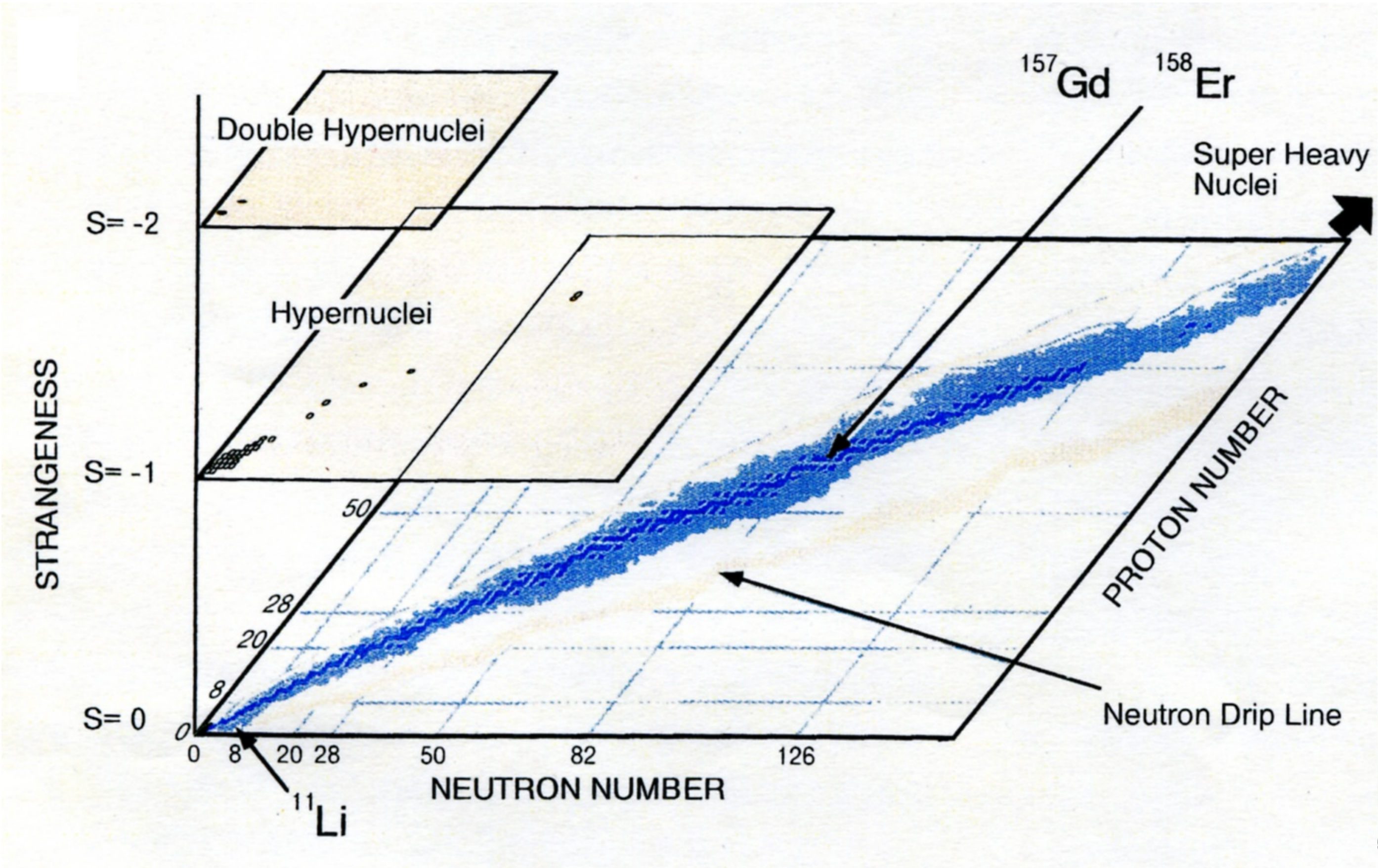
RIBF Mini Workshop
July 17, 2007

ハイパー核・中性子過剰核・ケイオン核を繋ぐ 一つのエキゾティクス

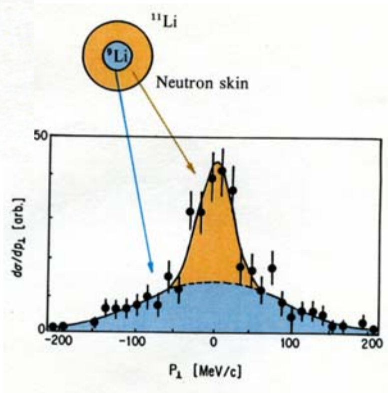
赤石　義紀

理研　・　日大理工

物理学会誌 44 (1989) 641
Exotic Nuclear Physics
大型ハドロン計画における核物理の柱

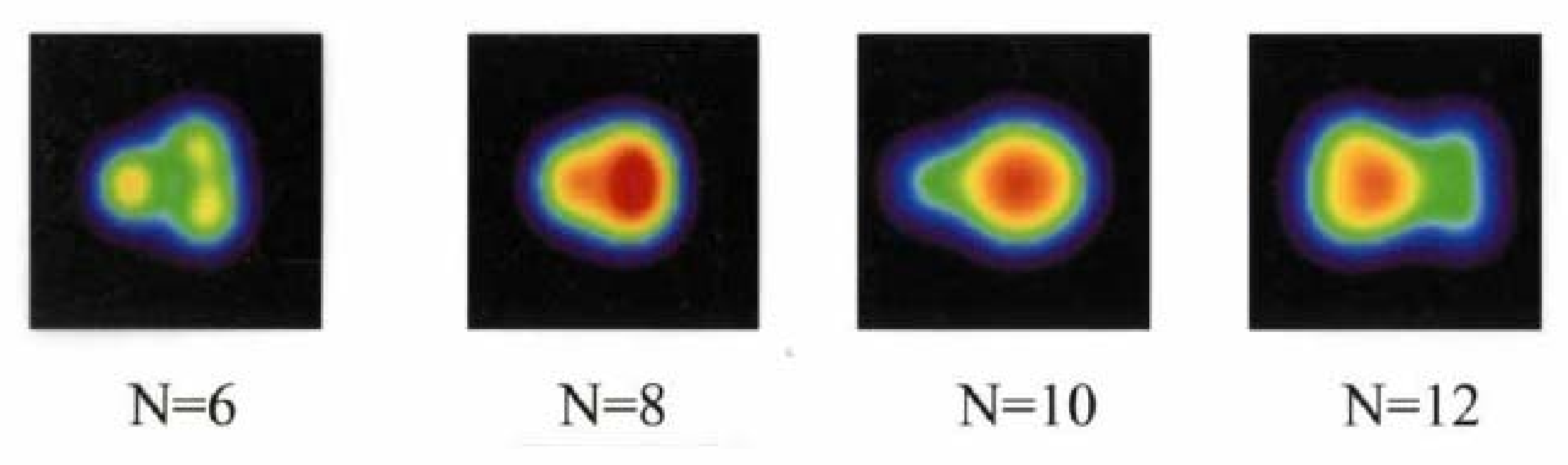


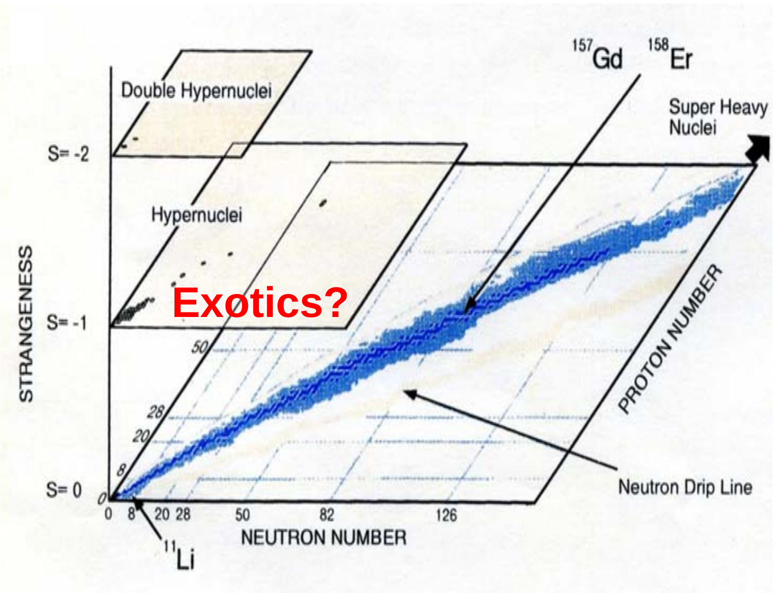
An exotic nucleus, ^{11}Li



Structure change of B isotopes

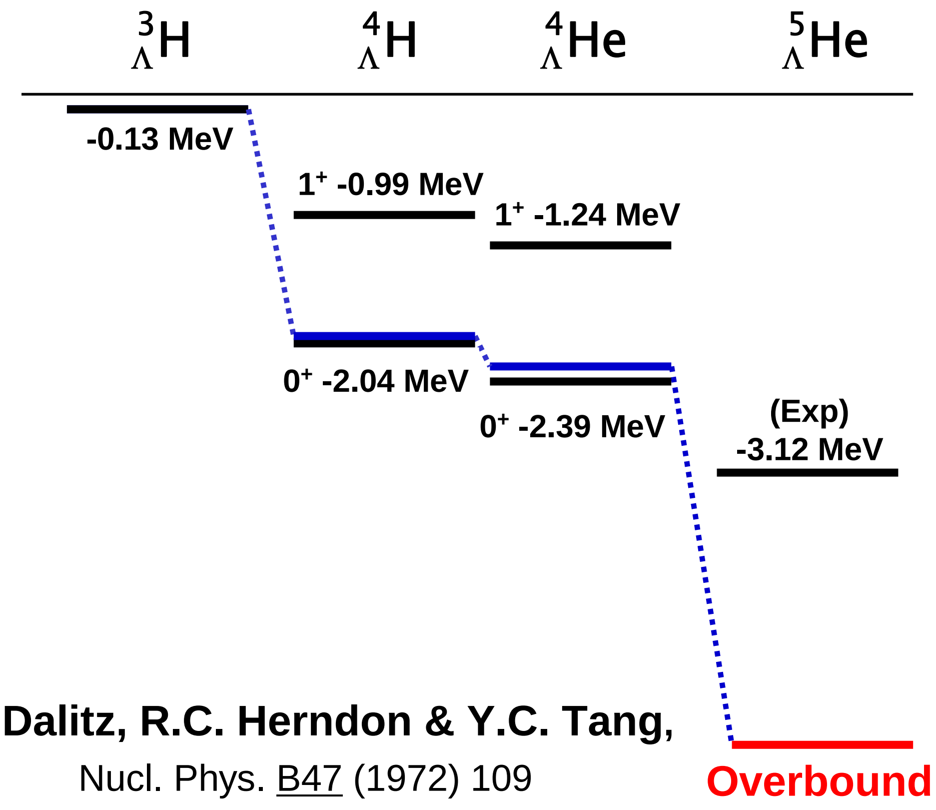
AMD calculation
by Y. Kanada-En'yo





Coherent Λ-Σ Coupling

The overbinding problem



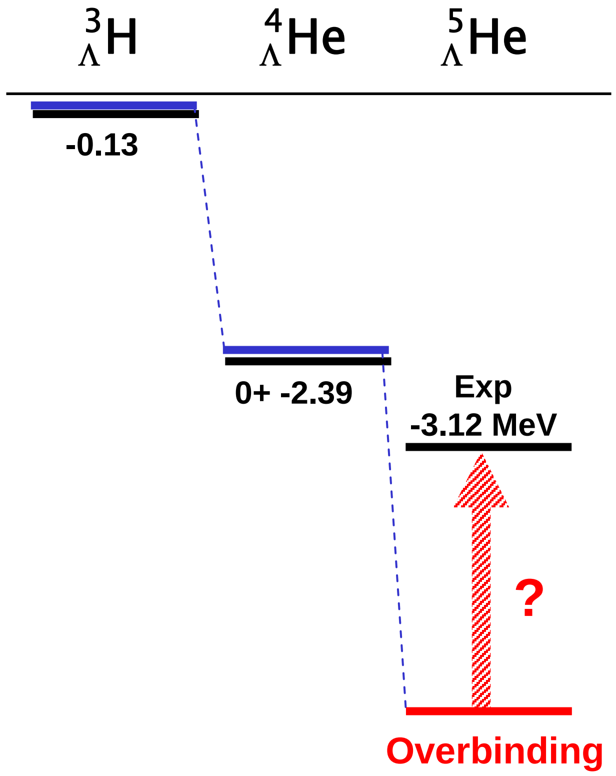
R.H. Dalitz, R.C. Herndon & Y.C. Tang,
Nucl. Phys. B47 (1972) 109

Two Pictures

ΛN int.

