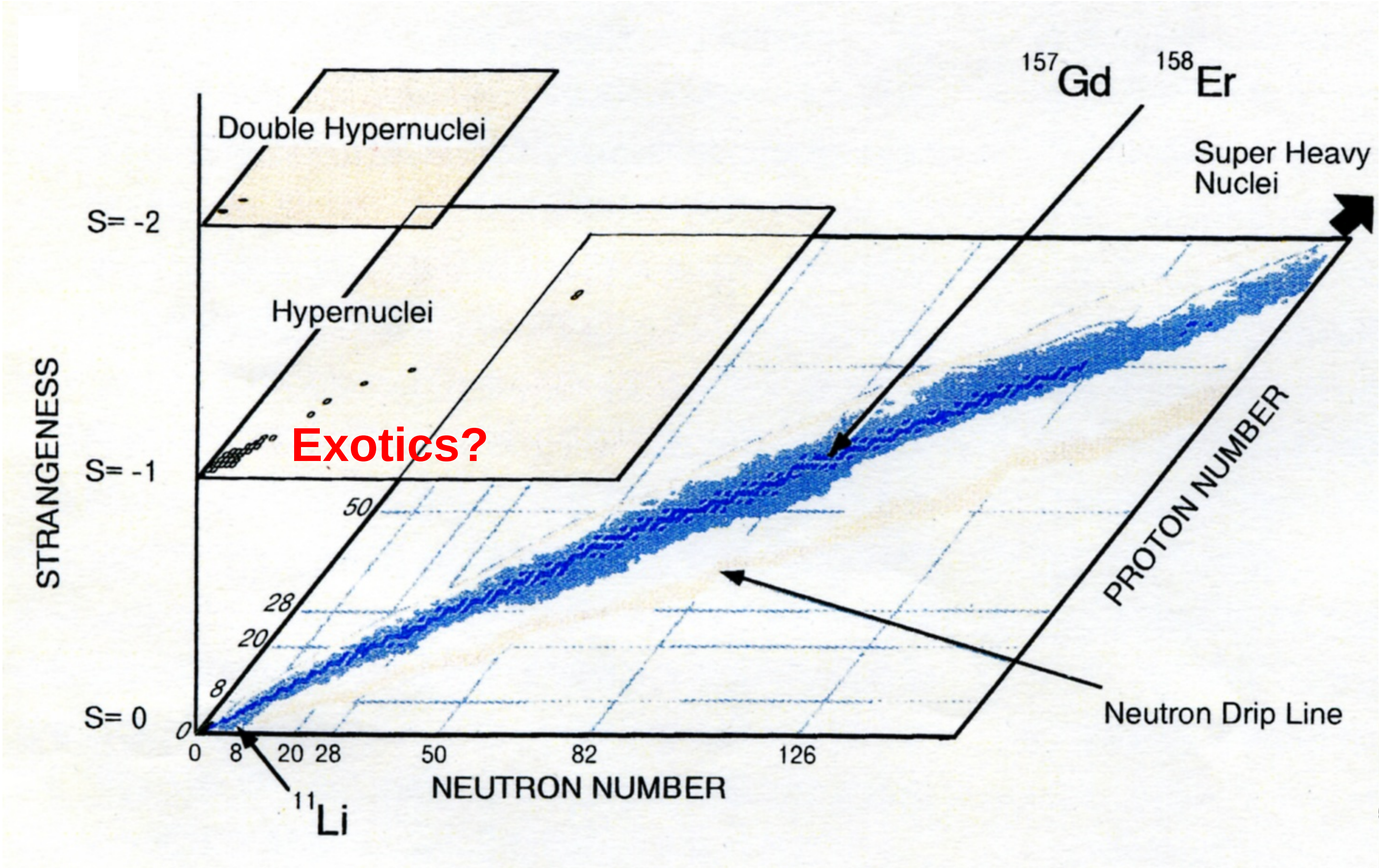
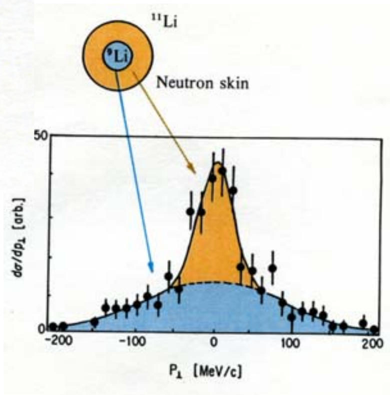
RIKEN Lecture
January 6, 2006

Coherent Λ-Σ Coupling in Neutron-rich Hypernuclei

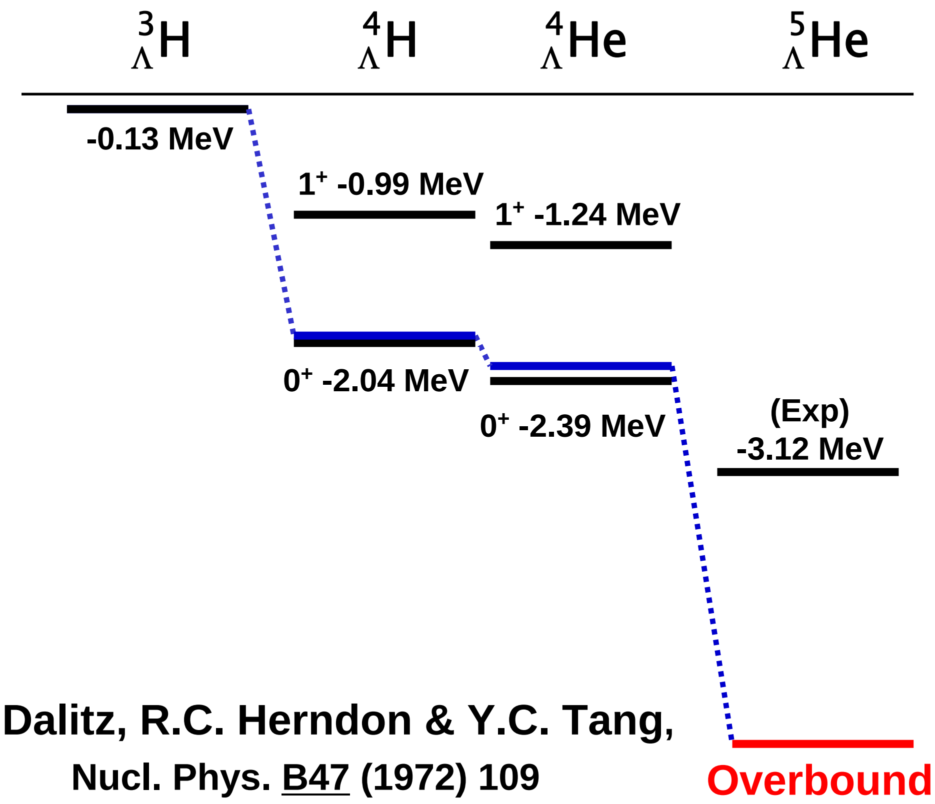
Yoshinori AKAISHI





The exotic nucleus, ^{11}Li

The overbinding problem

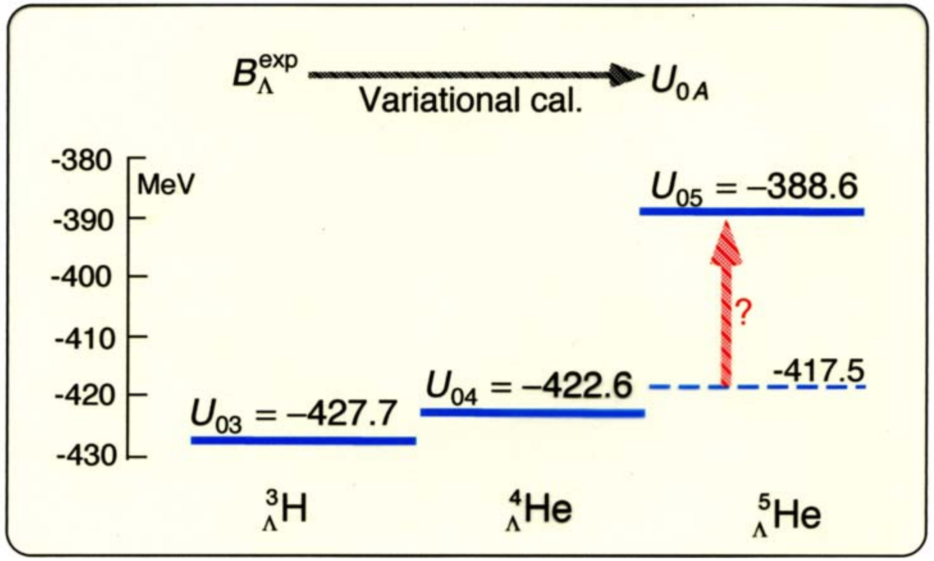


R.H. Dalitz, R.C. Herndon & Y.C. Tang,
Nucl. Phys. B47 (1972) 109

Dalitz et al's analysis

$$V_{\Lambda N}(r) = \begin{cases} \infty, & r < d \\ U_{0A} \exp[-\lambda(r-d)], & r > d \end{cases}$$

$\lambda = 3.219\ \mathrm{fm}^{-1}$, $d = 0.45$ fm



Singlet interaction is more attractive than triplet interaction.

$$U_{03} = \frac{1}{4}U_0^{\rm t} + \frac{3}{4}U_0^{\rm s}$$

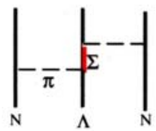
$$U_{04} = \frac{1}{2}U_0^{\rm t} + \frac{1}{2}U_0^{\rm s}$$

$$U_{05} = \frac{3}{4}U_0^{\rm t} + \frac{1}{4}U_0^{\rm s}$$

$$\frac{1}{2}(U_{03} + U_{05}) - U_{04} = 0 \quad .03\, W_3$$

$W_3 \approx 480$ MeV

$W_3 = 1.43$ MeV



Nogami's 3BF

$$V_{\Lambda NN} = -\frac{1}{3} W_3 (\vec{\sigma}_1 \vec{\sigma}_2)(\vec{\tau}_1 \vec{\tau}_2) \frac{\exp(-\mu r_{1\Lambda})}{\mu r_{1\Lambda}} \frac{\exp(-\mu r_{2\Lambda})}{\mu r_{2\Lambda}}$$

Central YN interaction

Pictures

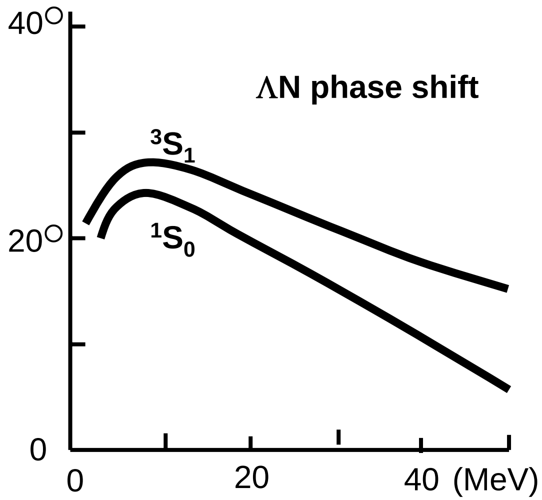
1-channel

2-channel

	ΛN	ΣN
D0	●	
D2	● ← Coupling →	●

A.R. Bodmer (1966)

Phase-equivalent to Nijmegen D

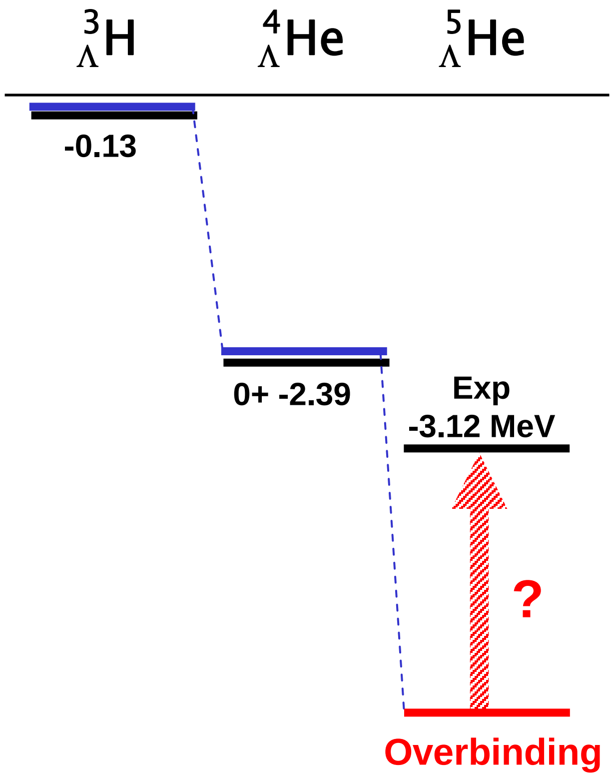


Two pictures

ΛN int.

D0

Overbinding problem

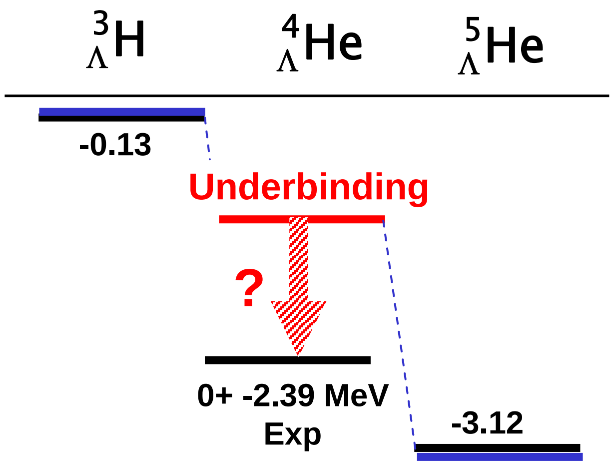


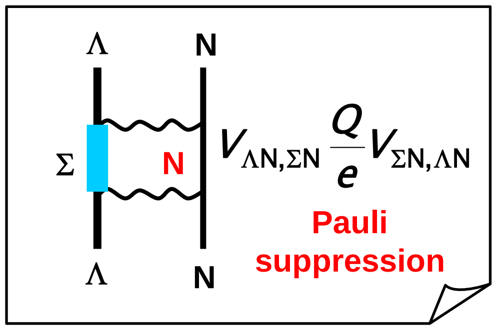
R.H. Dalitz et al. (1972)

ΛN-ΣN int.

