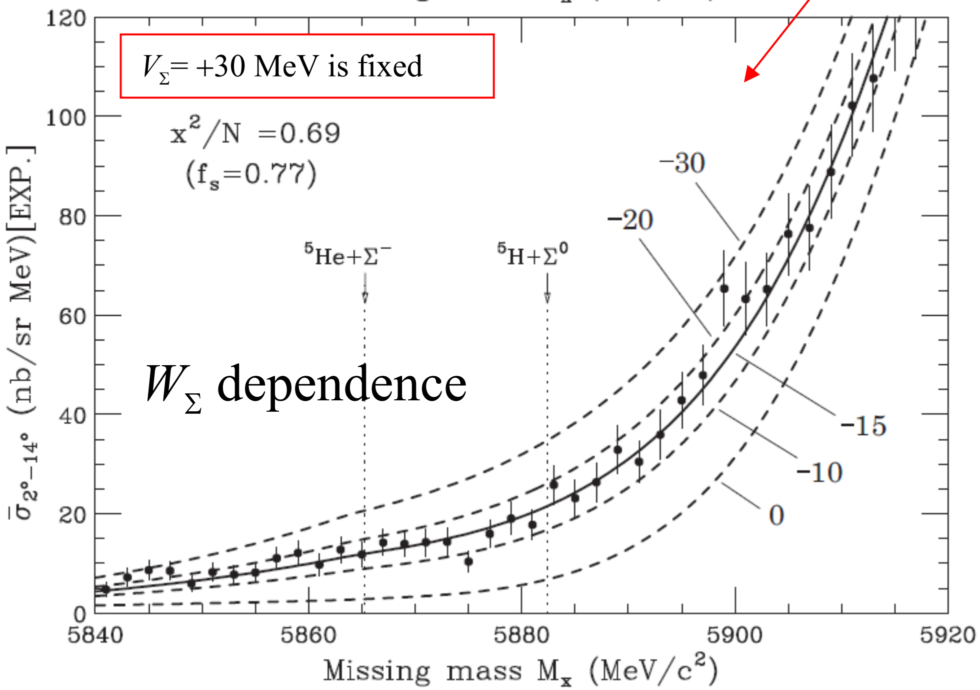
p_{π^-} =1.2 GeV/c

WS potential

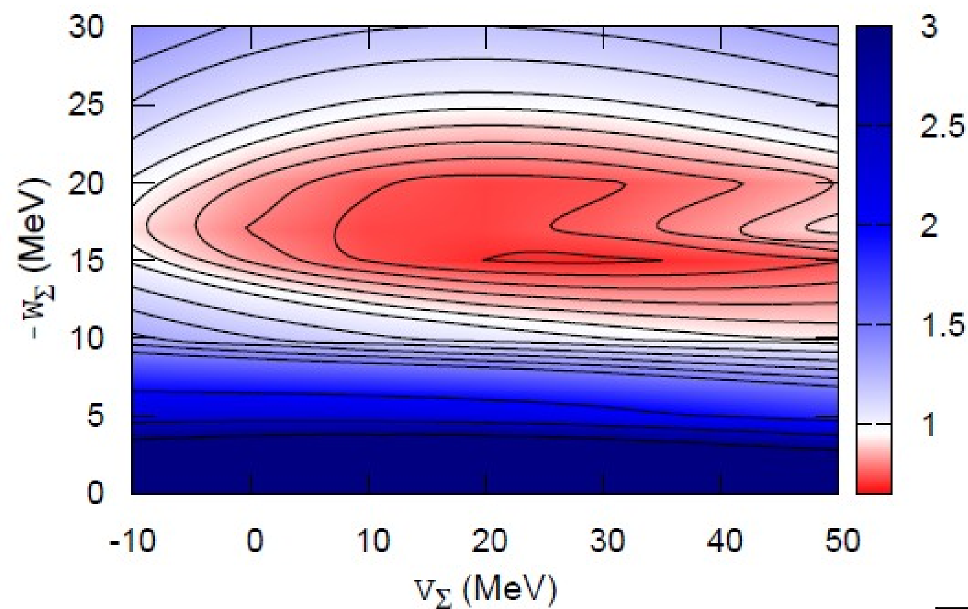


The shape and magnitude of the spectrum are sensitive to the strengths of (V_Σ, W_Σ).

