Hypernuclear weak decay :

-- present and future problems --

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Kakenhi-kenkyukai Atami2009
Atami   Feb.27-28 2009

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1 Experiment : Pi-Mesonic Weak Decay

- Mesonic decay rates

Data (~ 2000)

Hypernucleus		Ref.
${}^{4}_{\Lambda}\mathrm{H}$	Γ_{π^-}	Outa(1995)
${}^{4}_{\Lambda}\mathrm{He}$	Γ_{π^0} , Γ_{π^-}	Outa(1995,1998) Zeps(1998)
${}^{5}_{\Lambda}\mathrm{He}$	Γ_{π^0} , Γ_{π^-}	Szymanski(1991)
${}^{9}_{\Lambda}\mathrm{Be}$	Γ_{π}	Bando(1987) ?
${}^{11}_{\Lambda}\mathrm{B}$	Γ_{π} Γ_{π^0} Γ_{π^0} , Γ_{π^-}	Grace(1985) Sakaguchi(1991) Noumi(1995)
${}^{12}_{\Lambda}\mathrm{C}$	Γ_{π^0} , Γ_{π^-} Γ_{π^0} Γ_{π^0} , Γ_{π^-}	Szymanski(1991) Sakaguchi(1991) Noumi(1995)

Data (2000~)

Hypernucleus		Ref.
$^{11}{}_{\Lambda}$B	Γ_{π^-}	Sato(2005)
$^{12}{}_{\Lambda}$C	Γ_{π^-}	Sato(2005)
$^{28}{}_{\Lambda}$Si, $^{27}{}_{\Lambda}$Si	Γ_{π^-}	Sato(2005)
$_{\Lambda}$Fe	Γ_{π^-}	Sato(2005)
$^{7}{}_{\Lambda}$Li	π^- spectra, Γ_{π^-}	Botta(2008)
$^{9}{}_{\Lambda}$Be	π^- spectra, Γ_{π^-}	Botta(2008)
$^{11}{}_{\Lambda}$B	π^- spectra, Γ_{π^-}	Botta(2008)
$^{15}{}_{\Lambda}$N	π^- spectra, Γ_{π^-}	Botta(2008)

2 Experiment : Nonmesonic Weak Decay

- Decay rates, Γ_n/Γ_p, $\tau_{1/2}$

Data

Hypernucleus		Ref.
${}^{4}_{\Lambda}H$	Γ_{nm}	Szymanski(1991) Outa(1998)
${}^{4}_{\Lambda}He$	Γ_p , Γ_n	Szymanski(1991) Outa(1998) Zeps(1998)
${}^{5}_{\Lambda}He$	Γ_p , Γ_n	Szymanski(1991) Noumi(1995)
${}^{11}_{\Lambda}B$	Γ_{nm}, Γ_n/Γ_p Γ_{nm}	Szymanski(1991)Noumi(1995) Sato(2005)
${}^{12}_{\Lambda}C$	Γ_{nm}, Γ_n/Γ_p $\tau_{1/2}$	Szymanski(1991)Noumi(1995) Sato(2005) Bhang(1998)Park(2000)

Hypernucleus		Ref.
${}^{27}_{\Lambda}$Al	Γ_{nm}, Γ_n/Γ_p	Sato(2005)
${}^{28}_{\Lambda}$Si	Γ_{nm}, Γ_n/Γ_p $\tau_{1/2}$	Sato(2005) Bhang(1998) Park(2000)
${}_{\Lambda}$Fe	Γ_{nm}, Γ_n/Γ_p $\tau_{1/2}$	Sato(2005) Bhang(1998) Park(2000)
${}_{\Lambda}$Bi	$\tau_{1/2}$	Kulessa(1998)

Data : neutron, proton Energy Spectra (N_n, N_p)

n-n and n-p coincidence measurement, Γ_n/Γ_p

Hypernucleus		Ref.
$^{5}_{\Lambda}$He	N_n, N_p n-n, n-p	Okada(2004) Outa(2005) Kang(2006)
$^{12}_{\Lambda}$C	N_n, N_p N_p n-n, n-p	Okada(2004) Kim(2003) Hashimoto(2002) Outa(2005) Kim(2006)
$^{89}_{\Lambda}$Y	N_n	Okada(2004) Kim(2003)