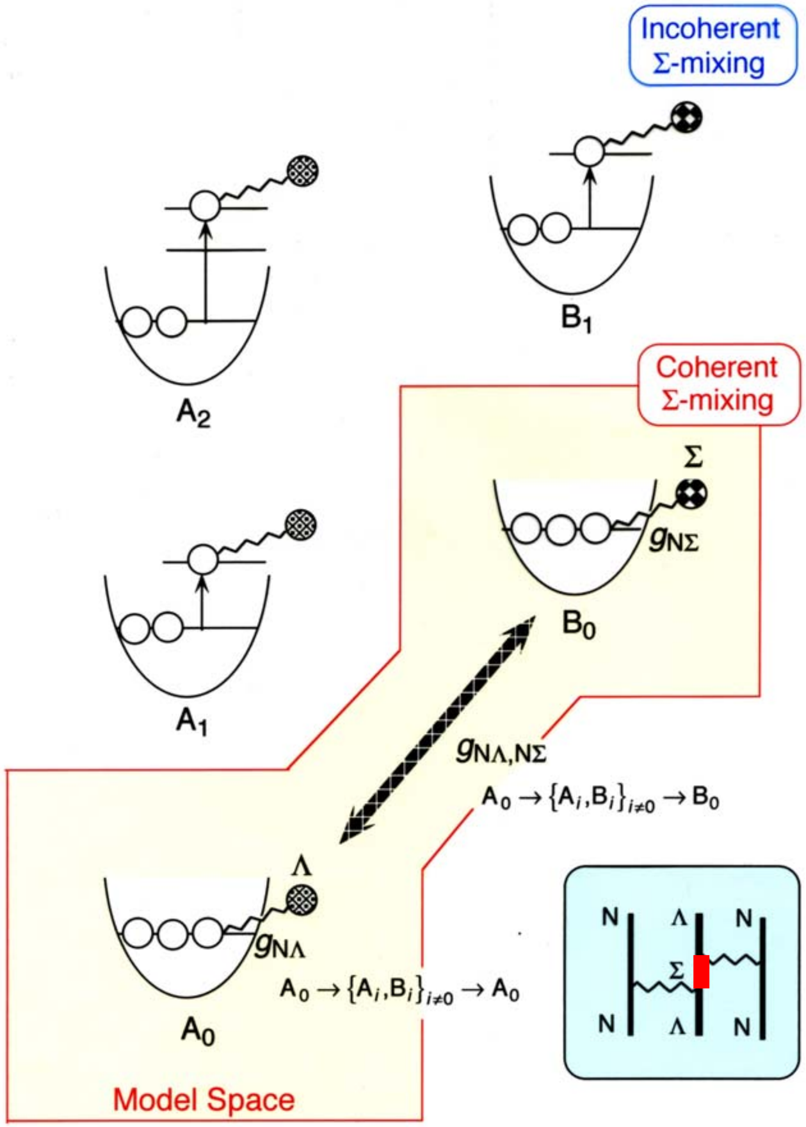
D2

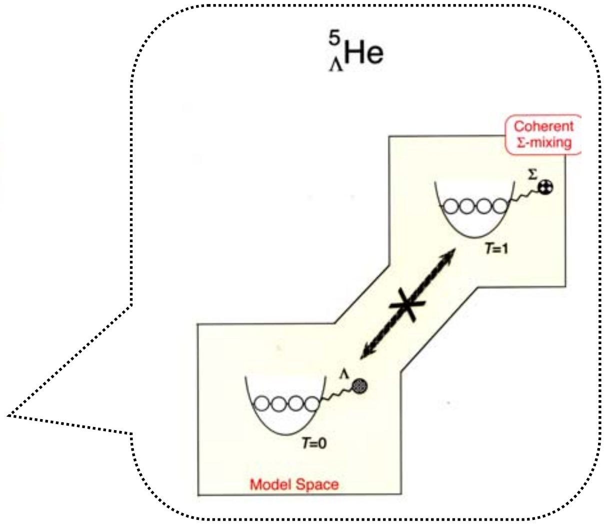
Underbinding problem



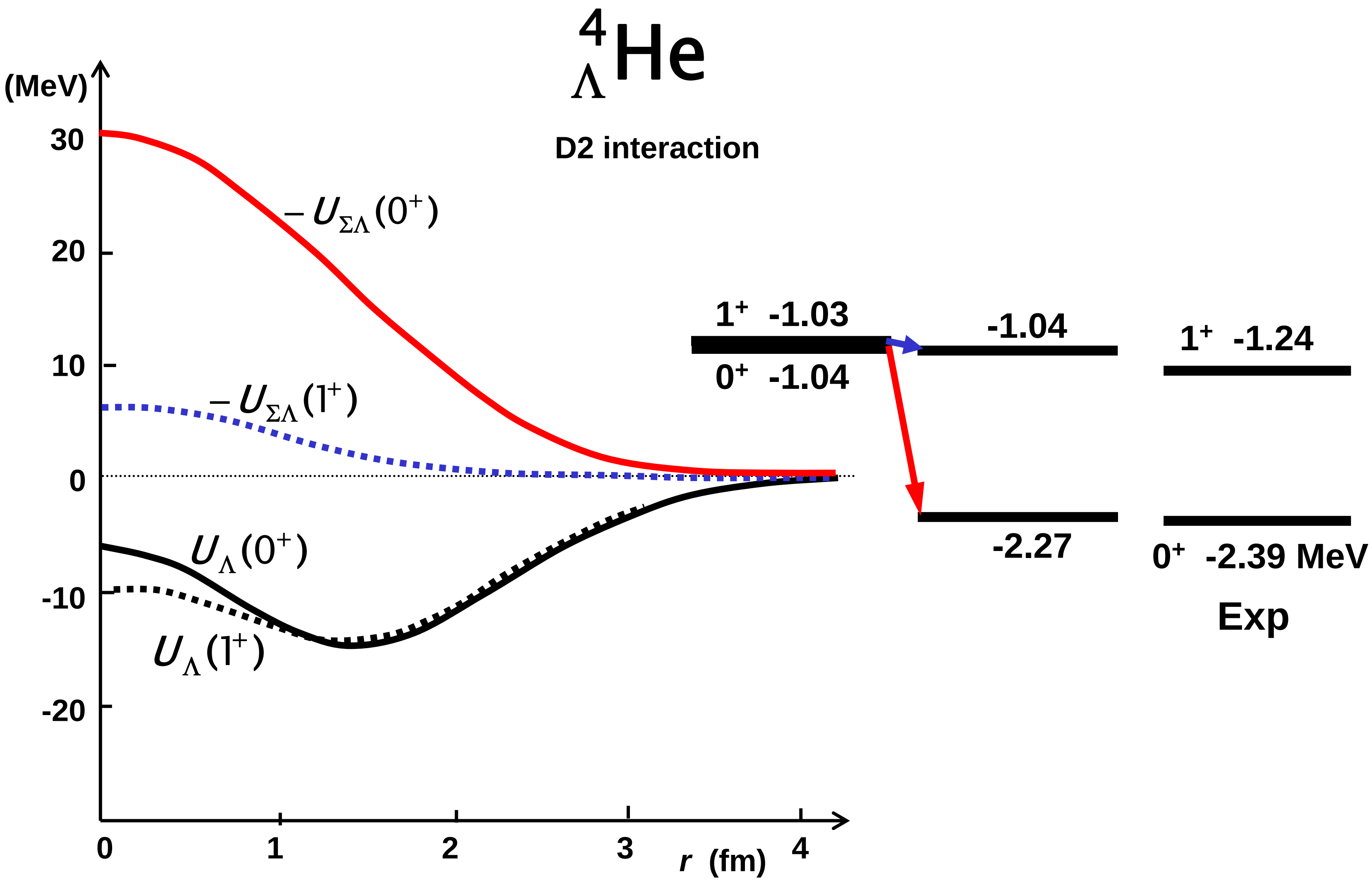


Coherent Λ-Σ coupling





Λ T=0 1116 MeV/c^2
Σ T=1 1193 MeV/c^2



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

S=1 pairs		$^{4}_{\Lambda}$H 1⁺	$^{4}_{\Lambda}$H 0⁺
$\Lambda p \Leftrightarrow -\sqrt{\frac{1}{3}}\Sigma^0 p + \sqrt{\frac{2}{3}}\Sigma^+ n$	$s_3 = 1$	-1/3	
	$s_3 = 0$		
	$s_3 = -1$	+1/3	+1/2
$\Lambda n \Leftrightarrow \sqrt{\frac{1}{3}}\Sigma^0 n - \sqrt{\frac{2}{3}}\Sigma^- p$	$s_3 = 1$		
	$s_3 = 0$	+1/2	+1/2
	$s_3 = -1$		+1/2
Contribution to $U_{\Sigma\Lambda}$		1/2	3/2
Λ-Σ coupling energy		1 :	9

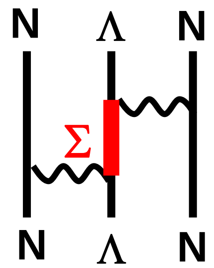
Cancel

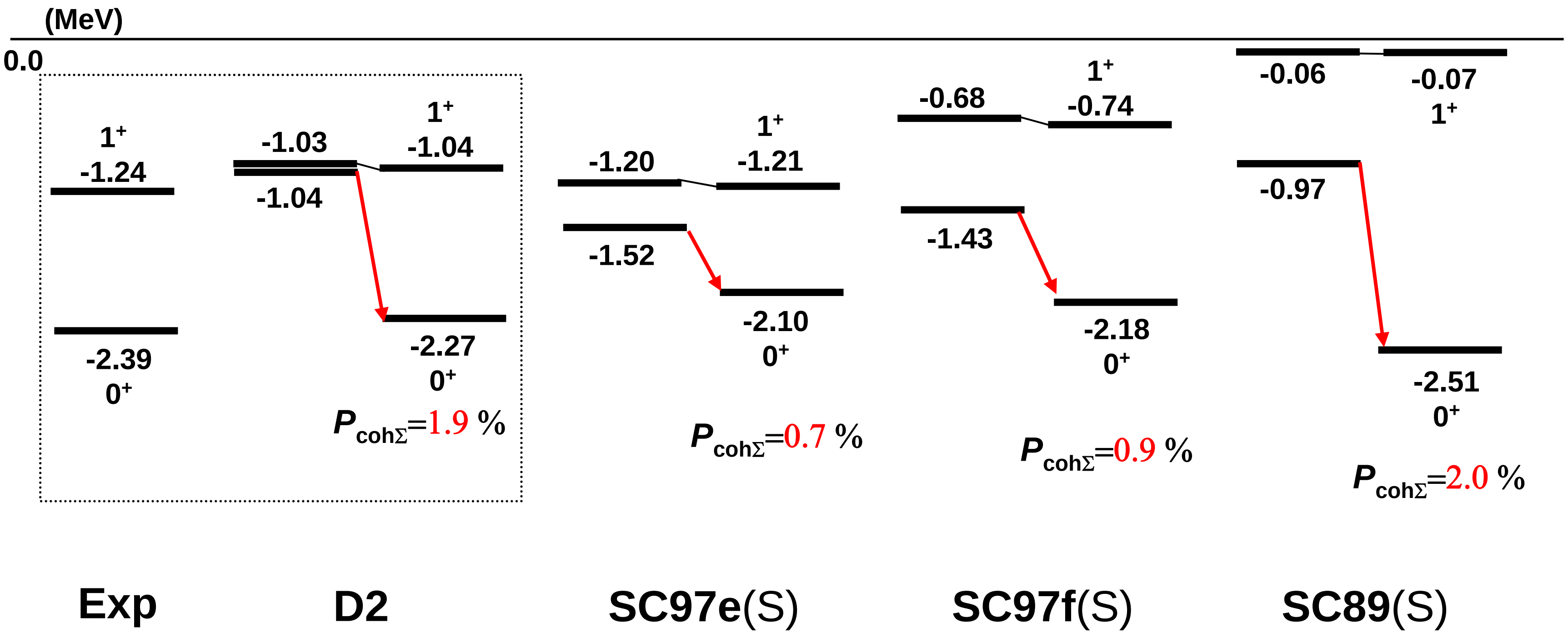
Coherently added

"The 0^+-1^+ difference is not a measure of ΛN spin-spin interaction."

B. Gibson (Maui, 1993)

$^4_\Lambda$He

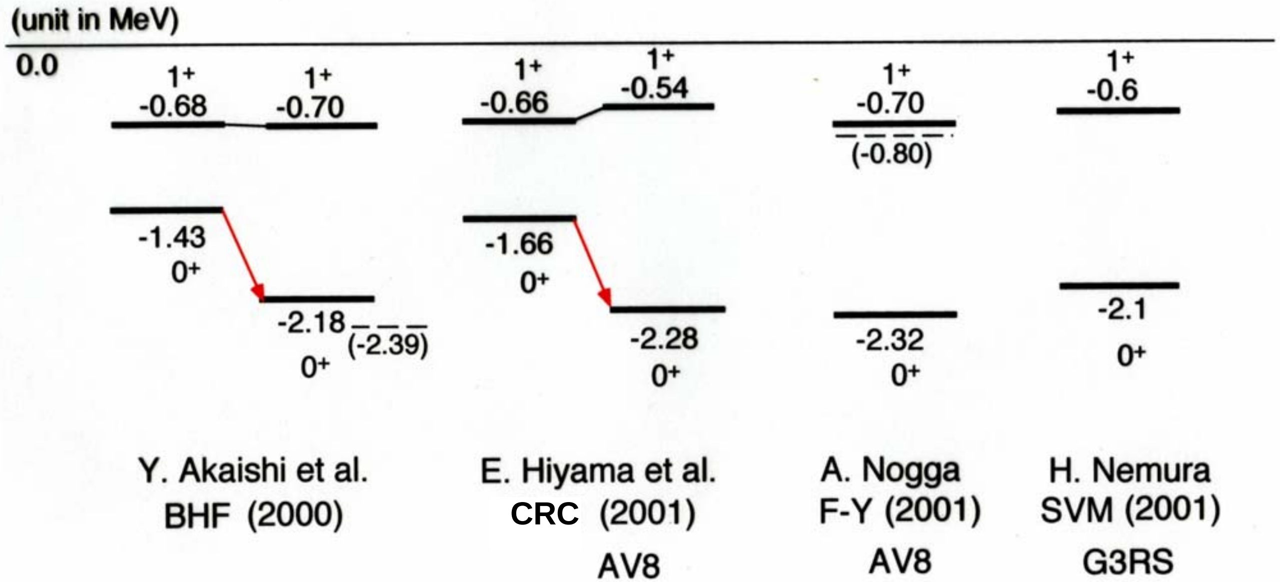




Th.A. Rijken

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

${}^{4}_{\Lambda}He$ SC97f(S)



E. Hiyama, M. Kamimura, T. Motoba, T. Yamada & Y. Yamamoto, Phys. Rev. C**65** (2001) 011301(R).
A. Nogga, Doctoral dissertation.

Real space

Faddeev-Yakubovsky calculation of $^4_\Lambda$He

A. Nogga, (2001)

SC97e

(MeV)

		0^+		1^+	
P_Σ		1.57%		1.08%	
^{1}E	$\langle V_\Lambda \rangle$	-5.30	-5.90	-1.34	-1.49
	$\langle V_\Sigma \rangle$	-0.43		-0.12	
	$\langle V_{\Lambda\Sigma} \rangle + \langle V_{\Sigma\Lambda} \rangle$	-0.17		-0.03	
^{3}E	$\langle V_\Lambda \rangle$	1.16	-9.64	1.55	-10.08
	$\langle V_\Sigma \rangle$	1.18		2.00	
	$\langle V_{\Lambda\Sigma} \rangle + \langle V_{\Sigma\Lambda} \rangle$	-11.98		-13.63	

Model space

1^+: $\frac{1}{2} V_{\Lambda N}(^1E) + \frac{5}{2} V_{\Lambda N}(^3E)$

0^+: $\frac{3}{2} V_{\Lambda N}(^1E) + \frac{3}{2} V_{\Lambda N}(^3E)$

★ "Is the $^1S_0$ YN int. more attractive than the $^3S_1$ YN int.?" **No !**

★ "Is there any evidence for coherently enhanced Λ-Σ coupling in 0^+?"

No !

