Hypernuclei (recent results from DAΦNE and CEBAF)

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EINN09 September 28-October 2 2009 Milos Island, Greece

Talk outline

- Hypernuclei: what do they are?

- Hypernuclei production/spectroscopy
  FINUDA @ DAΦNE & E94-107 @ JLAB-Hall A

- Hypernuclei weak decay:
  decay modes, FINUDA

- Neutron-rich hypernuclei

- Conclusions

Hypernuclei: what do they are?

- Hypernuclei: strange nuclear systems (S=-1,-2, …..)

  N (n, p, 2N) ➔ Y (Λ, Σ, Ξ)

  nuclei with a third dimension!

- S=-1 systems: Λ, Σ

  Λ hypernuclei: ~ 40 studied

  Σ hypernuclei: only $^{4}_{\Sigma}He$ exists (ΣN➔ΛN conversion)

- S=-2 systems: only 6 ΛΛ candidate events in emulsions

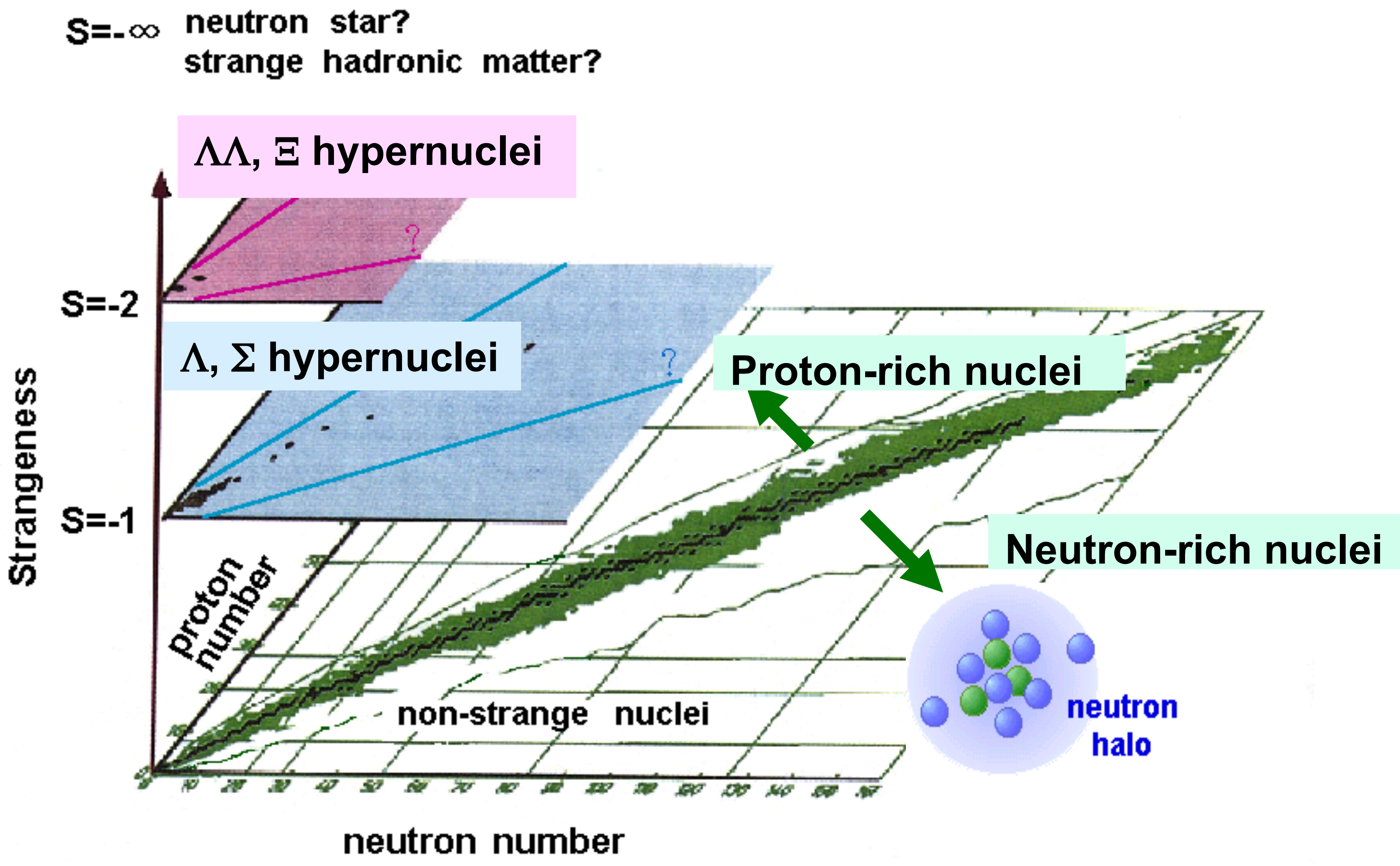
  $^{6}_{\Lambda\Lambda}He$, $^{10}_{\Lambda\Lambda}Be$, $^{11}_{\Lambda\Lambda}Be$, $^{12}_{\Lambda\Lambda}Be$, $^{13}_{\Lambda\Lambda}B$

  Ξ-hypernuclei not yet observed (ΣN➔ΛΛ conversion)

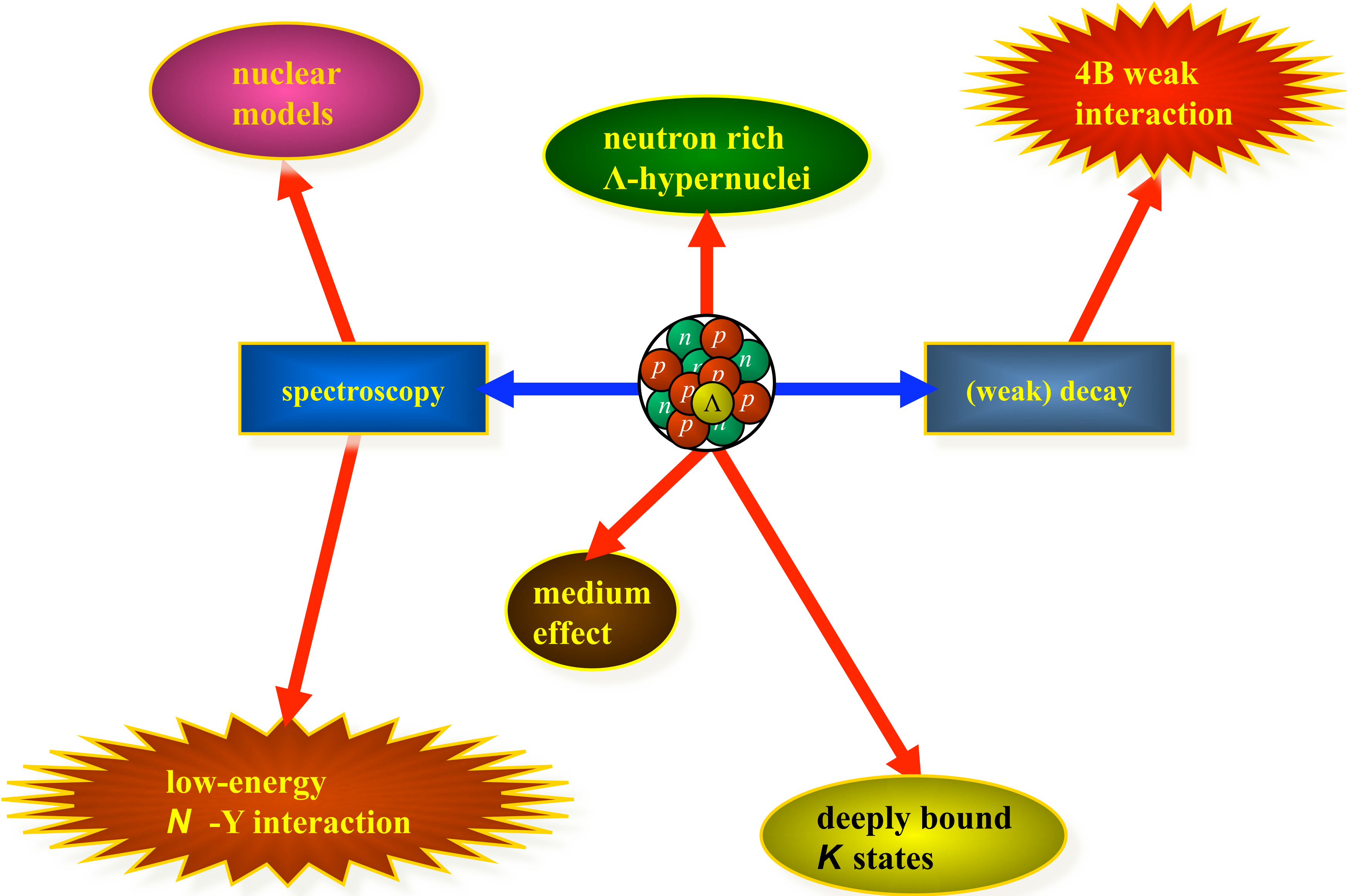
➔ Λ-hypernuclei

Duality: Nuclear ⟷ Particle Physics

Nuclei with a third dimension



Physics output (S=-1)



Why Strangeness Nuclear Physics ?

- Structure of baryons in nuclear medium and structure of nuclei as baryonic many-body systems can be better studied by introducing a strangeness degree of freedom into a nucleus

- Λ can be put deep inside a nucleus as an impurity and provides a sensitive probe of the nuclear interior

- A Λ doesn't suffer from Pauli blocking by the other N $\rightarrow$ it can penetrate into the nuclear interior and form deeply bound hypernuclear states

- In non strange nuclei the single particle strength is broadly fragmented with excitation energy and a deeply bound hole-state is so fragmented to be essentially unobservable

- In a hypernucleus the distinguishable Λ may occupy any orbital leading to well defined, sharp set of states

- Only practical way to study ΛN strong and weak interaction

Λ Hypernuclei production reactions

1) Strangeness Exchange (DAΦNE, BNL-AGS)

$$K^- + N \to \Lambda + \pi \qquad\qquad K^- + {}^{A}Z \to \pi^- + {}^{A}_{\Lambda}Z$$

2) Associated Production (BNL-AGS, KEK-12 GeV PS)

$$\pi^+ + n \to \Lambda + K^+ \qquad\qquad \pi^+ + {}^{A}Z \to K^+ + {}^{A}_{\Lambda}Z$$

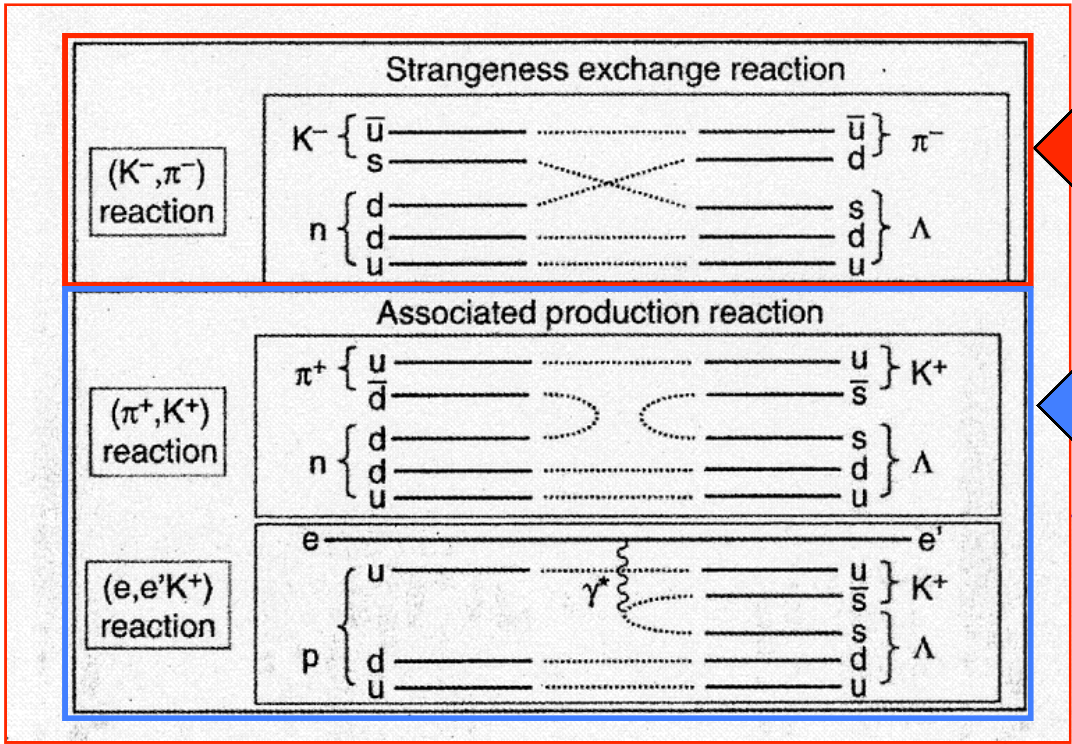
3) Electroproduction (JLAB)

$$\gamma\,(e) + p \to \Lambda + (e') + K^+ \qquad e + {}^{A}Z \to K^+ + {}^{A}_{\Lambda}Z + e'$$

4) Heavy ions collisions, antiproton annihilation

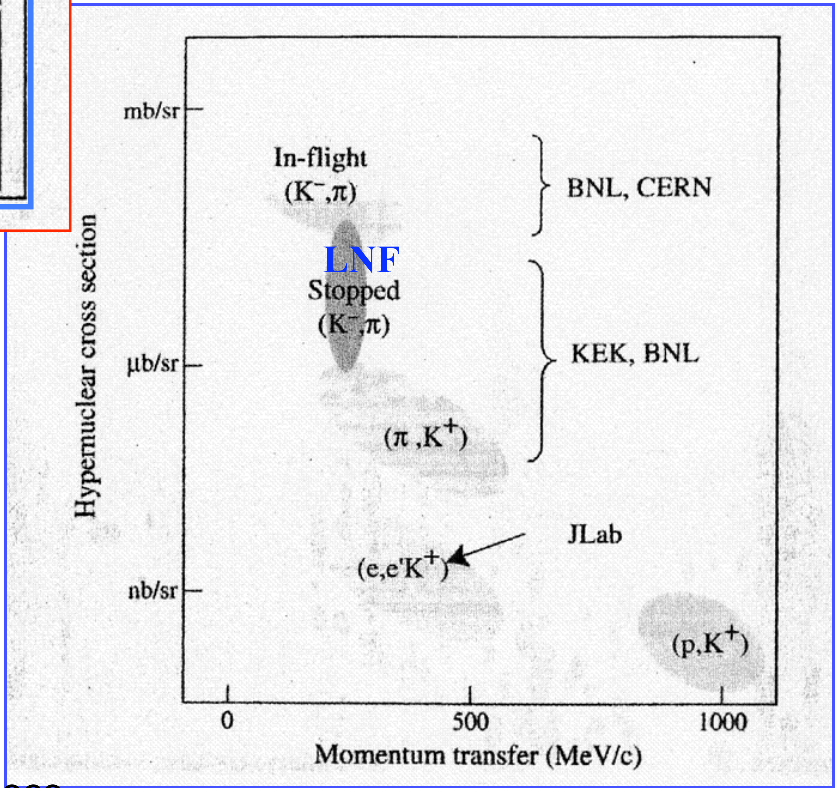
> 90% of the present information on Hypernuclear Physics comes from processes 1) and 2); 3) from ~2000