3 Theory : Mesonic weak decay

- π-decay hamiltonian :

$$H_\pi = \left[s_\pi X^{(s)}(r) + i p_\pi X^{(p)}(r) \frac{(\vec{\sigma}\vec{\nabla})}{q_0} \right] \chi^{(-)*}(\vec{q},\vec{r})$$

$$s_{\pi 0} = -s_{\pi -}/\sqrt{2}$$

$$p_{\pi 0} = -p_{\pi -}/\sqrt{2} \qquad (\Delta I = 1/2\,\mathrm{rule})$$

$$s_{\pi -}/p_{\pi -} = -3. \quad (\text{from } \pi \text{ decay asymmetry}$$

$$\vec{\Lambda} \rightarrow p + \pi^-$$

$$\alpha_1^{\pi} = -0.64 \qquad)$$

$\chi^{(-)*}(\vec{q},\vec{r})$: π-on distorted wave

Vertex form factor (depends on

$\pi-$Optical pot.)

$$\mathbf{X}^{(s)}(\mathbf{r}) = 1.0$$

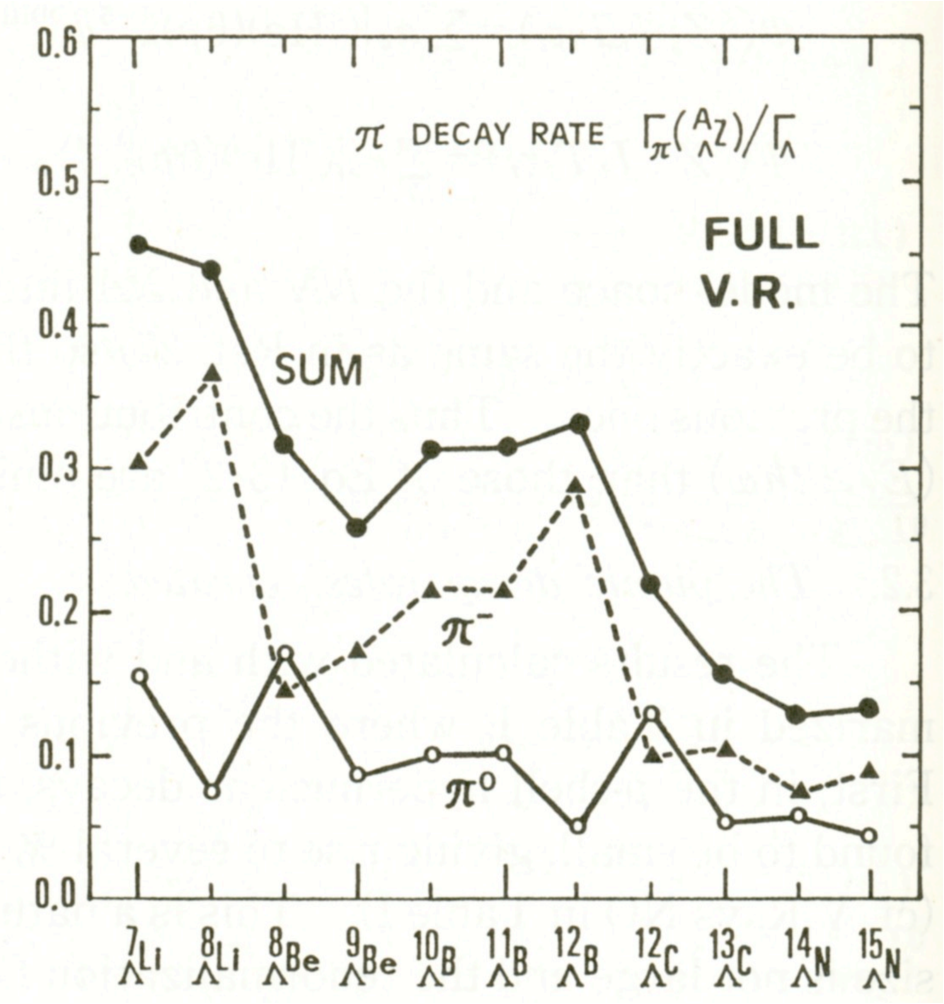
$$\mathbf{X}^{(p)}(\mathbf{r}) = L(\mathbf{r}) \qquad \text{(LLEE for MSU pot.)}$$