D0

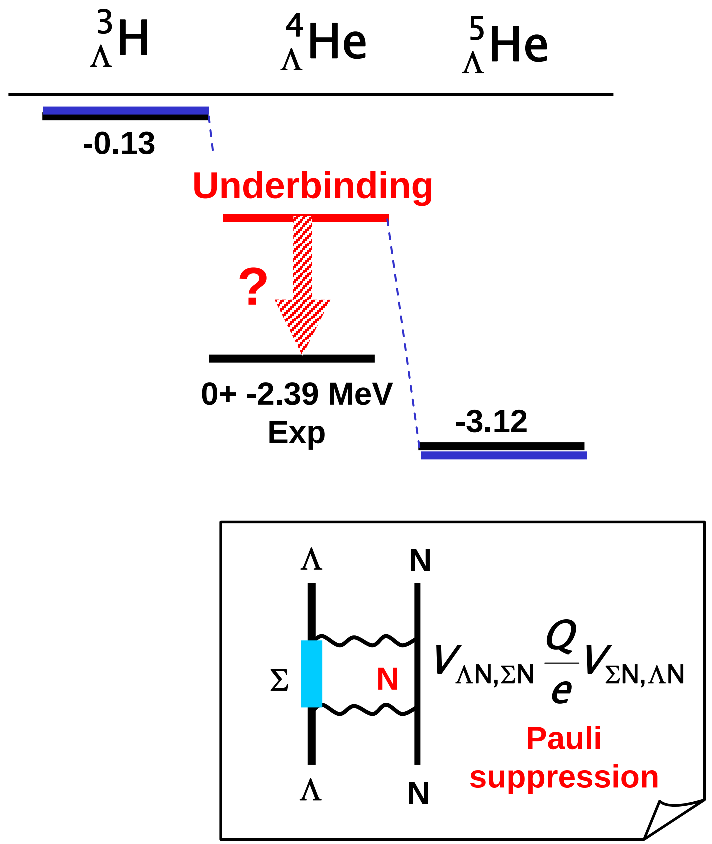
Overbinding problem



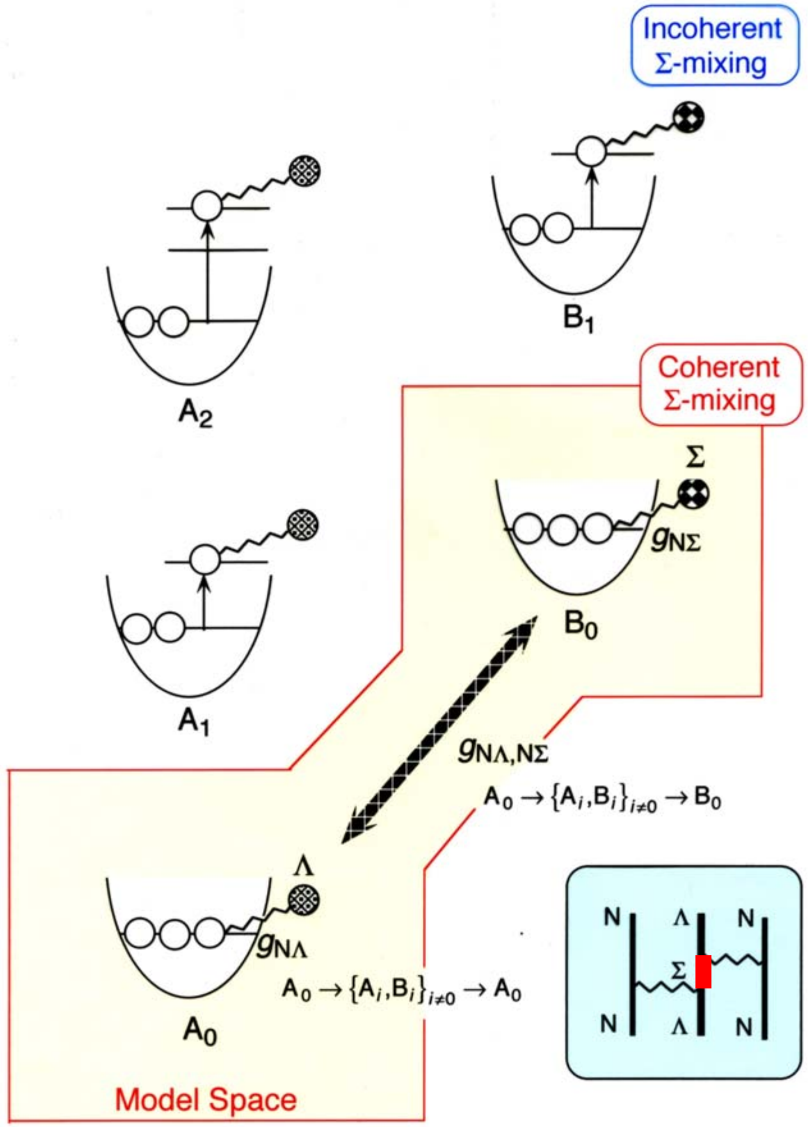
ΛN-ΣN int.

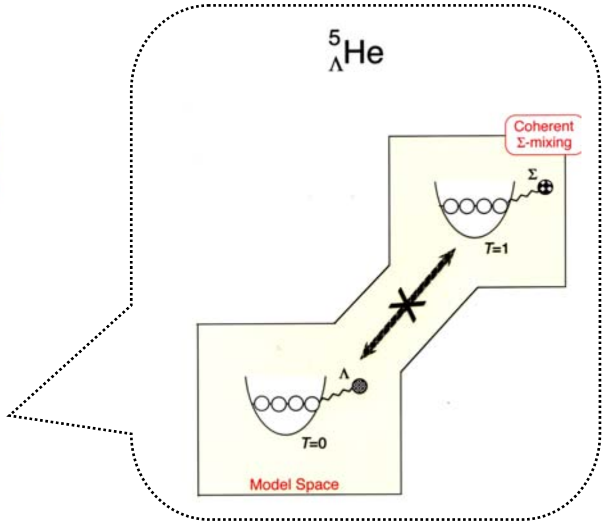
D2

Underbinding problem



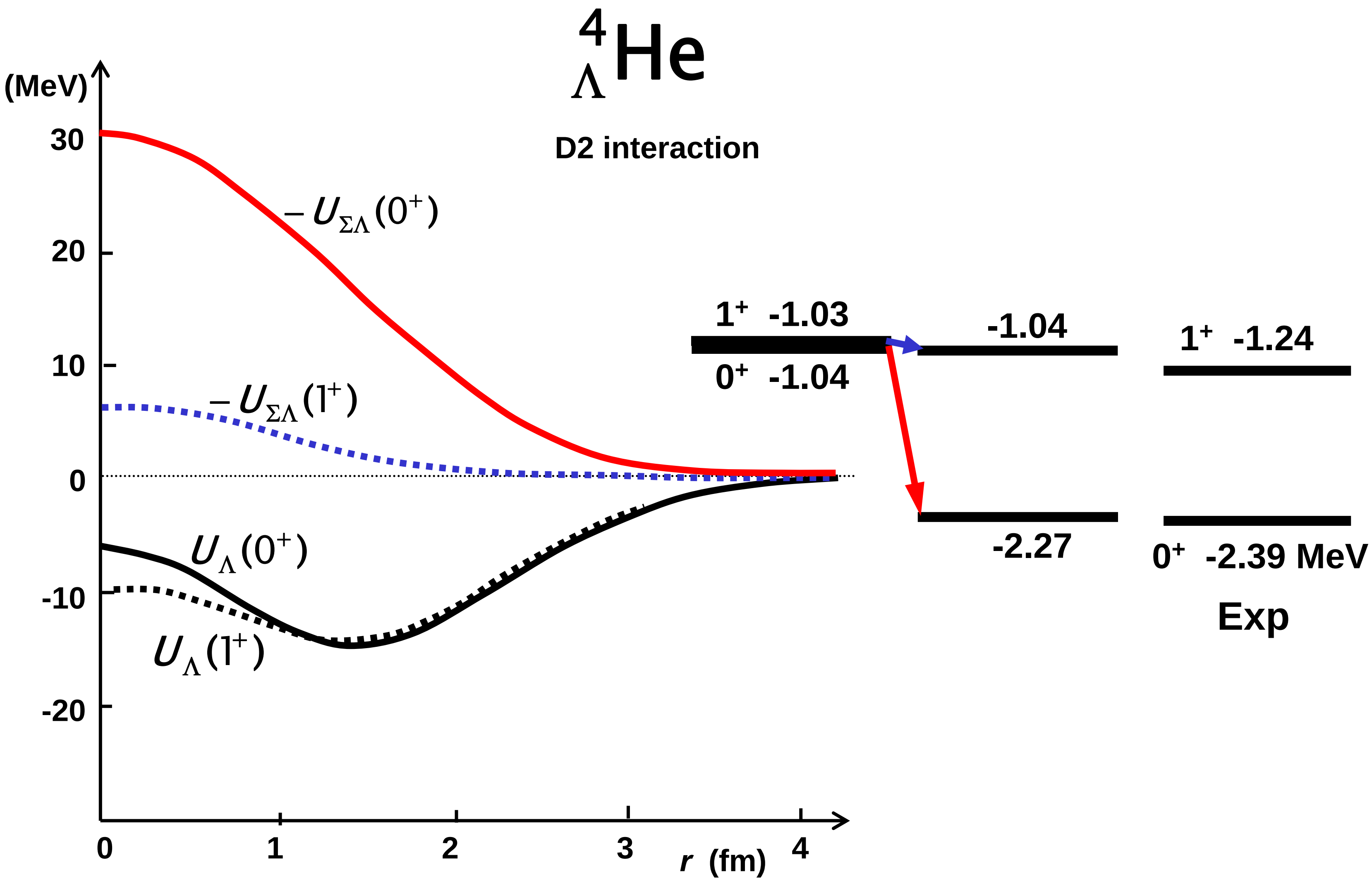
Coherent Λ-Σ Coupling





Λ T=0 1116 MeV/c²

Σ T=1 1193 MeV/c²



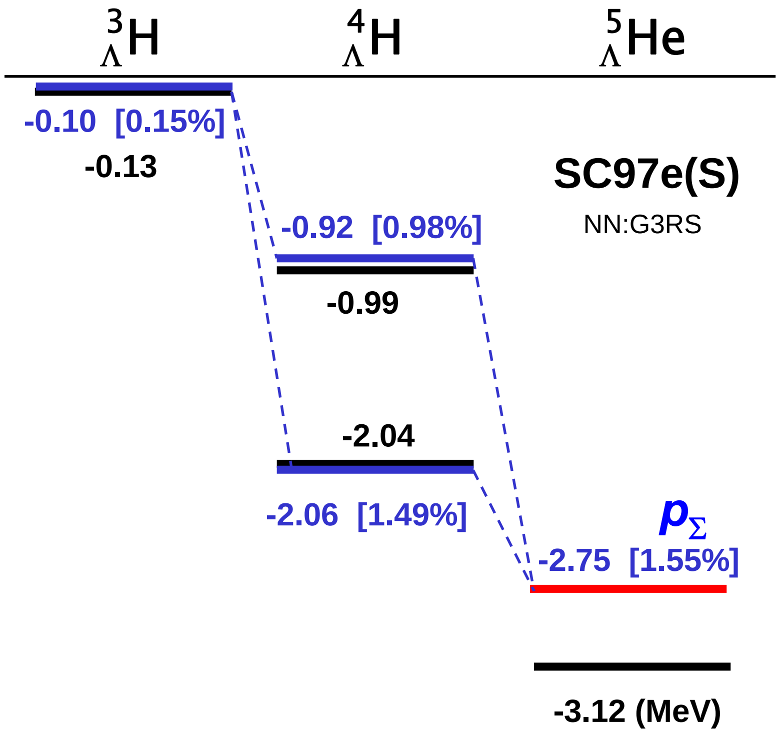
Y. Akaishi, T. Harada, S. Shinmura and Khin Swe Myint, Phys. Rev. Lett. 84 (2000) 3539