(V_Σ, W_Σ) = (+30, –15) MeV



The χ^2/N-value distribution in V_Σ, W_Σ



The detector resolution of 2.6 MeV FWHM

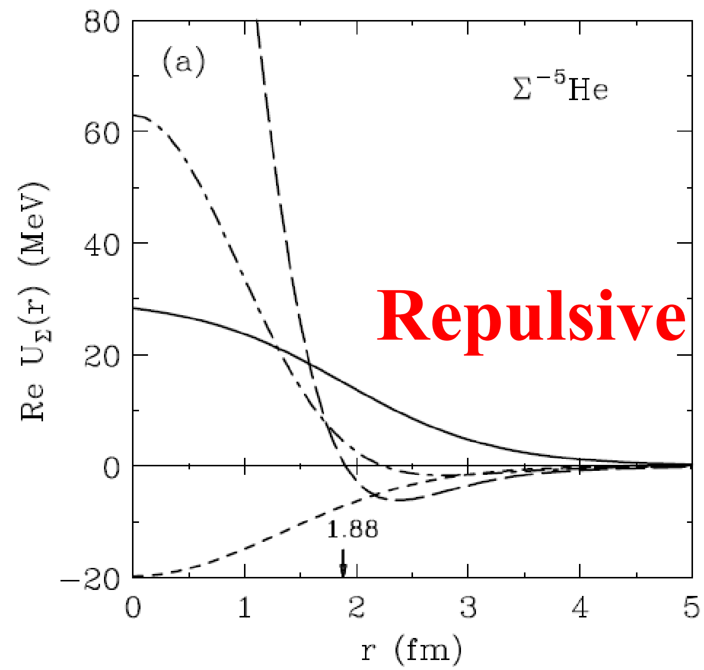
T. Harada

Remarks

T. Harada

- **The optimal Fermi-averaged amplitudes of $f_{\pi^- p \to K^+ \Sigma^-}$ in our DWIA calculations are essential to describe the energy and angular dependence of the data of the ^{6}Li(π^-, K$^+$) reaction at 1.2 GeV/c.**

- **The calculated spectrum indicates the repulsive and absorptive components of the Σ^--^{5}He potential.**



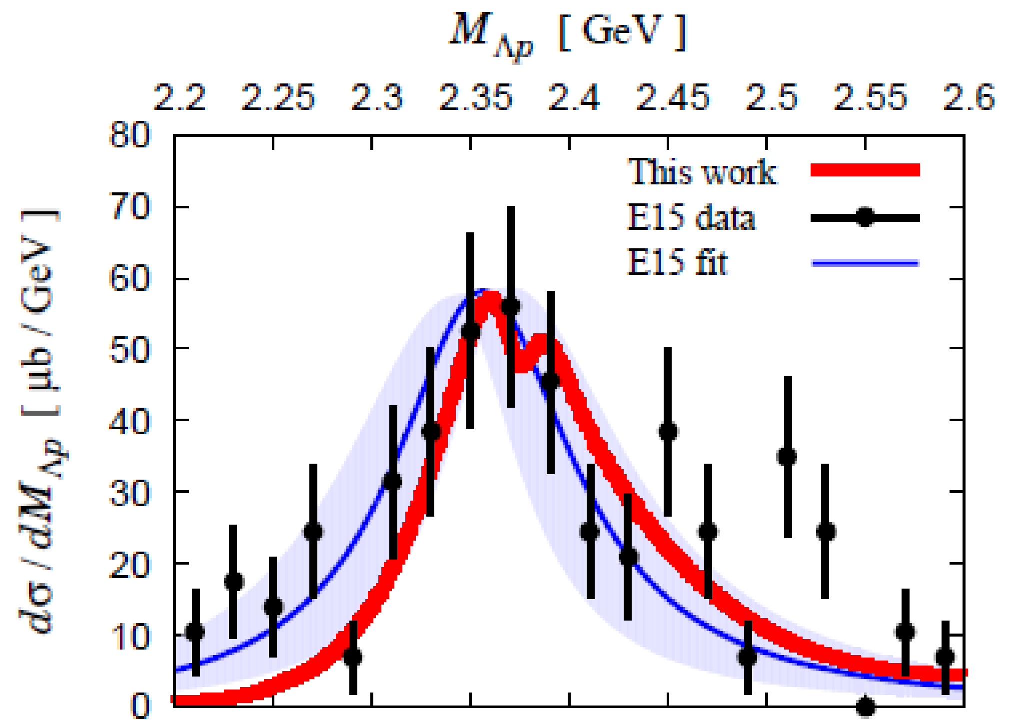
- **The repulsive Σ-nucleus potential for Σ^--^{5}He with (V_Σ, W_Σ)= (+30 MeV, −15 MeV) can fully reproduce the data of the ^{6}Li(π^-, K$^+$) reaction at 1.2 GeV/c.**

