Int. School on N-star
Yukawa Inst. Kyoto
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Strangeness in Nuclear Matter

--What can we learn from accelerator based experiments? --

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Introduction

Hyperons (Strange nucleons)

Λ 0(1/2$^+$) 1115.7MeV $c\tau$=7.89cm, $\rightarrow p\pi$-(0.64) $n\pi^0$(0.36)

Σ^+ 1(1/2$^+$) 1189.4MeV $c\tau$=2.04cm, $\rightarrow p\pi^0$(0.52) $n\pi^+$(0.48)

Σ^0 1(1/2$^+$) 1192.6MeV $c\tau$=2x10^{-9}cm, $\rightarrow \Lambda\gamma$

Σ^- 1(1/2$^+$) 1197.4MeV $c\tau$=4.43cm, $\rightarrow n\pi$-

Ξ^0 1(1/2$^+$) 1314.9MeV $c\tau$=8.71cm, $\rightarrow \Lambda\pi^0$

Ξ^- 1(1/2$^+$) 1321.7MeV $c\tau$=4.91cm, $\rightarrow \Lambda\pi^-$

Ω^- 0(3/2+) 1672.5MeV $c\tau$=2.46cm, $\rightarrow \Lambda K^-$(0.68) $\Xi^0\pi^-$ $\Xi^-\pi^0$

How to produce strange particles

- N+N → K+ Λ(Σ) +N, K-K+N, K+K+Ξ- N, ,,,
- π+N → K+Λ(Σ)
- K-N → π− Λ(Σ)
- K-N → K+Ξ−
- K-N → K+ K^0 Ω^-
- γ(e)N → K+ Λ(Σ), K+K+Ξ−,,,

N→A   A(Y)

- e+e- → b, c, → s (strange hadrons)

Where can we study strangeness?

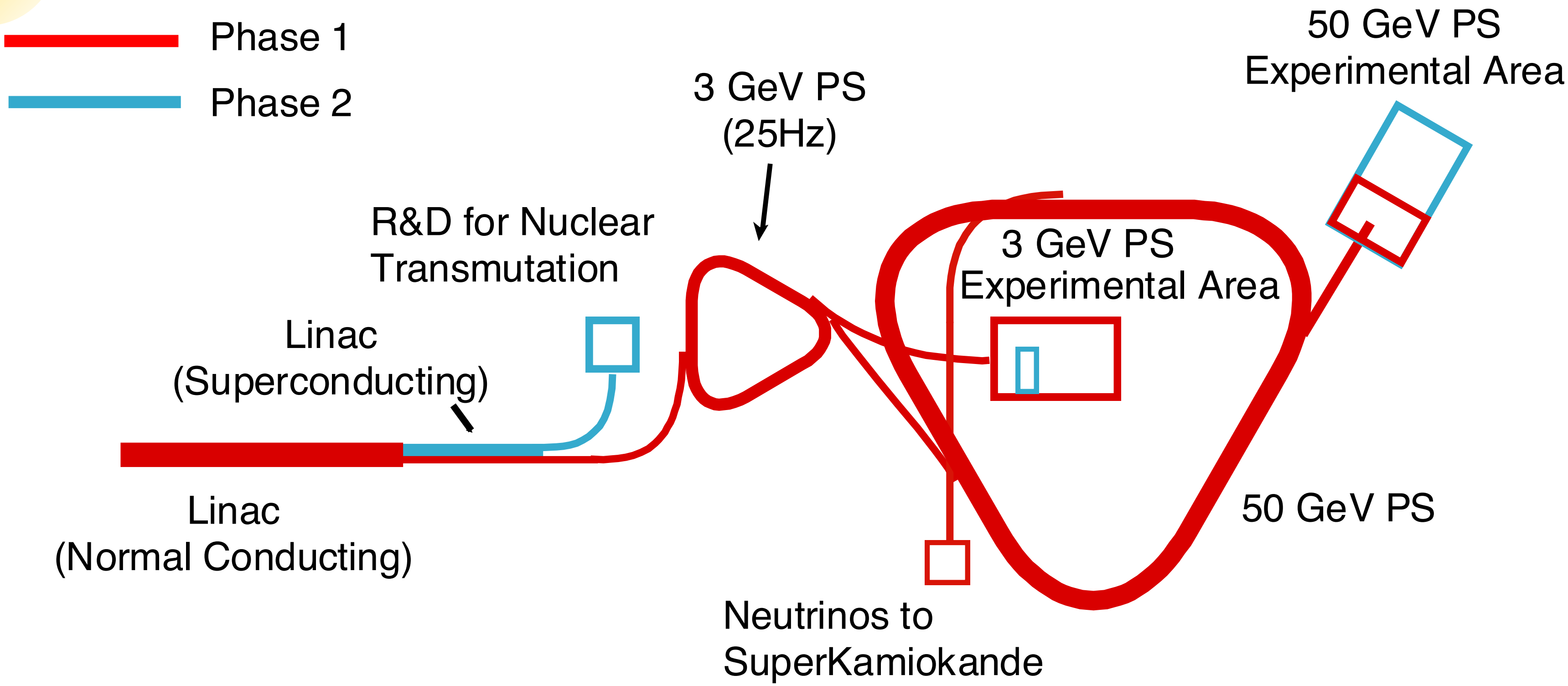
- π, K, p, p-bar,, →higher intensity
  (CERN-PS, BNL-AGS, KEK-PS)
  FNAL-MI, J-PARC, GSI-FAIR
- e, γ
  Mainz, ELPH, J-lab, Spring-8
- A
  GSI, RHIC, LHC, NICA, J-PARC
- e+e-
  DAΦNE(ϕ-factory), B-factory (Belle II)