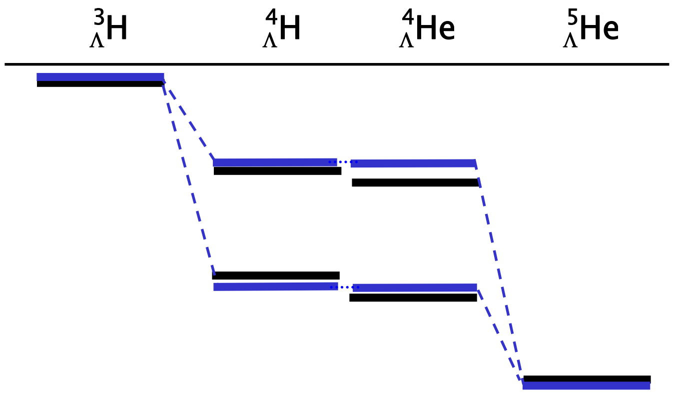
Stochastic Variational Calculation of $^{5}_{\Lambda}$He

H. Nemura et al.,
Phys. Rev. Lett. 89 (2002) 142504

The first successful *ab initio* 5-body calculation including Σ degrees of freedom

J.A. Carlson,
AIP Conf. Proc. 224 (1991) 198
SC89: unbound

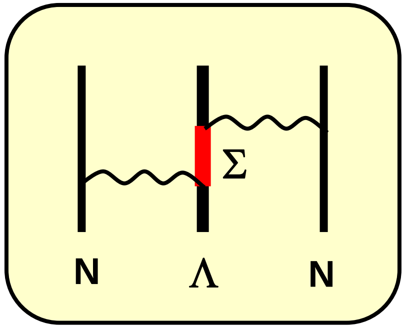




The overbinding problem has been virtually solved.

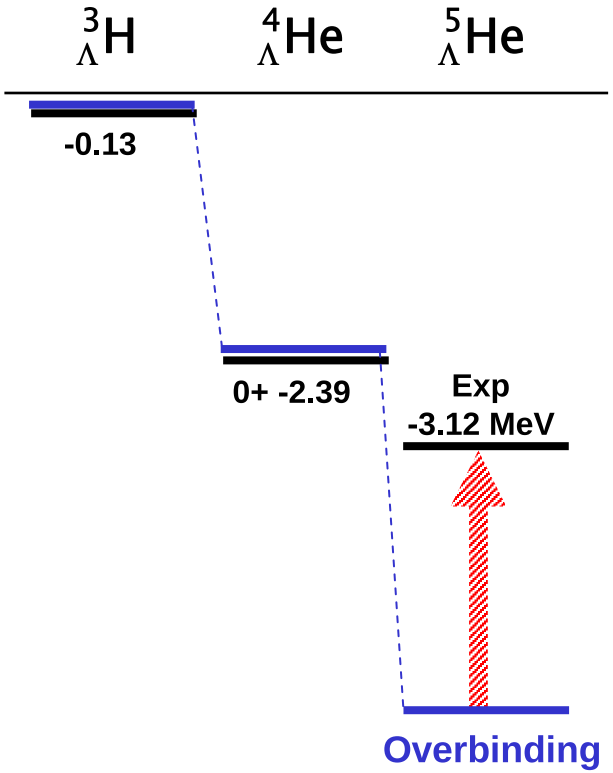
Repulsion?

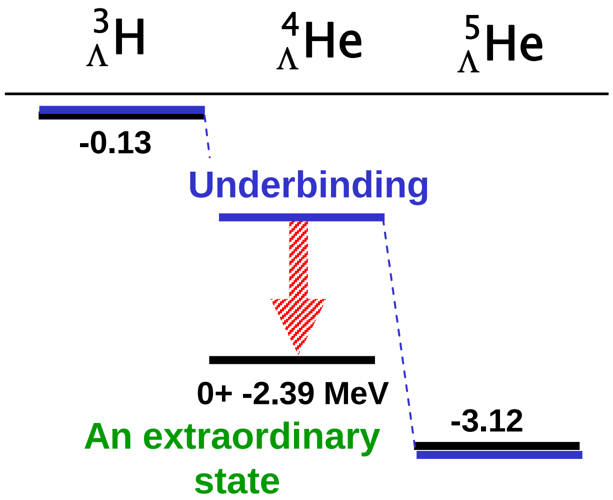
Y. Nogami et al.
Nucl. Phys. B19 (1970) 93



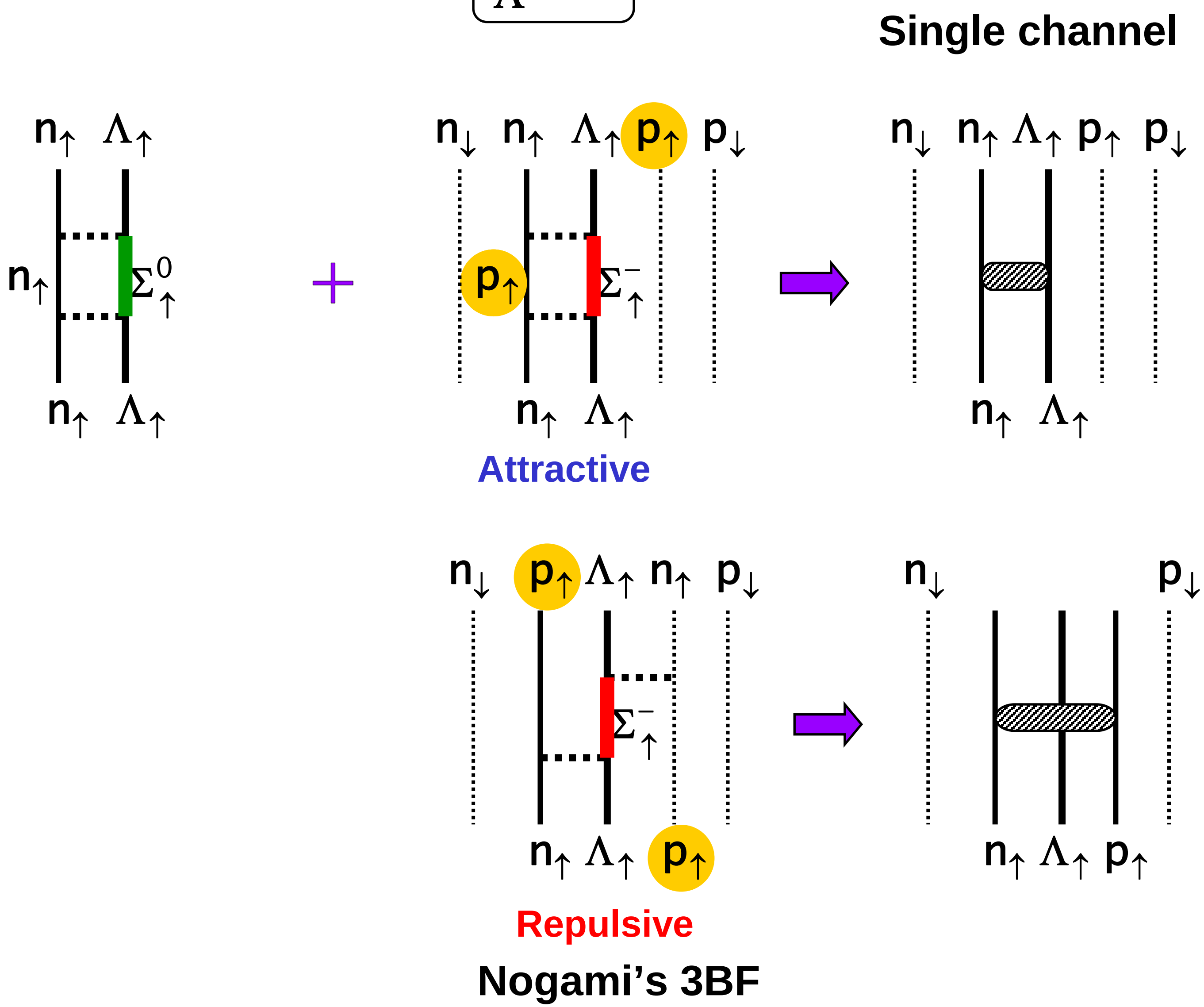
Attraction?

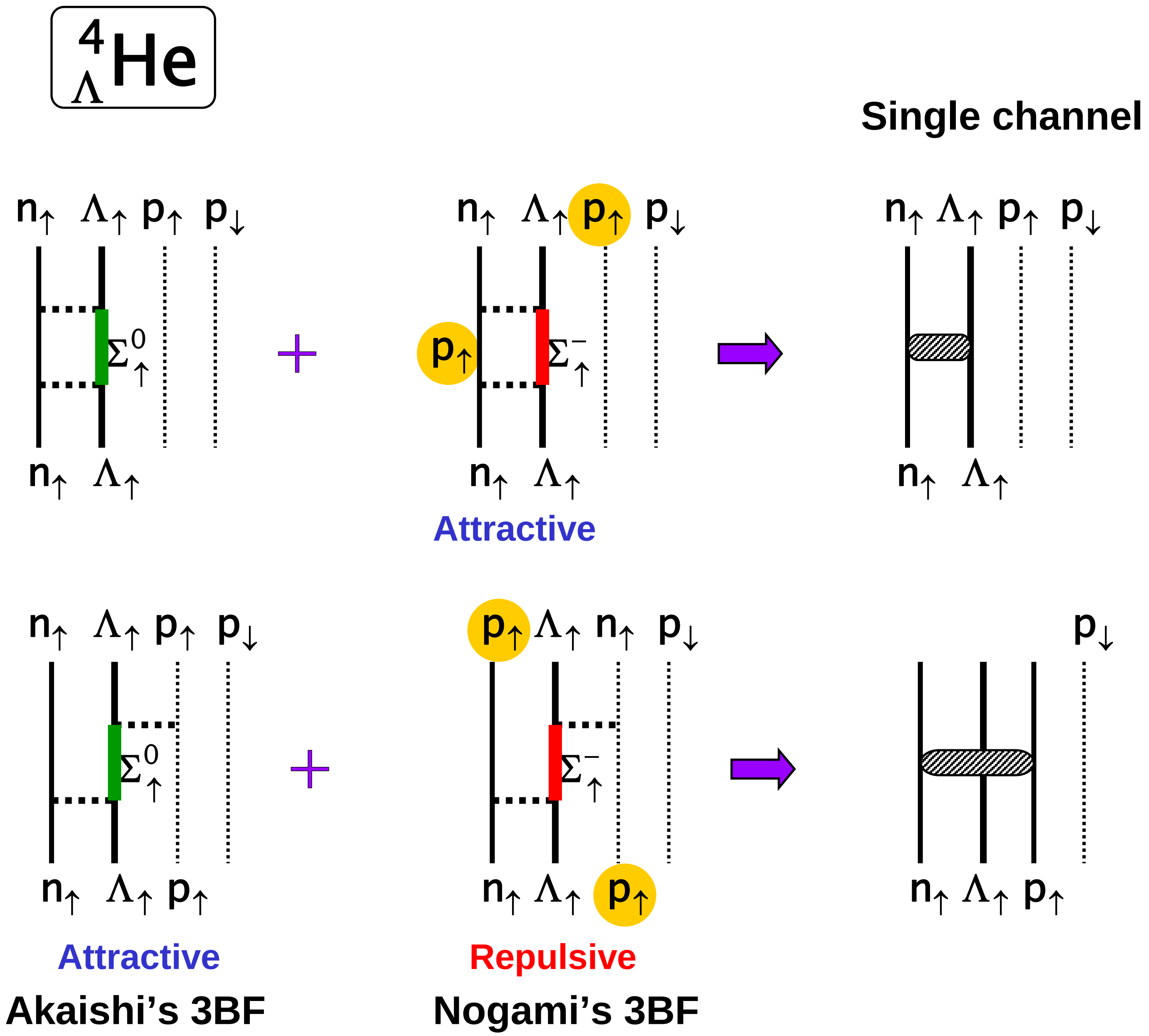
Y. Akaishi et al.
Phys. Rev. Lett. 84 (2000) 3539