Model space

Single-channel description of $^4_\Lambda$He

SC97e

(MeV)

		0^+		1^+	
^{1}E	$\langle V_\Lambda \rangle_{sc}$	-5.38	**-5.47**	-1.35	-1.37
	$\langle V_{\Lambda\Sigma,\Sigma\Lambda} \rangle_{sc}$	-0.09		-0.02	
^{3}E	$\langle V_\Lambda \rangle_{sc}$	1.18	**-4.91**	1.57	-5.32
	$\langle V_{\Lambda\Sigma,\Sigma\Lambda} \rangle_{sc}$	**-6.09**		**-6.89**	

x3/5

-4.13

★ **Coherently enhanced**

"Cooking"!

$$\langle V_{\Lambda\Sigma,\Sigma\Lambda} \rangle_{sc} = \langle V_{\Lambda\Sigma} \rangle + \langle V_{\Sigma\Lambda} \rangle + \langle V_\Sigma \rangle + \left\{ \langle T_\Sigma \rangle + P_\Sigma \Delta M \right\} - \frac{P_\Sigma}{1 - P_\Sigma} \left\{ \langle T_\Lambda \rangle + \langle V_\Lambda \rangle \right\}$$

$$= \frac{1}{1 - P_\Sigma} \langle V_{\Lambda\Sigma} \rangle$$

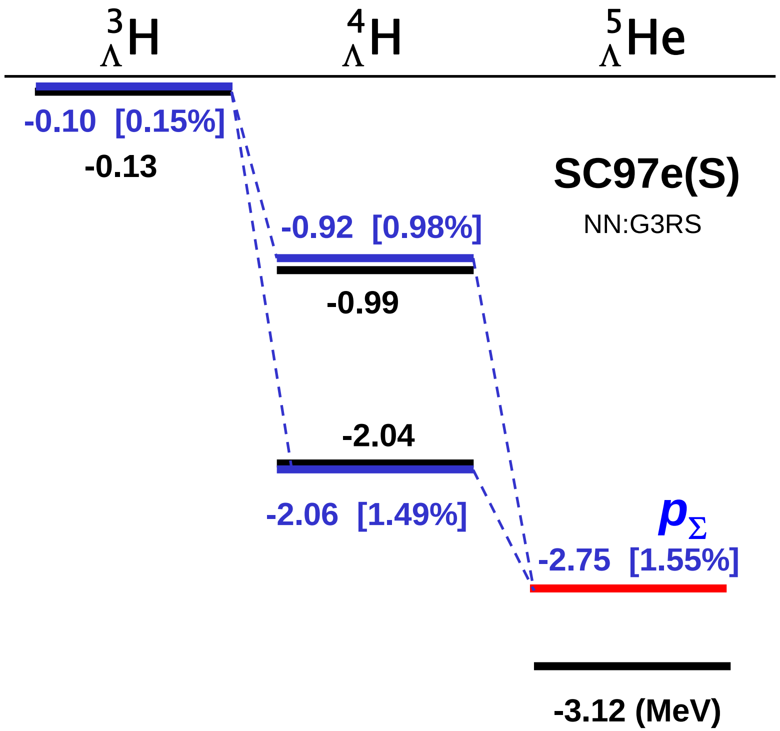
★ $\langle {}^1S_0 \rangle_{sc}$ **is more attractive than** $\langle {}^3S_1 \rangle_{sc}$ **.**

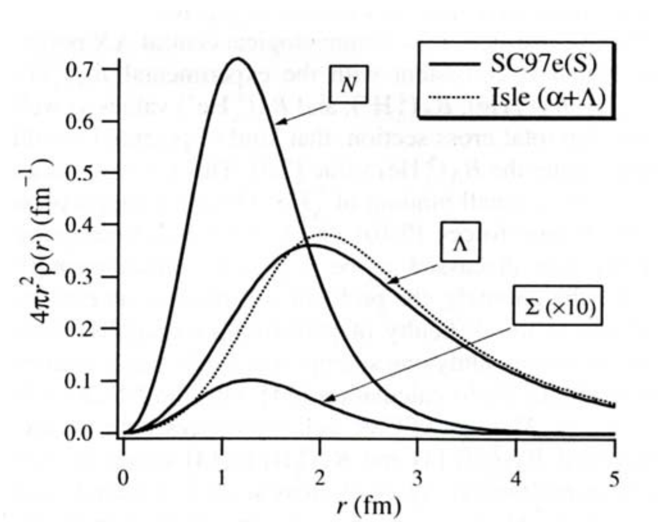
Stochastic variational calculation of $^{5}_{\Lambda}He$

H. Nemura, Y. Akaishi & Y. Suzuki,
Phys. Rev. Lett. 89 (2002) 142504

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

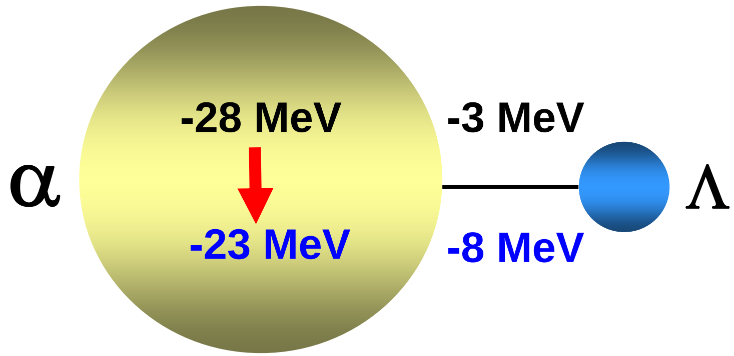
J.A. Carlson,
AIP Conf. Proc. 224 (1991) 198
SC89: unbound





Rearrangement of ^{4}He due to Λ sticking

Rearrangement in αΛΛ
M. Kohno et al.,
Phys. Rev. C68 (2003) 034302

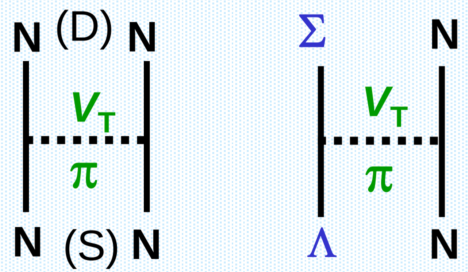


H. Nemura et al., Phys. Rev. Lett. 89 (2002) 142504

$P_D(\alpha)$=10.2%

↓

9.3%

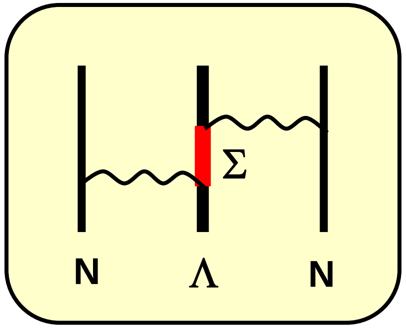


$\langle V_C(^1\mathrm{E})\rangle \approx \langle V_C(^3\mathrm{E})\rangle \approx -33$ MeV,

$\langle V_T(^3\mathrm{E})\rangle \approx -4$ **-44** /, $\langle T\rangle = 85$ MeV

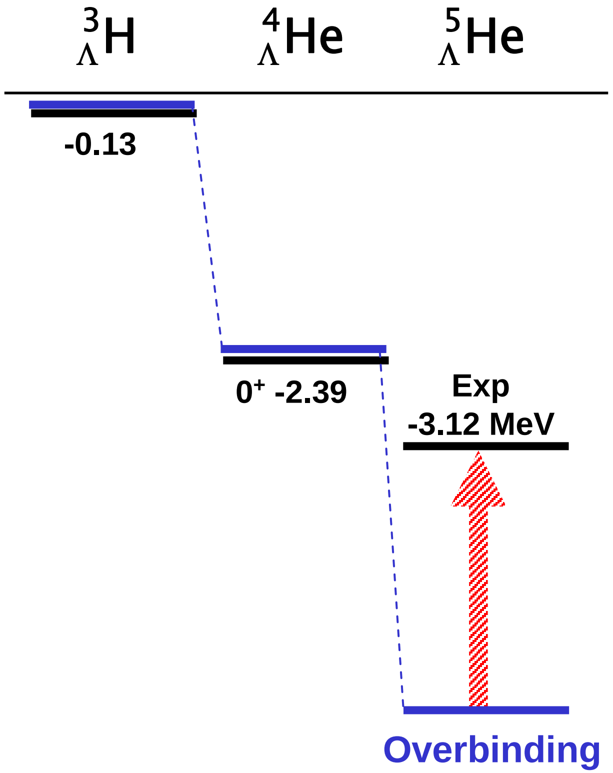
Repulsion?

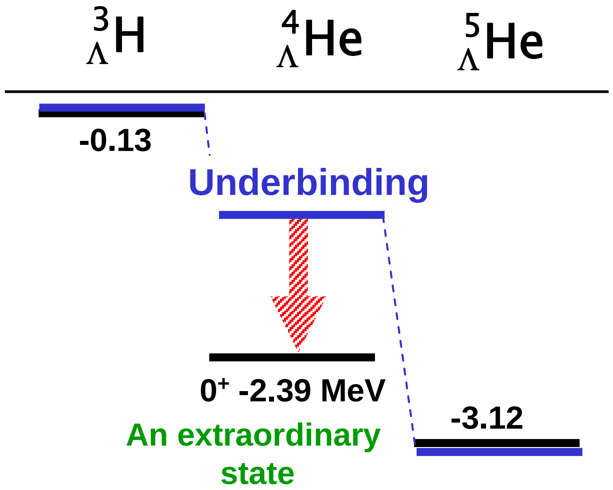
Y. Nogami et al.
Nucl. Phys. B19 (1970) 93



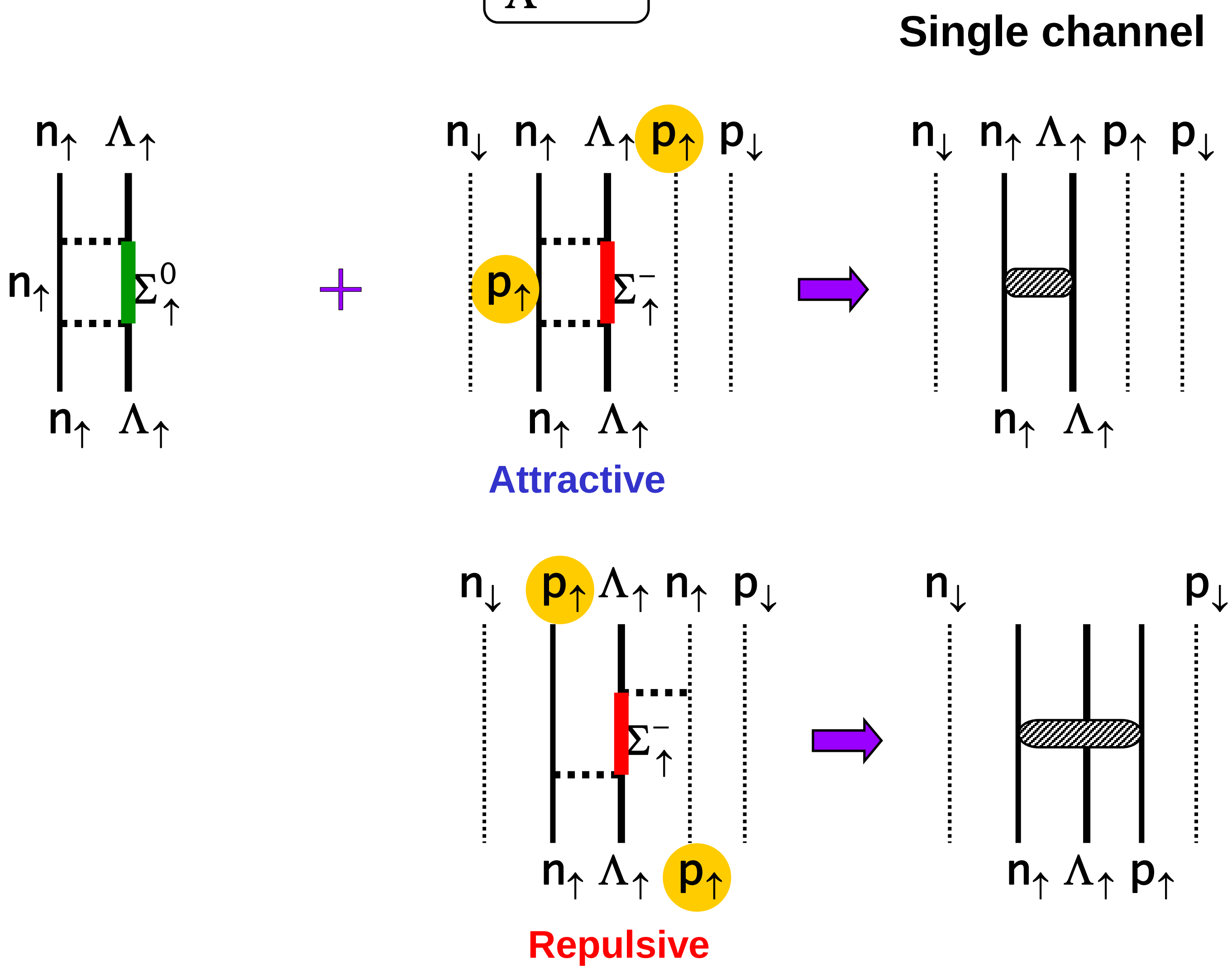
Attraction?