Λ Hypernuclei production reactions



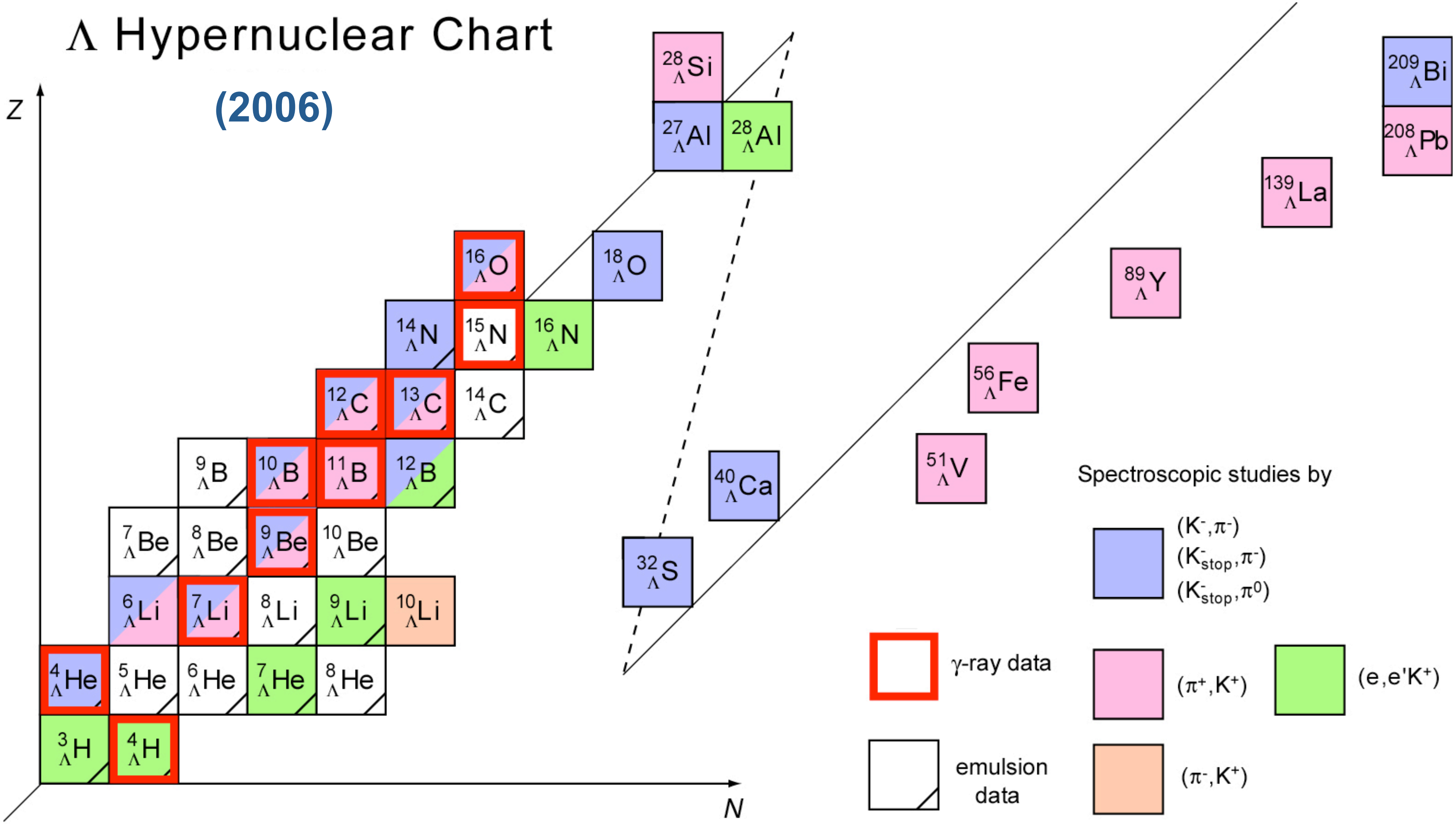
Substitutional states
N→Λ, ΔL=0

Large momentum transfer
population of excited
spin stretched states



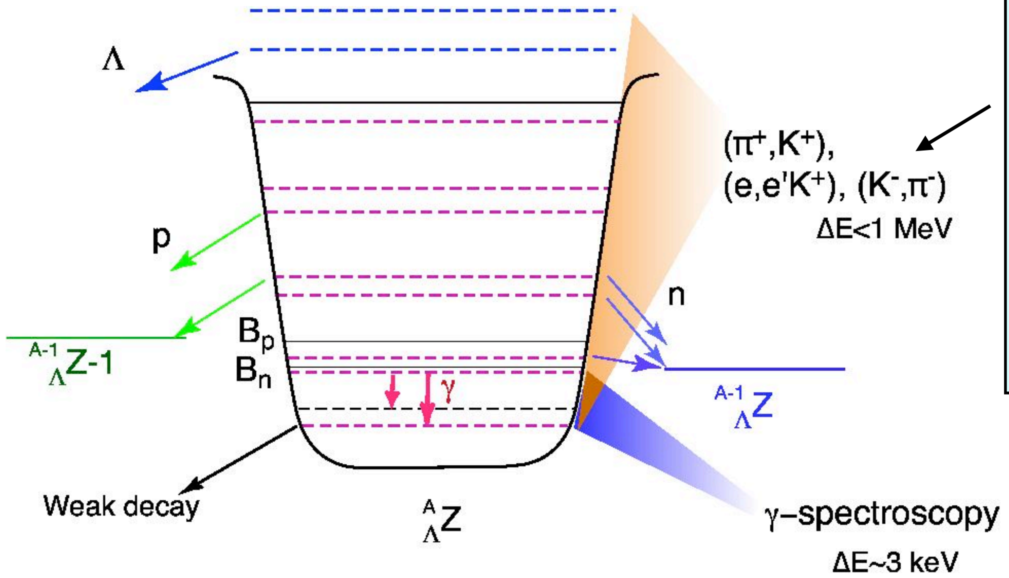
Momentum transfer controls population of hypernuclear states: larger Δp→ smaller σ

Present Status of
Λ Hypernuclear Spectroscopy



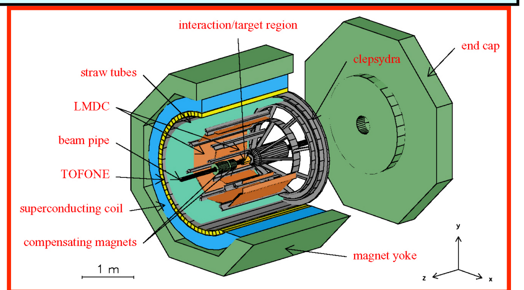
Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564

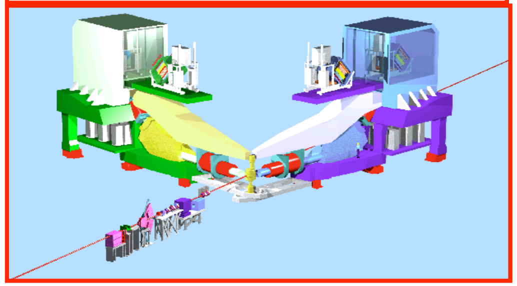
Hypernuclear spectroscopy



reaction spectroscopy (MM):

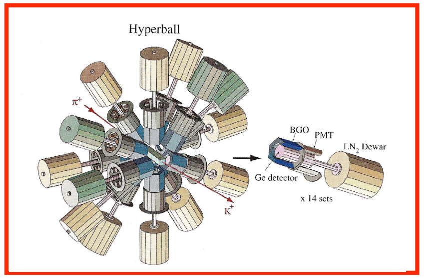
- level structure in Λ bound region
- excited states between N and Λ emission threshold
- information on Λ-hyp. structure through M_{hyp}, σ, angular distributions, …





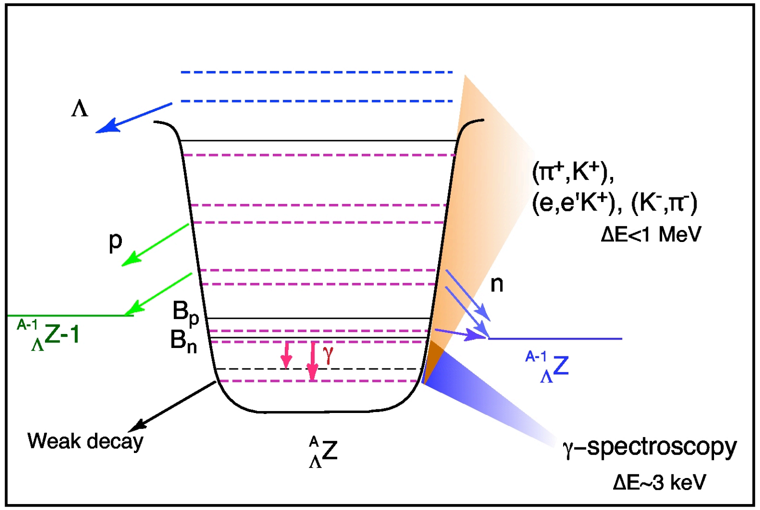
γ-spectroscopy:

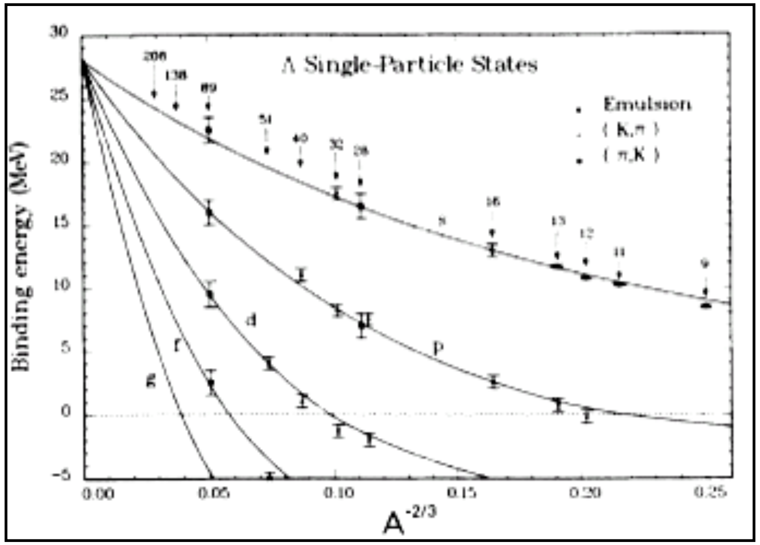
- low lying states only (s_Λ for p-shell)
- ultra-high resolution
- spin-dependent ΛN interaction



Highly complementary tools !!

Hypernuclear spectroscopy



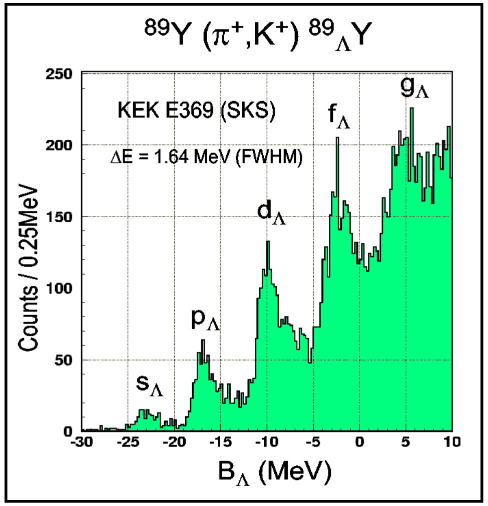


Binding energy proportional to A, 1 MeV/A

Purpose: to understand B-B interactions

- NN interaction known from elastic scattering data, well reproduced by phenomenological meson exchange and quark-cluster models
- YN, YY interaction poorly known, few scattering data, low yields, short lifetime

In Λ hypernuclei:



- no Pauli effect
- straightforward extraction of ΛN interaction
- Peak position well reproduced by simple Woods-Saxon potential

Hypernuclear spectroscopy

- hypernuclear wave function decomposed into a core nucleus and a Λ hyperon:

$$H = H_{core} + t_{\Lambda} + \Sigma V_{\Lambda N}^{eff}$$

- $V_{\Lambda N}^{eff}$ constructed from the two-body interaction in free space, $V_{\Lambda N}^{free}$
- s-shell hypernuclei (A≤5): $V_{\Lambda N}^{eff}$ calculated directly from $V_{\Lambda N}^{free}$, B of g.s. and excited states compared with experimental data
- p-shell hypernuclei (6≤A≤16): direct calculation not sufficient to describe the data → phenomenological (shell model) approach to the effective interaction

$$\underbrace{}_{}V_{\Lambda-N}(r) = V_0(r) + \overbrace{V_\sigma(r)\vec{s}_N\cdot\vec{s}_\Lambda}^{\Delta} + \overbrace{V_\Lambda(r)\vec{l}_{N\Lambda}\cdot\vec{s}_\Lambda}^{S_\Lambda} + \overbrace{V_N(r)\vec{l}_{N\Lambda}\cdot\vec{s}_N}^{S_N}$$
$$+ \underbrace{V_T(r)[3(\vec{\sigma}_N\cdot\vec{r})(\vec{\sigma}_\Lambda\cdot\vec{r} - \vec{\sigma}_N\cdot\vec{\sigma}_\Lambda)]}_{T}$$

Δ, S_Λ, T from s_Λ coupled to non-zero spin core states

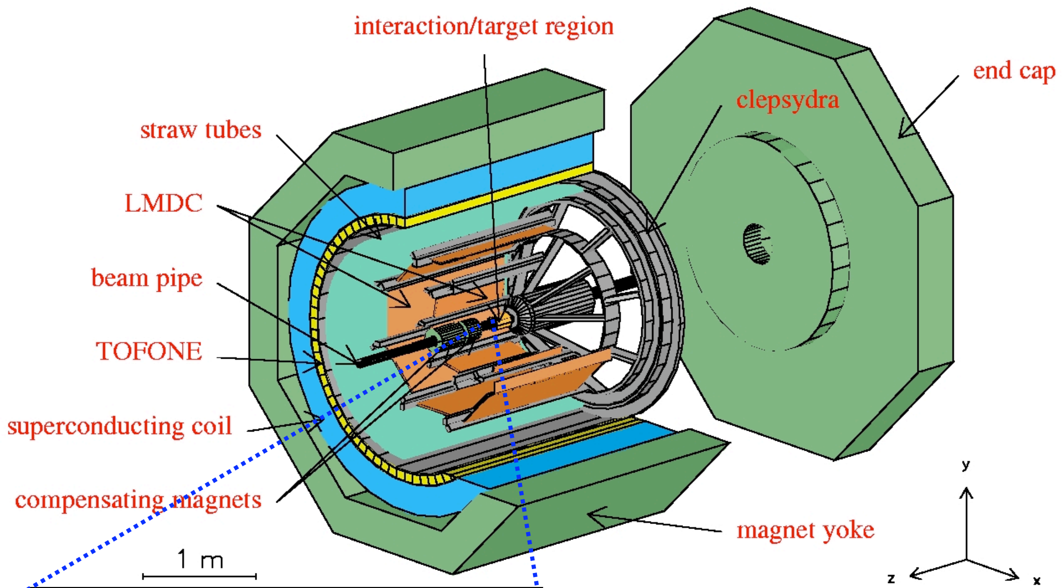
- need of high resolution spectroscopy

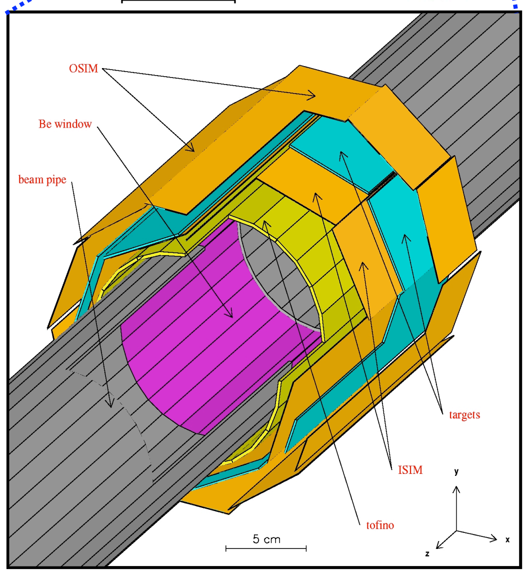
Each of the 4 terms (Δ, S_Λ, S_N, T) correspond to a radial integral that can be phenomelogically determined from the low-lying level structure of *p*-shell hypernuclei

FINUDA @ DAΦNE

$e^{+} + e^{-} \rightarrow \phi\,(1020) \rightarrow K^{+} + K^{-}$ (127 MeV/c) ~ 49.1%

$K^{-}_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^{-}$ (~ 270 MeV/c)





B=1T

- ✓ K^{-}: low energy, monochromatic (Γ_{ϕ}= 4.43 MeV), tagged, background free
- ✓ very thin nuclear targets (0.1 ÷ 0.3 g/cm^2)
- ✓ irradiation of different targets in the same run
- ✓ $\Delta\Omega$ ~ 2π srad
- ✓ PID: dE/dx vs p & TOF