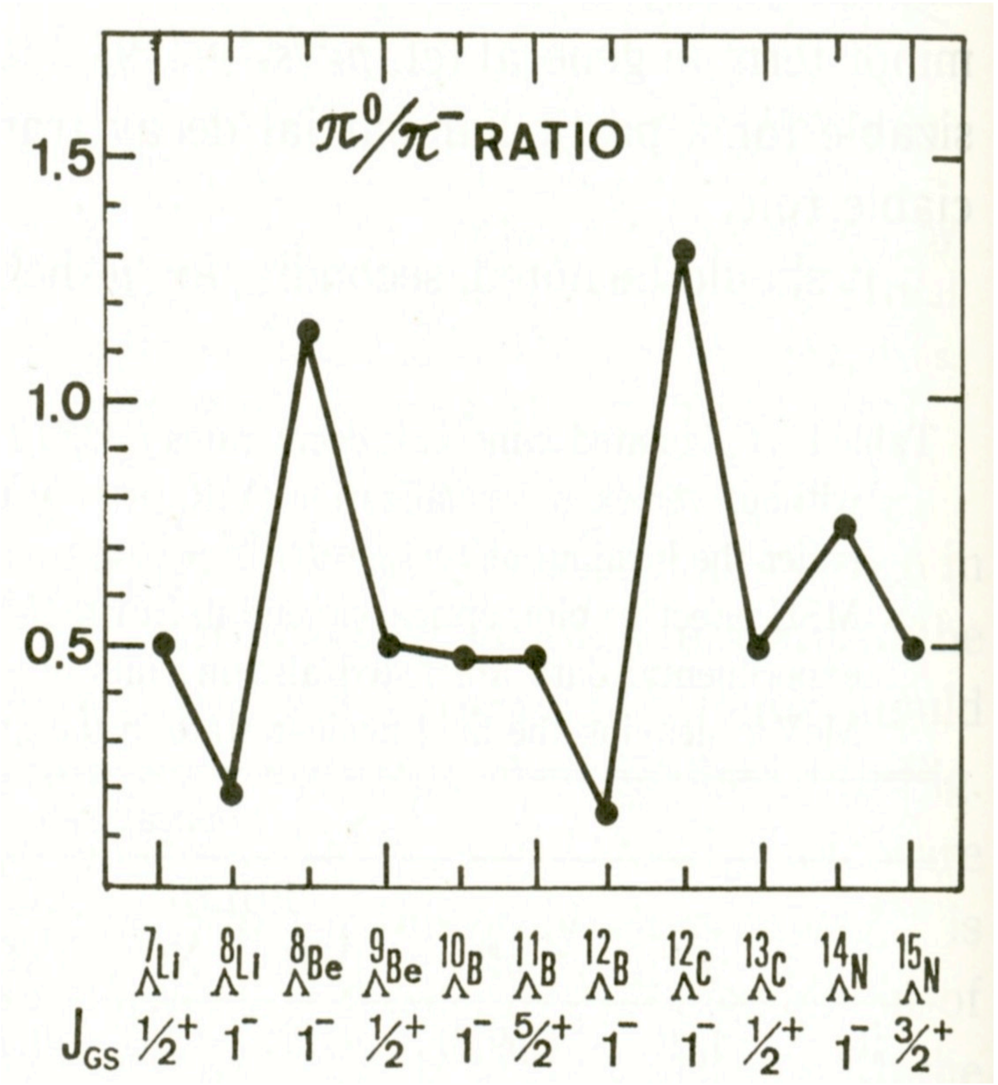
Lorentz – Lorenz – Ericson – Ericson

- $\Gamma_{\pi 0}$, $\Gamma_{\pi -}$, π^0/π^- , $\Gamma_{\pi}{}^{\mathrm{sum}}$

- Decay rates : sensitively depends on Hyp-structure
- Theor. Cal. → good agreement with available data
- A= 4 : ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$ → Γ_{π}'s data favor Isle-type