Anti-Kaon potential in Nuclear Matter ?

- **K^-pp binding energy (Takahashi (A02), Outa, Dote)**
  - **E15: One state at B.E.~ (15-30) MeV, Strength at B.E. ~ 100 MeV**
    E27: B.E.~100 MeV ?
  - **Dote: Higher pole B.E.~ 27 MeV, Lower pole B.E.~ 79 MeV (?)**
    Akaishi: B.E. ~ 100 MeV (DISTO, FINUDA)
    S.Ohnishi: Saturating B.E. in heavier kaonic nuclei

We need more work to confirm the fate of Kaon condensation

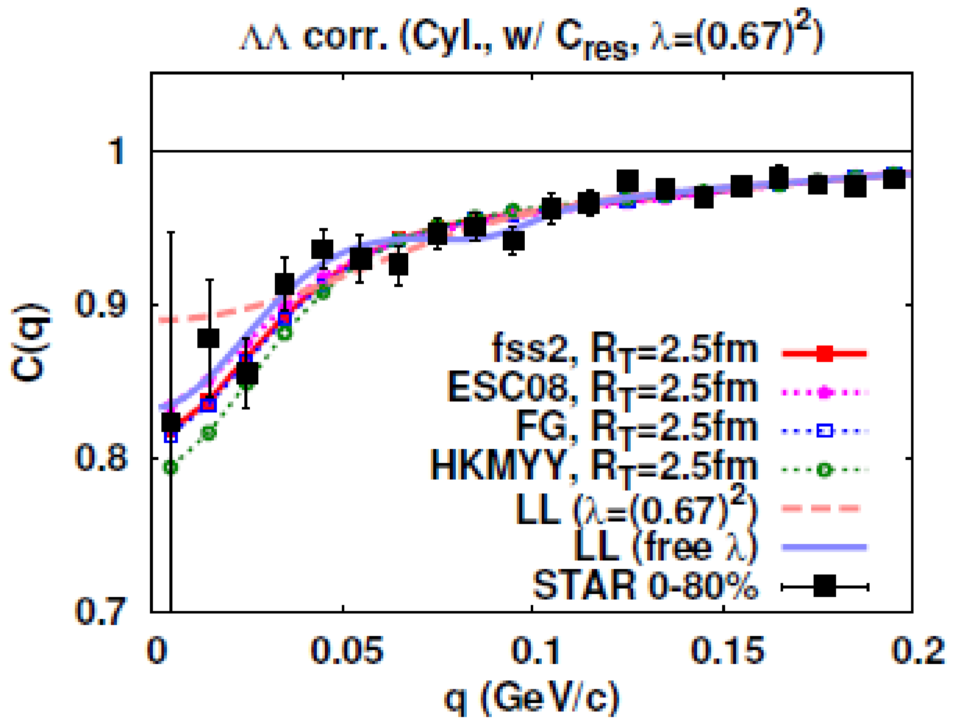