$M_{hyp} = [(m_K + M_A - E_{\pi-})^2 - p_{\pi-}^{2}]^{1/2}$

$B_{\Lambda} = M_{A-1n} + M_{\Lambda} - M_{hyp}$

MM spectroscopy

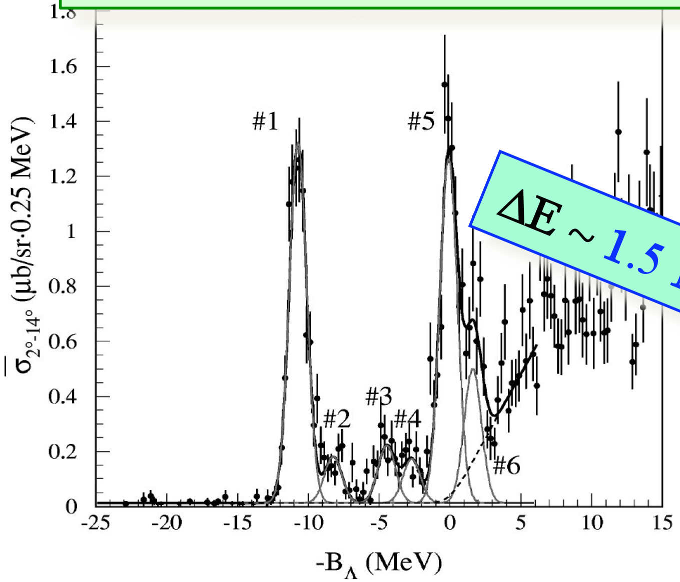
2003 data taking: 190 pb^{-1} (2x^{6}Li, ^{7}Li, 3x^{12}C, ^{27}Al, ^{51}V)

2006 data taking: 966 pb^{-1} (2x^{6}Li, 2x^{7}Li, 2x^{9}Be, ^{13}C, D_2O)

$^{12}_{\Lambda}$C: best known hypernucleus

Best KEK results

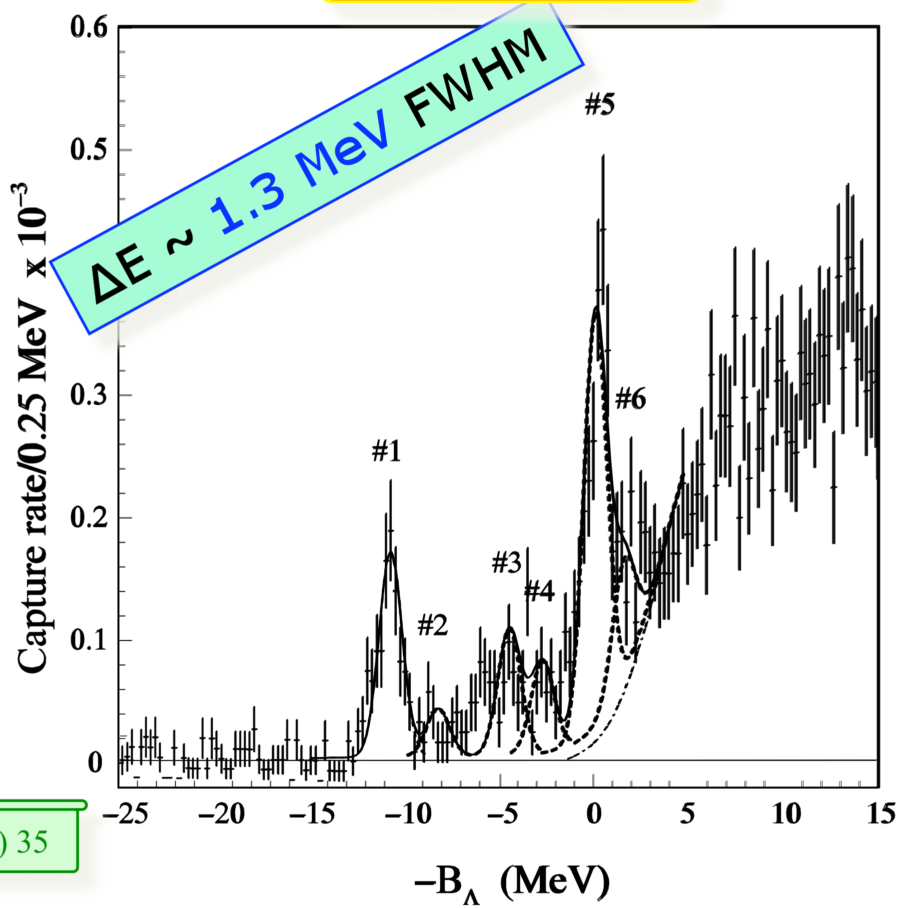
H. Hotchi *et al.*, Phys. Rev. C 64 (2001) 044302



$^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$

FINUDA results

$^{12}C(K^-_{stop},\pi^-)^{12}_{\Lambda}C$

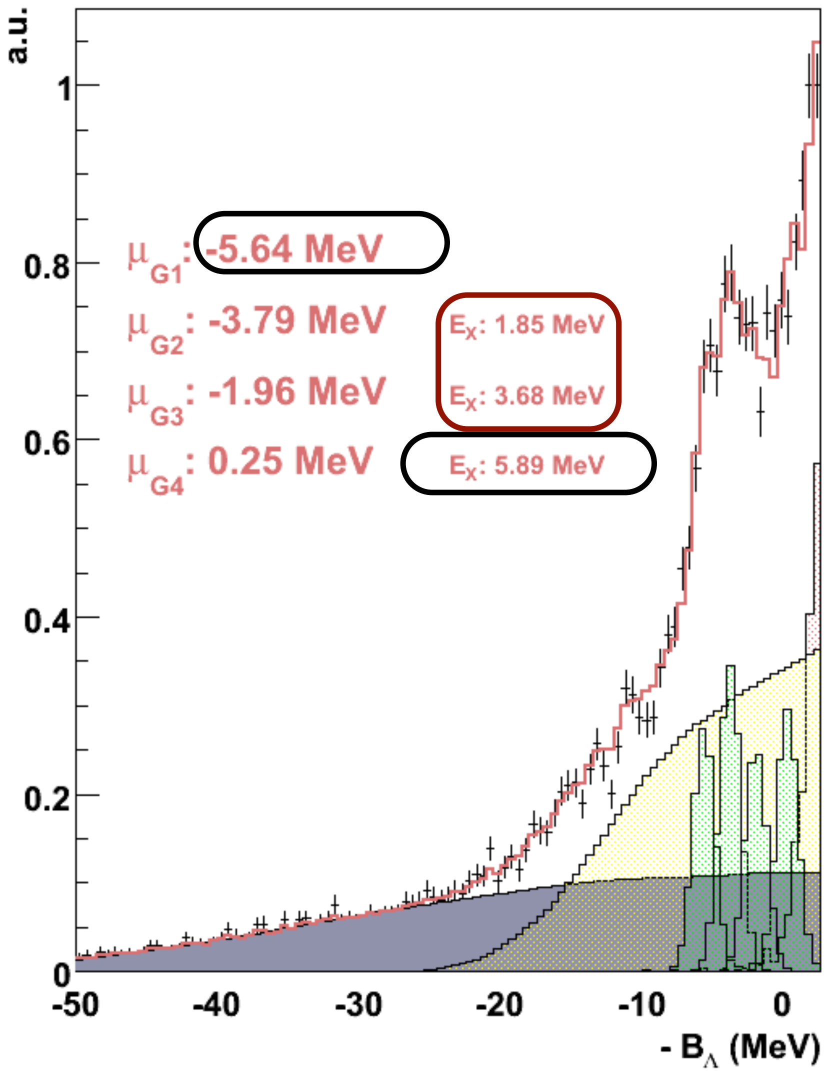


M. Agnello *et al.*, Phys. Lett. B 622 (2005) 35

Peak number	$-B_{\Lambda}$ (MeV) (Fixed at E369 values)	Capture rate/(stopped K^-)[$\times 10^{-3}$]
1	−10.76	$1.01 \pm 0.11_{stat} \pm 0.10_{syst}$
2	−8.25	0.23 ± 0.05
3	−4.46	0.62 ± 0.08
4	−2.70	0.45 ± 0.07
5	−0.10	2.01 ± 0.14
6	1.61	0.57 ± 0.11

$^{7}_{\Lambda}$Li hypernucleus

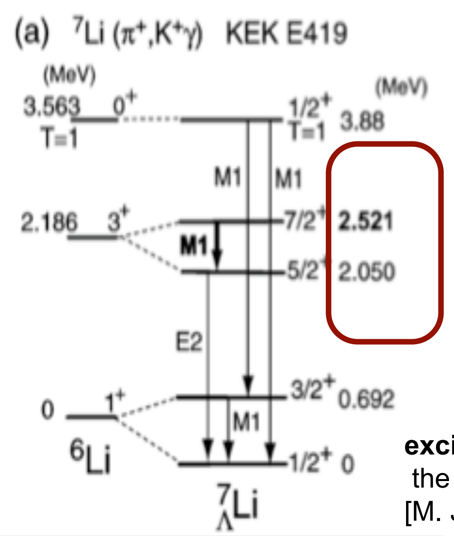
FWHM: 1.65 to 1.95 MeV



	$-B_\Lambda \pm stat. \pm syst.$ (MeV)	Yield (events)	Production rate (per K^- stop)
1	$-5.33 \pm 0.13 \pm 0.18$	52 ± 11	$0.47 \pm 0.12 \pm 0.11‰$
2	$-3.68 \pm 0.15 \pm 0.18$	44 ± 10	$0.39 \pm 0.11 \pm 0.11‰$

Proc. HYP2006, p.57

Peaks	B_Λ or E_X (MeV)	FWHM (MeV)
# 1	$B_\Lambda = 5.22 \pm 0.08$	1.81 (fixed)
# 2	$E_X = 2.05$ (fixed)	1.81 (fixed)
# 3	$E_X = 3.88$ (fixed)	1.81 (fixed)
# 4	$E_X = 5.61 \pm 0.24$	1.81 (fixed)
# 5	$E_X = 7.99 \pm 0.37$	3.81 ± 0.81



H. Tamura et al.
Nucl. Phys. A **754** (2005) 58c

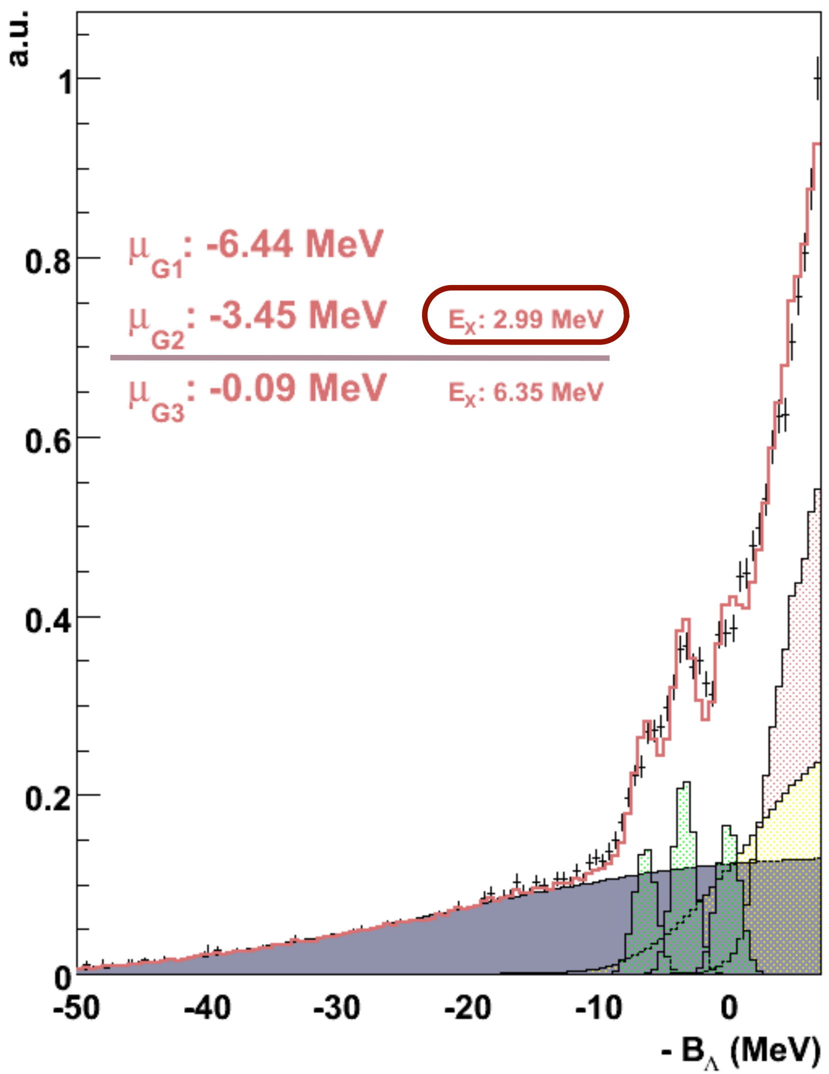
excitation energies are referred to the ground state **B_Λ = -5.58 ± 0.03 MeV**
[M. Juric et al. Nucl. Phys. B **52** (1973) 1]

O. Hashimoto, H. Tamura, Pr.Part.Nucl.Phys. 57 (2006) 564

capture Rate per stopped K^-
#1: 0.041 ± 0.006 ± 0.005 %
#2: 0.058 ± 0.008 ± 0.006 %
#3: 0.043 ± 0.006 ± 0.005 %
~~#4: 0.052 ± 0.007 ± 0.006~~ %

$^{9}_{\Lambda}$Be hypernucleus

B_Λ = -6.61 ± 0.04 MeV
M. Juric et al. Nucl. Phys. B **52** (1973) 1



588 O. Hashimoto, H. Tamura / Progress in Particle and Nuclear Physics 57 (2006) 564–653

Table 8
Excitation energies and cross sections of $^{9}_{\Lambda}$Be in the (π^+, K^+) reaction measured in the KEK E336 experiment

Peaks	B_Λ or E_X (MeV)	FWHM (MeV)	Cross sections $\sigma_{2^\circ-14^\circ}$ (μb)
# 1	$B_\Lambda = 5.99 \pm 0.07$	1.99 (fixed)	0.181 ± 0.009
# 2	$E_X = 2.93 \pm 0.07$	1.99 (fixed)	0.340 ± 0.012
# 3	$E_X = 5.80 \pm 0.13$	1.99 (fixed)	0.141 ± 0.009
# 4	$E_X = 9.52 \pm 0.13$	1.99 (fixed)	0.198 ± 0.013
# 5	$E_X = 14.88 \pm 0.10$	1.99 (fixed)	0.412 ± 0.024
# 6	$E_X = 17.13 \pm 0.20$	1.99 (fixed)	0.238 ± 0.022
# 7	$E_X = 19.54 \pm 0.32$	1.99 (fixed)	0.143 ± 0.021
# 8	$E_X = 23.40 \pm 0.21$	1.99 (fixed)	0.220 ± 0.027

capture Rate per stopped K^-

#1: 0.022 ± 0.006 ± 0.002 %
#2: 0.036 ± 0.008 ± 0.004 %
#3: ~~0.027 ± 0.006 ± 0.003~~ %

$^{13}_{\Lambda}C$ hypernucleus

B_{Λ} = -11.22 ± 0.08 MeV

M. Juric et al. Nucl. Phys. B **52** (1973) 1

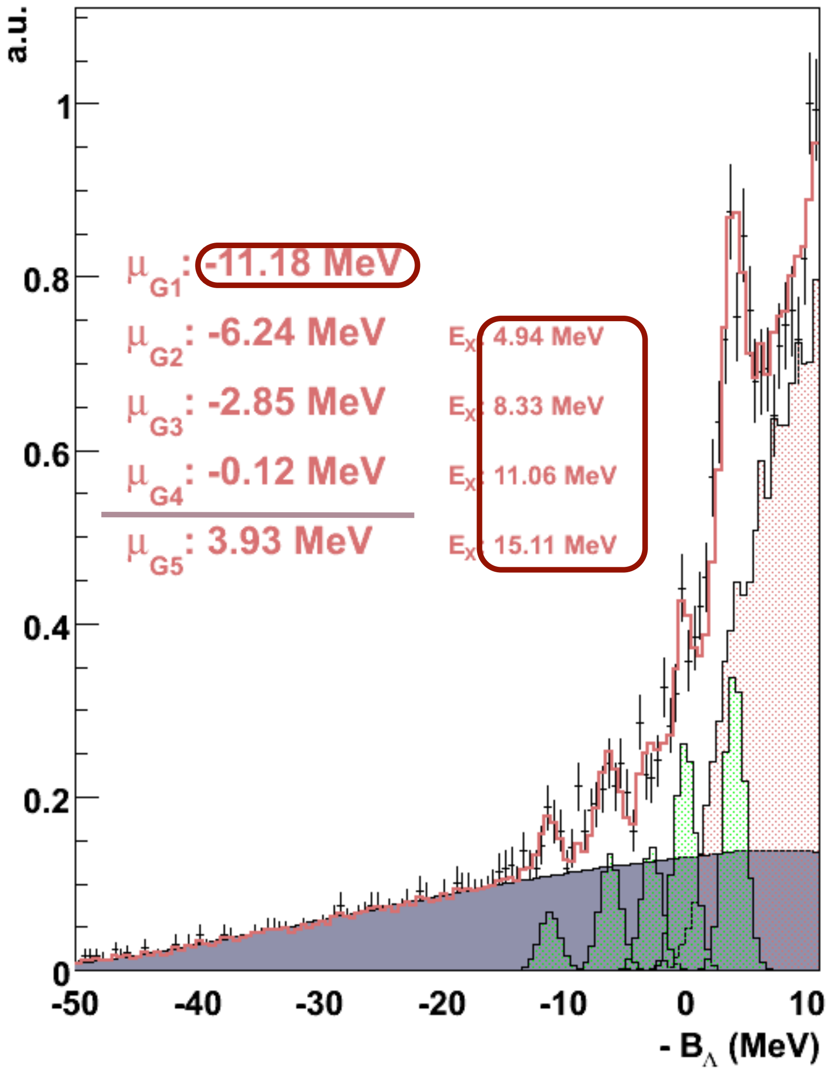


Table 10

Excitation energies and cross sections of $^{13}_{\Lambda}C$ states as populated by the (π^+, K^+) reaction