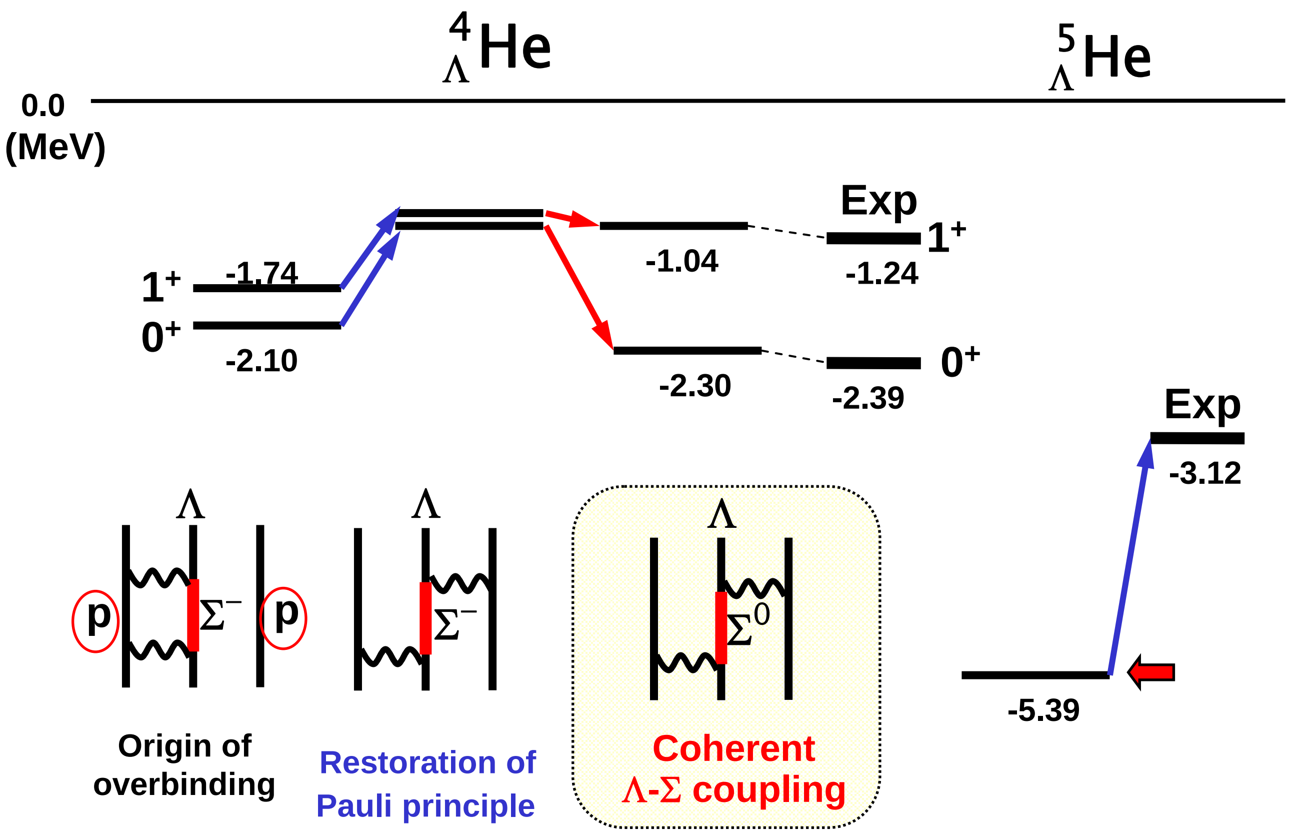
$^{5}_{\Lambda}$He


Single channel
n↑ Λ↑
n↑ Σ0↑
n↑ Λ↑
+
n↓ n↑ Λ↑ p↑ p↓
p↑ Σ−↑
n↑ Λ↑
Attractive
n↓ n↑ Λ↑ p↑ p↓
n↑ Λ↑
n↓ p↑ Λ↑ n↑ p↓
Σ−↑
n↑ Λ↑ p↑
Repulsive
Nogami's 3BF
n↓ p↓
n↑ Λ↑ p↑



$^{4}_{\Lambda}He$
Single channel
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$ $p_\downarrow$
$\Sigma^0_\uparrow$
$n_\uparrow$ $\Lambda_\uparrow$
+
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$ $p_\downarrow$
$p_\uparrow$
$\Sigma^-_\uparrow$
$n_\uparrow$ $\Lambda_\uparrow$
Attractive
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$ $p_\downarrow$
$n_\uparrow$ $\Lambda_\uparrow$
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$ $p_\downarrow$
$\Sigma^0_\uparrow$
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$
+
$p_\uparrow$ $\Lambda_\uparrow$ $n_\uparrow$ $p_\downarrow$
$\Sigma^-_\uparrow$
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$
$p_\downarrow$
$n_\uparrow$ $\Lambda_\uparrow$ $p_\uparrow$
Attractive
Repulsive
Akaishi's 3BF
Nogami's 3BF

ΛNN three-body force



Essential dynamics

$$U_{\Lambda NN} = \sum_{\alpha=tt,ts,ss}\left[a_\alpha + b_\alpha(\vec{\sigma}_1\vec{\sigma}_2) + c_\alpha \frac{1}{2}\vec{\sigma}_\Lambda(\vec{\sigma}_1+\vec{\sigma}_2)\right] W_3^\alpha(r_{1\Lambda}, r_{\Lambda 2})$$

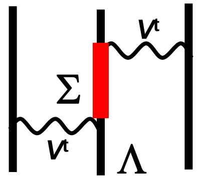
ΛNN spin-spin

Three-Body Force due to Coherent Λ-Σ Coupling : [for D0]

$$U_{\Lambda NN} = \sum_{\alpha=tt,ts,ss} W_3^{\alpha}(r_{1\Lambda}, r_{\Lambda 2})\left[a_\alpha + b_\alpha(\vec{\sigma}_1\vec{\sigma}_2) + c_\alpha \frac{1}{2}\vec{\sigma}_\Lambda(\vec{\sigma}_1+\vec{\sigma}_2)\right]$$

ΛNN spin-spin

$$\begin{Bmatrix} a_{tt} & b_{tt} & c_{tt} \\ a_{ts} & b_{ts} & c_{ts} \\ a_{ss} & b_{ss} & c_{ss} \end{Bmatrix} = \begin{Bmatrix} \frac{7}{16} & \frac{3}{16} & \frac{3}{8} \\ \frac{1}{8} & \frac{1}{8} & -\frac{1}{4} \\ \frac{5}{48} & \frac{1}{48} & -\frac{1}{8} \end{Bmatrix}$$



$$W_3^{tt}(r, r') = V^t_{\Lambda N,\Sigma N}(r)\frac{1}{\Delta M^*}V^t_{\Sigma N,\Lambda N}(r')$$

${}^5_\Lambda$He	$\frac{1}{2}(3+\beta^2)\left\langle W_3^{tt}\right\rangle_5$	**3 MeV**
${}^4_\Lambda$H(1$^+$)	$\frac{1}{8}(9+2\beta+\beta^2)\left\langle W_3^{tt}\right\rangle_4$	**1.0 MeV**
${}^4_\Lambda$H(0$^+$)	$\frac{1}{8}(-3-6\beta+5\beta^2)\left\langle W_3^{tt}\right\rangle_4$	**-0.44 MeV**
${}^3_\Lambda$H	$\frac{1}{8}(-1-6\beta+3\beta^2)\left\langle W_3^{tt}\right\rangle_3$	**-0.05 MeV**

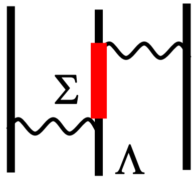
$$\left\langle V^s_{\Sigma N,\Lambda N}\right\rangle = -\beta\left\langle V^t_{\Sigma N,\Lambda N}\right\rangle, \quad \beta = 0.67$$

Three-Body Force due to Coherent Λ-Σ Coupling : [for D2]

$$U_{\Lambda NN} = \sum_{\alpha=tt,ts,ss} W_3^{\alpha}(r_{1\Lambda}, r_{\Lambda 2})\left[a_\alpha + b_\alpha(\vec{\sigma}_1\vec{\sigma}_2) + c_\alpha \frac{1}{2}\vec{\sigma}_\Lambda(\vec{\sigma}_1 + \vec{\sigma}_2)\right]$$

ΛNN spin-spin

$$\begin{Bmatrix} a_{tt} & b_{tt} & c_{tt} \\ a_{ts} & b_{ts} & c_{ts} \\ a_{ss} & b_{ss} & c_{ss} \end{Bmatrix} = \begin{Bmatrix} \frac{7-6\gamma}{16} & \frac{3}{16} & \frac{3-\gamma}{8} \\ \frac{1}{8} & \frac{1}{8} & -\frac{1}{4} \\ \frac{5-6\gamma}{48} & \frac{1}{48} & -\frac{1-\gamma}{8} \end{Bmatrix}, \quad \gamma = \frac{\#_{\Lambda N\ \mathrm{pairs}}}{\#_{\Lambda NN\ \mathrm{trios}}}$$



The essential part of coherent Λ-Σ coupling

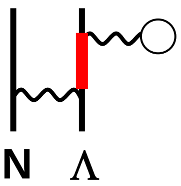
Nogami's term is removed.

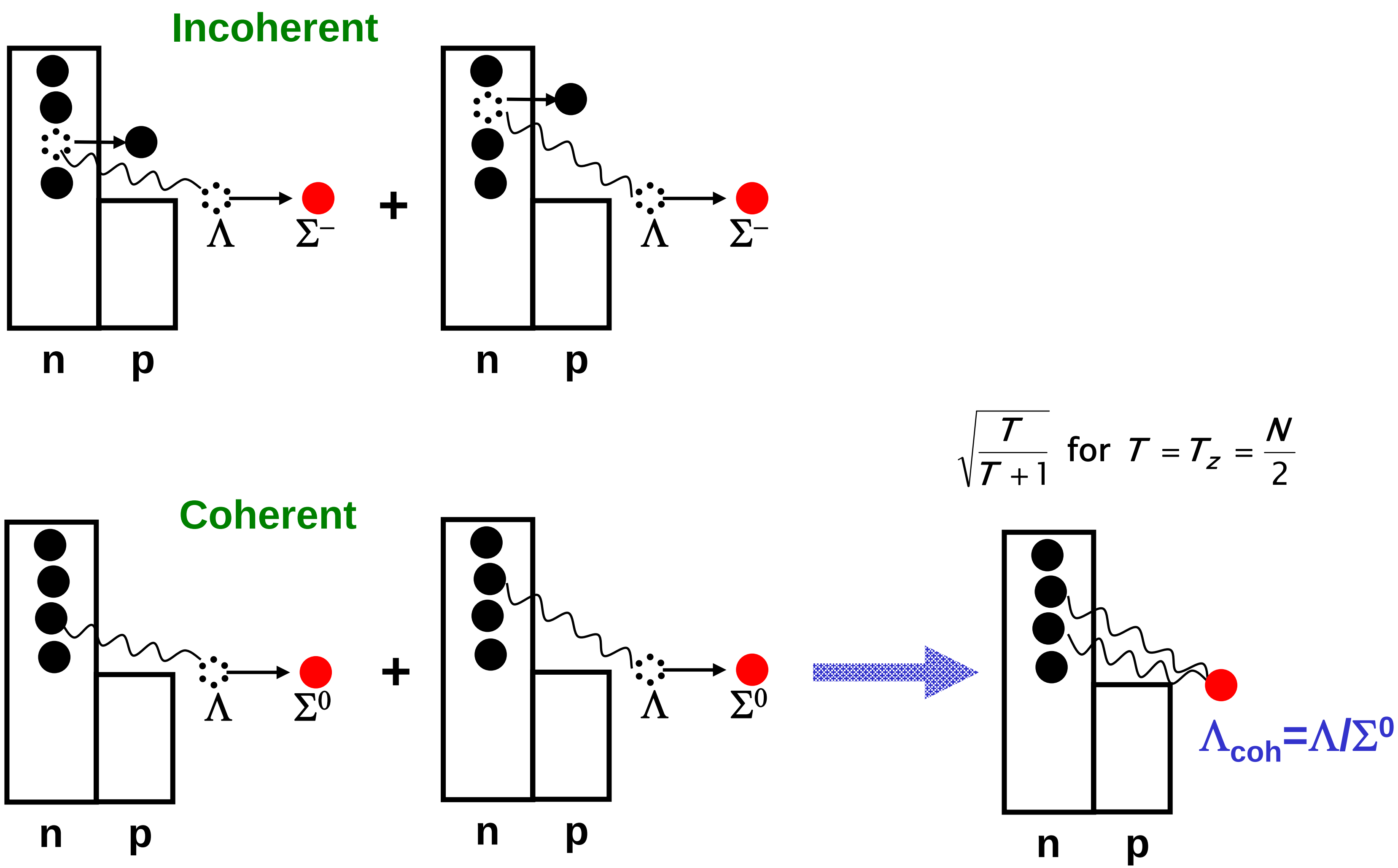
ΛNN force

Repulsive/attractive : "D0 picture"