Muto

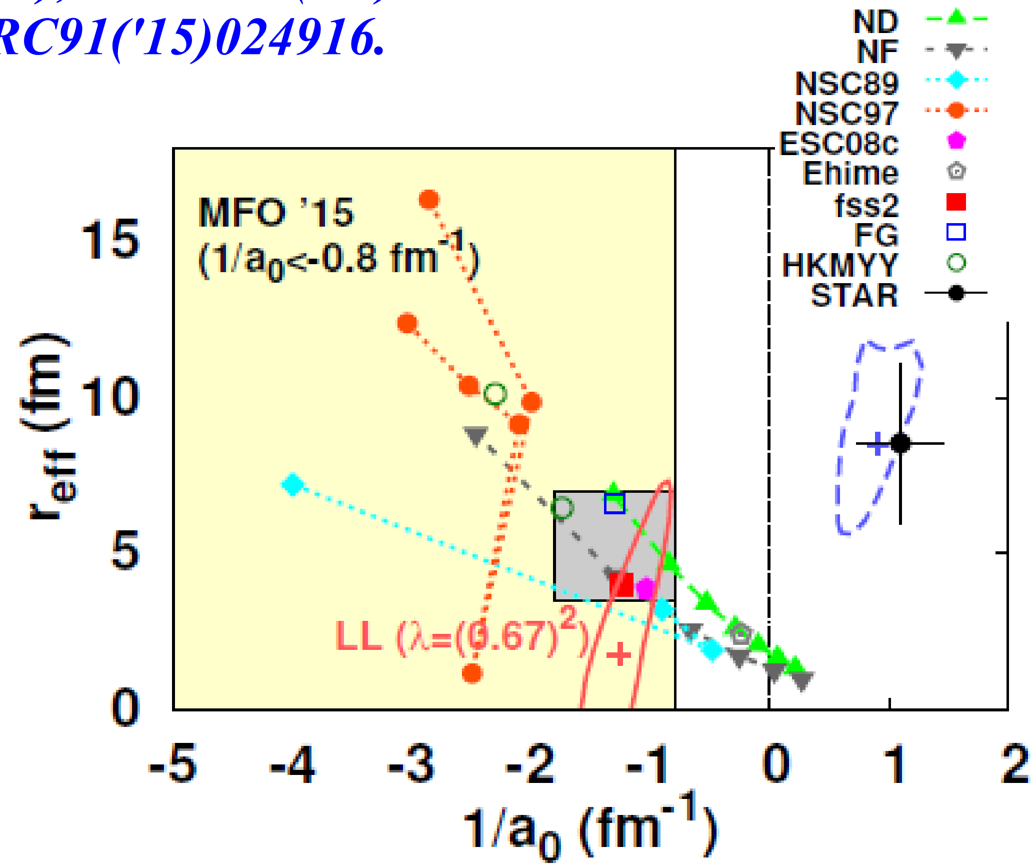


Sekihara, Oset, Ramos ('16)

ΛΛ potential ?

- **Nagara fit → $a_0(\Lambda\Lambda)$= - 0.575 fm or - 0.77 fm**
  Hiyama, Kamimura, Motoba, Yamada, Yamamoto ('02), Filikhin, Gal ('02)
- **New approach: ΛΛ correlation from HIC (Morita)**
  → -1.25 fm < $a_0(\Lambda\Lambda)$ < 0 (Consistent with Nagara)
  Exp: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  Theor.:Morita et al., T.Furumoto, AO, PRC91('15)024916.