Peaks	B_{Λ} or E_X (MeV)	FWHM (MeV)	Cross sections $\sigma_{2°-14°}$ (μb)
# 1	$B_{\Lambda} = 11.38 \pm 0.05$	2.23 ± 0.06	0.25 ± 0.02
# 2	$E_X = 4.85 \pm 0.07$	2.23 ± 0.06	0.42 ± 0.02
# 3	$E_X = 9.73 \pm 0.14$	2.23 ± 0.06	0.22 ± 0.02
# 4	$E_X = 11.75 \pm 0.15$	2.23 ± 0.06	0.30 ± 0.02
# 5	$E_X = 15.31 \pm 0.06$	2.46 ± 0.08	1.29 ± 0.04
# 6	$E_X = 23.68 \pm 0.16$	2.20 ± 0.29	0.33 ± 0.04
# 7	$E_X = 26.37 \pm 0.11$	2.41 ± 0.17	0.76 ± 0.06

O. Hashimoto, H. Tamura, Pr.Part.Nucl.Phys. 57 (2006) 564

capture Rate per stopped K-

#1: 0.006 ± 0.001 ± 0.001 %

#2: 0.014 ± 0.002 ± 0.002 %

#3: 0.018 ± 0.002 ± 0.002 %

#4: 0.024 ± 0.003 ± 0.003 %

~~#5: 0.035 ± 0.005 ± 0.004~~ %

$^{16}{}_{\Lambda}O/^{15}{}_{\Lambda}N$ hypernuclei

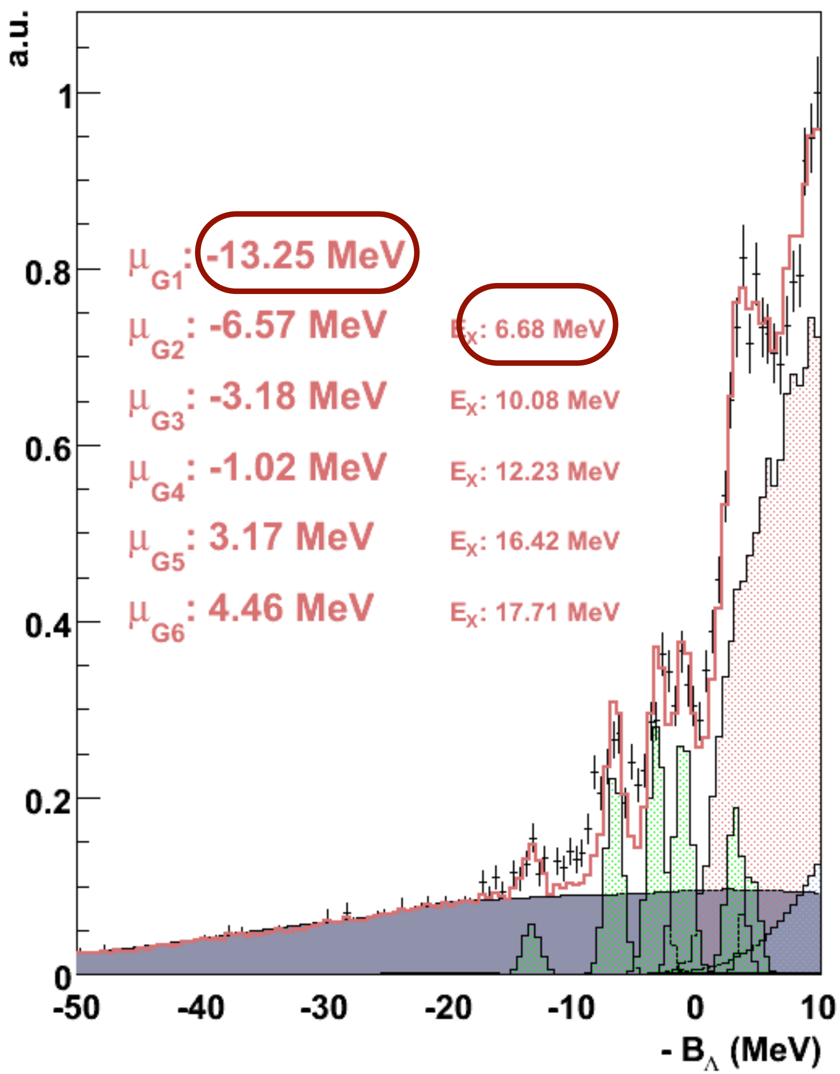


Table 11
Excitation energies and cross sections of $^{16}_{\Lambda}O$ in the (π^+, K^+) reaction

Peaks	B_Λ or E_X (MeV)	FWHM (MeV)	Cross sections $\sigma_{2°-14°}$ (μb)
# 1	$B_\Lambda = 12.42 \pm 0.05$	2.75 ± 0.05	0.41 ± 0.02
# 2	$E_X = 6.23 \pm 0.06$	2.75 ± 0.05	0.91 ± 0.03
# 3	$E_X = 10.57 \pm 0.06$	2.75 ± 0.05	1.05 ± 0.03
# 4	$E_X = 16.59 \pm 0.07$	3.13 ± 0.11	1.38 ± 0.06

O. Hashimoto, H. Tamura, Pr.Part.Nucl.Phys. 57 (2006) 564

Progress of Theoretical Physics Supplement No. 117, 1994

Study of Λ-Hypernuclei with Stopped K^- Reaction

Hirokazu TAMURA, Ryugo S. HAYANO, Haruhiko OUTA* and Toshimitsu YAMAZAKI*

	Hypernuclear states peak	state	B_Λ(MeV)	Formation Probability per stopped K^-(%)	per $\Lambda\pi^-$(%)
$^{16}_{\Lambda}O$	A	$(p_{1/2})_n^{-1}(s_{1/2})_\Lambda$	12.9±0.4	0.013±0.004	0.37±0.13
	B	$(p_{3/2})_n^{-1}(s_{1/2})_\Lambda$	6.53±0.18	0.030±0.005	0.86±0.30
	C	$(p_{1/2})_n^{-1}(p_{1/2,3/2})_\Lambda$	2.08±0.18	0.056±0.008	2.0±0.7
	D	$(p_{3/2})_n^{-1}(p_{1/2,3/2})_\Lambda$	−4.23±0.09	0.112±0.014	3.2±1.1

capture Rate per stopped K-

#1: 0.004 ± 0.002 ± 0.001 %

#2: 0.021 ± 0.004 ± 0.002 %

#3+4: 0.060 ± 0.014 ± 0.008 %

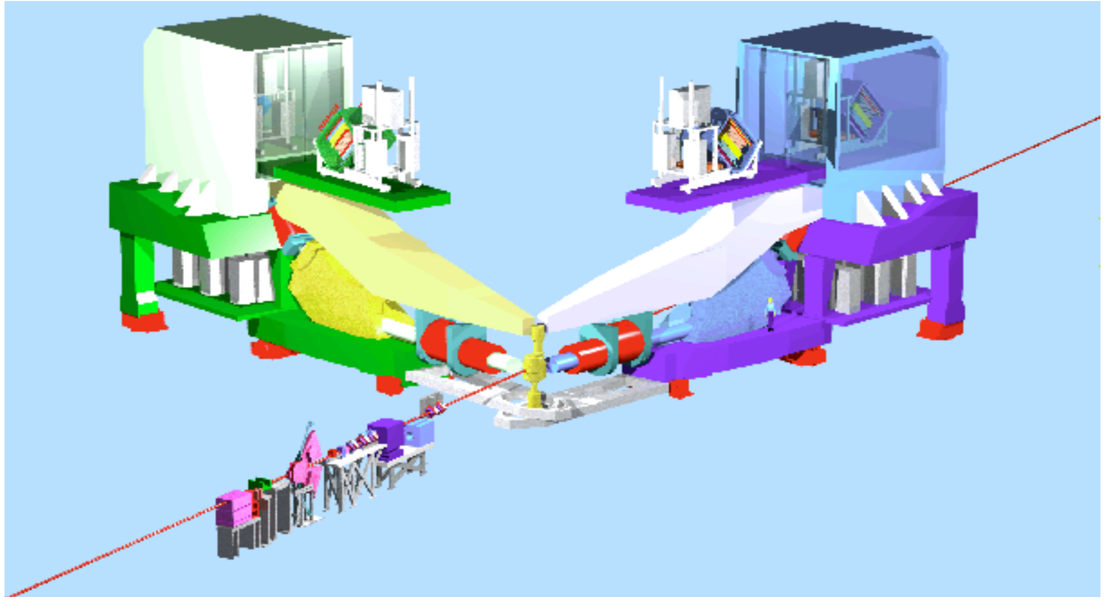
#5+6: 0.059 ± 0.013 ± 0.007 %

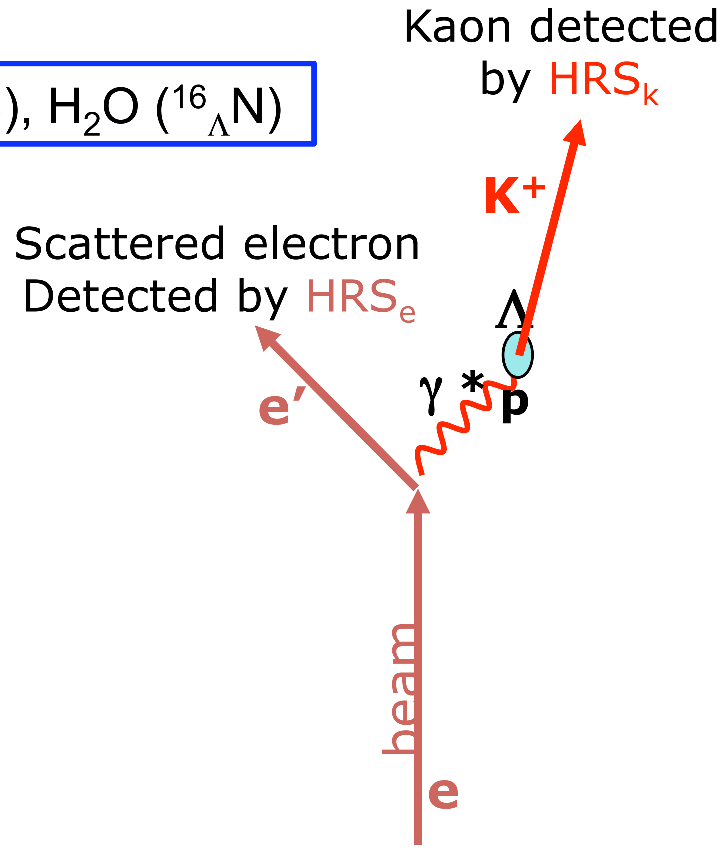
E94-107 JLAB Hall A @ CEBAF

$e + p \rightarrow e' + K^+ + \Lambda$

$e + {}^{A}Z \rightarrow e' + K^+ + {}^{A}_{\Lambda}(Z-1)$

Targets: ${}^{12}C$ (${}^{12}_{\Lambda}B$), H_2O (${}^{16}_{\Lambda}N$)





to maximize the cross section:

E_{beam} = 3.77 (3.66) GeV

P_k= 1.96 GeV/c

P_e= 1.56 (1.45) GeV/c

$\theta_e = \theta_K = 6°$

$\omega = E_\gamma \sim 2.2$ GeV – $Q^2 = 0.079$ (GeV/c)^2

target thickness : 100 (75) mg/cm^2

Hadron & electron HRS:

Momentum range: 0.3-4 GeV/c

$\Delta P/P = 1\ 10^{-4}$

$\Delta\Omega$ 5-6 msr

Septum magnets (min. angle 12.5°)

PID K+: Cherenkov (2 aerogel thershold**+**

C_6F_{14}/CsI proximity focusing RICH)

PID e: gas Cherenkov

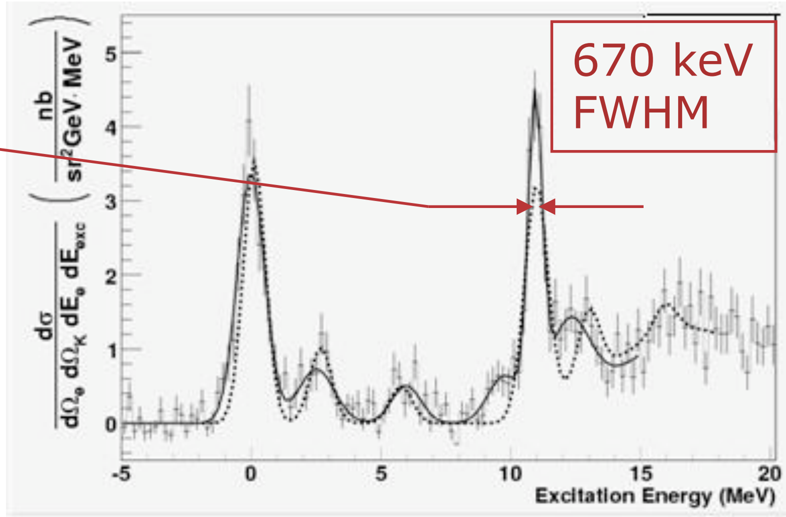
Results on ^{12}C target – Hypernuclear Spectrum of $^{12}B_{\Lambda}$

Position (MeV)	Width (FWHM, MeV)	SNR	Cross section ($nb/sr^2/GeV$)
	Experimental data		
0.0 ± 0.03	1.15 ± 0.18	19.7	$4.48 \pm 0.29(stat) \pm 0.63(syst)$
2.65 ± 0.10	0.95 ± 0.43	7.0	$0.75 \pm 0.16(stat) \pm 0.15(syst)$
5.92 ± 0.13	1.13 ± 0.29	5.3	$0.45 \pm 0.13(stat) \pm 0.09(syst)$
9.54 ± 0.16	0.93 ± 0.46	4.4	$0.63 \pm 0.20(stat) \pm 0.13(syst)$
10.93 ± 0.03	0.67 ± 0.15	20.0	$3.42 \pm 0.50(stat) \pm 0.55(syst)$
12.36 ± 0.13	1.58 ± 0.29	7.3	$1.19 \pm 0.36(stat) \pm 0.35(syst)$