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

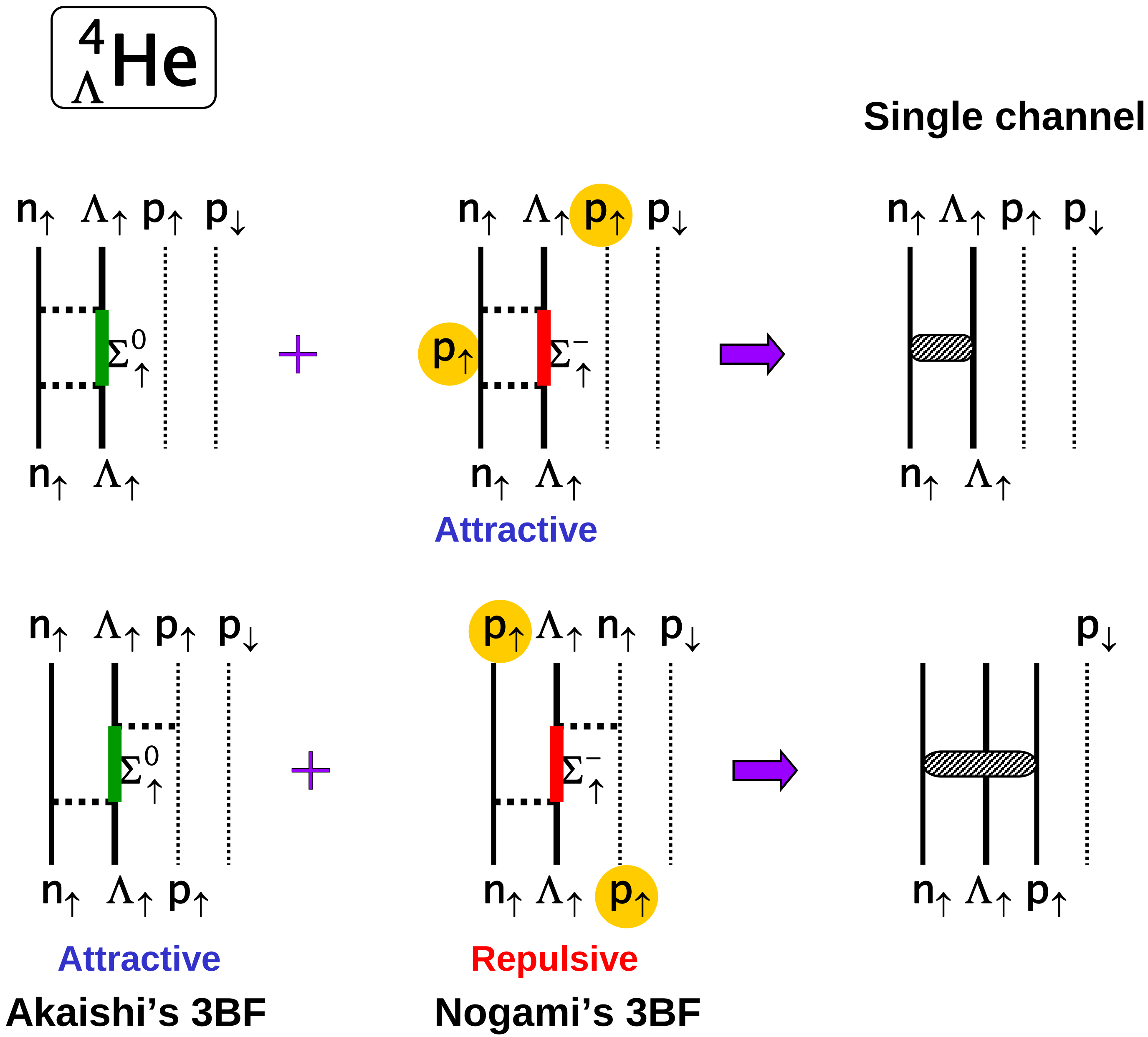




$^{5}_{\Lambda}\mathrm{He}$

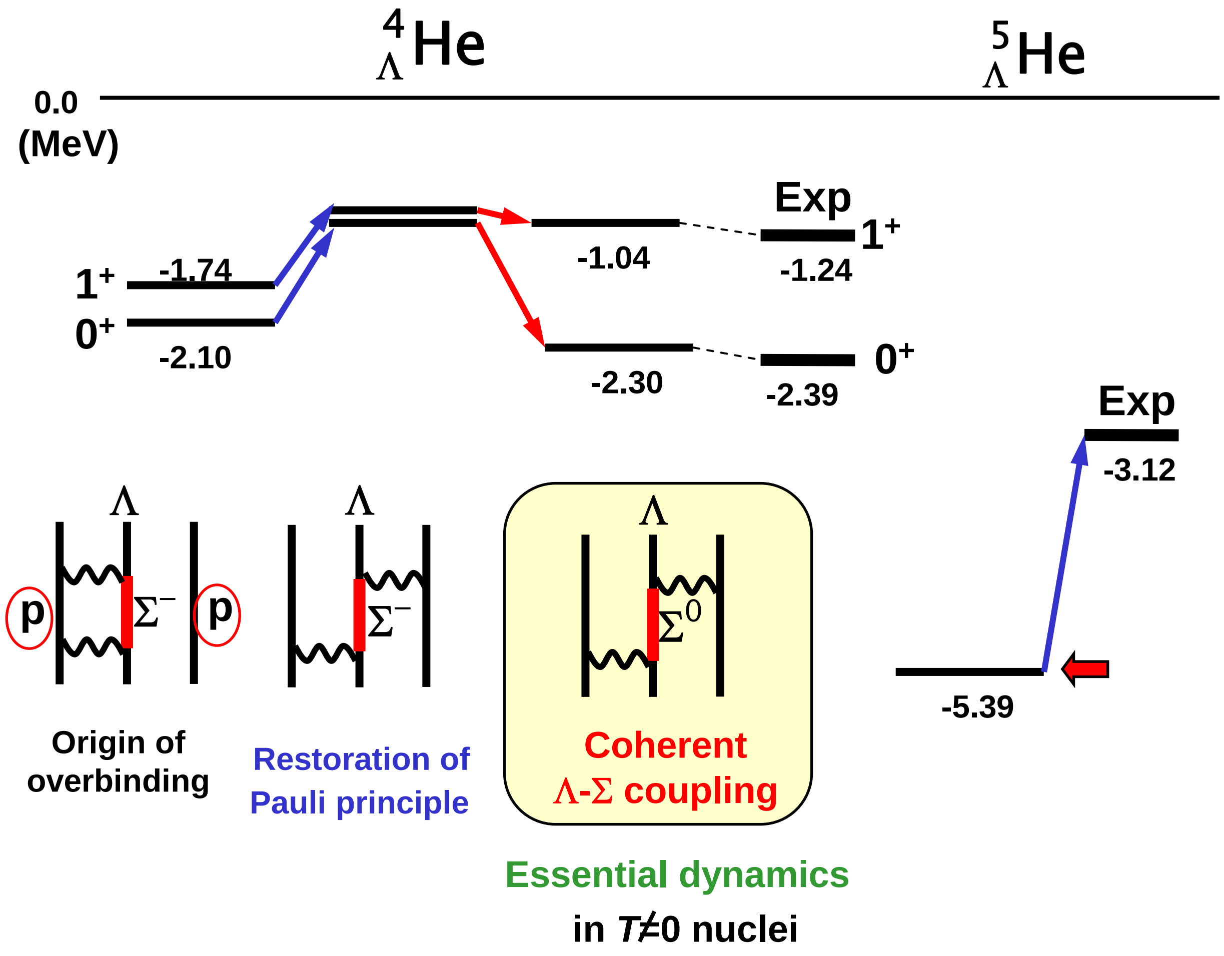


Nogami’s 3BF



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

Effects of ΛNN three-body force

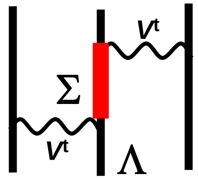


Three-body force due to coherent Λ-Σ coupling : [for D0]

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

ΛNN spin-spin

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



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

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

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

Light hypernuclei

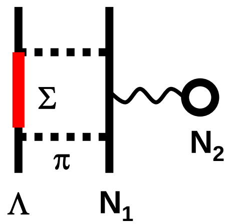
A.R. Bodmer & Q.N. Usmani, Nucl. Phys. A477 (1988) 621
R. Sinha & Q.N. Usmani, Nucl. Phys. A684 (2001) 586c

$$V_{\Lambda N} = \left[(V_{\rm core}(r) - \bar{V})(1 - \varepsilon + \varepsilon P_x) + \frac{1}{4} V_\sigma \vec{\sigma}_\Lambda \vec{\sigma}_N \right] T_\pi^2(r)$$

Spin-spin

$$V_{\Lambda NN}^{DS} = W_0 T_\pi^2(r_{i\Lambda}) T_\pi^2(r_{j\Lambda}) \left[1 + \frac{1}{6} \vec{\sigma}_\Lambda (\vec{\sigma}_i + \vec{\sigma}_j) \right]$$

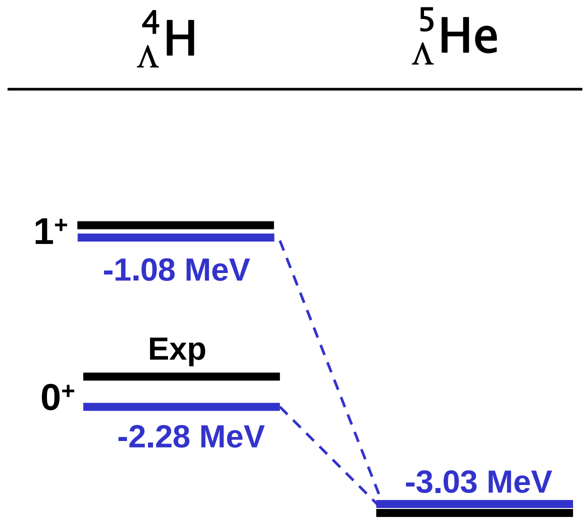
Spin-spin



0$^+$-1$^+$ splitting
0.38 + 0.86 MeV
(70%)

The major part is attributed to ΛNN and not to ΛN.

0.56 + 0.92 (62%) MeV for SC97f

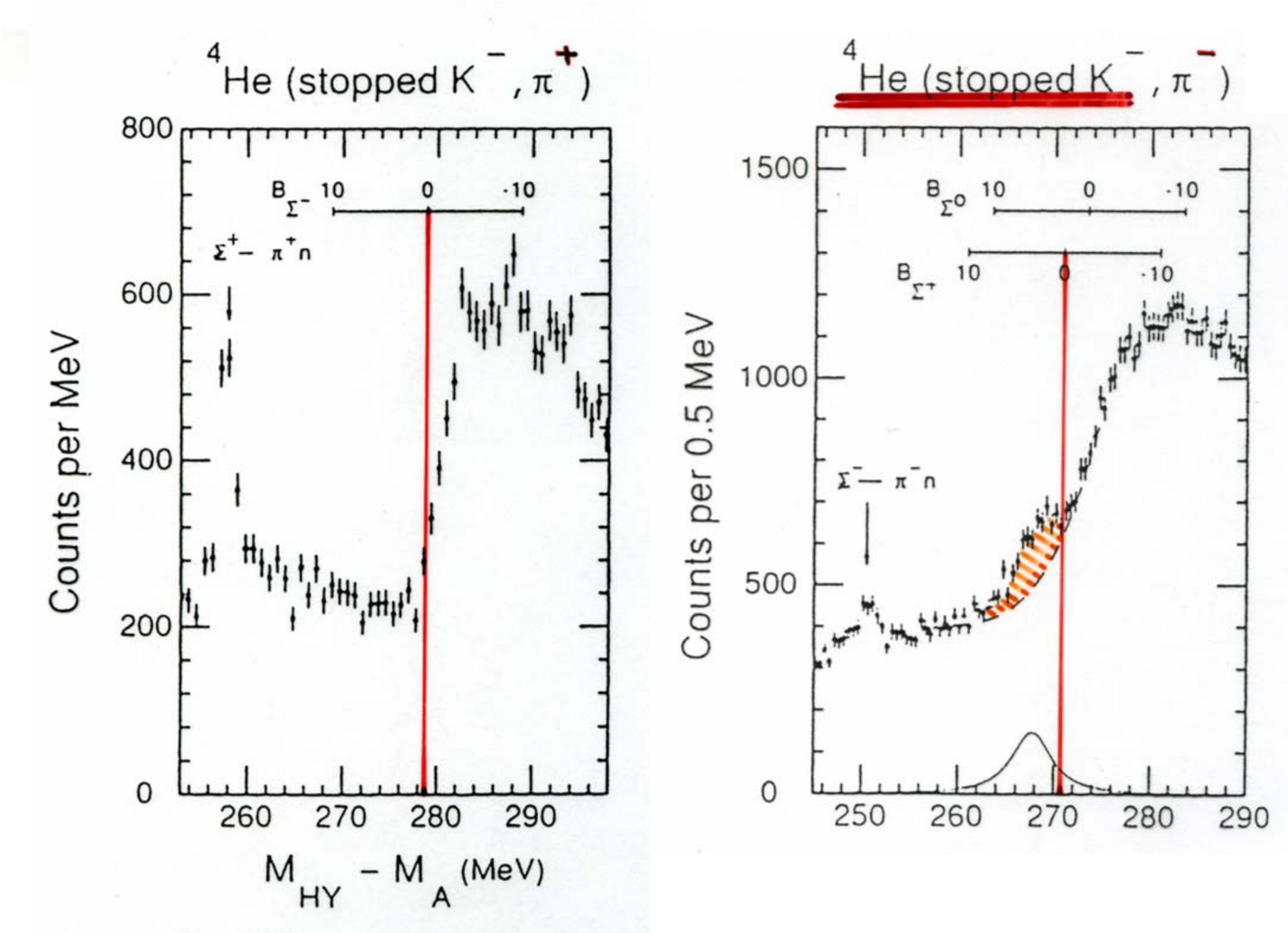


Variational Monte Carlo

J. Lomnitz-Adler, V.R. Pandharipande & R.A. Smith, Nucl. Phys. A361 (1981) 399

The first observation of a bound Σ state

E167 : Phys. Lett. 231 (1989) 355

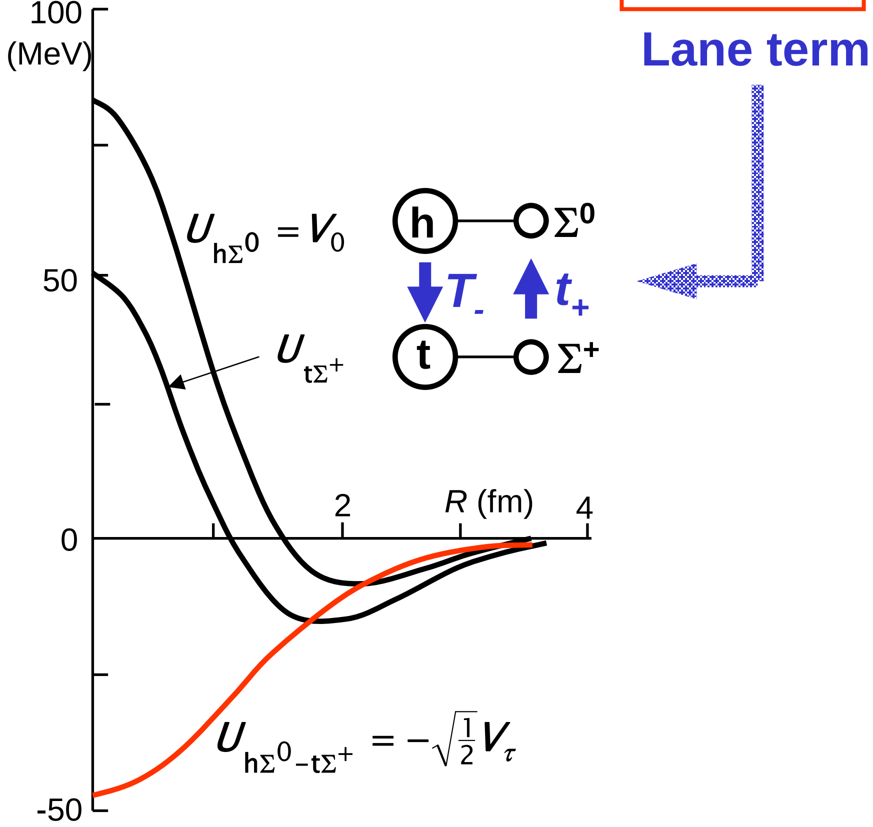


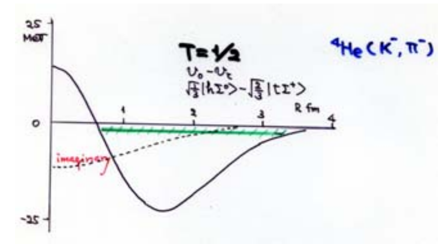
R.S. Hayano
T. Ishikawa
M. Iwasaki
H. Outa
E. Takada
H. Tamura
A. Sakaguchi
M. Aoki
T. Yamazaki

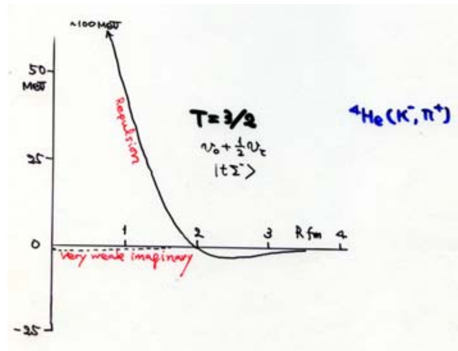
Σ – Nucleus, ${}^{4}_{\Sigma}$He

T. Harada, S. Shinmura, Y.Akaishi & H. Tanaka, Nucl. Phys. A507 (1990) 715

$$U_{\Sigma-\text{nucl}} = V_0 + V_\tau \cdot \vec{T}_{\text{nucl}}\, \vec{t}_\Sigma$$