Attractive : "D2 picture"

consistency ⟷ **Effective ΛN interaction**




Incoherent
n
p
Λ
Σ⁻
+
n
p
Λ
Σ⁻
$\sqrt{\frac{T}{T+1}}$ for $T = T_z = \frac{N}{2}$
Coherent
n
p
Λ
Σ⁰
+
n
p
Λ
Σ⁰
n
p
Λ_{coh}=Λ/Σ⁰

Relativistic mean field model

Baryons: ***n, p, Λ, Σ***

Mesons: ***σ, ρ, ω***

For Λ and Σ^0

$$\left(\not\partial - \gamma^0 g_{\Lambda\Lambda\omega}\omega_0 - M_\Lambda + g_{\Lambda\Lambda\sigma}\sigma\right)\Lambda - \gamma^0 g_{\Lambda\Sigma\rho}\rho_0\,\Sigma^0 = 0$$

$$\left(\not\partial - \gamma^0 g_{\Sigma\Sigma\omega}\omega_0 - M_\Sigma + g_{\Sigma\Sigma\sigma}\sigma\right)\Sigma^0 - \gamma^0 g_{\Sigma\Lambda\rho}\rho_0\,\Lambda = 0$$

Coherent Λ-Σ mixing

For mesons

$$m_\sigma^{\;2}\sigma = \sum g_{BB\sigma}\langle \bar{B}B\rangle$$

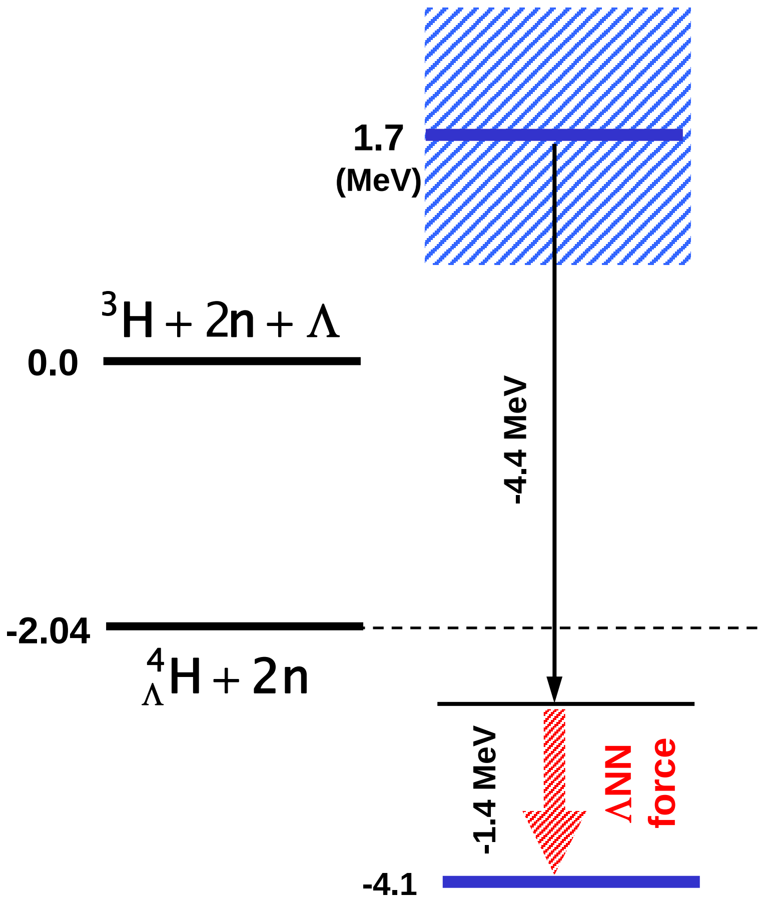
$$m_\omega^{\;2}\omega^0 = \sum g_{BB\omega}\langle \bar{B}\gamma^0 B\rangle$$

$$m_\rho^{\;2}\rho^0 = \sum g_{BB\rho}\langle \bar{B}\gamma^0 B\rangle + g_{\Lambda\Sigma\rho}\left(\langle \bar{\Lambda}\gamma^0\Sigma\rangle + \langle \bar{\Sigma}\gamma^0\Lambda\rangle\right)$$

"Normal state of infinite matter"

Baryons in the medium carry the same quantum numbers in vacuum.

N.K. Glendenning, Astrophys. J. 293 (1985) 470



$^1H(^6He, ^2He)$ ^5H

Superheavy hydrogen

A.A. Korsheninnikov et al,
Phys. Rev. Lett. 87 (2001) 092501

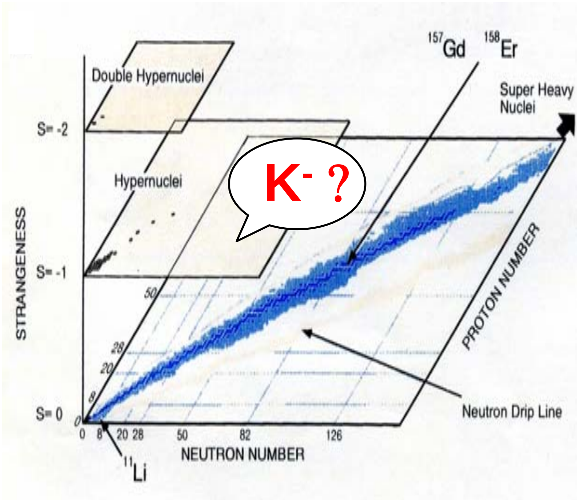
Neutron-rich hypernuclei
can provide additional evidences for coherent Λ-Σ coupling.

$^6Li(\pi^-, K^+)$ $^6_\Lambda H$

$^7_\Lambda H$ $^8_\Lambda H$ ← H.I.

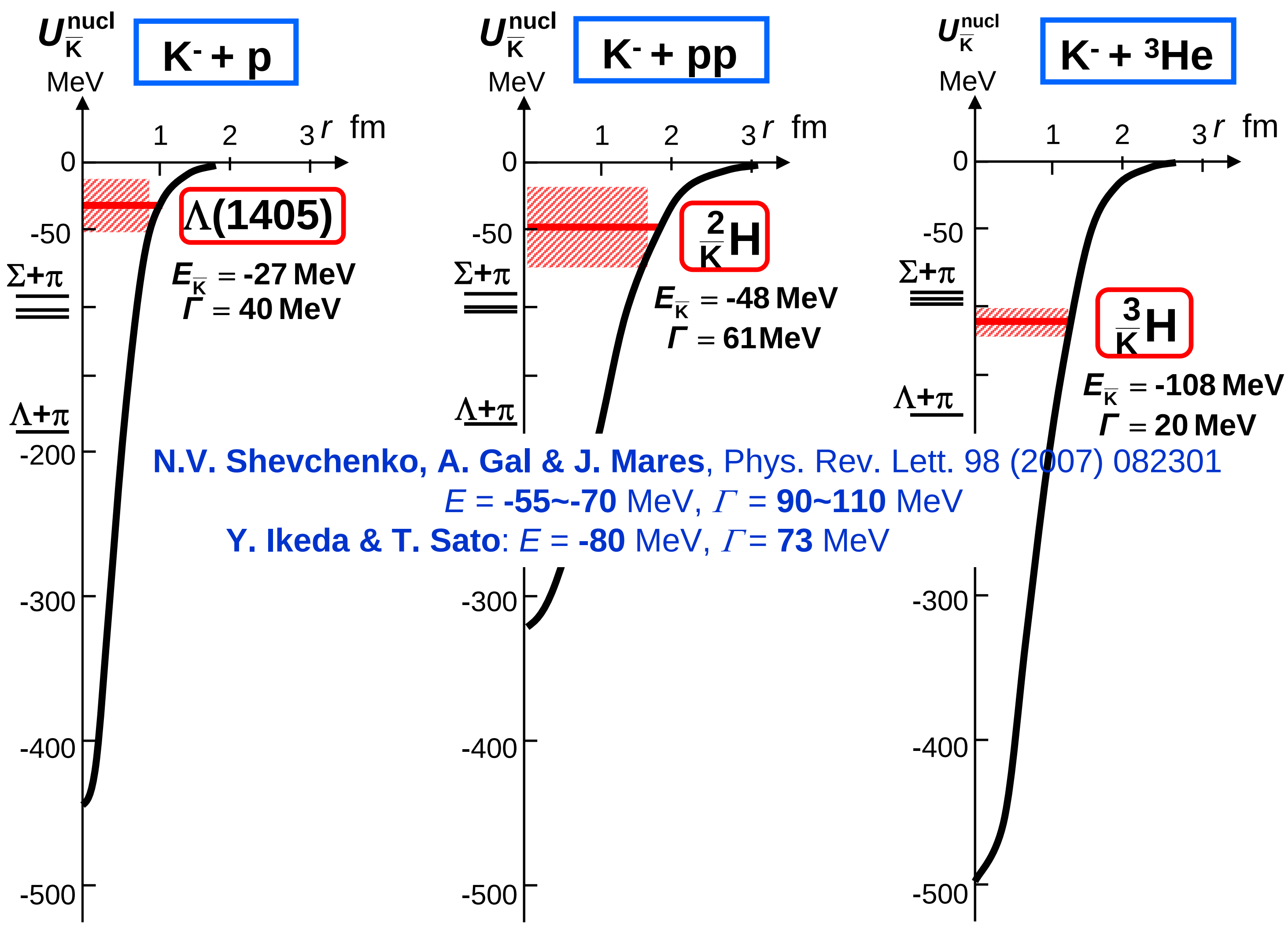
"Hyperheavy hydrogen"

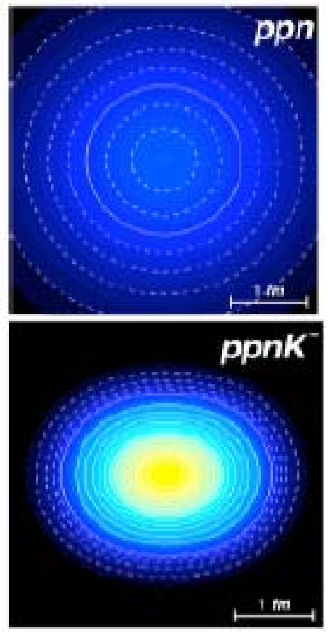
Khin Swe Myint & Y. Akaishi,
Prog. Theor. Phys. Suppl. 146 (2002) 599



Double Hypernuclei
Hypernuclei
K- ?
157Gd 158Er
Super Heavy Nuclei
STRANGENESS
S= -2
S= -1
S= 0
PROTON NUMBER
Neutron Drip Line
NEUTRON NUMBER
0 8 20 28 50 82 126
11Li

K^{bar} Nuclei





Shrinkage!