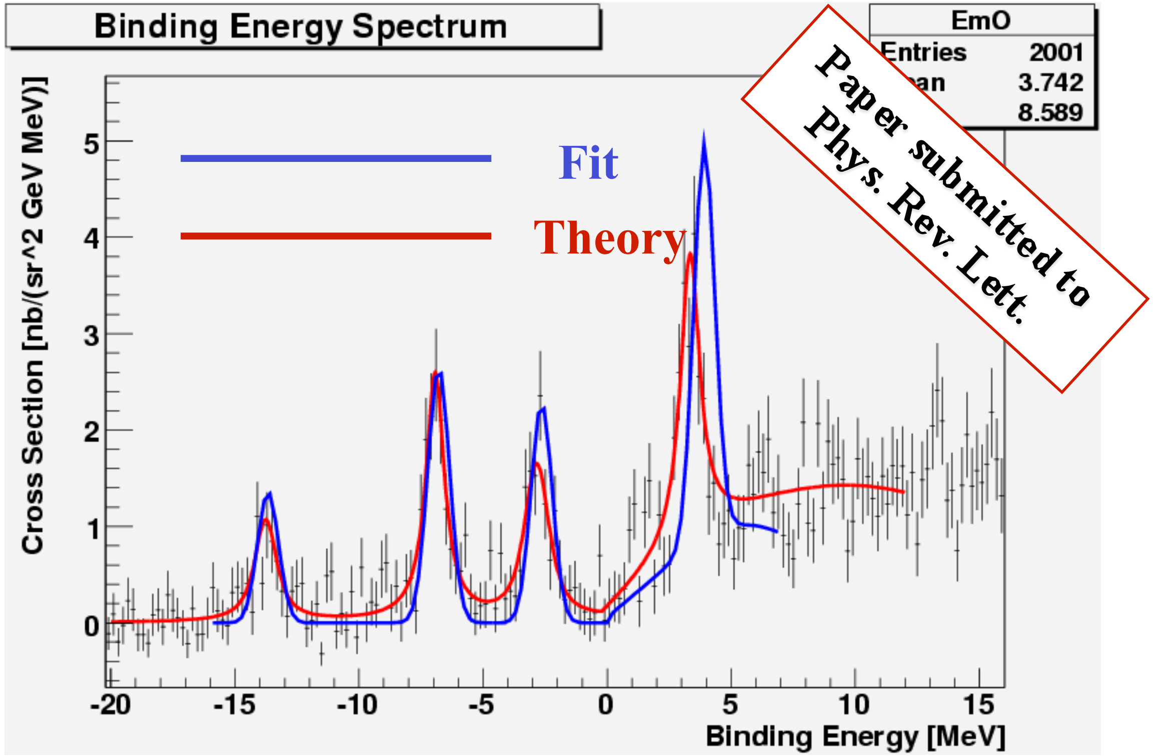
M.Iodice et al., Phys. Rev. Lett. 99 (2007) 052501

Narrowest peak is doublet at 10.93 MeV
⇒ experiment resolution < 700 keV

Precise detection of core-excited states, strong indication of a mixture state



Results on ^{16}O target – Hypernuclear Spectrum of $^{16}N_{\Lambda}$



E_x (MeV)	Width (FWHM, MeV)	Cross section ($nb/sr^2/GeV$)
0.00 / 13.76 ±0.16	1.71 ± 0.70	1.45 ± 0.26
6.83 ± 0.06	0.88 ± 0.31	3.16 ± 0.35
10.92 ± 0.07	0.99 ± 0.29	2.11 ± 0.37
17.10 ± 0.07	1.00 ± 0.23	3.44 ± 0.52

Measured for the first time with this level of accuracy!

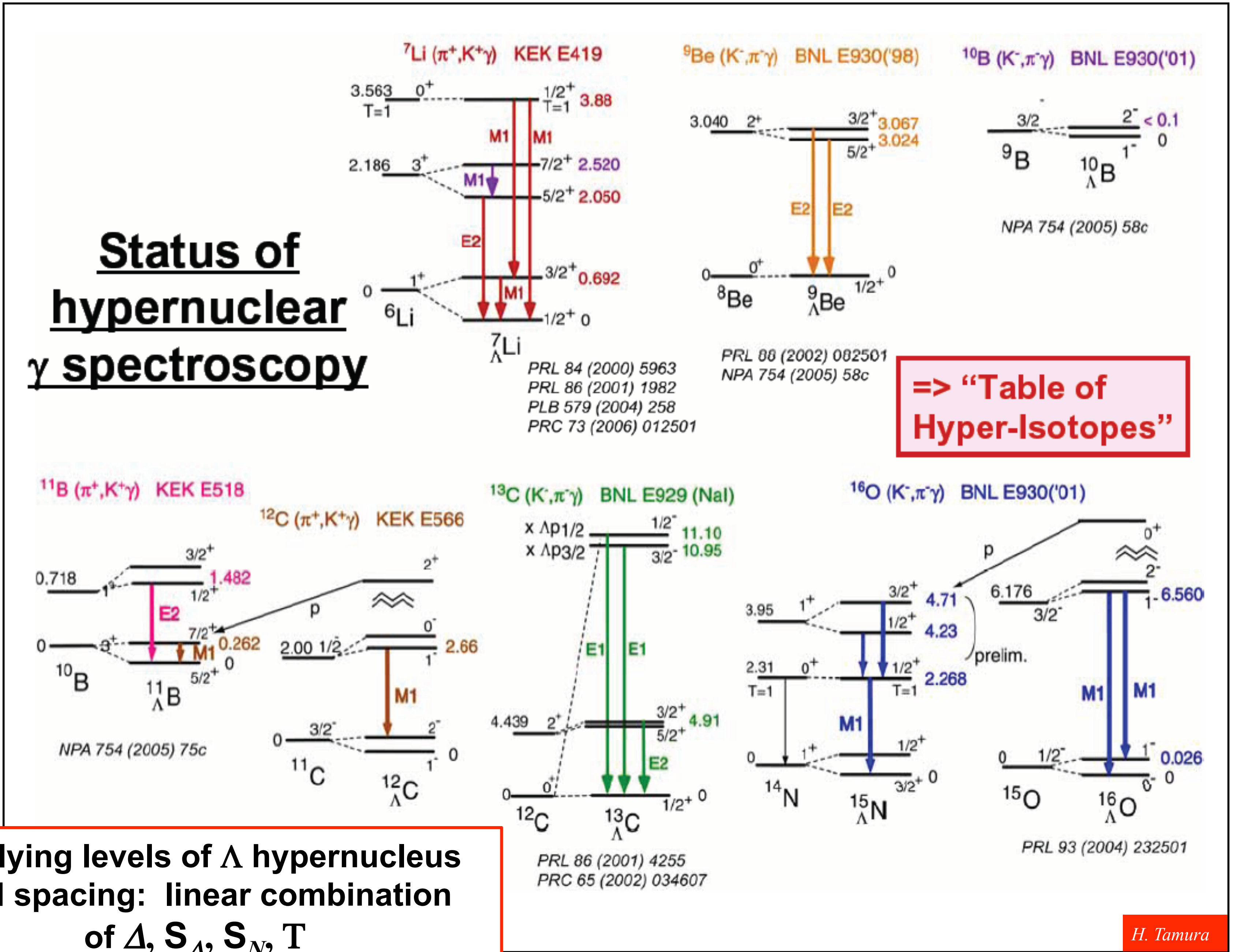
- ✓ Theoretical model (blu line) based on :
  - i) SLA p(e,e'K+)Λ (elementary process)
  - ii) ΛN interaction fixed parameters from KEK and BNL $^{16}{}_{\Lambda}O$ spectra (J. Millener)

Mirror hypernucleus: $^{16}{}_{\Lambda}N$ – $^{16}{}_{\Lambda}O$

	$(e,e'K^{+})$ This expt.	(π^{+},K^{+}) KEK	(K^{-},π^{-}) CERN	(K^{-}_{stop},π^{-}) KEK
$B_{\Lambda}(\#1)$	13.76(16)	12.42(5)	13.28(36)	13.40(40)
$E_x(\#2)$	6.83	6.23	5.96	6.39
$E_x(\#3)$	10.92	10.57	10.62	10.84
$E_x(\#4)$	17.10	16.59	17.15	17.15

F. Cusanno, Hyp-X Conference

Hyperball @ KEK & BNL (from 1998)



Status of hypernuclear γ spectroscopy

=> "Table of Hyper-Isotopes"

Low-lying levels of Λ hypernucleus
Level spacing: linear combination of Δ, S_Λ, S_N, T

Weak decay of hypernuclei

- Λ free weak decay:
  - $\Lambda \rightarrow p\pi^-$ B.R. 63.9%
  - $\Lambda \rightarrow n\pi^0$ B.R. 35.8%

  N momentum ~ 100 MeV/c
- $\Delta I = \frac{1}{2}$ rule holds for weak decays involving strange quarks
  - Phenomenological rule

- Hypernucleus decay:
  - E* $\rightarrow$ E*' (γ, N, α, …) (standard Nuclear Physics)

    $\rightarrow$ g.s. (γ, N, α, …)
  - Constituent Λ weak decay, from g.s.

- The Λ mesonic decay (ΓM) is suppressed in nuclear matter due to the Pauli blocking of the nucleon in the final state
  - Non mesonic decays in hypernuclei: <u>4 body interactions</u> (medium effect!!)
    - $\Lambda p \rightarrow pn$ branching ratio: Γp
    - $\Lambda n \rightarrow nn$ branching ratio: Γn
    - $\Lambda NN \rightarrow NNN$ branching ratio: Γ2

      $\Gamma tot = \Gamma M + \Gamma p + \Gamma n + \Gamma 2$
    - ${}^{A}_{\Lambda}Z \rightarrow {}^{(A-2)}(Z-1) + n + p$
    - ${}^{A}_{\Lambda}Z \rightarrow {}^{(A-2)}Z + n + n$
    - ${}^{A}_{\Lambda}Z \rightarrow {}^{(A-3)}(Z-1) + n + n + p$

    N momentum ~ 400 MeV/c
  - $\Gamma p/\Gamma n$ ratio measurements to assess the validity of the $\Delta I = \frac{1}{2}$ rule (non π case)
  - $\Gamma p/\Gamma n$ puzzle: "solved" with Γ2 and coincidence measurements

Hypernuclear decay

FINUDA Strategy: coincidence measurement

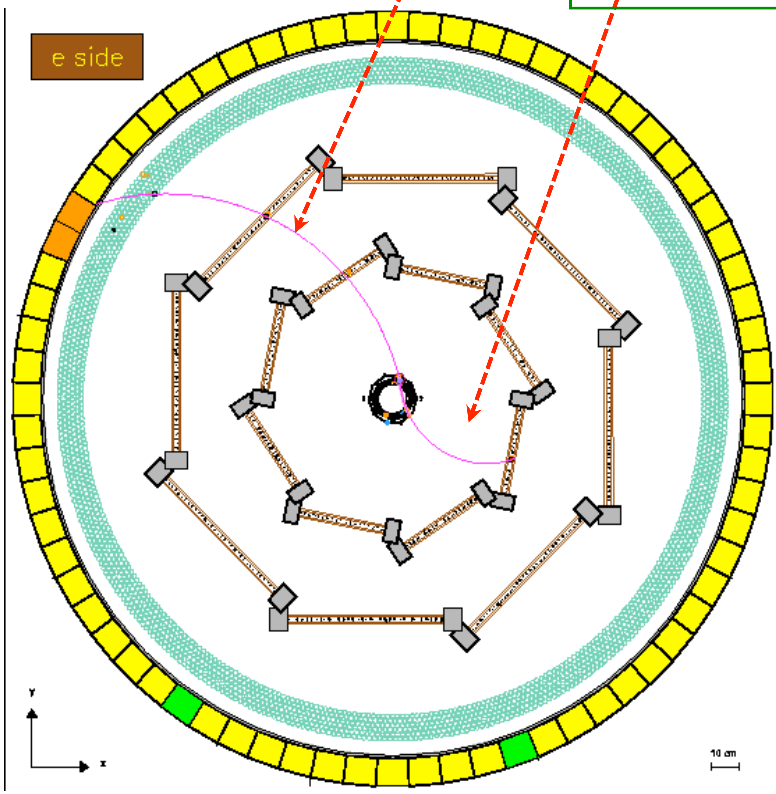
charged Mesonic channel

$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$

${}^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \pi^-$

S-EX
260-280 MeV/c

MWD
80-110 MeV/c

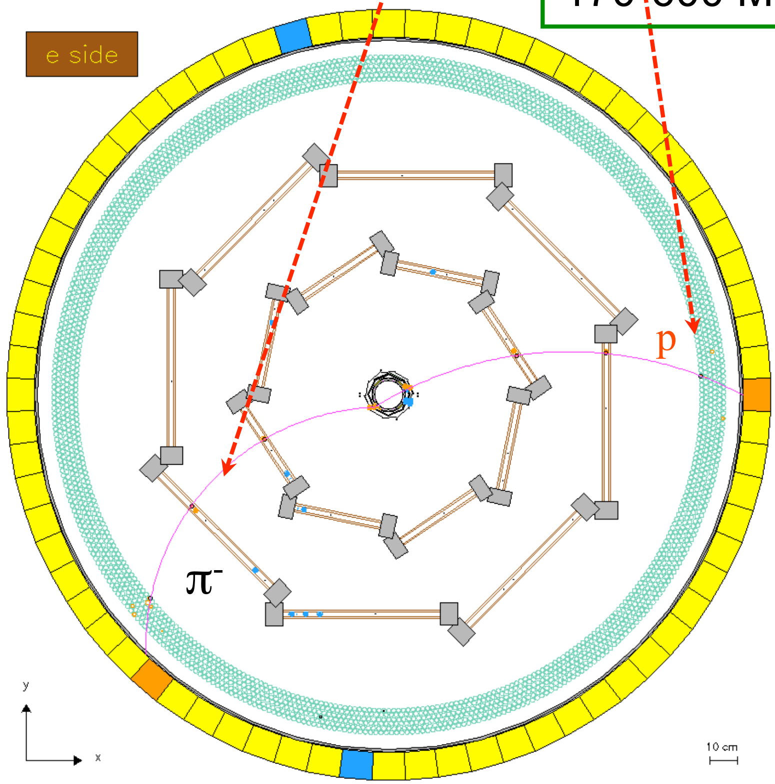


charged Non-Mesonic channel

$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$

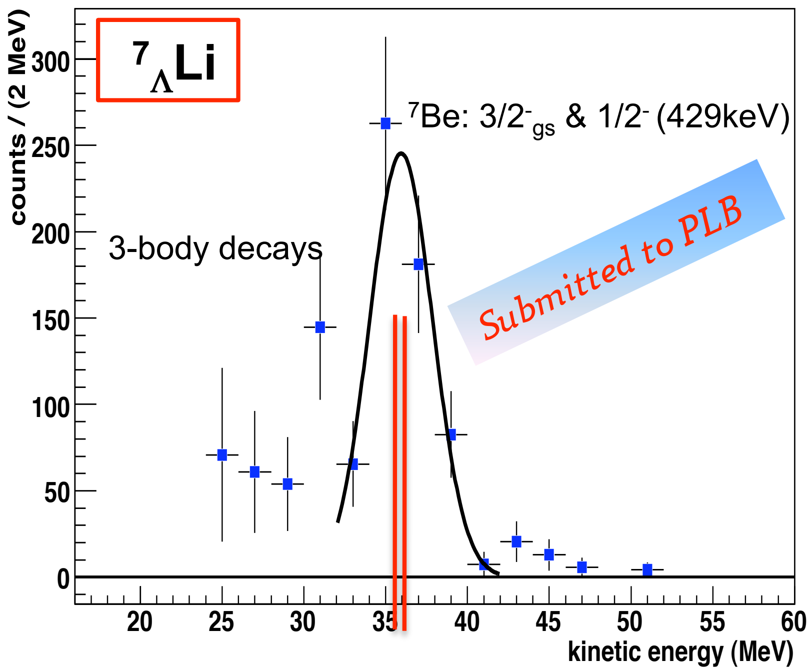
${}^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + p + n$