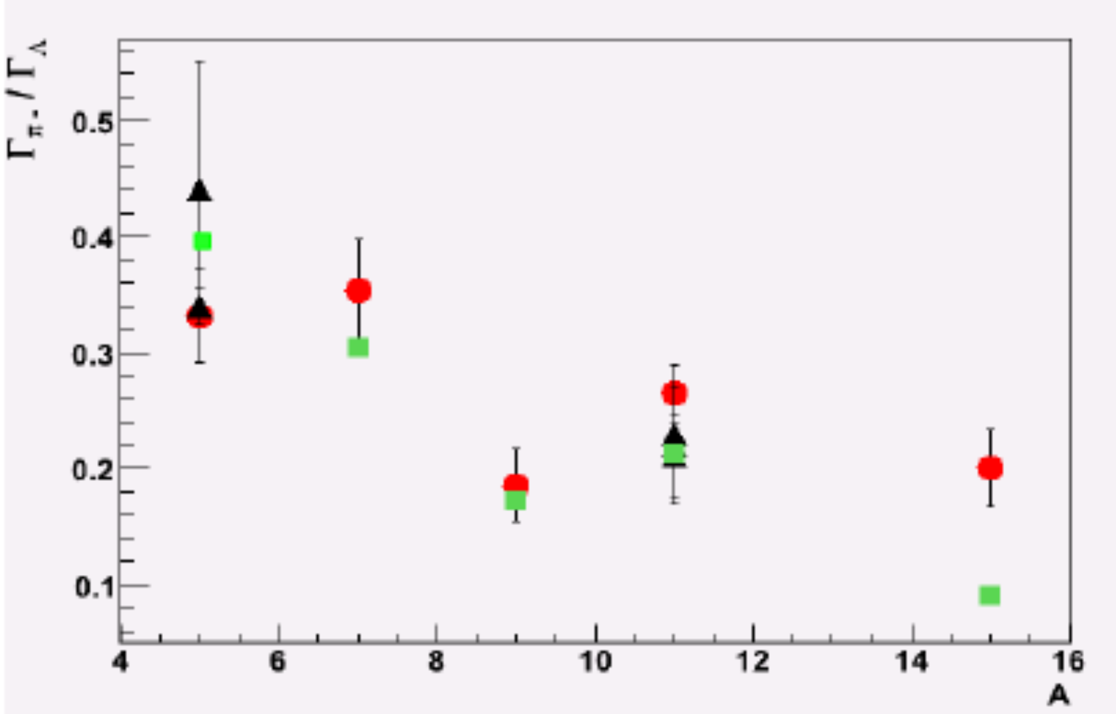
  for $V_{\Lambda\text{-nucleus}}$ pot.


π DECAY RATE $\Gamma_\pi({}^{A}_{\Lambda}Z)/\Gamma_\Lambda$
FULL
V. R.
SUM
π^-
π^0
0.6
0.5
0.4
0.3
0.2
0.1
0.0
${}^{7}_{\Lambda}$Li
${}^{8}_{\Lambda}$Li
${}^{8}_{\Lambda}$Be
${}^{9}_{\Lambda}$Be
${}^{10}_{\Lambda}$B
${}^{11}_{\Lambda}$B
${}^{12}_{\Lambda}$B
${}^{12}_{\Lambda}$C
${}^{13}_{\Lambda}$C
${}^{14}_{\Lambda}$N
${}^{15}_{\Lambda}$N


π^0/π^- RATIO
1.5
1.0
0.5
${}^{7}_{\Lambda}$Li
${}^{8}_{\Lambda}$Li
${}^{8}_{\Lambda}$Be
${}^{9}_{\Lambda}$Be
${}^{10}_{\Lambda}$B
${}^{11}_{\Lambda}$B
${}^{12}_{\Lambda}$B
${}^{12}_{\Lambda}$C
${}^{13}_{\Lambda}$C
${}^{14}_{\Lambda}$N
${}^{15}_{\Lambda}$N
J_{GS}
$1/2^+$
1^-
1^-
$1/2^+$
1^-
$5/2^+$
1^-
1^-
$1/2^+$
1^-
$3/2^+$

- A= 15 : ${}^{15}_{\Lambda}\mathrm{N}$ π^{-}–spectrum, $\Gamma_{\pi-}$ data

(FINUDA 2008)→ cal. factor 2 small ?