N.V. Shevchenko, A. Gal & J. Mares, Phys. Rev. Lett. 98 (2007) 082301

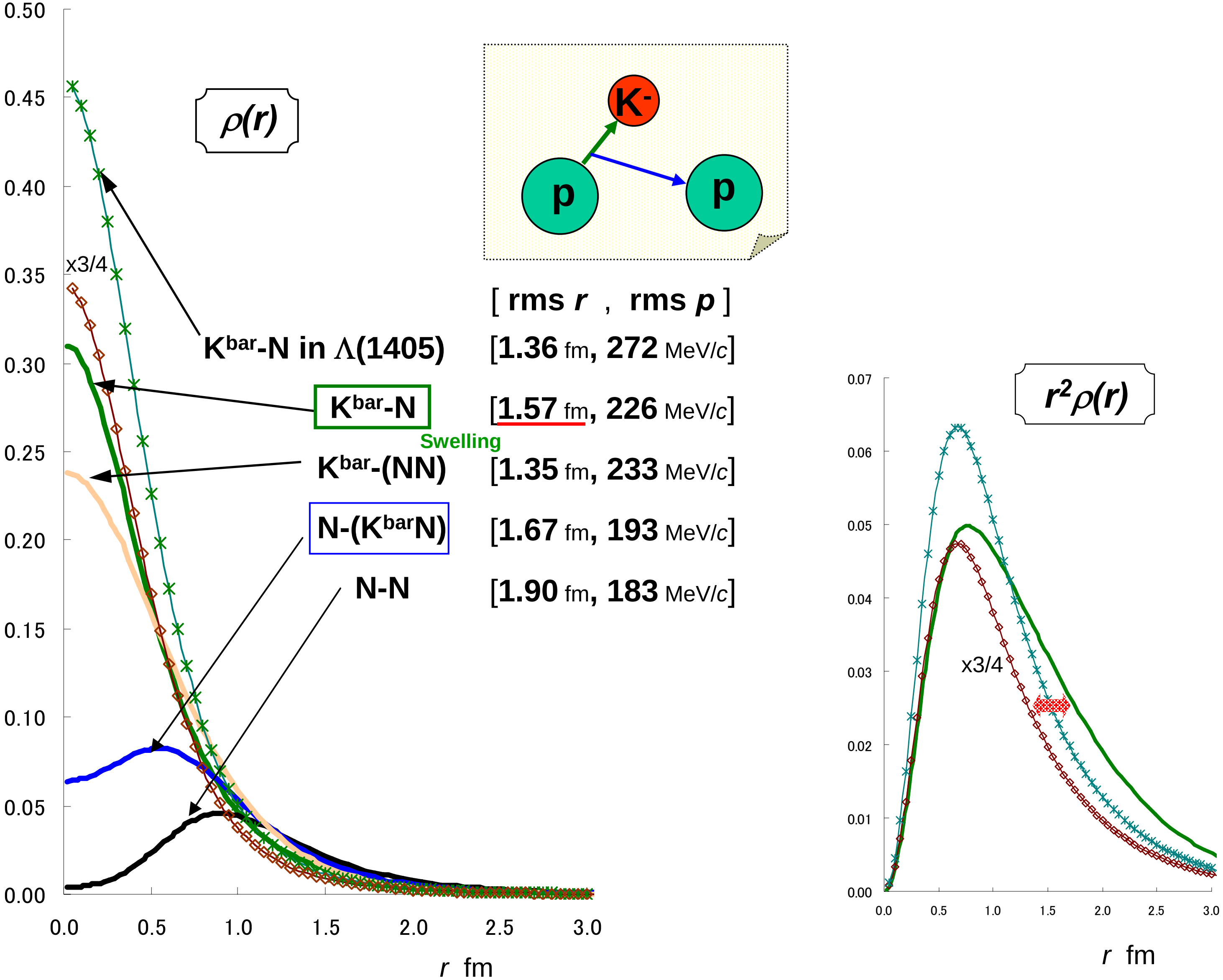
E = **-55~-70** MeV, Γ = **90~110** MeV

Y. Ikeda & T. Sato: E = **-80** MeV, Γ = **73** MeV

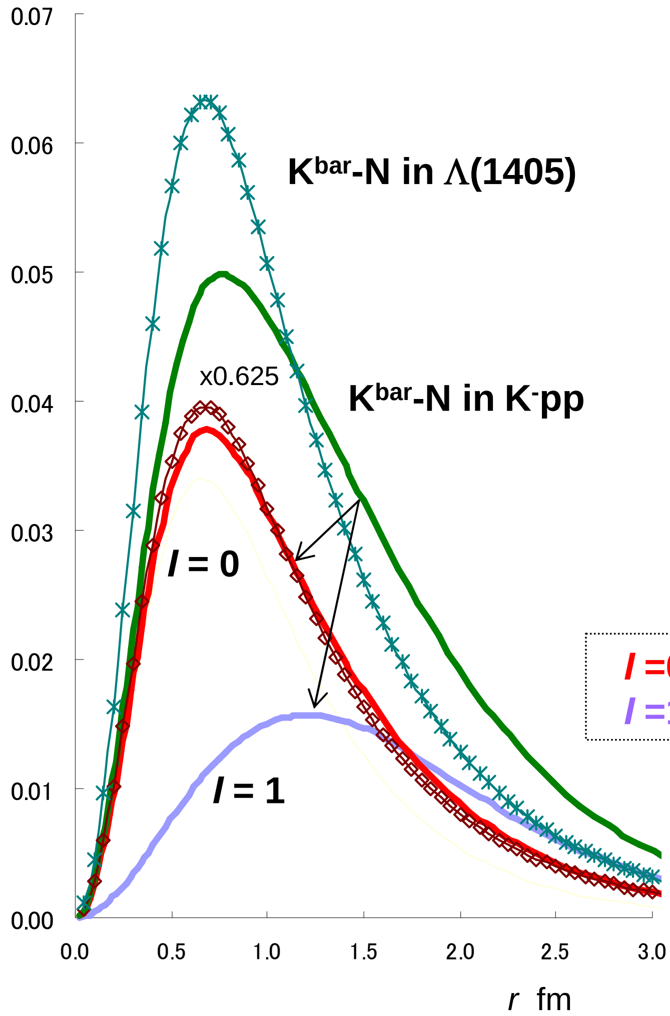
Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005

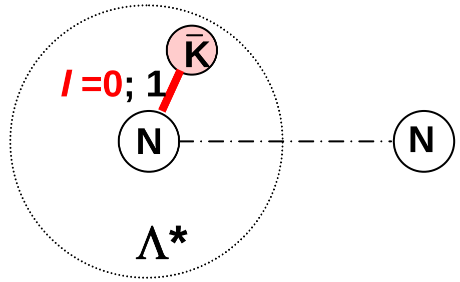
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70