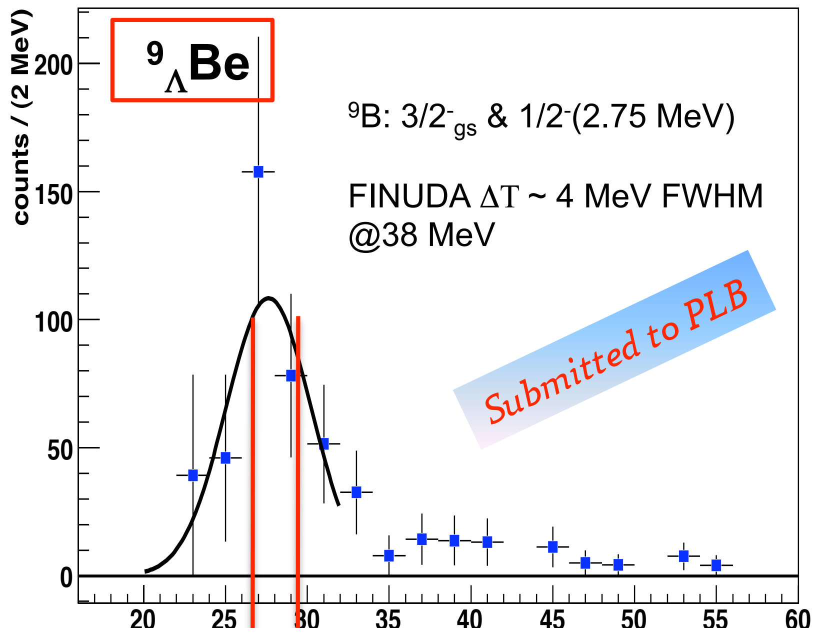
NMWD
170-600 MeV/c

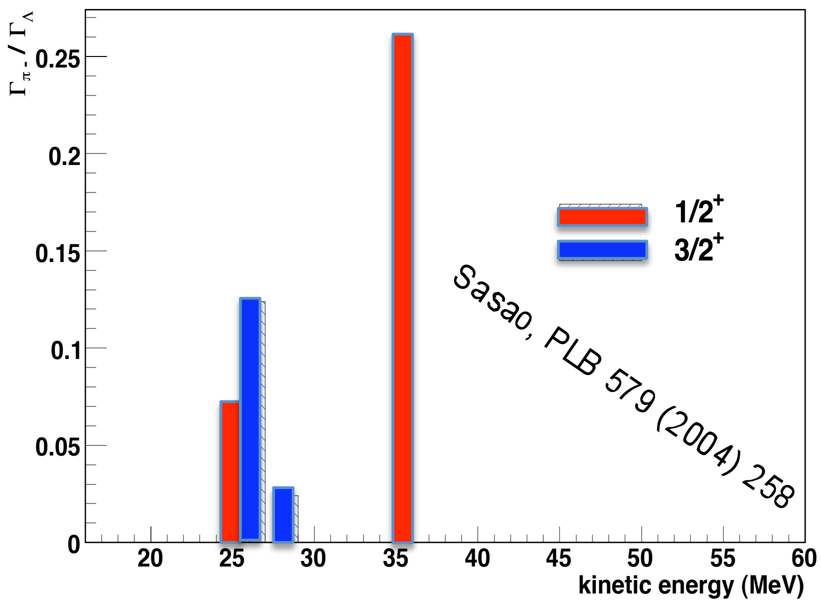


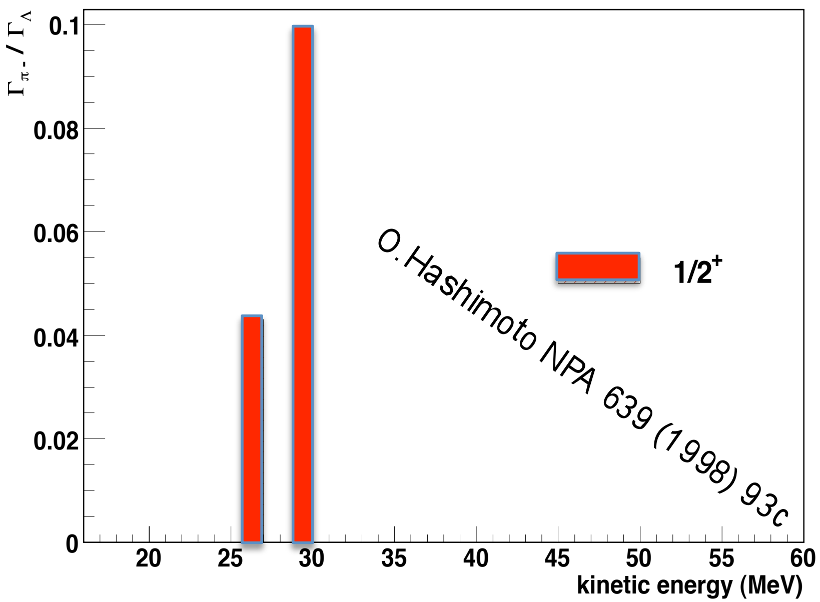
Mesonic weak decay spectra

T. Motoba et al, Progr. Theor. Phys. Suppl. 117 (1994) 477.









A. Gal, Nucl. Phys. A 828 (2009) 72

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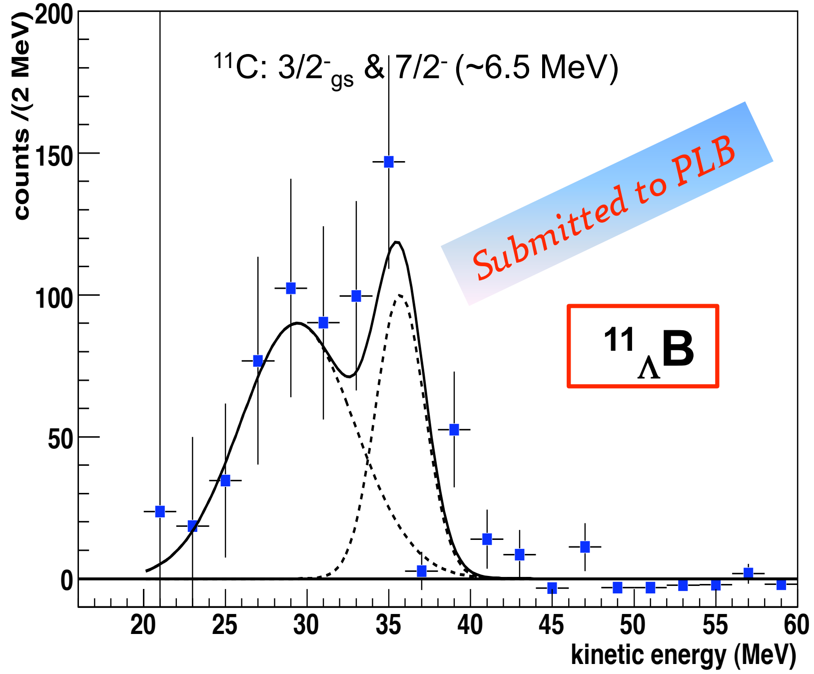
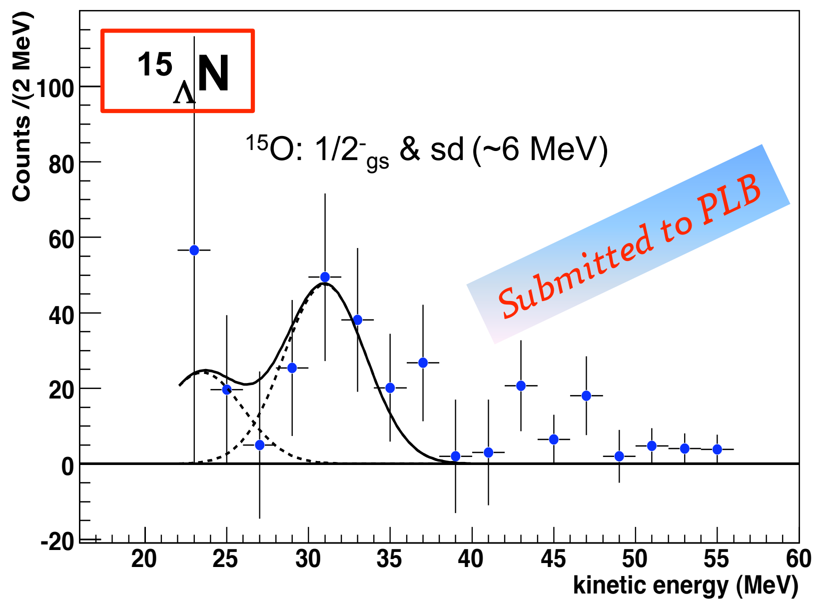
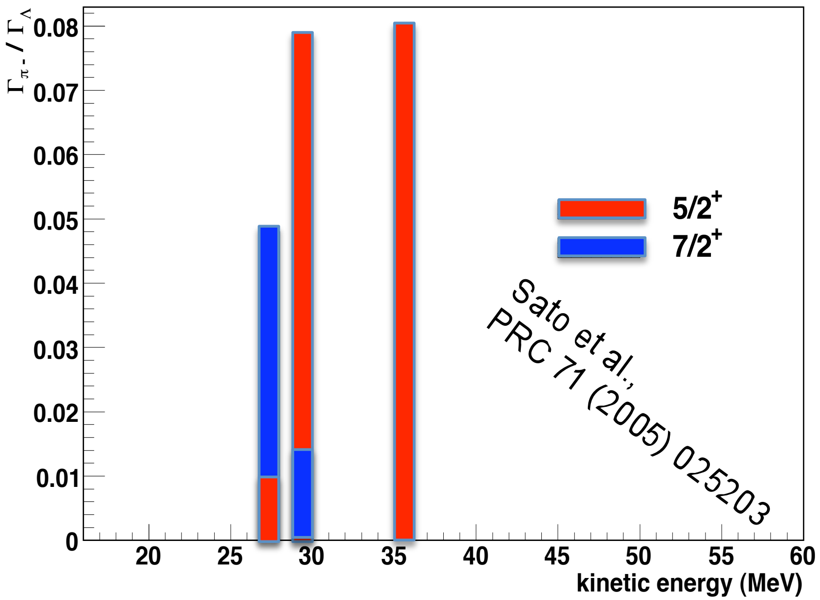
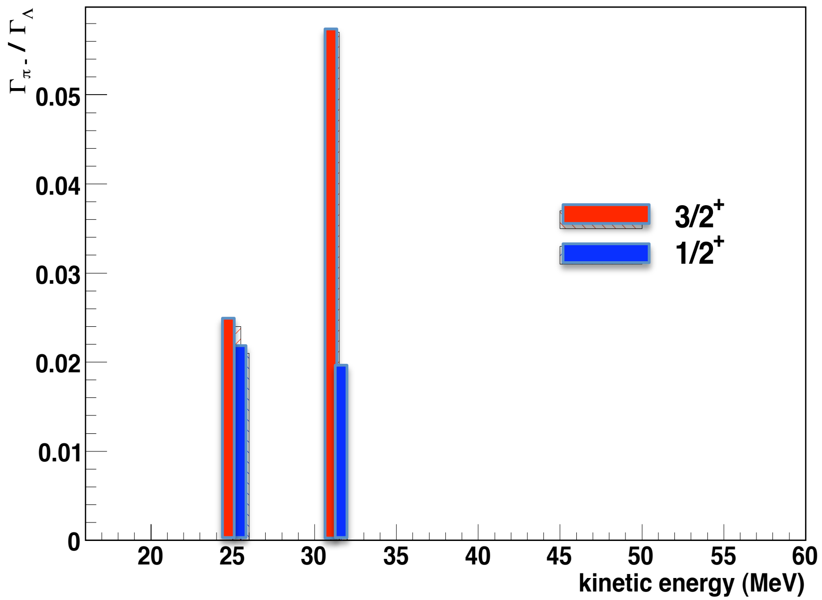






A. Gal, Nucl. Phys. A 828 (2009) 72

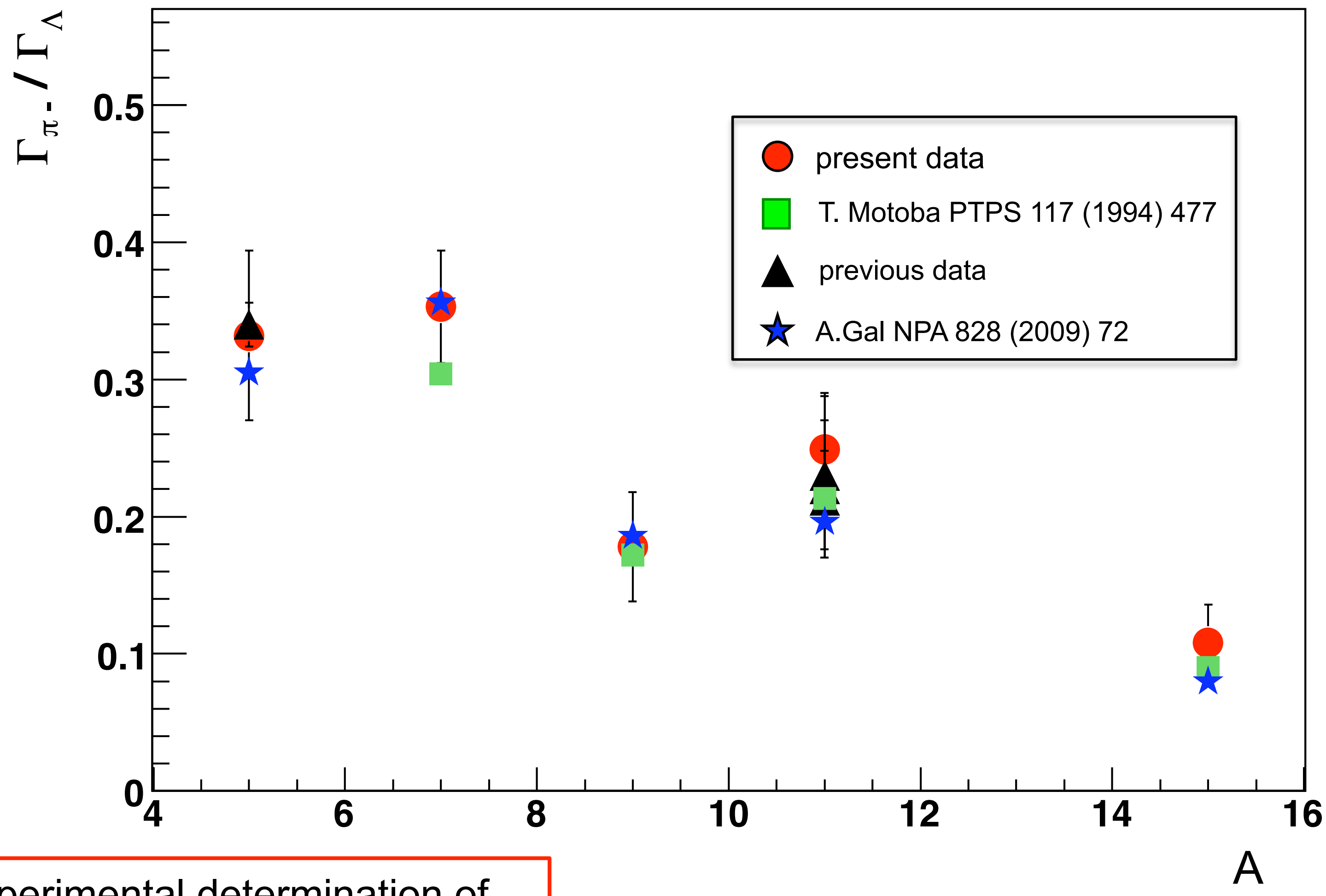


A. Gal, Nucl. Phys. A 828 (2009) 72

Mesonic decay ratio: $\Gamma_{\pi-} / \Gamma_{\Lambda}$

$\Gamma_{tot} / \Gamma_{\Lambda}$ = (0.990±0.094) + (0.018±0.010) •A

fit from measured values for A=4-12 hypernuclei



First experimental determination of J^{π} ($^{15}_{\Lambda}N_{g.s.}$) = $3/2^{+}$ from decay rate value (and spectrum shape)