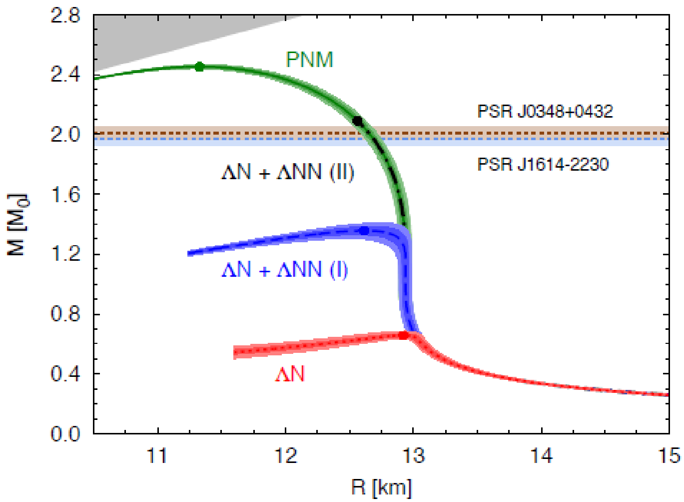




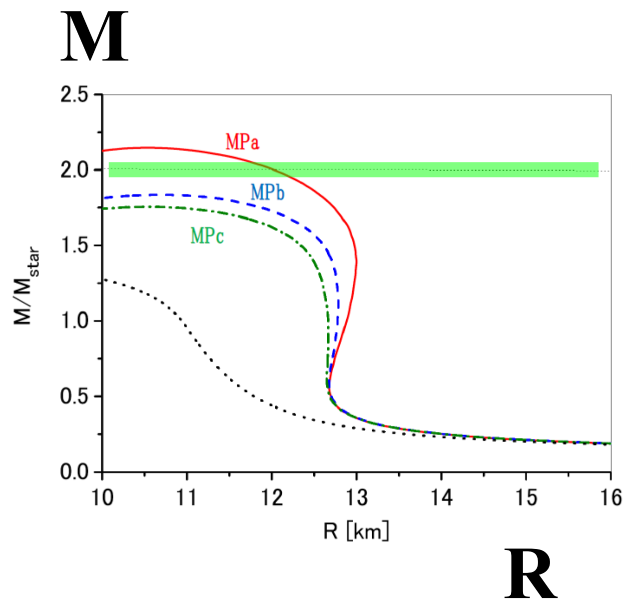
Remaining possibilities

- **Three-baryon (3B) interaction ?**
  - **"Universal" 3B repulsion**
    Nishizaki, Takatsuka, Yamamoto ('02), Tamagaki ('08), Yamamoto, Furumoto, Yasutake, Rijken ('13)
  - **Repulsive ΛNN potential (or density dep. ΛN pot.)**
    Lonardoni, Lovato, Gandolfi, Pederiva ('15), Togashi, Hiyama, Yamamoto, Takano ('16), Tsubakihara, Harada, AO ('16)
  - **Medium modification of baryons (Quark Meson Coupling model)**
    J.Rikovska-Stone, P.A.M.Guichon, H.H.Matevosyan, A.W.Thomas ('07), Miyatsu, Yamamuro, Nakazato ('13)
- **Quark matter NS core ?**
  - **First order phase transition**
    L. Bonanno, A. Sedrakian, Astron. Astrophys. 539 (2012) A16; M. Bejger, D. Blaschke, P. Haensel, J. L. Zdunik, M. Fortin, arXiv:1608.07049.
  - **Crossover transition to quark matter** *Masuda, Hatsuda, Takatsuka ('12)*
- **Modified Gravity** *Astashenok et al. ('14), M.-K. Cheoun's talk*