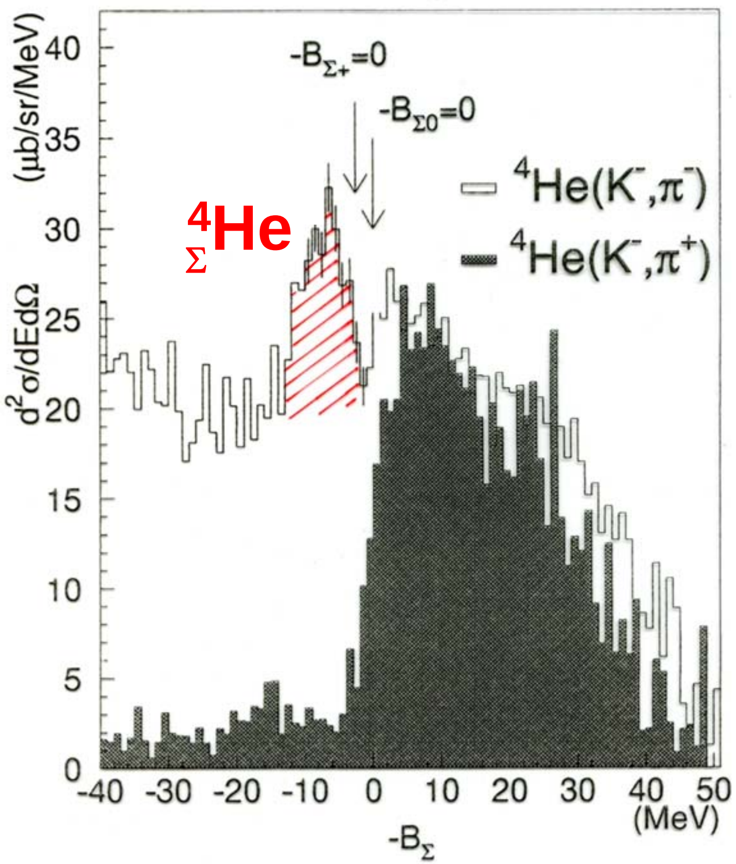






Observation of a $^{4}_{\Sigma}$He bound state

T. Nagae, R.E. Chrien et al.,
Phys. Rev. Lett. 80 (1998) 1605



$$B_{\Sigma^+} = 4.4 \pm 0.3 \pm 1\,\mathrm{MeV}$$

$$\Gamma = 7.0 \pm 0.7^{+1.2}_{-0.0}\ \mathrm{MeV}$$

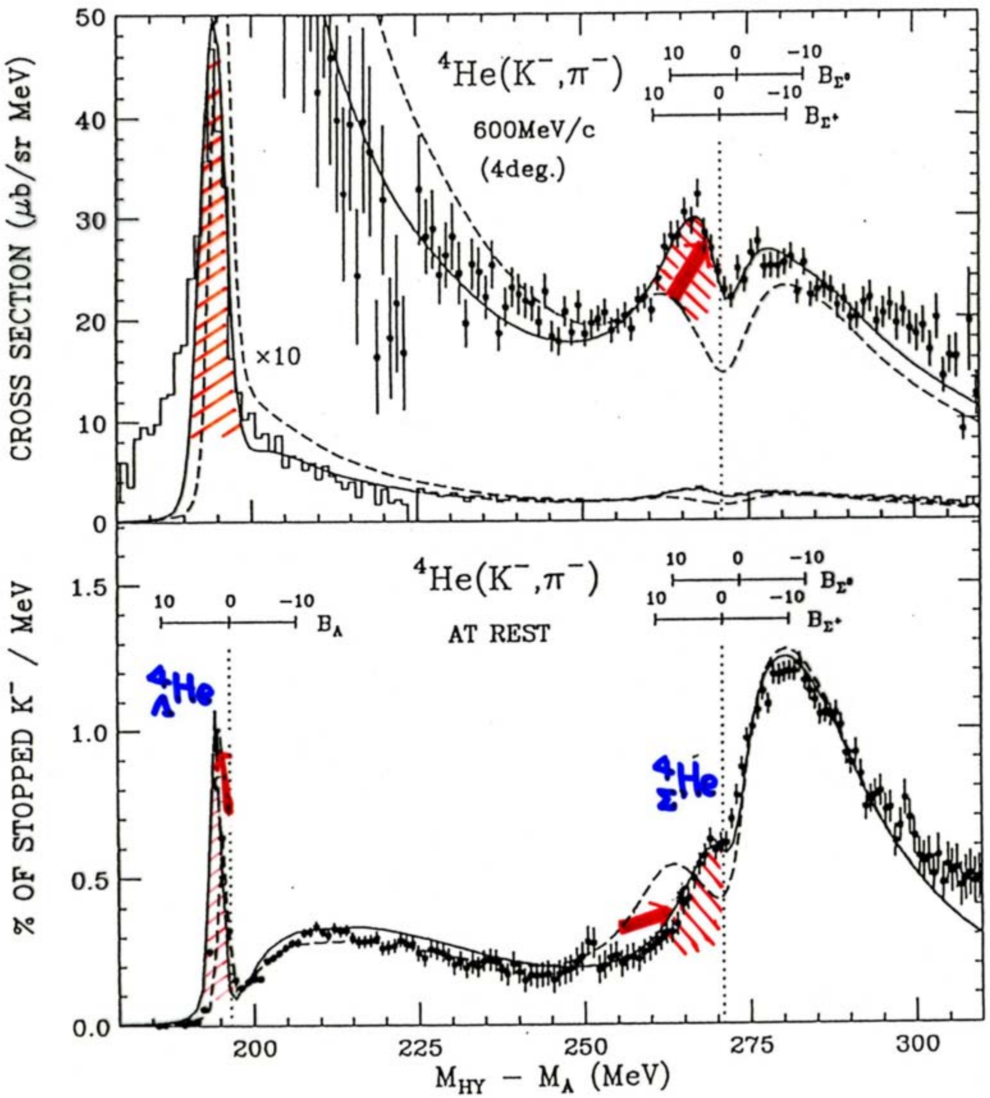
4.6 MeV

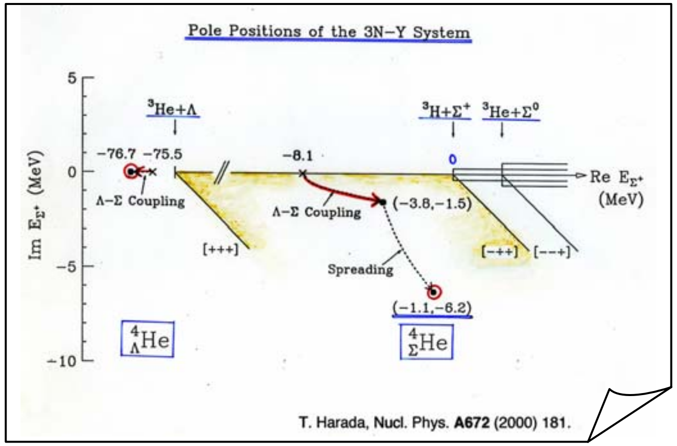
7.9 MeV

T. Harada, Y.Akaishi et al.,
Nucl. Phys. A507 (1990) 715

Theory:

T. Harada,
Phys. Rev. Lett. 81 (1998) 5287





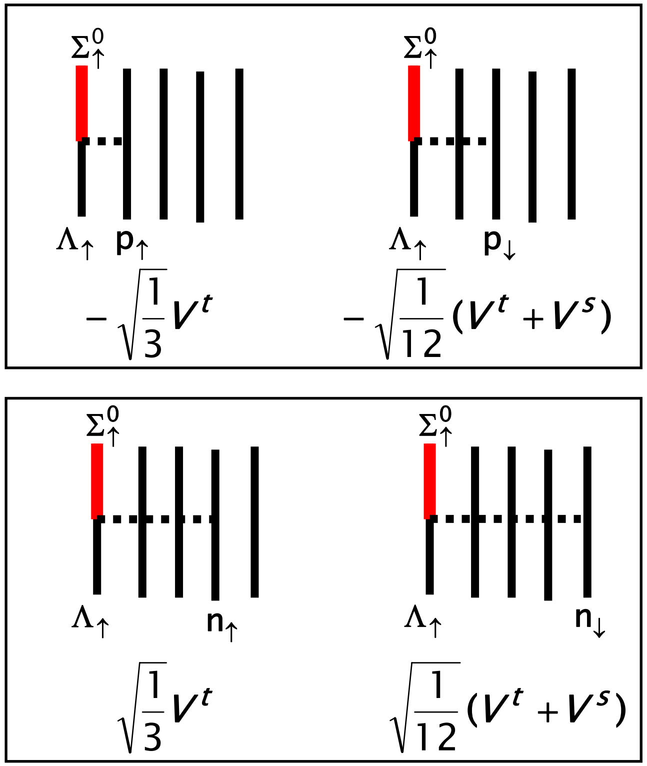
BNL : (1998)

T. Nagae, R.E. Chrien et al.,
Phys. Rev. Lett. **80** (1998) 1605.

KEK : (1989)

R. Hayano et al.,
Phys. Lett. **231** (1989) 355.

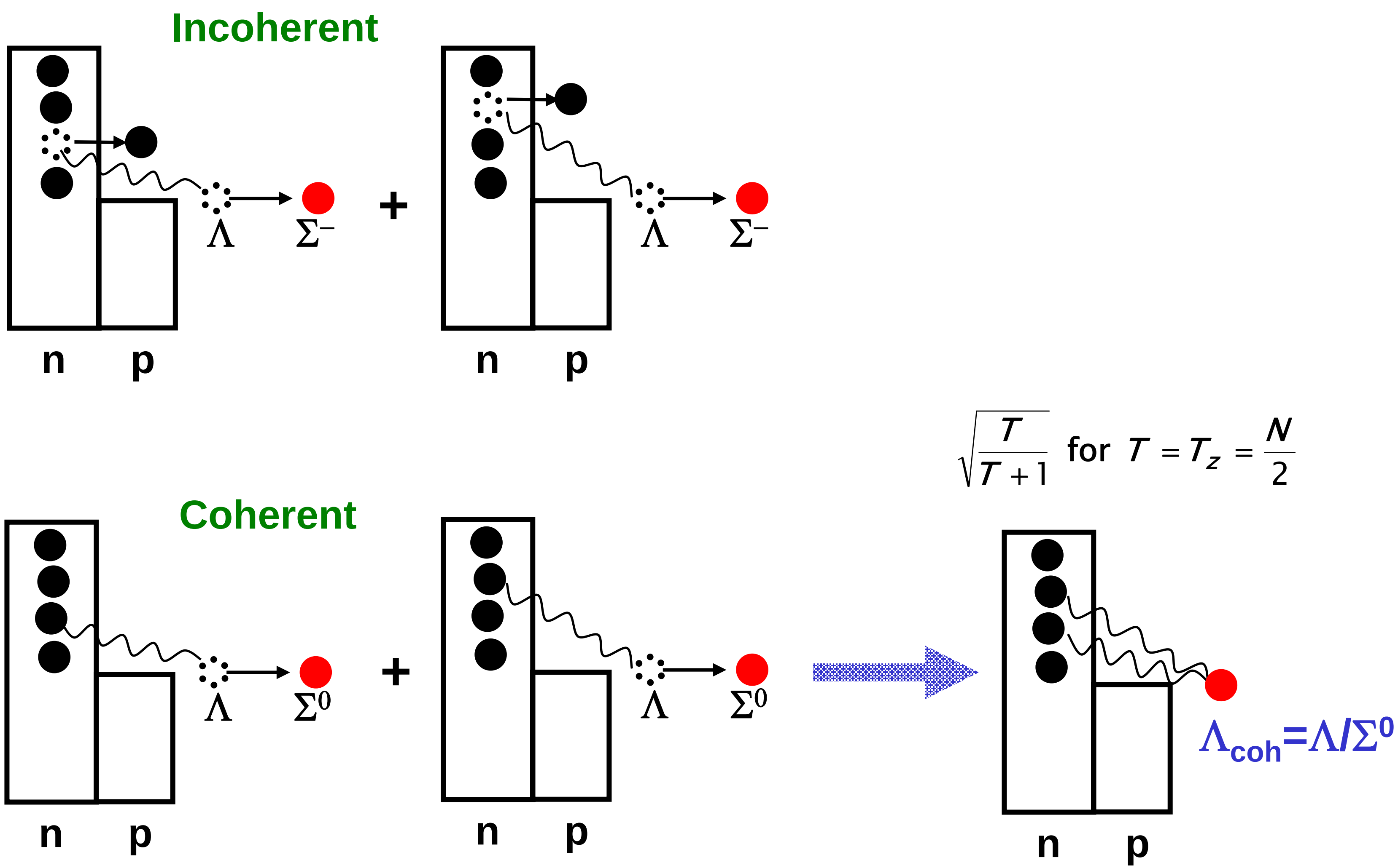
Neutron-excess hypernuclei



Proton induced

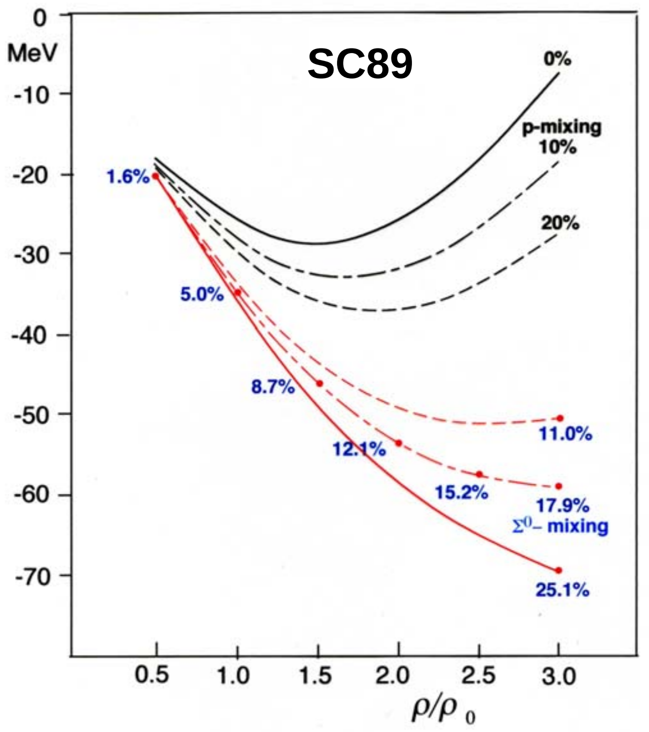
Cancellation due to isospin selection

Neutron induced

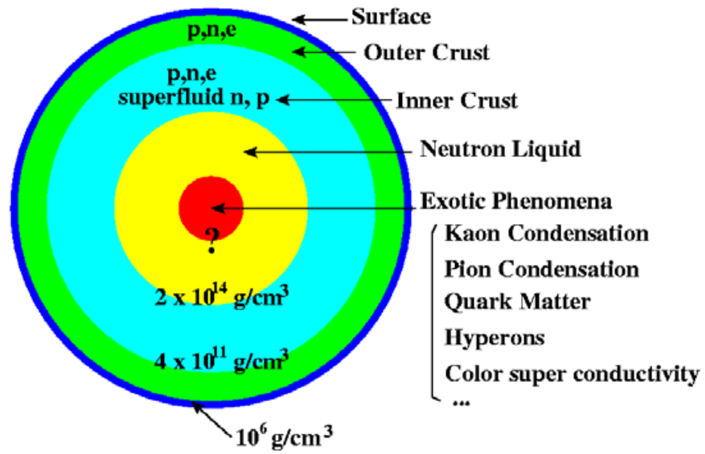


Incoherent
Λ
Σ⁻
+
Λ
Σ⁻
n p
n p
$\sqrt{\frac{T}{T+1}}$ for $T = T_z = \frac{N}{2}$
Coherent
Λ
Σ⁰
+
Λ
Σ⁰
n p
n p
$\Lambda_{coh}=\Lambda/\Sigma^0$
n p

U_Λ in neutron matter



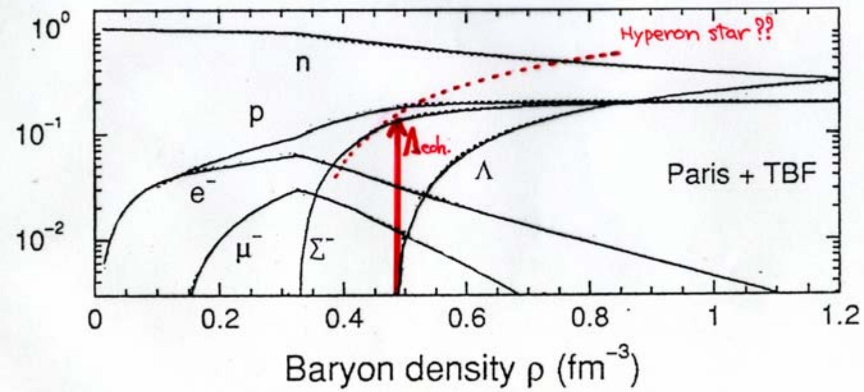
S. Shinmura et al.