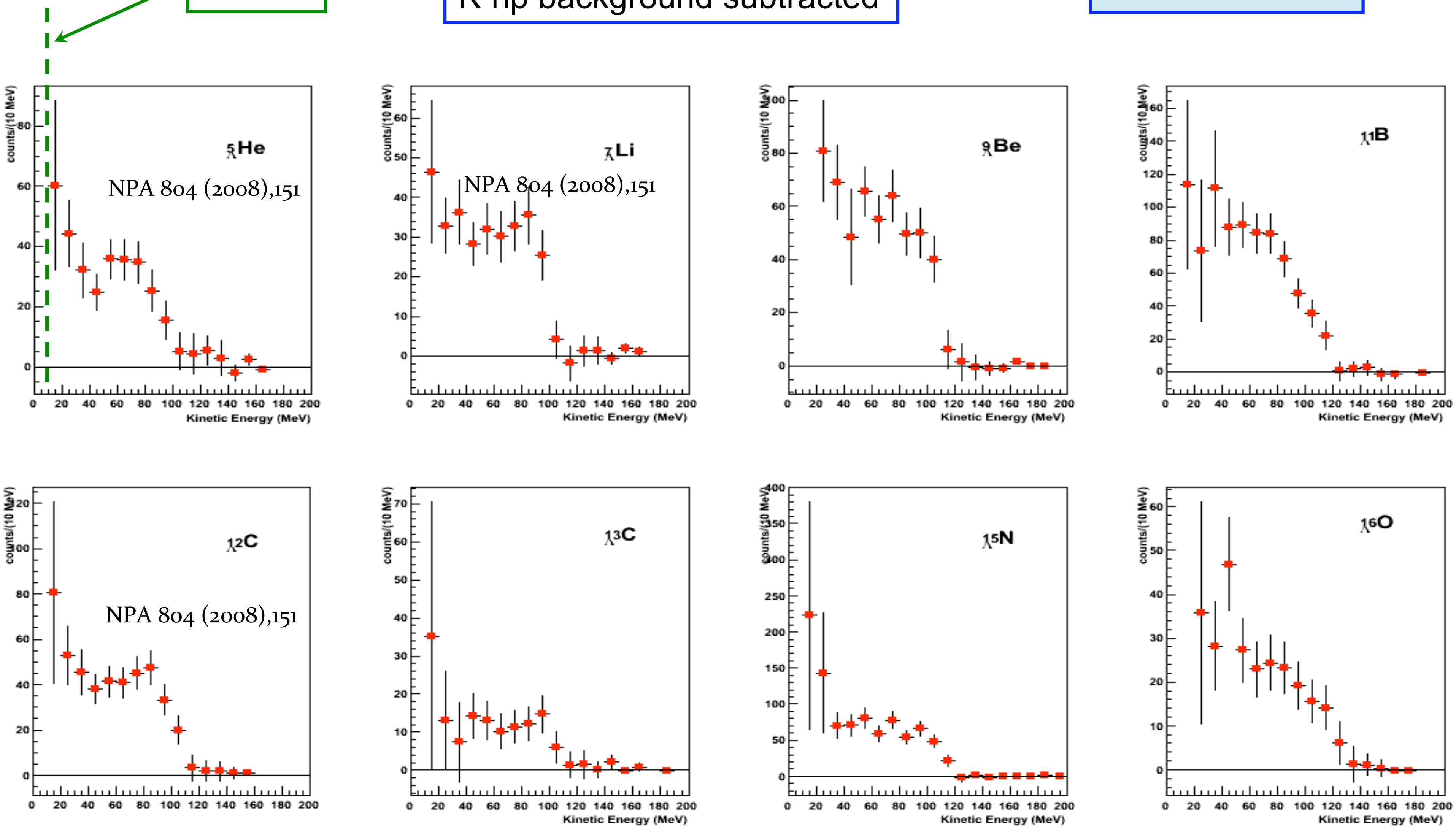
strong nuclear structure effects

Non Mesonic Weak Decay spectra

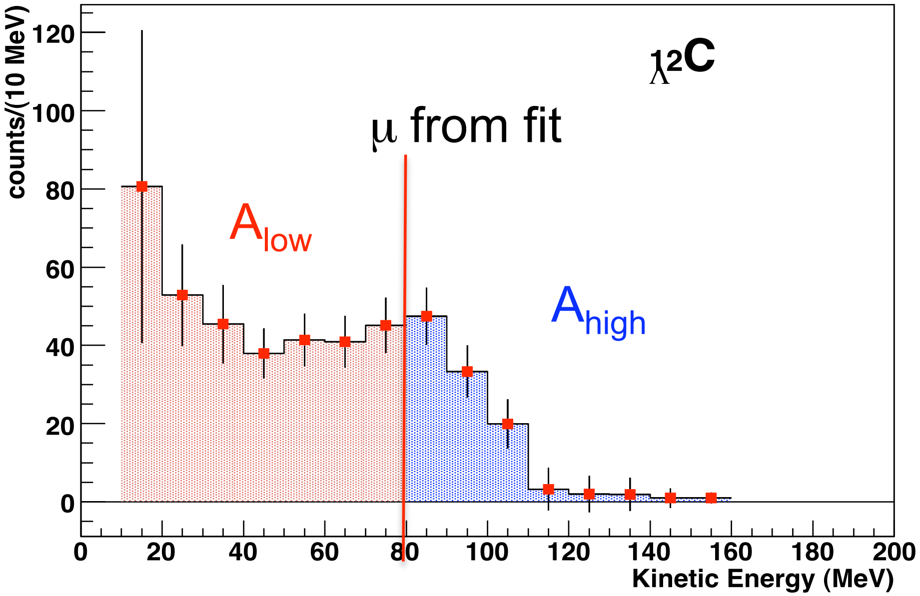
15 MeV

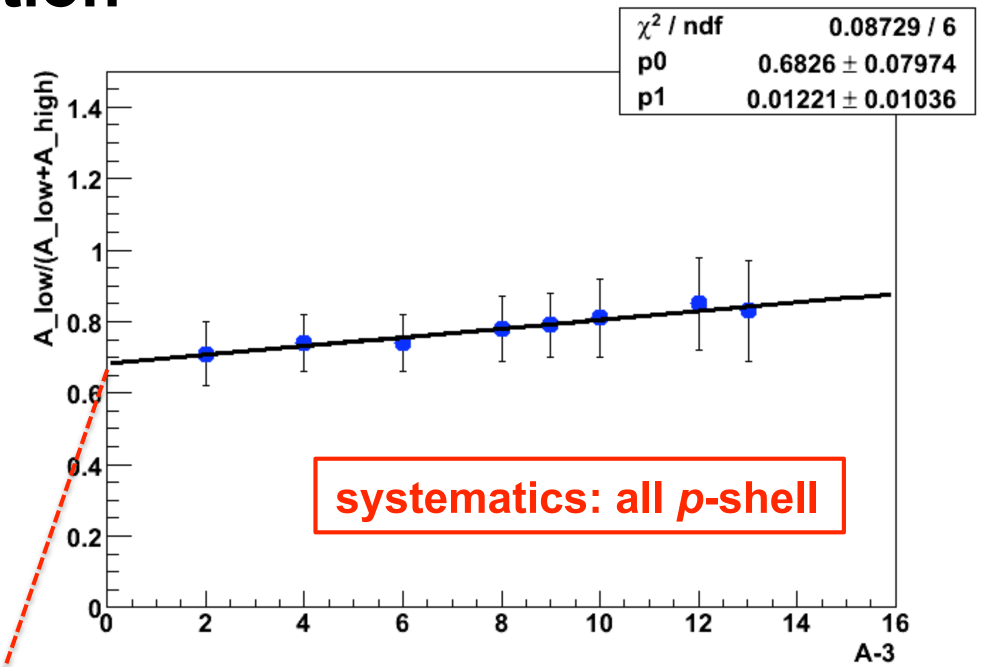
K⁻np background subtracted

1N + 2N + FSI !!



FSI & ΛNN contribution evaluation





R= 0.68±0.08

$$\frac{\Gamma_2}{\Gamma_p} = 0.56 \pm 0.11$$

✓ theoretical calculations: 0.16-0.29 to reproduce experimental Γn/Γp and Γtot values
✓ experimental indirect determination: ~0.4

$$\frac{\Gamma_2}{\Gamma_{NMWD}} = \frac{\Gamma_2/\Gamma_p}{\Gamma_n/\Gamma_p + 1 + \Gamma_2/\Gamma_p} = 0.27 \pm 0.06$$

~ 0.22 with FSI down to A=0

Search for neutron-rich hypernuclei

- Hypernuclei with a large neutron excess
- Their existence has been theoretically predicted (*L. Majling, NP A 585 (1995) 211c*) but not experimentally observed yet

The Pauli principle does not apply to the Λ inside the nucleus
→ A larger number of neutrons may occupy the bound nuclear levels
→ *extra* binding energy (Λ "*glue-like*" role)

✓ Study of the hypernuclear structure properties (size, shape, …) at very high *N/Z*;
✓ Feedback with the astrophysics field: phenomena related to *high-density nuclear matter* in neutron stars

HYPER-NUCLEUS	HYPERNUCL. STATE	B_Λ (MeV)	PRODUCTION RATE / K^-_{stop}	REFERENCES
$^{12}_{\Lambda}Be$	1^- (g.s.)	11.4 &	$< 6.1 \cdot 10^{-5}$ + $1.8 \cdot 10^{-5}$ °	+ *MEASURED* (90% C.L. *Upper Limit*) K. Kubota et al., *NP A 602 (1996) 327* ° *THEORETICAL EVALUATION* T. Tretyakova, D. Lanskoy, *NP A 691 (2001) 351c*
	0^+ (exc.s.)	?	$6.0 \cdot 10^{-6}$ °	
$^{6}_{\Lambda}H$	0^+ (g.s.)	4.1 * 4.2 &	?	* *THEORETICAL EVALUATION* Y. Akaishi, *Frascati Phys. Series, Vol. XVI (1999) 59*
$^{7}_{\Lambda}H$	0^+ (g.s.)	5.2 &	?	& *EXTRAPOLATION FROM DATA* L. Majling, *NP A 585 (1995) 211c*

Neutron-Rich Hypernuclei production in FINUDA

Reaction mechanisms:

1) Double charge exchange:
   $K^- + p \rightarrow \Lambda + \pi^0$; $\pi^0 + p \rightarrow n + \pi^+$
2) Strangeness exchange & Σ−Λ coupling:
   $K^- + p \rightarrow \Sigma^- + \pi^+$ $(\Sigma^- + p \leftrightarrow \Lambda + n)$

In FINUDA we searched for:

$^{12}_{\Lambda}$Be (N/Z = 7/4) from ^{12}C (K^-_{stop}, π^+) $^{12}_{\Lambda}$Be

$^{6}_{\Lambda}$H (N/Z = 4) from ^{6}Li (K^-_{stop}, π^+) $^{6}_{\Lambda}$H

$^{7}_{\Lambda}$H (N/Z = 5) from ^{7}Li (K^-_{stop}, π^+) $^{7}_{\Lambda}$H

Event selection:

- Reconstruction of a π^+ with a momentum value in the hypernucleus bound region (~250 MeV/c)
- P.ID.: p + d contamination

main background:

$K^- + p \rightarrow \Sigma^+ + \pi^-$

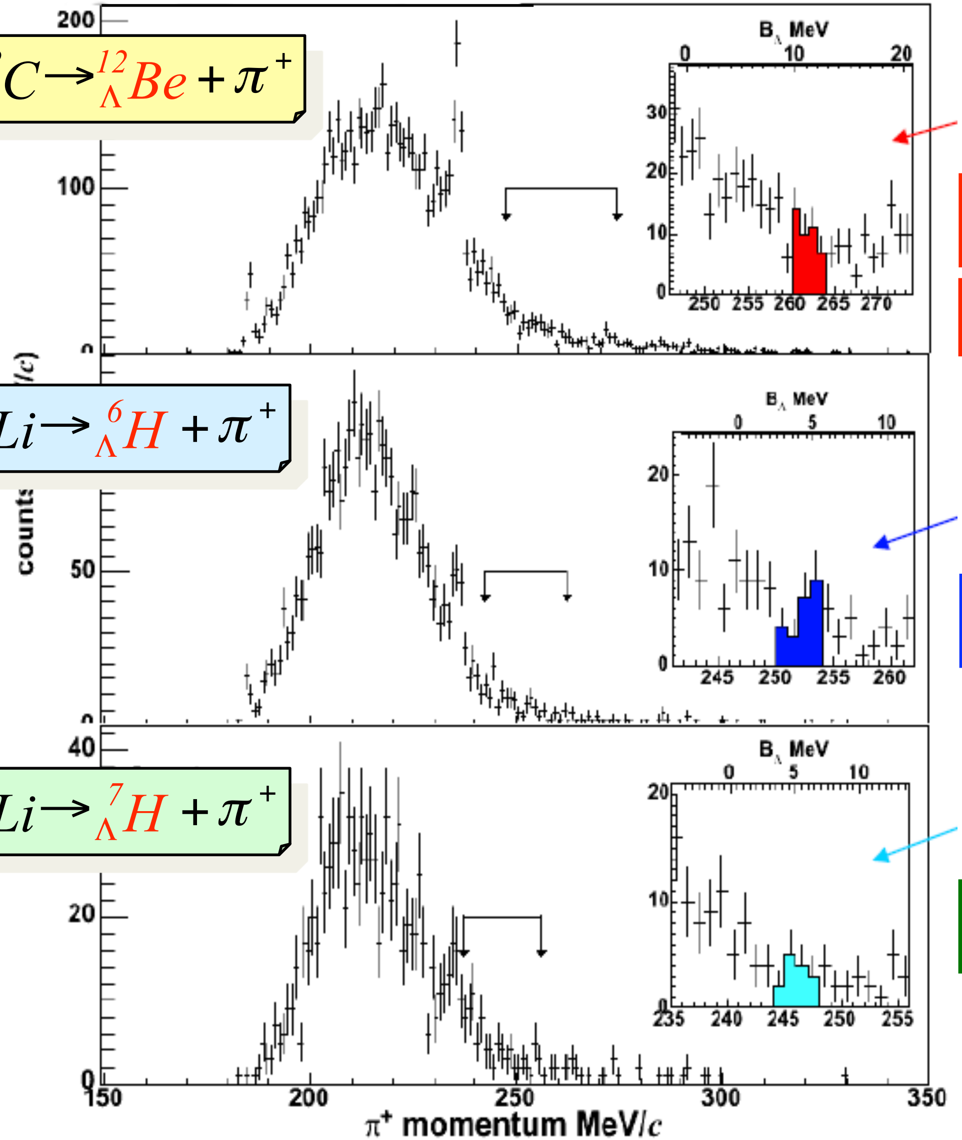
$\quad \hookrightarrow n + \pi^+ \quad (\sim 130 < p_{\pi^+} < \sim 250 \text{ MeV}/c)$

$K^- + pp \rightarrow \Sigma^+ + n$

$\quad \hookrightarrow n + \pi^+ \quad (\sim 100 < p_{\pi^+} < \sim 320 \text{ MeV}/c)$

simulated and subtracted

FINUDA results on NRH



$K^{-}_{stop} + {}^{12}C \rightarrow {}^{12}_{\Lambda}Be + \pi^{+}$

$p_{\pi^+} = 262.9\ \mathrm{MeV}/c\ \pm\ 2\sigma_{p_{\pi^+}}$

$< (2.0 \pm 0.4_{stat}\ {}^{+0.3}_{-0.1}\ {}_{syst}) \times 10^{-5}$

$< 6.1 \times 10^{-5}$

M. Kubota *et al.*, Nucl. Phys. A 602 (1996) 327

$K^{-}_{stop} + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + \pi^{+}$

$p_{\pi^+} = 249.1\ \mathrm{MeV}/c\ \pm\ 2\sigma_{p_{\pi^+}}$

$< (2.5 \pm 0.4_{stat}\ {}^{+0.4}_{-0.1}\ {}_{syst}) \times 10^{-5}$

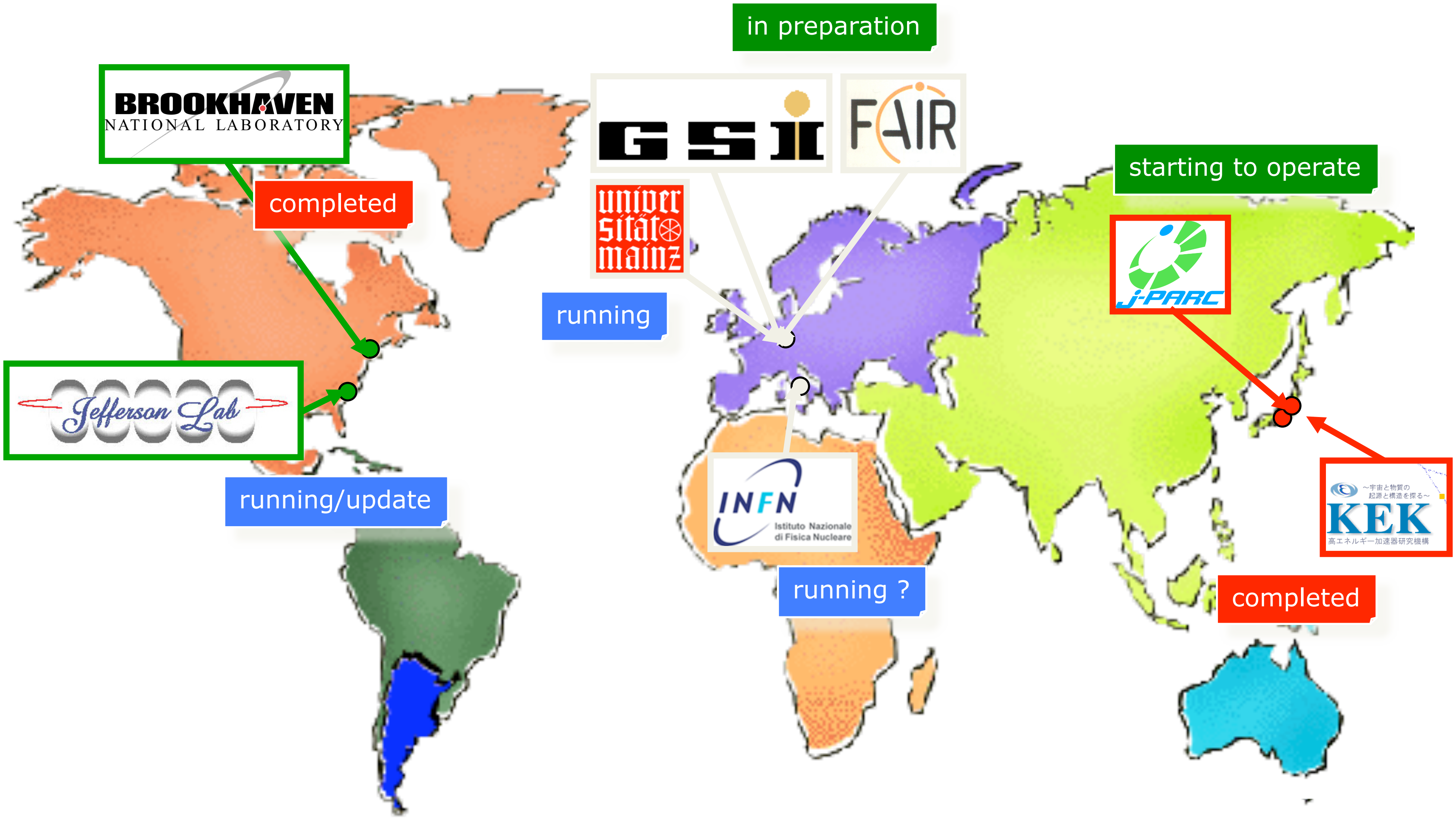
$K^{-}_{stop} + {}^{7}Li \rightarrow {}^{7}_{\Lambda}H + \pi^{+}$