- π-on asymmetry from polarized hypernuclei

$$ {}^{A}_{\Lambda}\mathbf{Z}(\mathbf{J_i}\ \mathbf{M_i}\ \mathbf{T_i}\ \tau_{\mathbf{i}},\mathbf{P_H}) \to {}^{A}\mathbf{Z}'(\mathbf{J_f}\ \mathbf{T_f}\ \tau_{\mathbf{f}}) + \pi(\vec{\mathbf{q}}) $$

- Angular distribution

$$ \begin{aligned} &\Gamma_\pi(\mathbf{J_i}\ \mathbf{M_i}\ \mathbf{T_i}\ \tau_{\mathbf{i}},\mathbf{J_f}\ \mathbf{T_f}\ \tau_{\mathbf{f}}\ ;\hat{\mathbf{q}}) \\ &= \sum_{\mathbf{Q}} \Gamma_\pi^{\mathbf{Q}}(\mathbf{J_i}\ \mathbf{M_i}\ \mathbf{T_i}\ \tau_{\mathbf{i}},\mathbf{J_f}\ \mathbf{T_f}\ \tau_{\mathbf{f}}\ ;\mathbf{q})\,\mathbf{P_Q}(\hat{\mathbf{q}}) \\ &= \Gamma_\pi^{\mathbf{Q}=0}(\mathbf{J_i}\ \mathbf{M_i}\ \mathbf{T_i}\ \tau_{\mathbf{i}},\mathbf{J_f}\ \mathbf{T_f}\ \tau_{\mathbf{f}}\ ;\mathbf{q})\,(1+\alpha_1\mathbf{P}_1(\hat{\mathbf{q}})+\alpha_2\mathbf{P}(\hat{\mathbf{q}})+\cdots) \end{aligned} $$

$$ \alpha_{\mathbf{Q}} = \frac{\Gamma_\pi^{\mathbf{Q}}}{\Gamma_\pi^{\mathbf{Q}=0}} \qquad (\mathbf{M_i}=\mathbf{J_i}\ \ 100\%\ \text{polarlized}) $$

α_1 : asymmetry parameter

■ π-on asymmetry

- $^{5}_{\Lambda}\mathbf{He}$: measured, Ajimura(1998)

Asymmetry $A^{\pi} = P\alpha_1^{\pi}\varepsilon$

Measured A^{π} , ε : reduct.factor (=0.81)

assumed $\alpha_1^{\pi} = -0.64$ (free Λ val.)

→ Deduced Polarization P

P = 0.249 +/- (θ=2−7 deg)

P = 0.393 +/- (θ=7−15 deg) < - > Consistent with cal.

Theory (prediction) NP. A489(1988)683

$$^{9}_{\Lambda}\mathbf{B}(1/2^{+}) \quad , \quad \alpha_1^{\pi} = -0.64 \quad (\text{cal.})$$

$$^{13}_{\Lambda}\mathbf{C}(1/2^{+}) \quad , \quad \alpha_1^{\pi} = -0.16 \quad (\text{cal.})$$

■ Δ I = ½ rule for Λ → N + π decay

- Λ ◊ p + π^- (63.9 +/− 0.5) %

  ◊ n + π^0 (35.8 +/− 0.5) %

Rule : established empirically

$$\frac{\Gamma_{\pi}^{\mathrm{exp}}(\Lambda \to \mathbf{p} + \pi^{-})}{\Gamma_{\pi}^{\mathrm{exp}}(\Lambda \to \mathbf{n} + \pi^{0})} \cong \frac{2}{1} = \frac{(1/2\,1/2\;1\,-1\,|\,1/2\,-1/2)^2}{(1/2\,-1/2\;1\,0\,|\,1/2\,-1/2)^2}$$

∗ Theoretical foundation, however,

not yet clarified well

∗ see, Hiyama et al. PTP 112(2004)99

quark-quark correlations, $(us)^0$ → $(ud)^0$ considered.