Composition of neutron star matter

M. Baldo and G.F. Burgio, Phys. Rev. C61 (2000) 055801.

(Brueckner-Bethe-Goldstone theory)



Relativistic mean field model

Baryons: ***n, p, Λ, Σ***

Mesons: ***σ, ρ, ω***

For Λ and Σ0

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

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

For mesons

Coherent Λ-Σ mixing

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

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

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

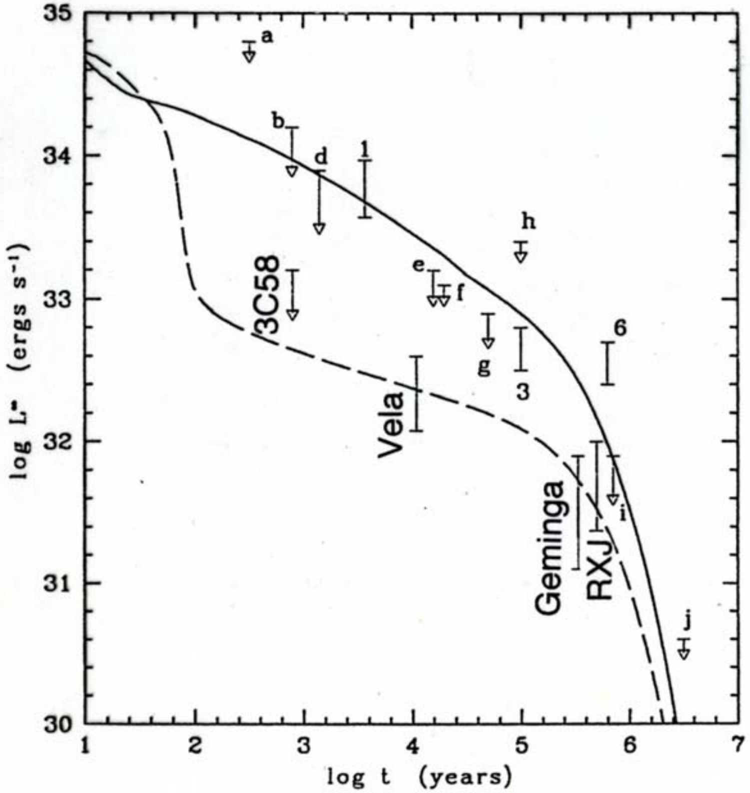
“Normal state of infinite matter”

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

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

Cooling of Neutron Stars

S. Tsuruta, M.A. Teter, T. Takatsuka, T. Tatsumi & R. Tamagaki, ApJ **571** (2002) L571.



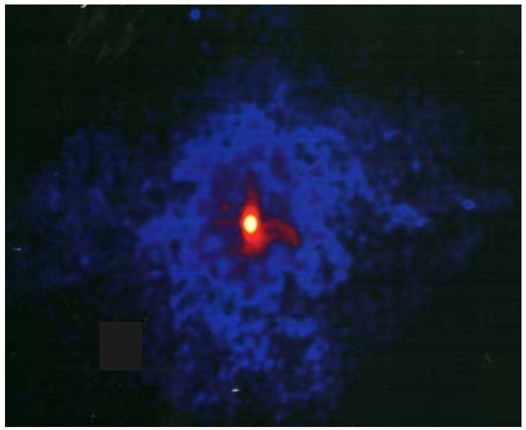
—— Standard cooling (1.2 $M_\odot$)

- - - Pion cooling (1.4 $M_\odot$)

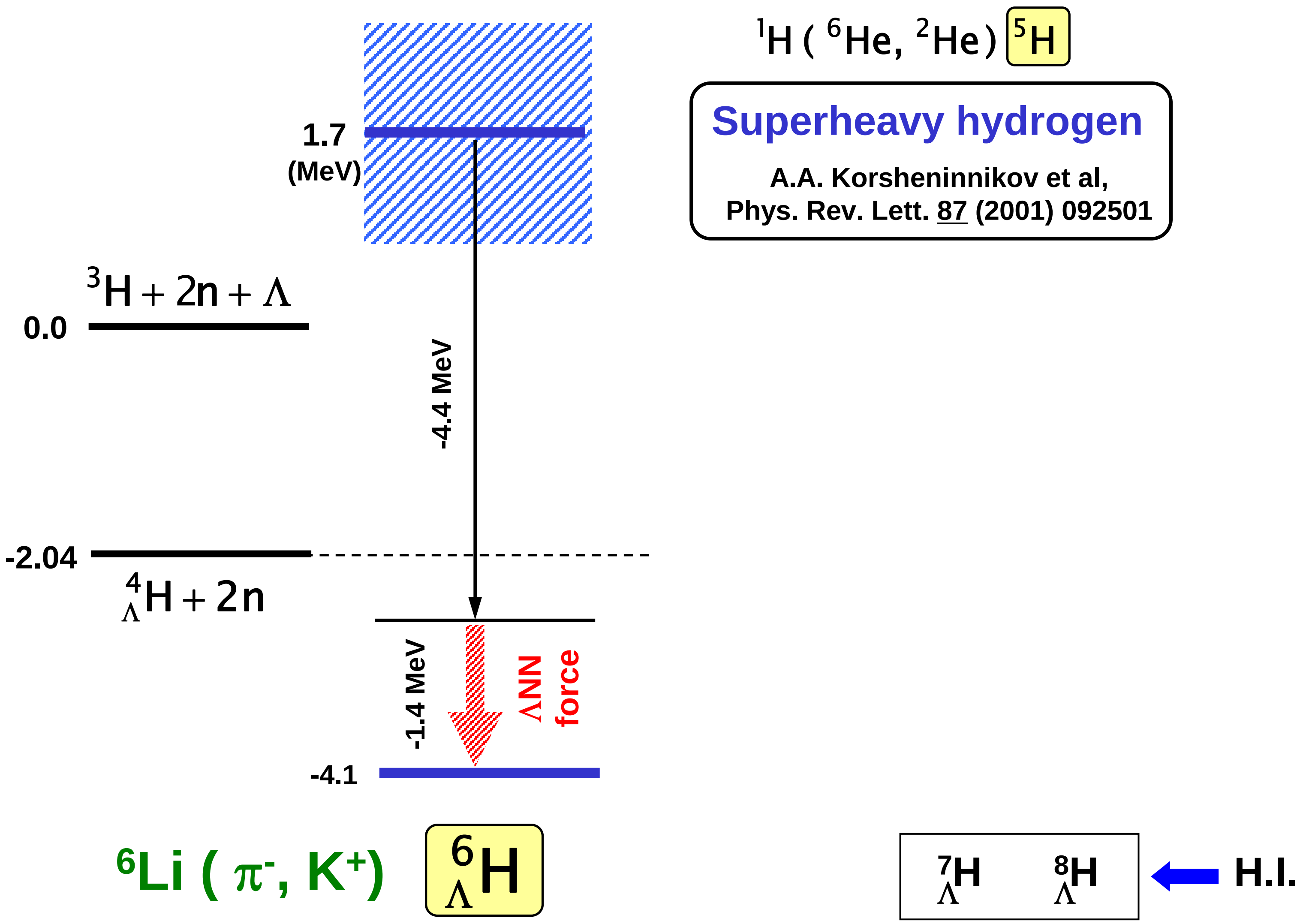
$n + e^- \rightarrow \langle \pi^c \rangle + n + \nu_e$

$\langle \pi^c \rangle + n \rightarrow n + e^- + \bar{\nu}_e$

AD1181



3C58



"Hyperheavy hydrogen"

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

Double-charge & strangeness exchange reaction

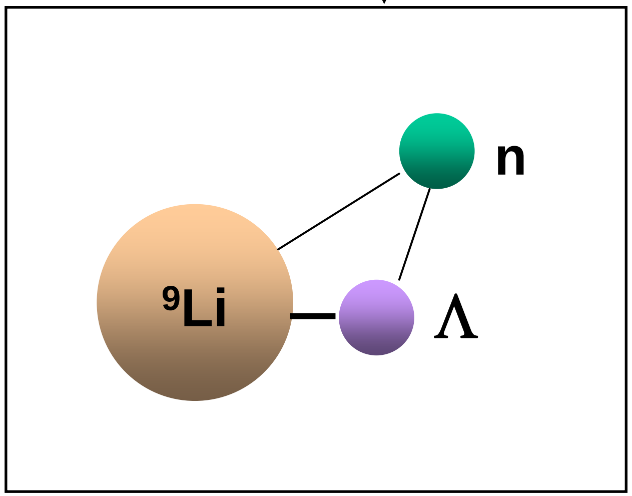
E521 @KEK

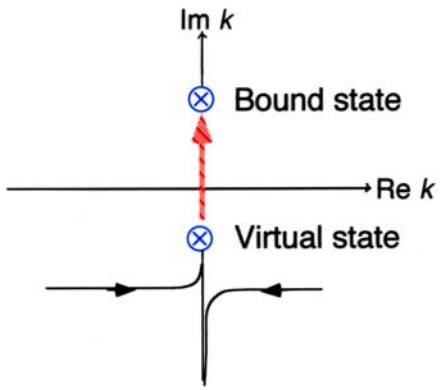
P.K. Saha, T. Fukuda

$$^{10}B(\pi^-,K^+)\,^{10}_{\Lambda}Li = \,^{6}_{\Lambda}H + \alpha = \,^{4}_{\Lambda}H + 2n + \alpha$$

Stabilizer

$$^{11}B(\pi^-,K^+)\,^{11}_{\Lambda}Li$$



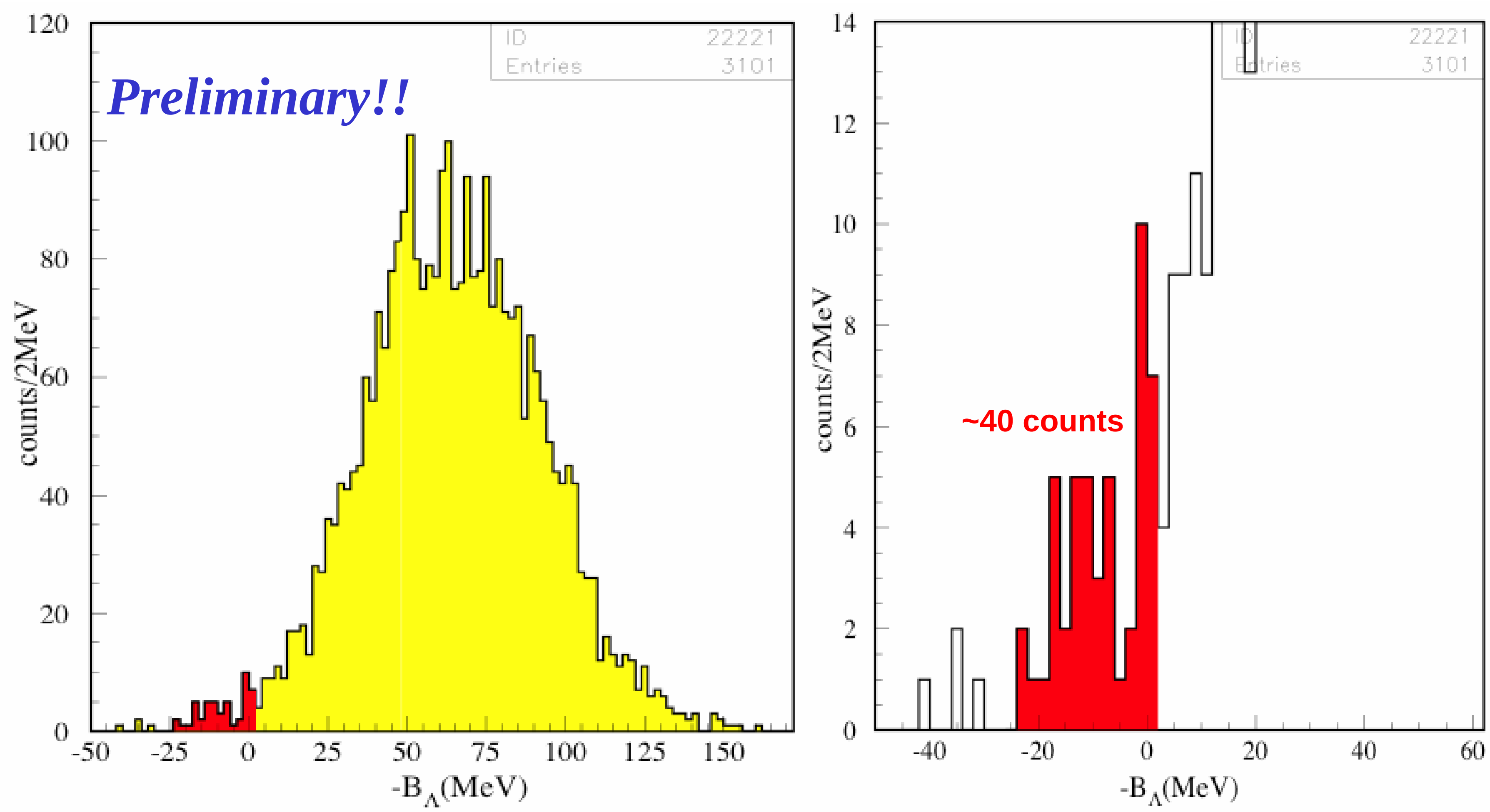


C. Kurokawa et al.

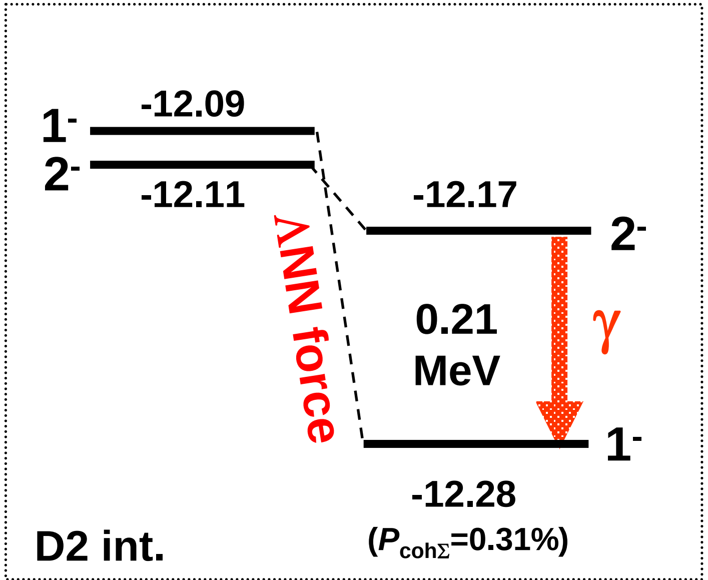
$^{10}B(\pi^-,K^+)$ spectrum

J-PARC

P.K. Saha, T. Fukuda et al., Phys. Rev. Lett. 94 (2005) 952502



$^{10}_{\Lambda}\mathrm{Li}$



BHF cal.