$p_{\pi^+} = 246.4\ \mathrm{MeV}/c\ \pm\ 2\sigma_{p_{\pi^+}}$

$< (4.5 \pm 0.9_{stat}\ {}^{+0.4}_{-0.1}\ {}_{syst}) \times 10^{-5}$

M. Agnello *et al.*, Phys. Lett. B 640 (2006) 145

Perspectives for hypernuclear physics



RHIC, LHC ??

A. Feliciello

Double Λ hypernuclei
present status

	$^{A}_{\Lambda\Lambda}Z$	Ξ^- Captured	$B_{\Lambda\Lambda} - B_{\Xi^-}$ [MeV]	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ [MeV]	Assumed level	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
NAGARA	$^{6}_{\Lambda\Lambda}He$	^{12}C	$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-}$ (+/- 0.16) $\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-}$ (+/- 0.17) $B_{\Xi^-} < 1.86$		3D	6.91 +/- 0.16	0.67 +/- 0.17
MIKAGE	$^{6}_{\Lambda\Lambda}He$	^{12}C	9.93 +/- 1.72	3.69 +/- 1.72	3D	10.06 +/- 1.72	3.82 +/- 1.72
DEMACHI-YANAGI	$^{10}_{\Lambda\Lambda}Be^*$	^{12}C	11.77 +/- 0.13	-1.65 +/- [illegible] cf. $Ex = 3.0$	3D	11.90 +/- 0.13	-1.52 +/- 0.15 cf. $Ex = 3.0$
HIDA	$^{11}_{\Lambda\Lambda}Be$	^{16}O	20.26 +/- 1.15	2.04 +/- 1.23	3D	20.49 +/- 1.15	2.27 +/- 1.23
	$^{12}_{\Lambda\Lambda}Be$	^{14}N	[illegible] +/- 1.15	------	3D	22.23 +/- 1.15	------
E176	$^{13}_{\Lambda\Lambda}B$ -> $^{13}_{\Lambda}C^*$		------ $Ex = 4.9$	-------	3D	23.3 +/- 0.7	0.6 +/- 0.8
	$^{10}_{\Lambda\Lambda}Be$ -> $^{9}_{\Lambda}Be^*$		------ $Ex = 3.0$	-------	not checked, yet.	14.7 +/- 0.4	1.3 +/- 0.4

Preliminary

M.Danysz et al., PRL.11(1963)29;
R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

K. Nakazawa – HYP-X (2009)

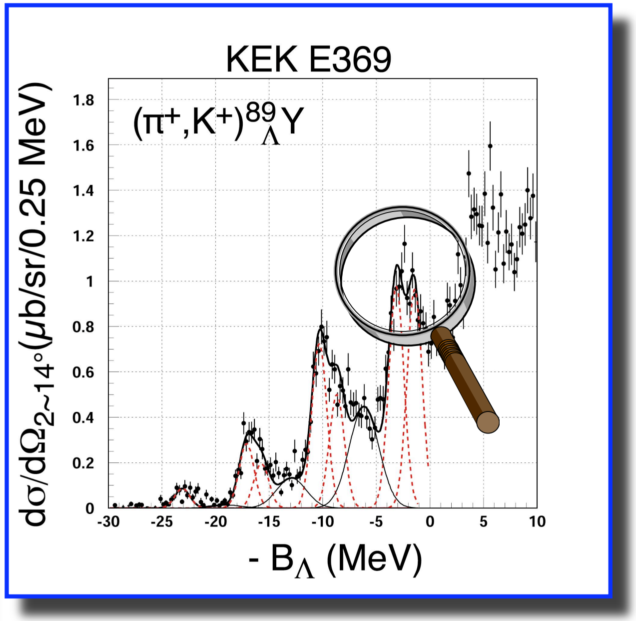
The status of the art

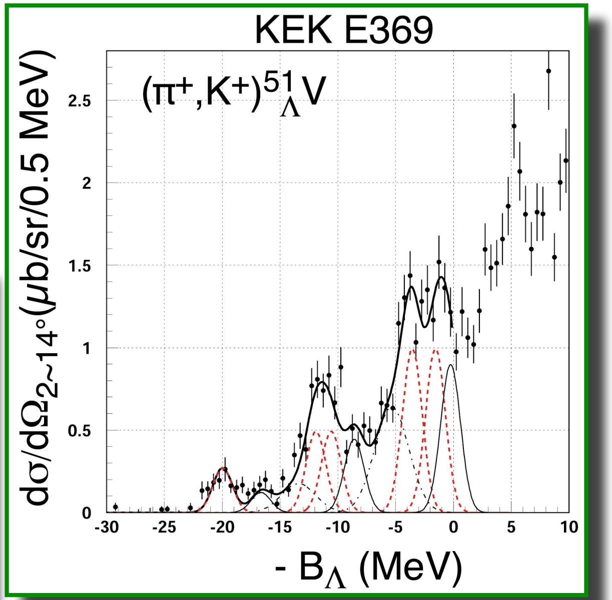
MM spectroscopy
magnetic spectrometers

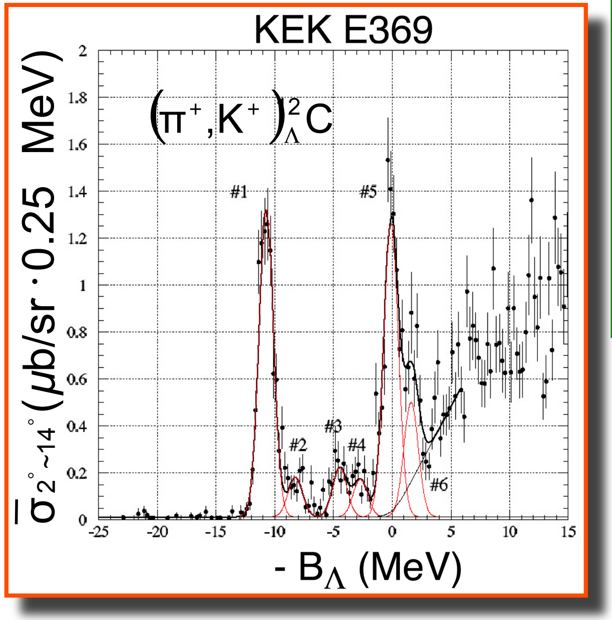
ΔE ~ 1.65 MeV FWHM

ΔE ~ 1.95 MeV FWHM

ΔE ~ 1.45 MeV FWHM

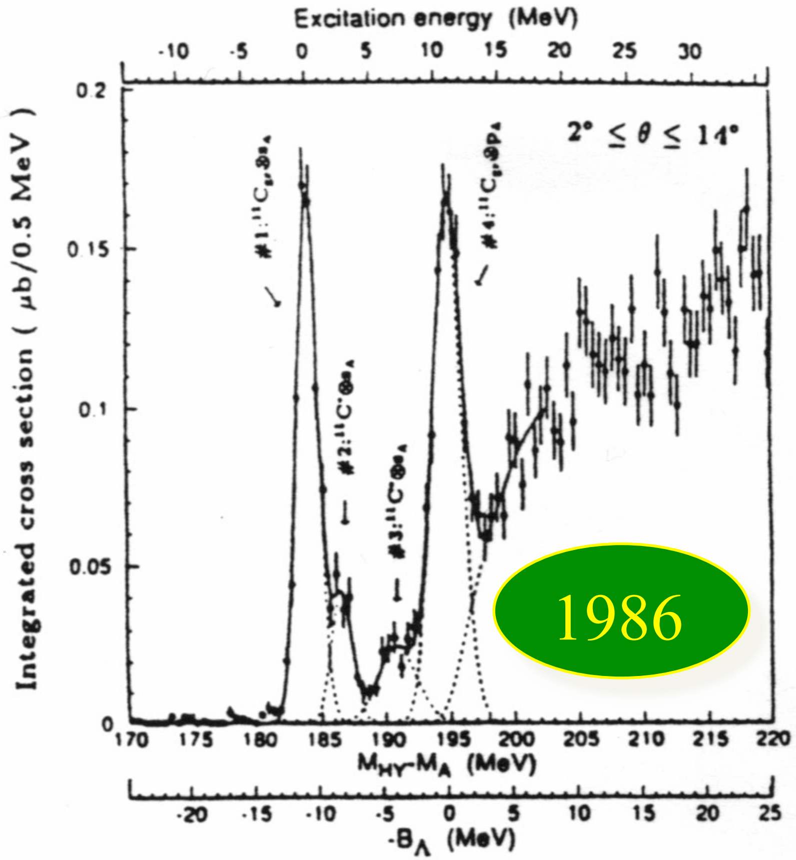






f-orbit splitting
into two peaks observed?

The status of the art



$^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$

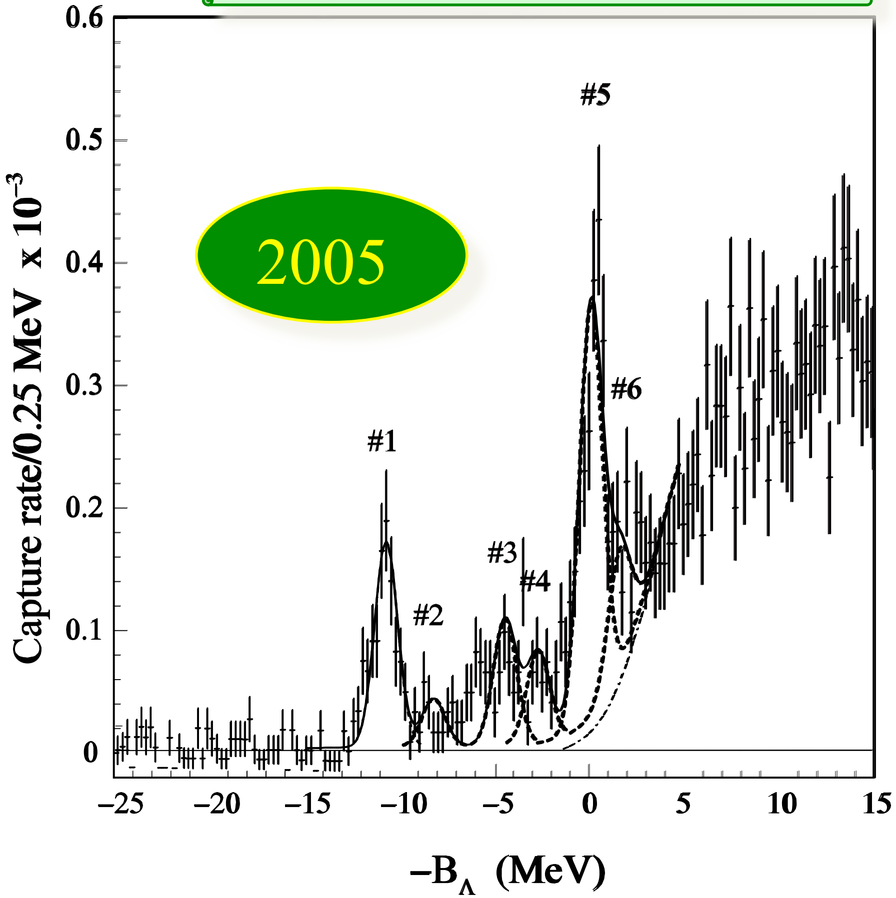
ΔE ~ 1.9 MeV FWHM

T. Hasegawa *et al.*, Phys. Rev. C 53 (1996) 1210

$^{12}C(K^-_{stop},\pi^-)^{12}_{\Lambda}C$

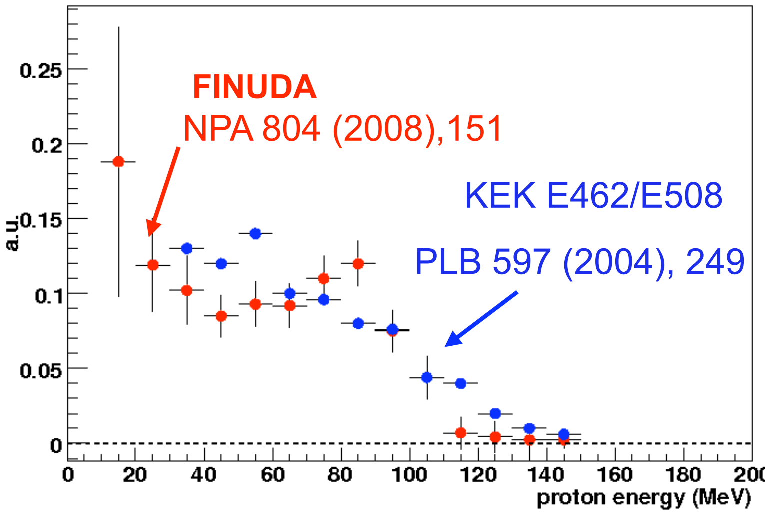
ΔE ~ 1.3 MeV FWHM

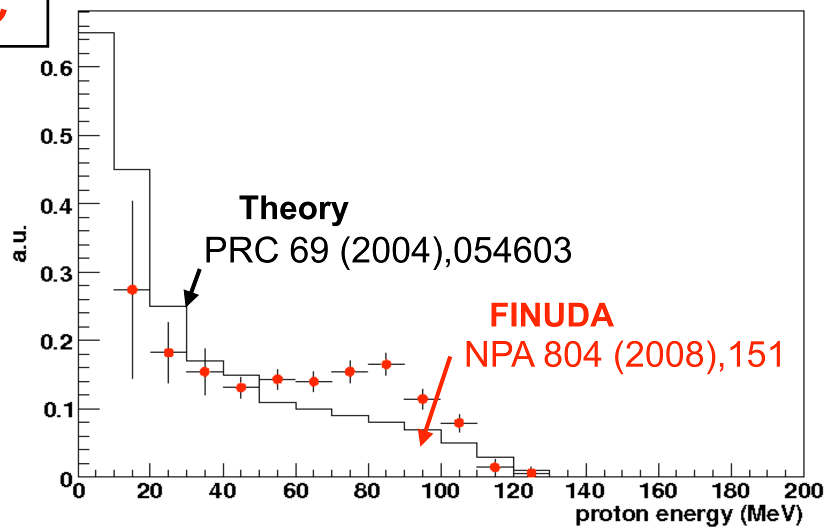
M. Agnello *et al.*, Phys. Lett. B 622 (2005) 35



Comparisons with theory and KEK results

$^{12}_{\Lambda}C$





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