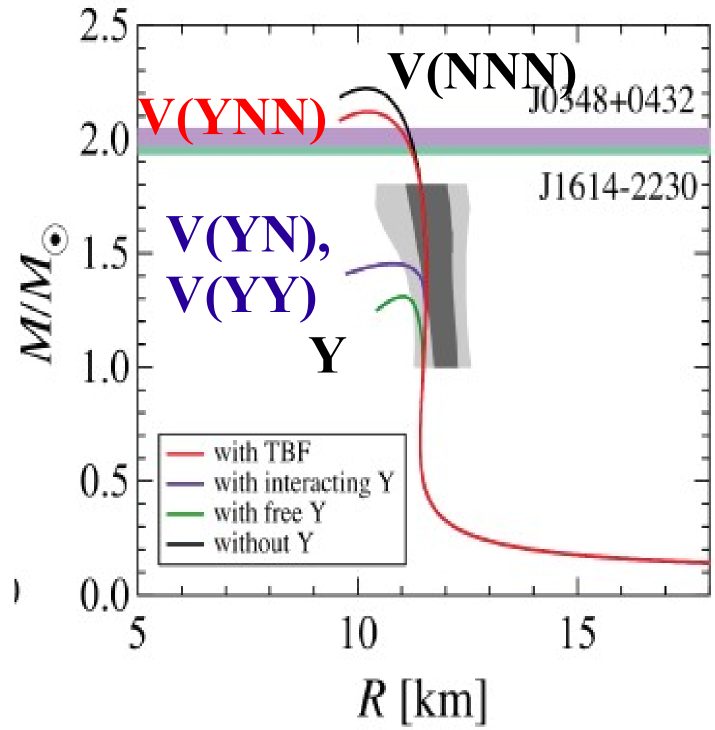
Hyperon Puzzle



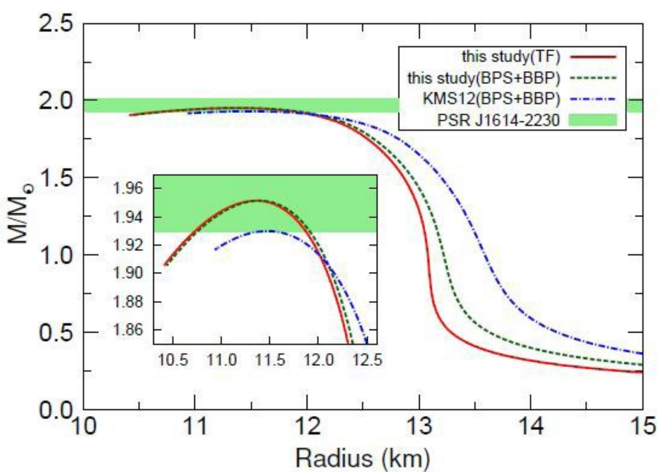
Lonardoni, Lovato, Gandolfi, Pederiva ('15),



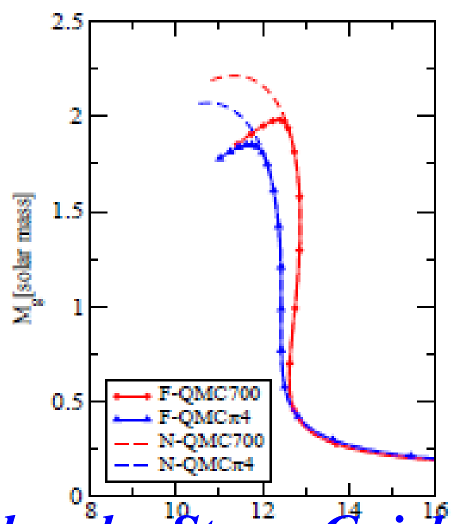
Yamamoto, Furumoto, Yasutake, Rijken ('13)



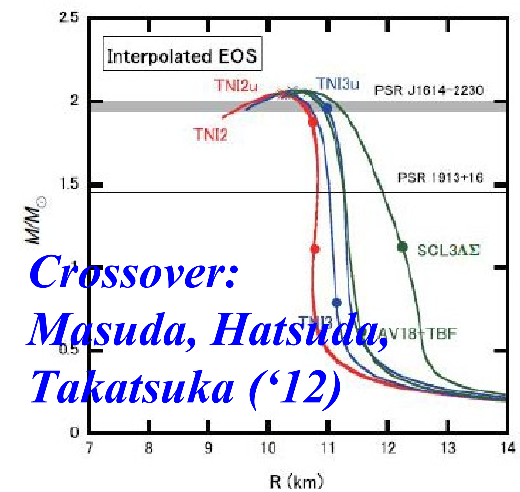
Togashi, Hiyama, Takano, Yamamoto ('16).



QMC, Miyatsu,Yamamuro, Nakazato ('13)



Rikovska-Stone, Guichon, Matevosyan, Thomas ('07),



Crossover: Masuda, Hatsuda, Takatsuka ('12)

Summary

- ハドロン - 原子核反応を記述する、現時点で「最良」の方法
  - 束縛状態の生成
    → 正確な核構造計算
    (配位混合を取り入れた Shell 模型計算、クラスター計算、....)
    + 歪曲波インパルス近似 (DWIA)
    (spectroscopic factor と光学ポテンシャルによる
    入射波・出射波の歪曲を考慮)
  - 連続状態のスペクトル
    → 正しい境界条件を与える Green's Function Method を
    用いた DWIA
- Hyperon Puzzle
  - $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV
  - Hyperon, Kaon の混在を考慮した EOS では、$2M_\odot$ を支えられない。
  - 新たなデータも Hyperon Puzzle 解決とならない。
  - 3B repulsion, Quark Matter or Modified gravity