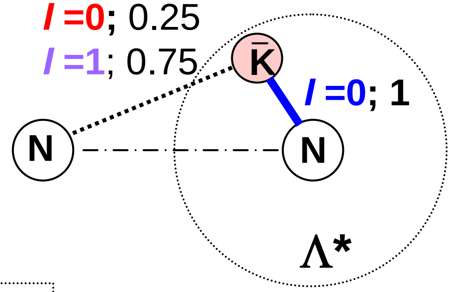
Density distributions in K^-pp



Density distributions of K^{bar}-N



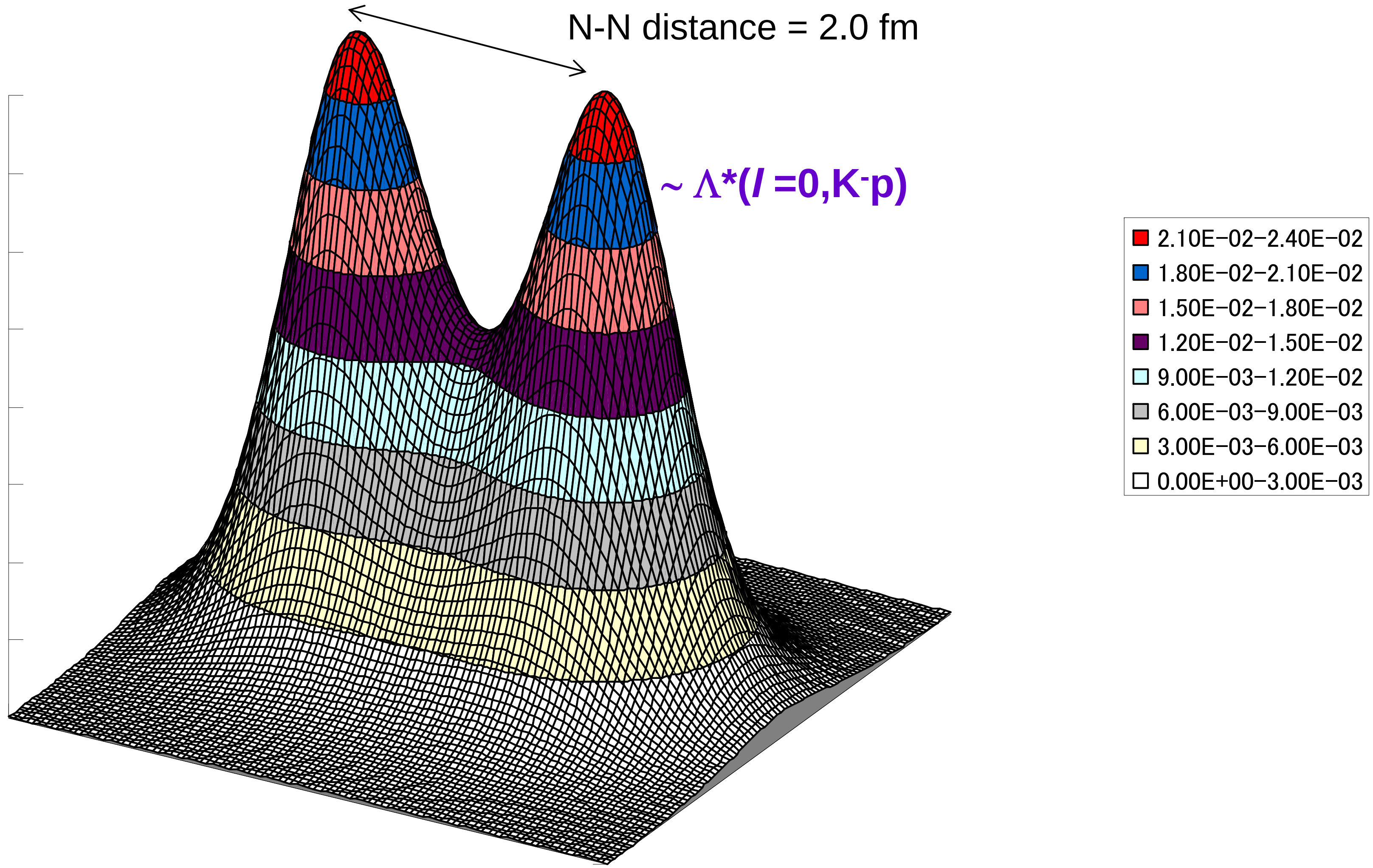




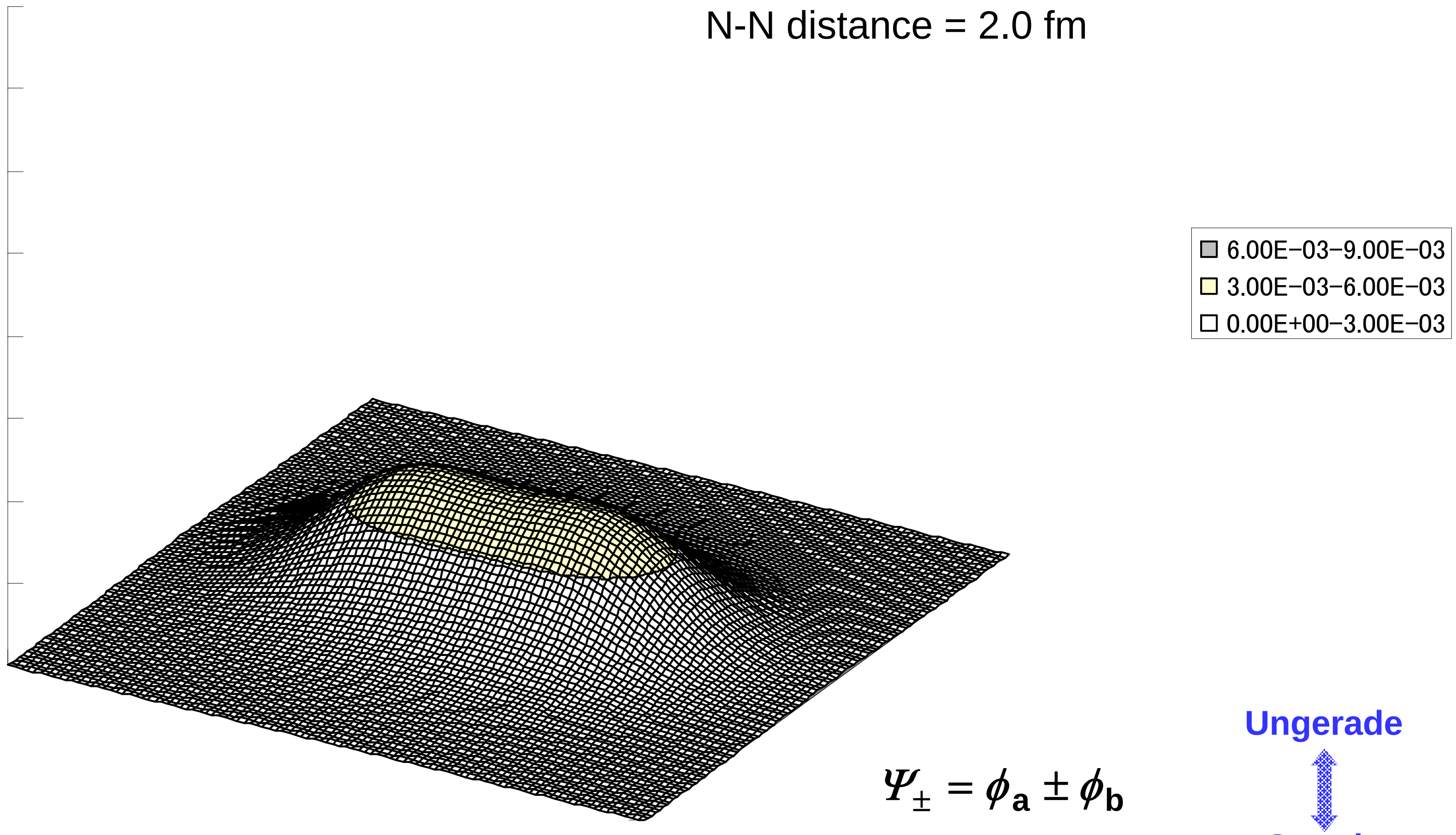
I =0: 0.5x(1+0.25)=**0.625**
I =1: 0.5x0.75= **0.375**

***I* =0 pair: 1.5 –> 1.25**
***I* =1 pair: 0.5 –> 0.75**
Dynamically favorable

K$^-$ distribution in K$^-$pp



Covalent part of K^- distribution



$$\Psi_\pm = \phi_a \pm \phi_b$$

Ungerade

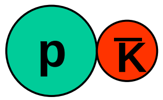
⇕

Gerade

$$\int d\tau \left|\Psi_\pm\right|^2 = \int d\vec{r}_a \left|\phi_a(\vec{r}_a)\right|^2 + \int d\vec{r}_b \left|\phi_b(\vec{r}_b)\right|^2 \pm \int d\tau \boxed{\phi_a^*(\vec{r}_a)\,\phi_b(\vec{r}_b) + \phi_b^*(\vec{r}_b)\,\phi_a(\vec{r}_a)}$$

Covalent bonding

Heitler-London picture of $K^- pp$

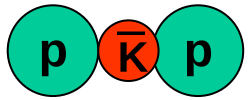


Λ(1405)

[MeV]

E	−27.8	−20.0*i*
KE	115.3	
PE	−143.1	−20.0*i*

$\frac{1}{2}[\Lambda^* \, p + p \, \Lambda^*]$



$K^- pp$

[MeV]

E	−47.5	−30.6*i*
KE	167.0	
PE	−214.5	−30.6*i*
$\langle v_{NN} \rangle$	−19.0	
$\langle 2v_{\bar{K}N} \rangle$	−195.5	−30.6*i*
$\langle 2v_{\bar{K}N}^{I=0} \rangle$	−188.2	−26.2*i*
$\langle 2v_{\bar{K}N}^{I=1} \rangle$	−7.3	−4.4*i*
$\langle 2v_{\bar{K}N}^{dir} \rangle$	−143.0	−23.3*i*
$\langle 2v_{\bar{K}N}^{exc} \rangle$	−52.6	−7.3*i*