* also, Oka's group and other QCD works

4 Theory : $\Lambda N \rightarrow NN$ nonmesonic weak decay

- $\Delta S = 1$, $Q = 176.$ MeV, q ~400 MeV/c (free Λ)
- High momentum transfer process
- Short-range part of interactions contributes
- NMWD – dominant decay mode in medium-to-heavy Λ-hypernuclei

A. Nonmesonic decay interactions, $V(\Lambda N - NN)$

Models :

1 one-pion exchange, V_π

basic but not dominant

lightest 0^- meson → long-ranged, strong tensor

→ fail to explain Γ_n/Γ_p (n/p –ratio) data

2 octet-meson exchanges :

0⁻ pseudo-scalar (π, K, η) exch.

1⁻ vector (ρ, K*, ω) exch.

π + K : work additively for ${}^3S_1$ → ${}^3P_1$,

destructively for parity-cons. channels

→ enhance the n/p ratios, which explains features of exp. data (Good !)

→ but not enough to explain Γ_{nm}

other mesons : necessary to explain Γ_{nm}

octet-meson exch. : not successful to explain asymmetry parameter α_Λ of ${}^{5}_{\Lambda}\mathrm{He}$, ${}^{12}_{\Lambda}\mathrm{C}$

3 correlated-2π , uncorrelated-2π exchanges :

2π/σ : 0^+ scalar exch.

enhance the decay rates

2π/ρ : 1^- vector exch.

tensor force, opposite sign to V_π

correlated-2π + uncorrelated-2π (+ octet-mesons) :

→ work favorably to explain α_Λ

(Chumillas et al. 2007)

4 Axial vector meson exchange :

a_1 : $J^\pi = 1^+$, ←→ chiral partner of ρ, like π ←→ σ

modeled as $\rho\pi/a_1$, $\sigma\pi/a_1$ –exch.

(+ π, K, ω, 2π/σ, 2π/ρ) → work favorably for α_Λ

${}^{5}_{\Lambda}\mathbf{He}$, ${}^{12}_{\Lambda}\mathbf{C}$

5 Direct quark interaction :

short-ranged

ΔI = 1/2 & 3/2 contributions

ΔI = 3/2 contributions, large for J = 0 trans.

Direct quark int. alone → not enough to explain Γ_{nm}

Direct quark + π + K + σ :

→ can explain α_Λ of ${}^{5}_{\Lambda}\mathbf{He}$ (Sasaki et al. 2005)

6 Effective field theory :

low order effective field theory (LO pc +pv)

high mom. (short-distance) modes → contact oprator

π, K → treated as dynamical field, long-range part

➔ stress, importance of scalar-isoscalar contact int.

to fit data including α_Λ ${}^{5}_{\Lambda}\mathbf{He}$, ${}^{12}_{\Lambda}\mathbf{C}$

B. Γ_n / Γ_p (n/p ratio)

Exp.			
	$^{5}_{\Lambda}\mathrm{He}$	0.45 +/- 0.11+/- 0.03	Kang(2006)
	$^{12}_{\Lambda}\mathrm{C}$	0.56 +/- 0.12 +/-0.04	Outa(2005)
		0.51 +/- 0.13 +/-0.05	Kim (2006)

Theory :

$V_\pi + V_K$: important role to explain the large n/p ratios

mechanisms:

$^3S_1 \rightarrow {}^3P_1$, PV-channel (I = 1)

interference works additively

$^{1,3}S \rightarrow {}^{13}S$, $^3S_1 \rightarrow {}^3D_1$, PC-channels

interferences work destructively

($V_\pi + V_K$ alone : → not enough to explain Γ_{nm})

C. Asymmetry parameter α_1, α_Λ

Exp. ${}^{5}_{\Lambda}\mathrm{He}$ 0.11 +/- 0.08+/- 0.04 Outa, Maruta(2005)

0.07 +/- 0.08 (+0.08/-0.00) Maruta(2006)

0.24 +/- 0.22 Ajimura(2000)

${}^{12}_{\Lambda}\mathrm{C}$ −0.20 +/- 0.26 +/-0.04 Outa, Maruta(2005)

−0.16 +/- 0.28(+0.18/-0.00) Maruta(2006)