Y. A. & K.S. Myint

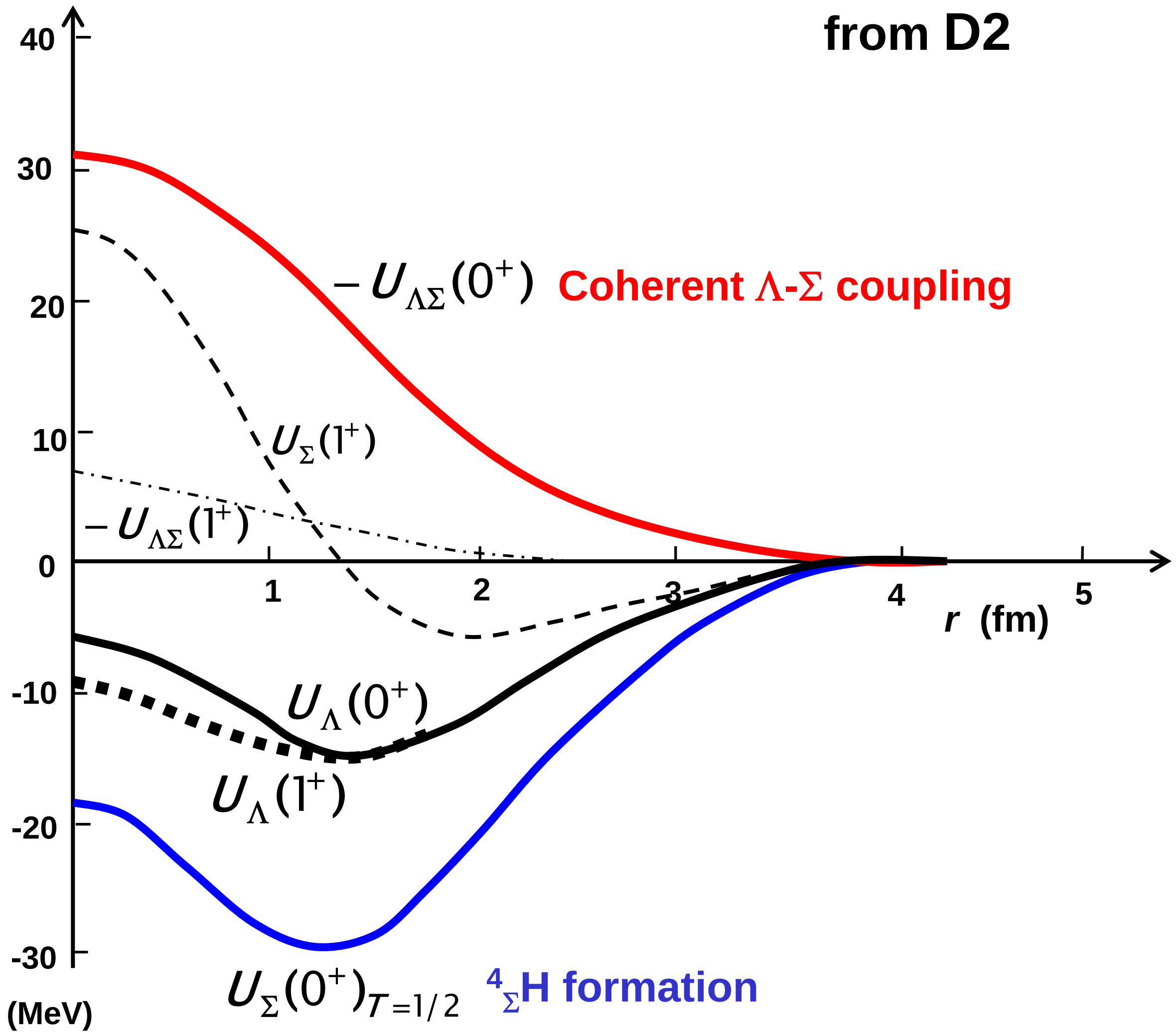
SVM cal.