ΔE = -20

ΔKE = 49 $+3_K$

$(+20_{NN})$

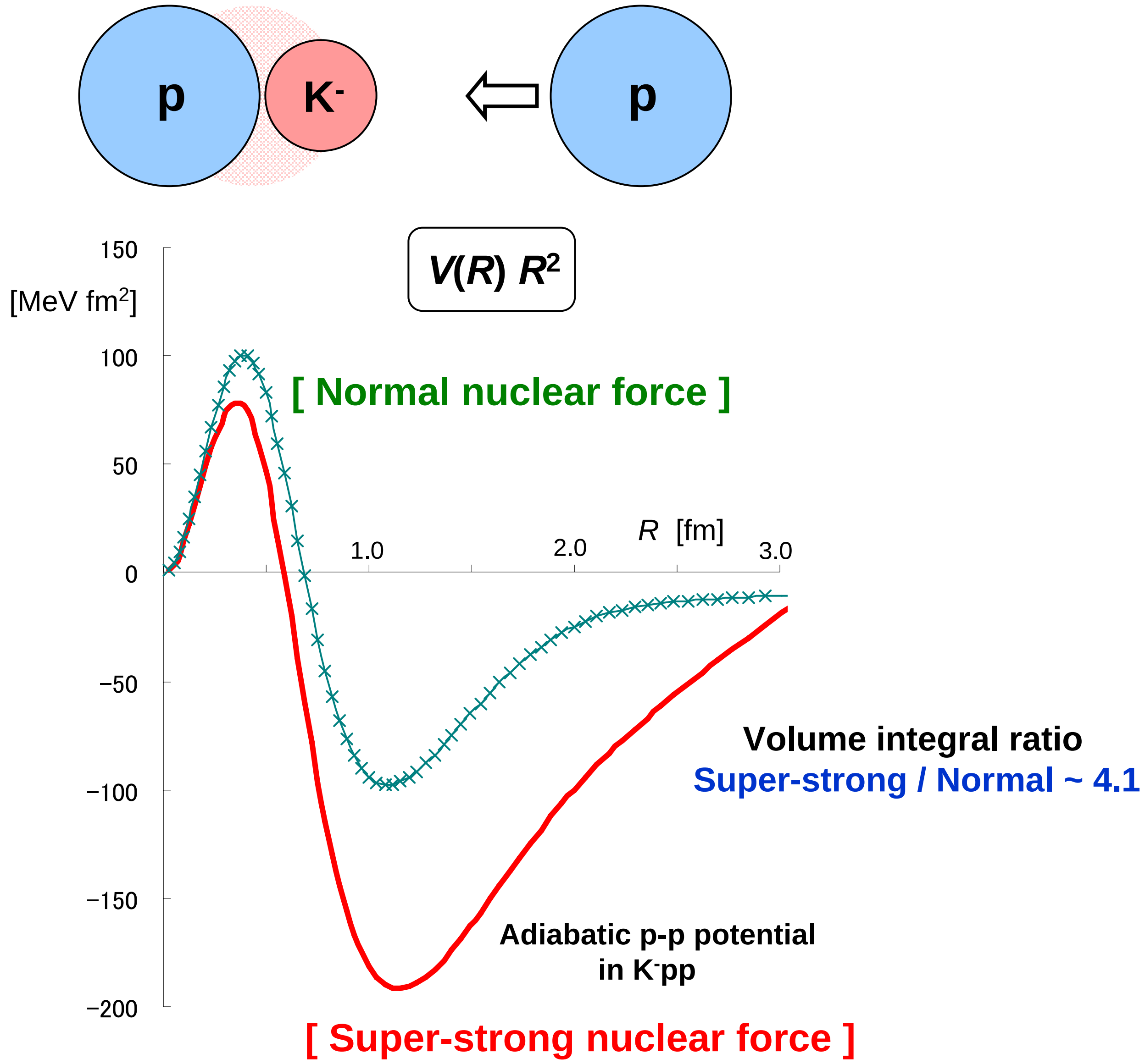
ΔV_{NN} = -19

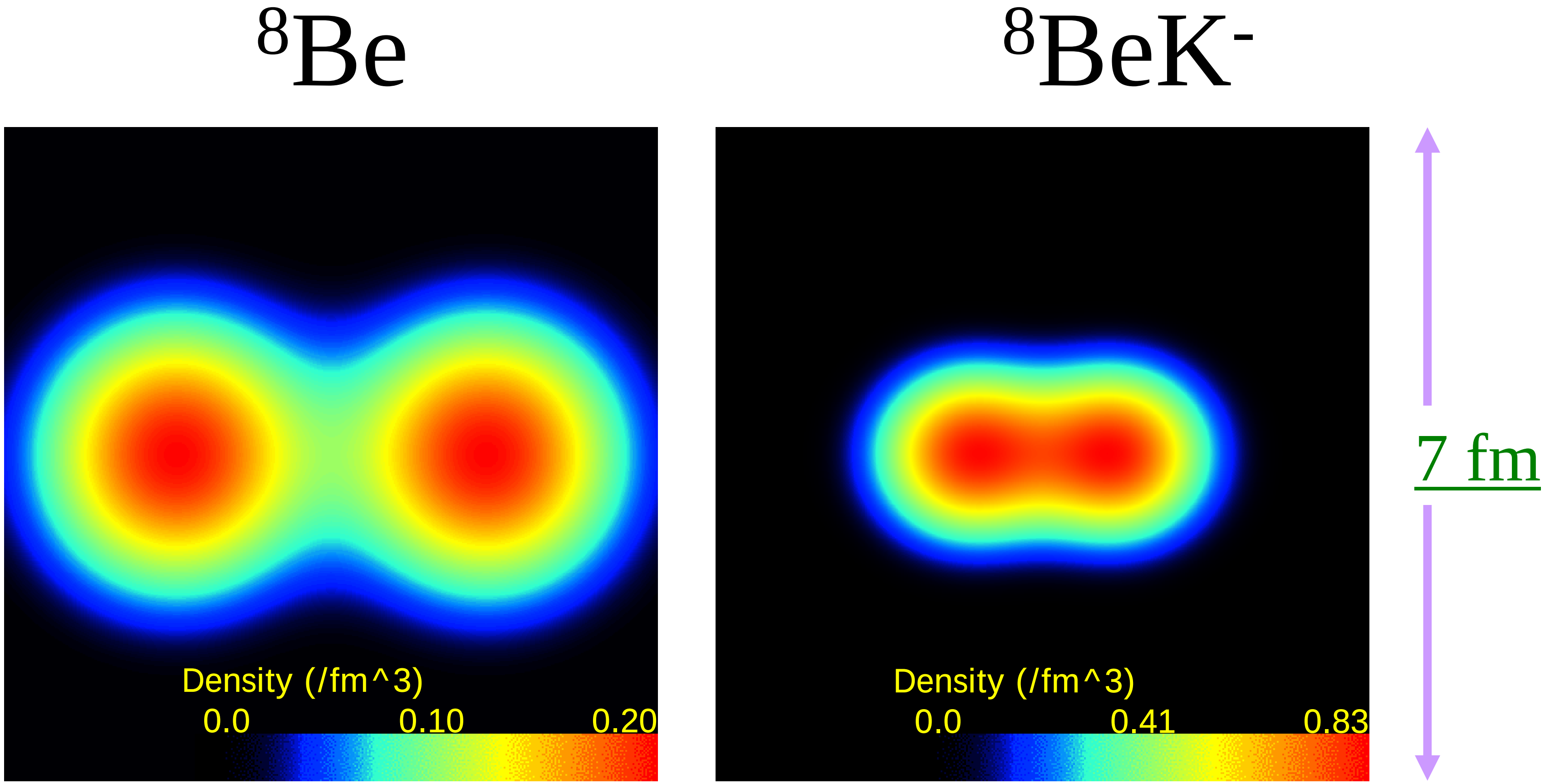
ΔV^{exc} = -53

Real K^{bar} exchange attraction

T. Yamazaki

Adiabatic p-p potential in K⁻pp

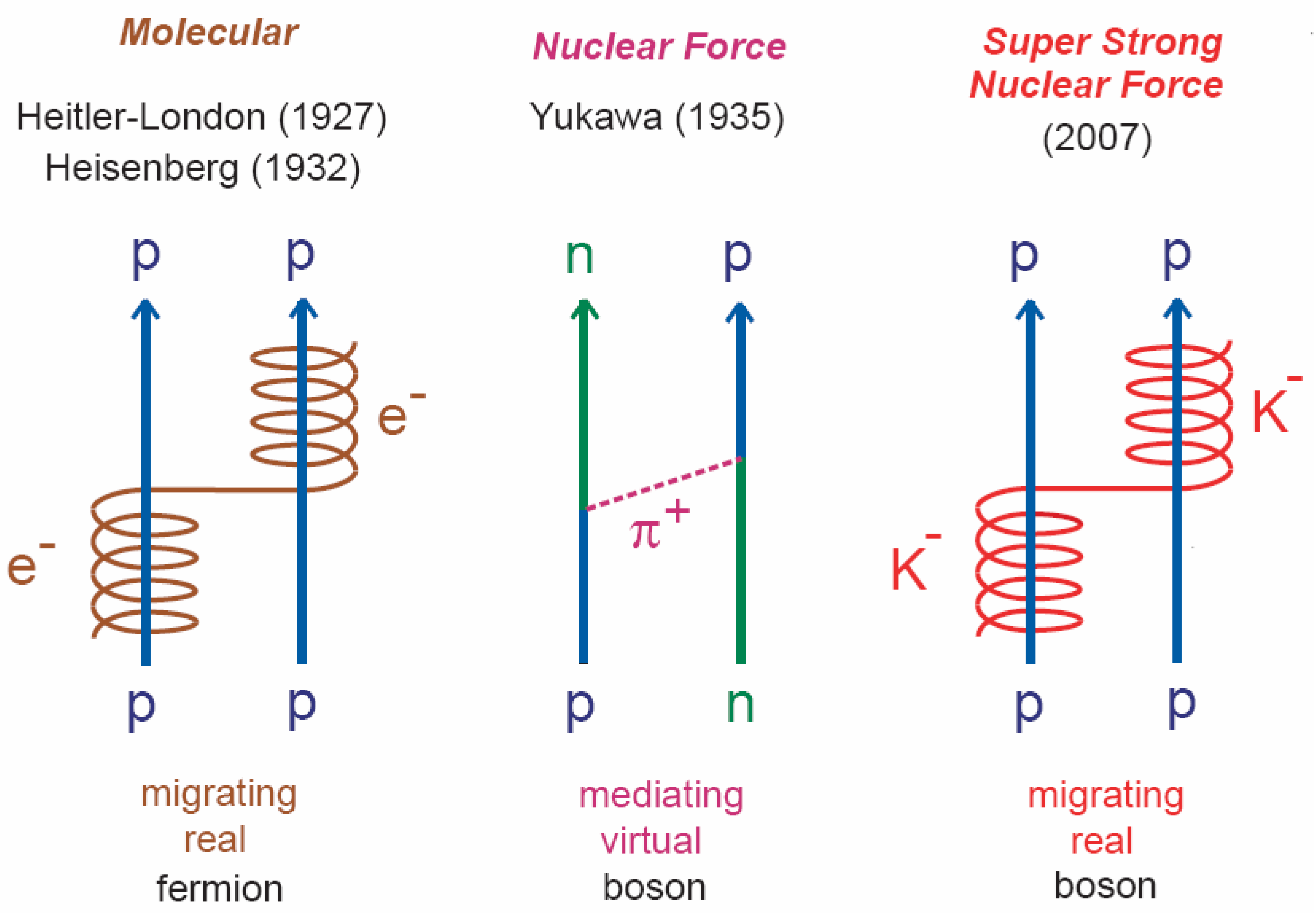




Dense & Cold

Antisymmetrized**M**olecular**D**ynamics calculation

A. Dote, H. Horiuchi, Y. Akaishi & T. Yamazaki, Phys. Lett. B590 (2004) 51

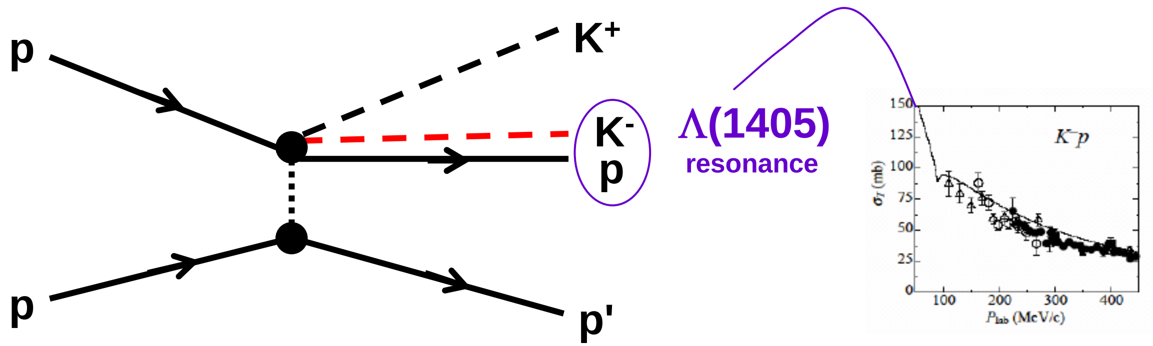


T. Yamazaki & Y. Akaishi,
Proc. Japan Academy, B 83 (2007) 144
arXiv: nucl-th/0706.3651v2

Production of

$K^{-}pp$

Production of K⁻pp by p(p, K⁺) reaction



The p --> p+K⁻+K⁺ process, where a K⁺K⁻ pair is assumed to be created at zero range from a proton, is of highly off-energy shell ($\Delta E \sim 2m_K$). This process is realized with a large momentum transfer to the second proton, which is done efficiently by the pp short-range interaction, exp($-m_B r$)/r.

Effective interaction for the elementary process

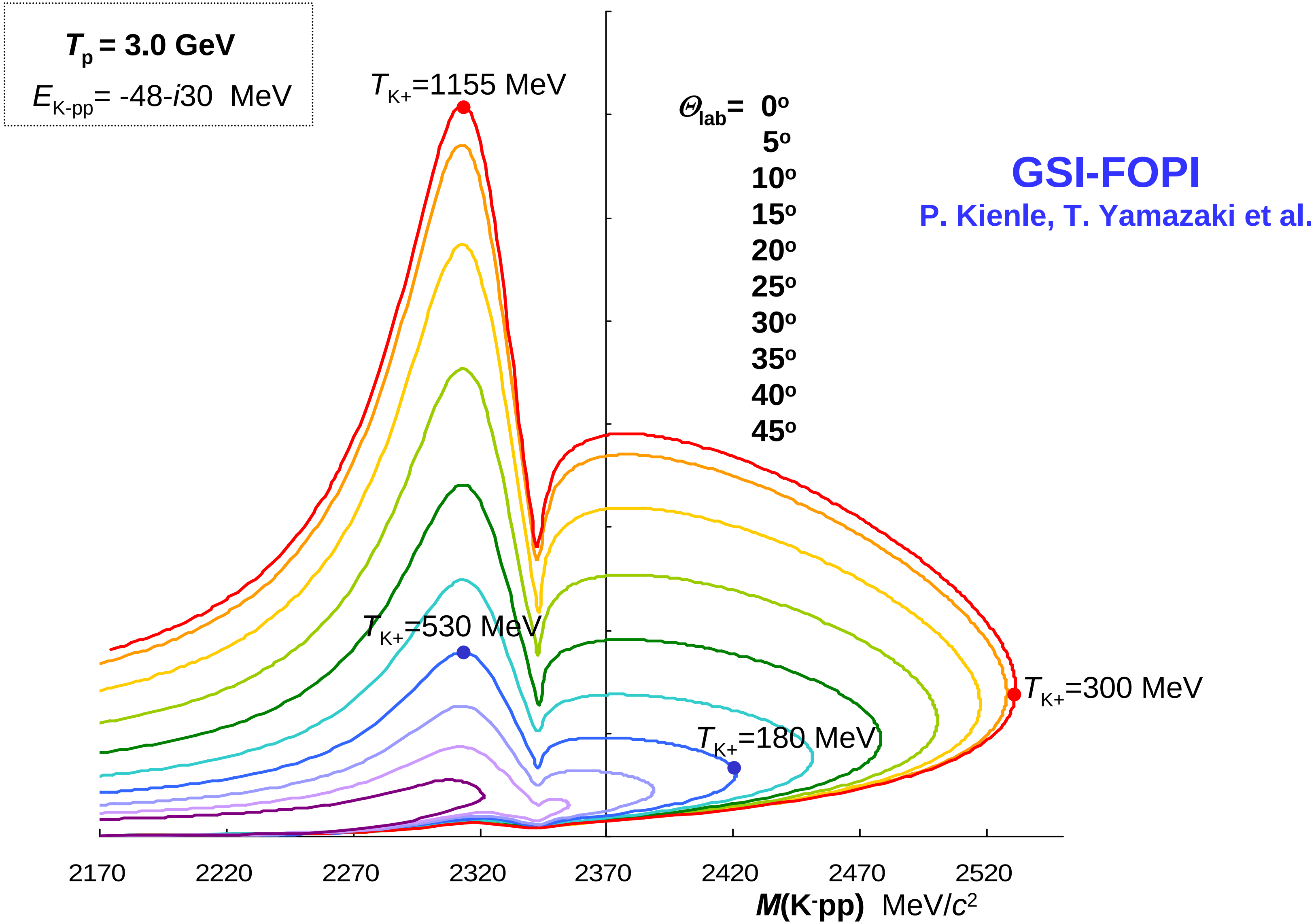
$$\left\langle \vec{r}_{K^+(K^-pp')}, \vec{r}_{(K^-p)p'}, \vec{r}_{K^-p} \middle| t \middle| \vec{r}_{pp'} \right\rangle = V_0 \int d\vec{r}\ F(\vec{r})\ \delta(\vec{r}_{K^+(K^-pp')} - \eta \vec{r})\ \delta(\vec{r}_{(K^-p)p'} - \vec{r})\ \delta(\vec{r}_{K^-p})\ \delta(r_{pp'} - \vec{r}),$$

$$\eta = \frac{M_p}{M_{K^-pp}}$$

$$F(\vec{r}) = \frac{\beta}{r} \exp\left(-\frac{r}{\beta}\right), \qquad \beta = \frac{\hbar}{m_B c}$$

Differential cross section of

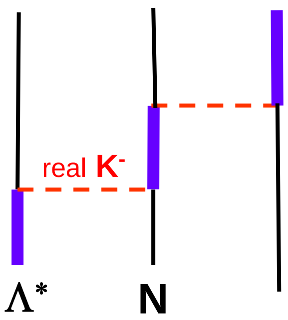
p + p → (Λ*+ p) + K⁺



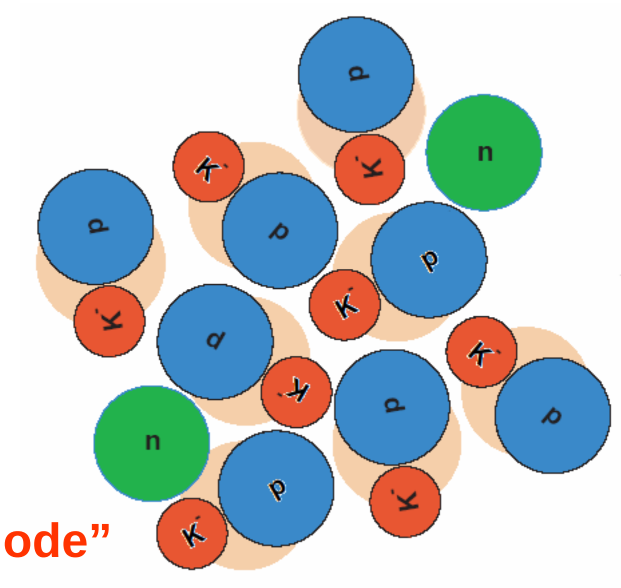
Conclusion

The Λ(1405) plays an essential role in forming "K^{bar} Nuclear Clusters".

Λ*–hole mode



K^-p (Λ*)- condensed matter



"Kaon migrating mode"

T. Yamazaki

Thank you very much!