Theory :

1 effective field theory (Parreno, 2004,2005)

α_Λ (${}^{5}_{\Lambda}\mathrm{He}$) , fitted to data Ajimura(2000)

$A_1({}^{11}_{\Lambda}\mathrm{B}) > 0$, exp. - 0.20 +/- 0.10

$A_1({}^{12}_{\Lambda}\mathrm{C}) > 0$, exp. - 0.01 +/- 0.10

stressed : importance of scalar-isoscalar
contact (short-ranged) interaction

2 σ -exchange

Sasaki et al. (2005)

DQ + π + K + σ -exch. → explain α_Λ (${}^{5}_{\Lambda}\mathrm{He}$)

Barbero et al. (2006)

octet-meson + σ -exch. → not succeed to explain α_Λ

Itonaga et al. π + 2π /σ + 2π /ρ + ω + K

→ cannot explain α_Λ

➔ still controversial on σ -exchange

3 2π -exchange (correlated & uncorrelated)

Chumillas et al. (2007) :

adopted $V_{2\pi}$ by Jido et al.(2000)

Chumillas et al. (2007)

octet-meson + correl.-2π (2π /σ) + uncorrel.-2π

→ well explain α_Λ of ${}^{5}_{\Lambda}\mathrm{He}$ & ${}^{12}_{\Lambda}\mathrm{C}$

Itonaga et al. π + 2π /σ + 2π /ρ + ω + K

→ cannot explain α_Λ

→ still controversial

4 axial vector a_1-exchange

a_1 : mass = 1230. MeV, $J^\pi = 1^+$

$a_1(1^+)$ ←→ $\rho(1^-)$, $\pi(0^-)$ ←→ $\sigma(0^+)$

- new approach (?) , chiral partner mesons exch.

→ compatible with available data of α_Λ

D. Problems (theory)

1 ● α_Λ expression differs by authors? (free $\Lambda + p \rightarrow n + p$)

W. A. Alberico, A.Ramos et al. (2005)

$$\alpha_\Lambda = \frac{2\sqrt{3}\,\mathrm{Re}\,[\,ae^* - b(c - \sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c + d)^*]}{|a|^2 + |b|^2 + 3\,[\,|c|^2 + |d|^2 + |e|^2 + |f|^2]}$$

Sasaki, Izaki and Oka (2005)

$$\alpha_\Lambda = \frac{2\sqrt{3}\,\mathrm{Re}\,[\,-ae^* - b(c - \sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c + d)^*]}{|a|^2 + |b|^2 + 3\,[\,|c|^2 + |d|^2 + |e|^2 + |f|^2]}$$

Itonaga et al.

$$\alpha_\Lambda = \frac{2\sqrt{3}\,\mathrm{Re}\,[\,-ae^* + b(c - \sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c + d)^*]}{|a|^2 + |b|^2 + 3\,[\,|c|^2 + |d|^2 + |e|^2 + |f|^2]}$$

What is the origin of the difference?

2 ● necessary to check the proposed mechanism (model) to explain α_Λ

- contact int.
- σ-exch. $2\pi/\sigma$, uncorrelated-2π
- a_1-exch.
- direct-quark

3 ● New and different approach, possible ?

- ??
- strange-meson $K_1(1400)$, $J = 1^+$?

  ← →$K_1 = (\pi K^*)$?

- role of $\Delta I = 3/2$?
- What else ?

4 ● nonmesonic decay of ${}_{\Lambda\Lambda}Z$ hypernuclei

5 J-PARC 実験に期待する

A. Mesonic Decay

1 $\Gamma_{\pi 0}$ measurement of hypernuclei

: $^{7}_{\Lambda}\mathbf{Li}$, $^{9}_{\Lambda}\mathbf{Be}$, $^{11}_{\Lambda}\mathbf{B}$, $^{12}_{\Lambda}\mathbf{C}$, $^{15}_{\Lambda}\mathbf{N}$, $^{27,28}_{\Lambda}\mathbf{Si}$, $^{56}_{\Lambda}\mathbf{Fe}$

* $\Gamma_{\pi -}$, measured at FINUDA & Sato et al.(2005)

* $\Gamma_{\pi 0}$ data of $^{12}_{\Lambda}\mathrm{C}$ → still large error-bar

* high quality data <-> more informations for pion behavior or U_{π}^{opt} inside the nucleus

* $$\left| < \phi^{\mathbf{N}}_{\mathbf{n}\ell\mathbf{j}} \left| \tilde{\mathbf{j}}^{\pi}_{\ell} \right| \varphi^{\Lambda}_{0\mathbf{s}} > \right|^{2}$$

2 $\Gamma_{\pi-}$,$\Gamma_{\pi0}$ measurement of neutron-rich Hyp-nucl.