beyond 4-body model

α + t + Λ + n + n

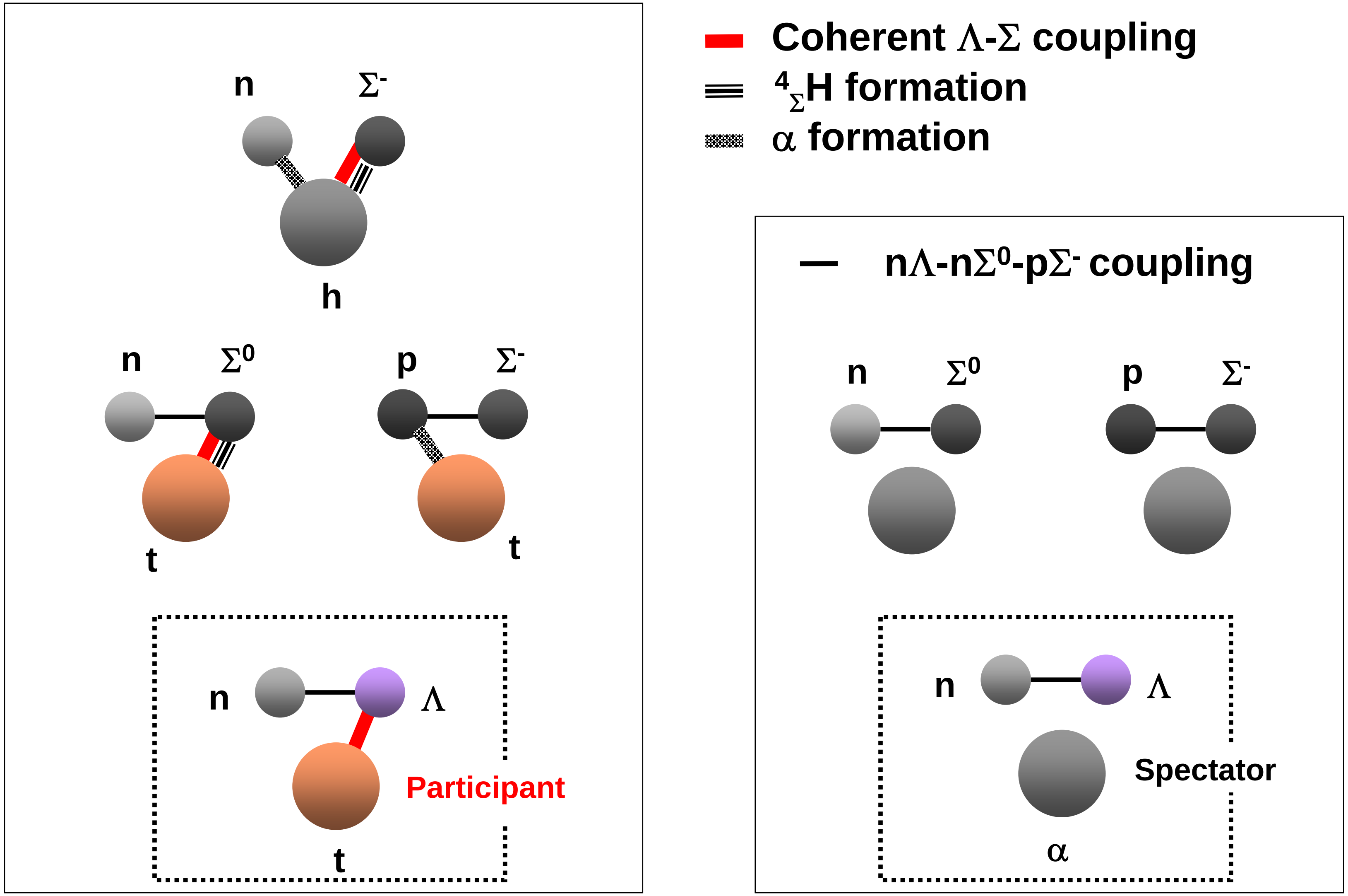
Coherent Λ-Σ coupling

Y- [NNN]$_{T=1/2}$: interactions

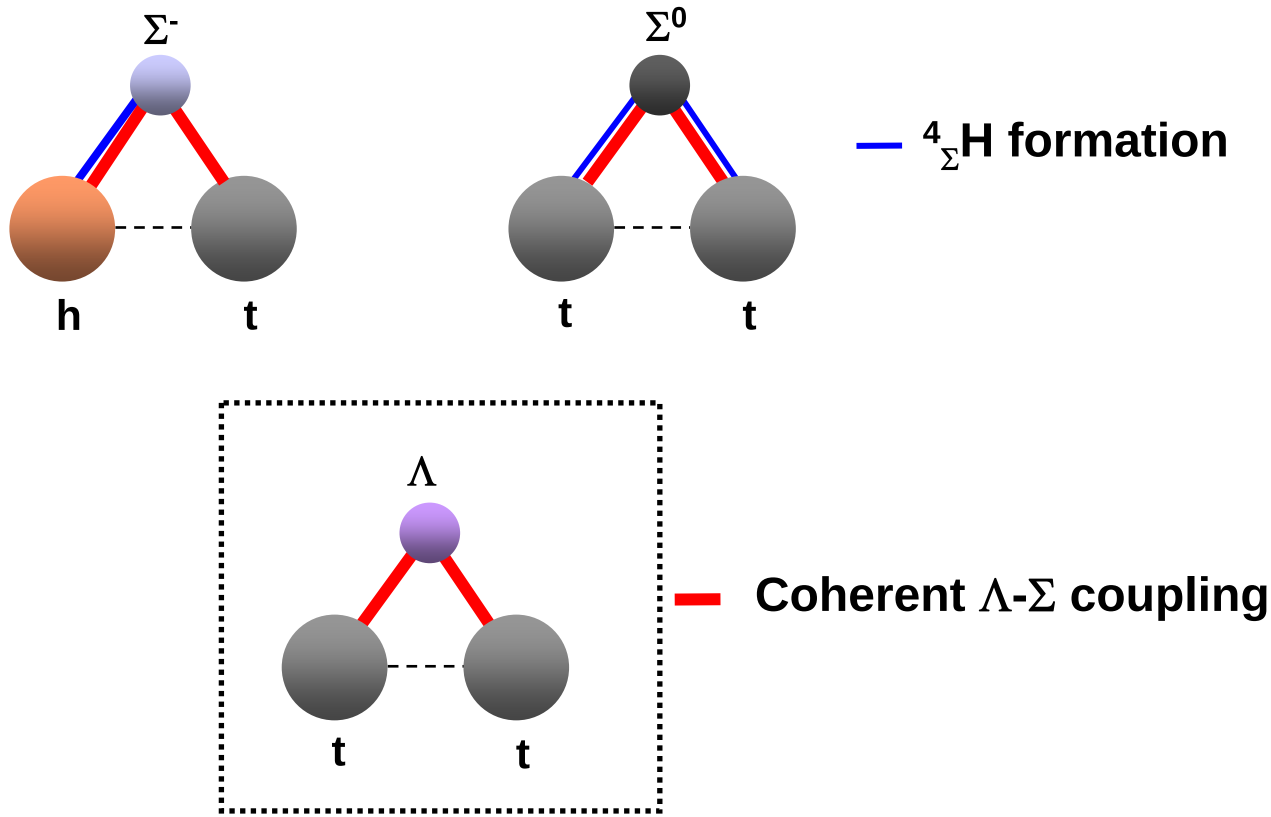


San Dar Myint Oo

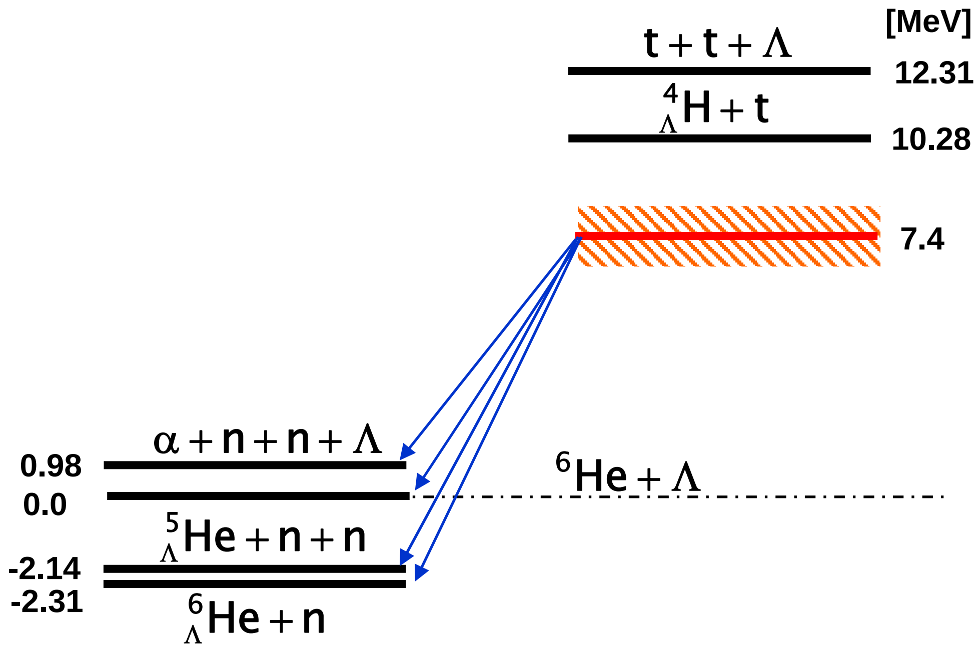
Coupling scheme



Coupling scheme of t-t-Λ



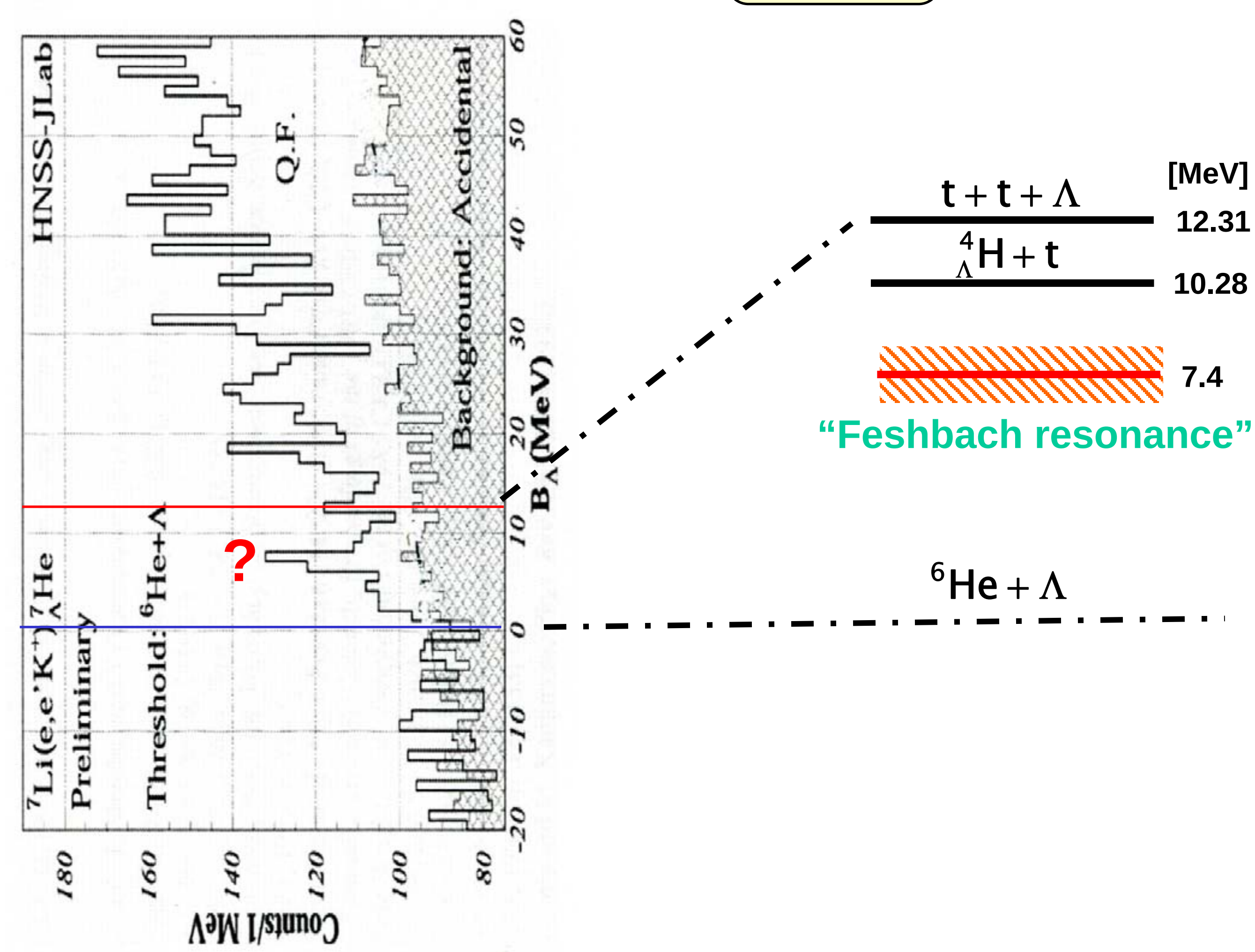
$^{7}_{\Lambda}He$



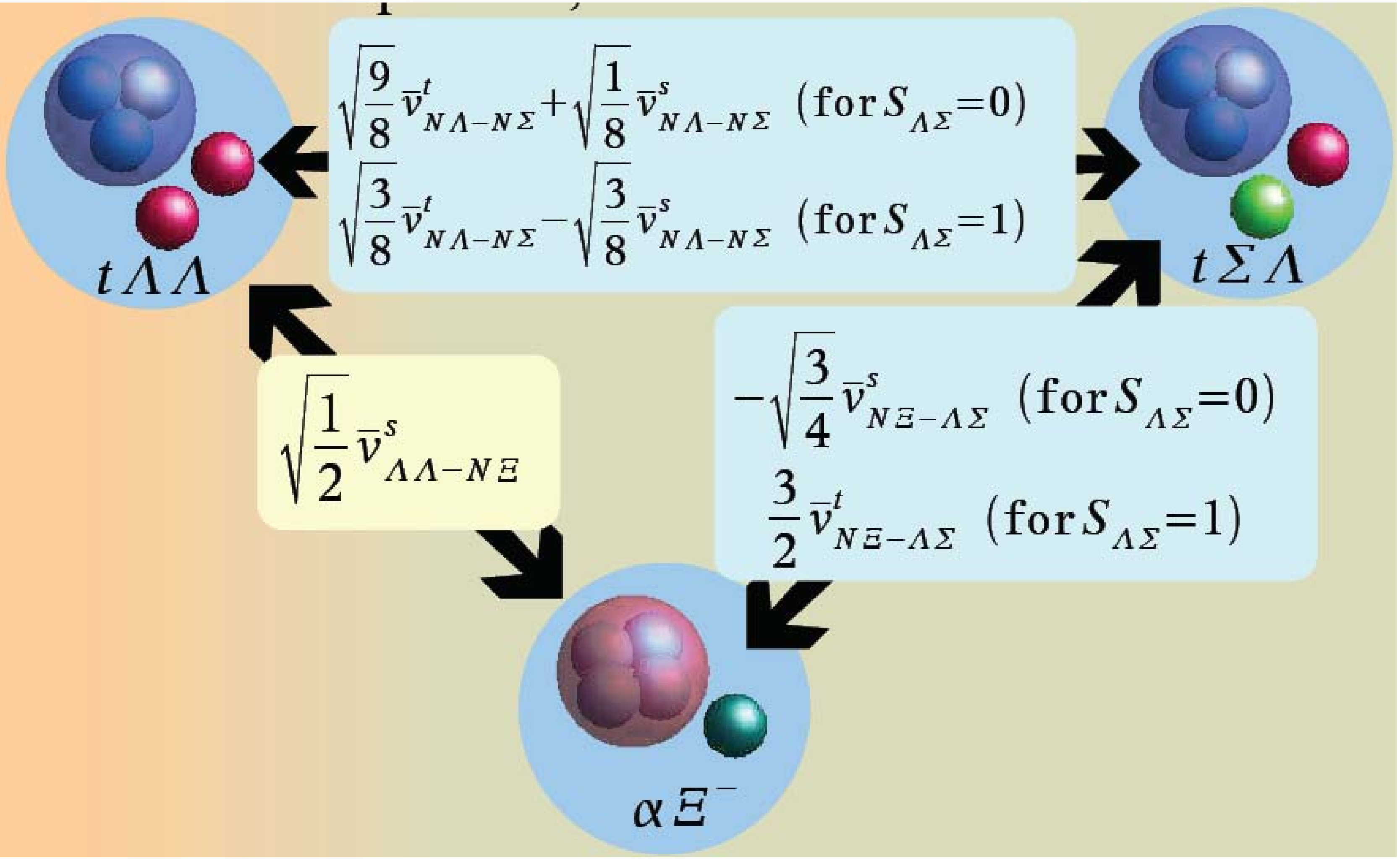
[MeV]
t + t + Λ
12.31
⁴ΛH + t
10.28
7.4
α + n + n + Λ
0.98
⁶He + Λ
0.0
⁵ΛHe + n + n
-2.14
-2.31
⁶ΛHe + n

J-Lab
O. Hashimoto et al.

$^{7}_{\Lambda}$He



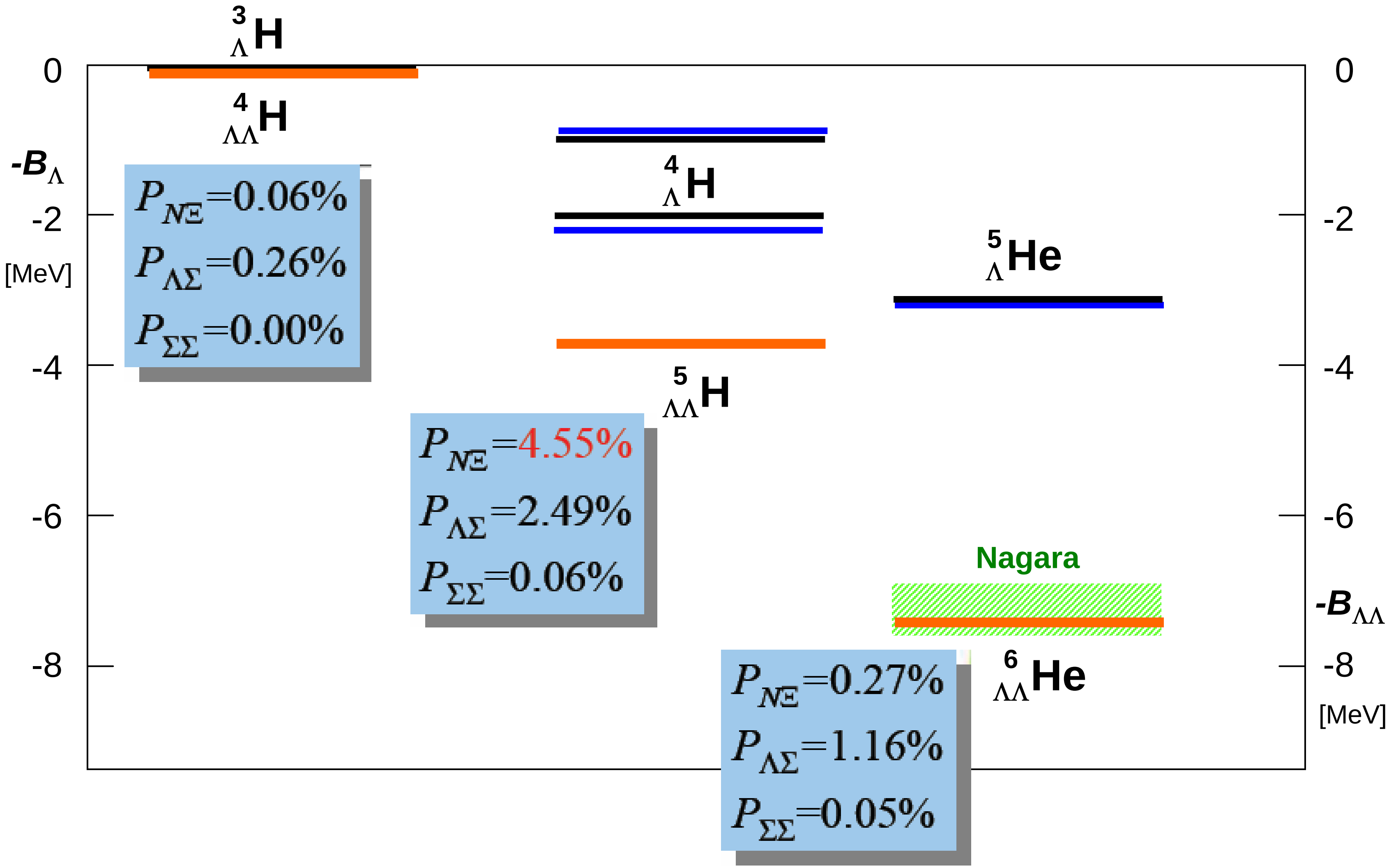
Hyperon mixing in $^{5}_{\Lambda\Lambda}H$



H. Nemura et al.

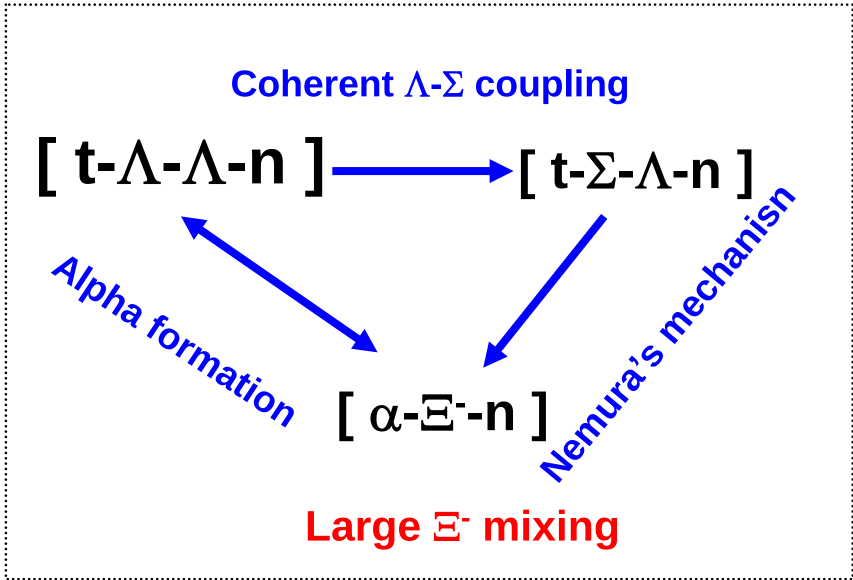
Fully coupled channel (ΛΛ-NΞ-ΛΣ-ΣΣ) calculations

H. Nemura, S. Shinmura, Y. Akaishi & K.S. Myint, Phys. Rev. Lett. 94 (2005) 202502



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

$^{6}_{\Lambda\Lambda}H$ =



Missing-mass spectroscopy in *S*=-2 sector via one-step process !

Concluding remarks

The overbinding problem of ${}^{5}_{\Lambda}$He
has been virtually solved.

ΛNN force

Repulsive/attractive : "D0 picture"
Attractive : "D2 picture"

A necessary condition for YN interaction to study $_{\Lambda\Lambda}$A.

consistency

Effective ΛN interaction

Coherent Λ-Σ coupling is essential dynamics.

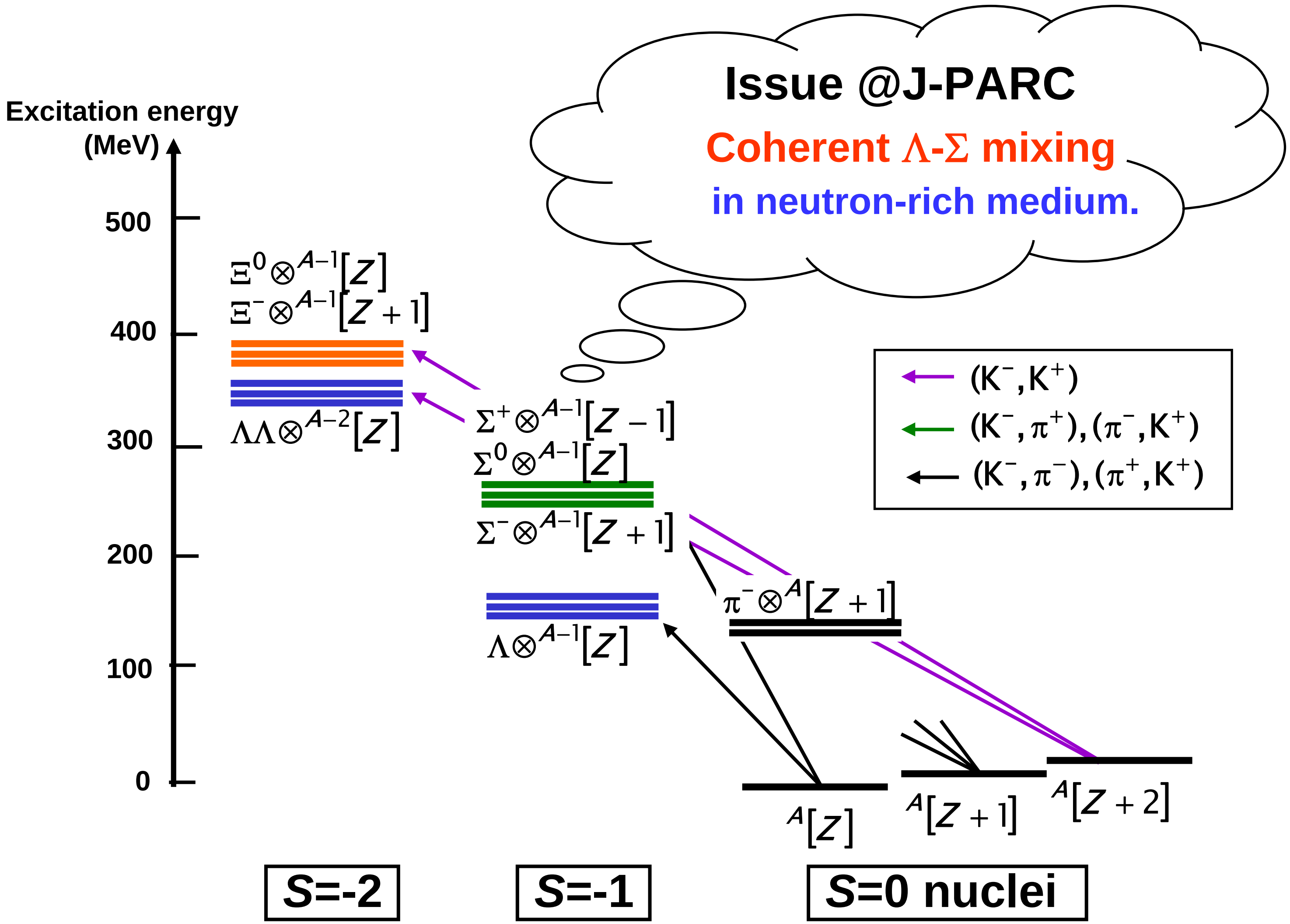
${}^{4}_{\Lambda}\mathrm{He}(0^+) - {}^{4}_{\Sigma}\mathrm{He}(0^+)$

Λ_{coh}(Λ-Σ^0 mixing) in dense neutron matter

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

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

H.I. ${}^{7}{}_{\Lambda}$H, ${}^{8}{}_{\Lambda}$H, …, ${}^{5}{}_{\Lambda\Lambda}$H, ${}^{7}{}_{\Lambda\Lambda}$H,… etc.



Issue @J-PARC
Coherent Λ-Σ mixing
in neutron-rich medium.
Excitation energy
(MeV)
500
400
300
200
100
0
$\Xi^0 \otimes {}^{A-1}[Z]$
$\Xi^- \otimes {}^{A-1}[Z+1]$
$\Lambda\Lambda \otimes {}^{A-2}[Z]$
$\Sigma^+ \otimes {}^{A-1}[Z-1]$
$\Sigma^0 \otimes {}^{A-1}[Z]$
$\Sigma^- \otimes {}^{A-1}[Z+1]$
$\Lambda \otimes {}^{A-1}[Z]$
$\pi^- \otimes {}^{A}[Z+1]$
${}^{A}[Z]$
${}^{A}[Z+1]$
${}^{A}[Z+2]$
(K^-, K^+)
$(K^-, \pi^+), (\pi^-, K^+)$
$(K^-, \pi^-), (\pi^+, K^+)$
S=-2
S=-1
S=0 nuclei

Thank you very much!