: ${}^{9}_{\Lambda}\mathbf{He}$, ${}^{10}_{\Lambda}\mathbf{Li}$

- E-10 proposal (Sakaguchi)
- π^- (π^0) spectra may serve to determine the hypernuclear spin J^π

3 Measurement of decay asymmetry α_1^π of

: ${}^{9}_{\Lambda}\mathbf{Be}$, ${}^{13}_{\Lambda}\mathbf{C}$

- Theoretical prediction exists for some typical Hyp.
- weak decay mechanism and pion behaviors are rather well known

B. Nonmesonic Decay

1 Measurement of decay rates, Γ_{nm}, Γ_n/Γ_p , are desirable for p-shell and heavier Hy.

: ${}^{7}_{\Lambda}\mathbf{Li}$, ${}^{9}_{\Lambda}\mathbf{Be}$, ${}^{10}_{\Lambda}\mathbf{B}$, ${}^{13}_{\Lambda}\mathbf{C}$, ${}^{16}_{\Lambda}\mathbf{O}$, ${}^{89}_{\Lambda}\mathbf{Y}$, ${}^{209}_{\Lambda}\mathbf{Bi}$

* High quality data of n/p ratios exst only for ${}^{5}_{\Lambda}\mathbf{He}$ and ${}^{12}_{\Lambda}\mathbf{C}$

* mass-A dependence of Γ_{nm}, Γ_n/Γ_p are known → weak decay int. range will be deduced

* neutron-excess (N > Z) effect on decay rats are studied

2 More asymmetry parameter α_Λ measurements are desirable

: ${}^{7}_{\Lambda}\mathbf{Li}(1/2^{+})$, ${}^{13}_{\Lambda}\mathbf{C}(1/2^{+})$, ${}^{14}_{\Lambda}\mathbf{N}(1^{-})$

* $\alpha_\Lambda^{\mathrm{NM}}$'s have HY-mass (shell) dependence or not ??

$\alpha_\Lambda^{\mathrm{NM}}$ (${}^{5}_{\Lambda}\mathbf{He}$) and $\alpha_\Lambda^{\mathrm{NM}}$ (${}^{12}_{\Lambda}\mathbf{C}$) are sign different ?

* What is the decisive mechanisms for the small $\alpha_\Lambda^{\mathrm{NM}}$?

-- What type of the decay interactions ?

-- final-state interactions ?

-- effect of $\Delta I = 3/2$?

3 Measurement of A = 4 hypernuclei

: ${}^{4}_{\Lambda}\mathbf{H}$, ${}^{4}_{\Lambda}\mathbf{He}$

Test of Δ = 1/2 rule

$\Gamma_{nm}({}^{4}_{\Lambda}\mathbf{H})$ ~ 3Rn1 + Rn0 + 2Rp0

$\Gamma_{nm}({}^{4}_{\Lambda}\mathbf{He})$ ~ 2Rn0 + 3Rp1 + Rp0

$$\frac{\Gamma_{\mathbf{n}}({}^{4}_{\Lambda}\mathbf{He})}{\Gamma_{\mathbf{p}}({}^{4}_{\Lambda}\mathbf{H})} = \frac{\mathbf{R}_{\mathbf{n}0}}{\mathbf{R}_{\mathbf{p}0}} = 2 \quad (\text{if } \Delta I = 1/2)$$

4 Measurement of decay rate of double-Λ hypernuclei

* $\Lambda\Lambda \lozenge n\Lambda$, $p\Sigma^{-}$, $n\Sigma^{+}$

5 Hope to explore flavor nuclei including Λ_c