Table.3. Summary of high intensity proton accelerators

LANSCE	LINAC +AR	800 MeV	100kW
TRIUMF	Cyclotron	500 MeV	75 kW
PSI	Cyclotron	590 MeV	1.3 MW
ISIS	Synchrotron	800 MeV	180 kW
SNS	LINAC+AR	1.0 GeV	1.0 MW
ESS	LINAC	2.5 GeV	5.0 MW
MI	Synchrotron	8.0 GeV	
	Synchrotron	150 GeV	0.70 MW
J-PARC	LINAC+RCS	3.0 GeV	1.0 MW
	Synchrotron	50 GeV	0.75 MW
FAIR (SIS100)	Synchrotron	29 GeV	0.20 MW

K.Imai
Rev. Accel. Sci. Tech. (2014)

J-PARC (Phase 1 and Phase 2)



- Phase 1 + Phase 2 = 1,890 Oku Yen (= $1.89 billion if $1 = 100 Yen).
- Phase 1 = 1,513 Oku Yen .

J-PARC (Tokai)

Table 1. Summary of electron accelerators

ELPH (Tohoku)	synchrotron	1.3 GeV	
ELSA (Bonn)	synchrotron	3.5 GeV	
MAMI (Mainz)	microtron	1.5 GeV	150KW
CEBAF (Jlab)	recirculation	12 GeV	1MW

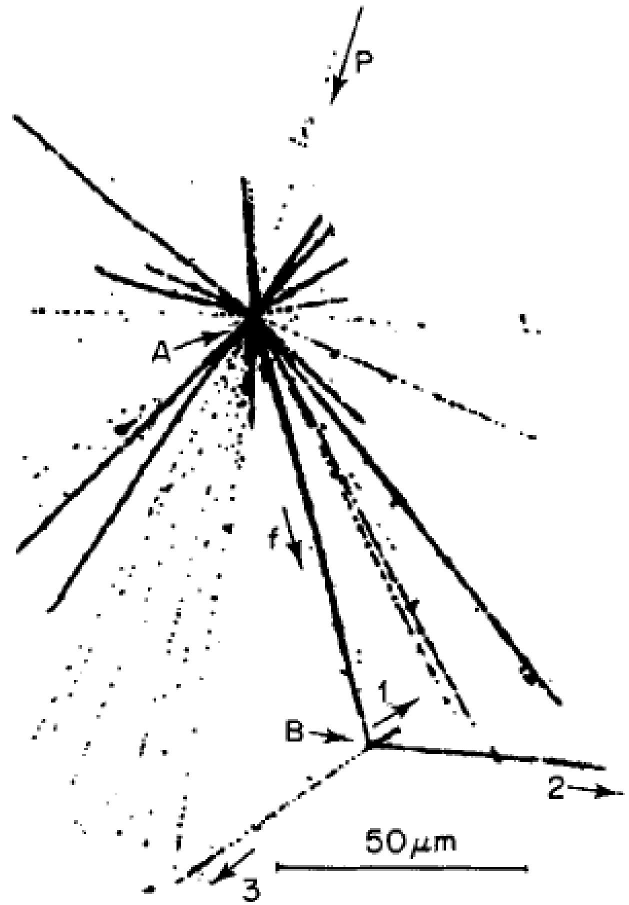
SPring-8 LEPS ~3 GeV Laser Compton γ

$10^6\ \gamma$ ◊ $10^7\ \gamma$

Λ-hypernuclei

First hypernucleus

Danysz and Pniewski found a hyperfragment in the nuclear emulsion in 1953.



hypernuclei in emulsion experiments

27000 hypernuclei (π^- decay) from 3×10^6 K^- star (at rest) found under microscopes. (AGS K- beam)

Juric et al., Nucl. Phys. B52 (1973) 1.

ranges of tracks from hypernuclear decay → T of decay particles

→ mass of hypernucleus → B_Λ: binding energy (separation energy) of Λ

$$M_{HF}c^2 = (M_{core} + M_\Lambda)c^2 - B_\Lambda$$

$$= \sum_i M_i c^2 + \sum_i T_i$$

Precision depends on the range-energy relation. Λ decay was also measured.

M_Λ = 111.57 +- 0.03 MeV (PDG: 1115.683 +- 0.006 MeV)

Weak decay of hypernuclei

- Free $\Lambda \rightarrow p\pi^-$ (2/3) $n\pi^0$ (1/3)

- Mesonic decay $A_\Lambda \rightarrow \pi^- + X(p), \pi^0 + X$

  small Q-value ~ (37-B_Λ) MeV

  only for light hypernuclei due to Pauli blocking

- Non-mesonic decay

  NL→NN (pΛ→pn, nΛ→nn, NNΛ→NNN)

  large Q-value ~ 176 MeV

  dominant for heavy hypernuclei

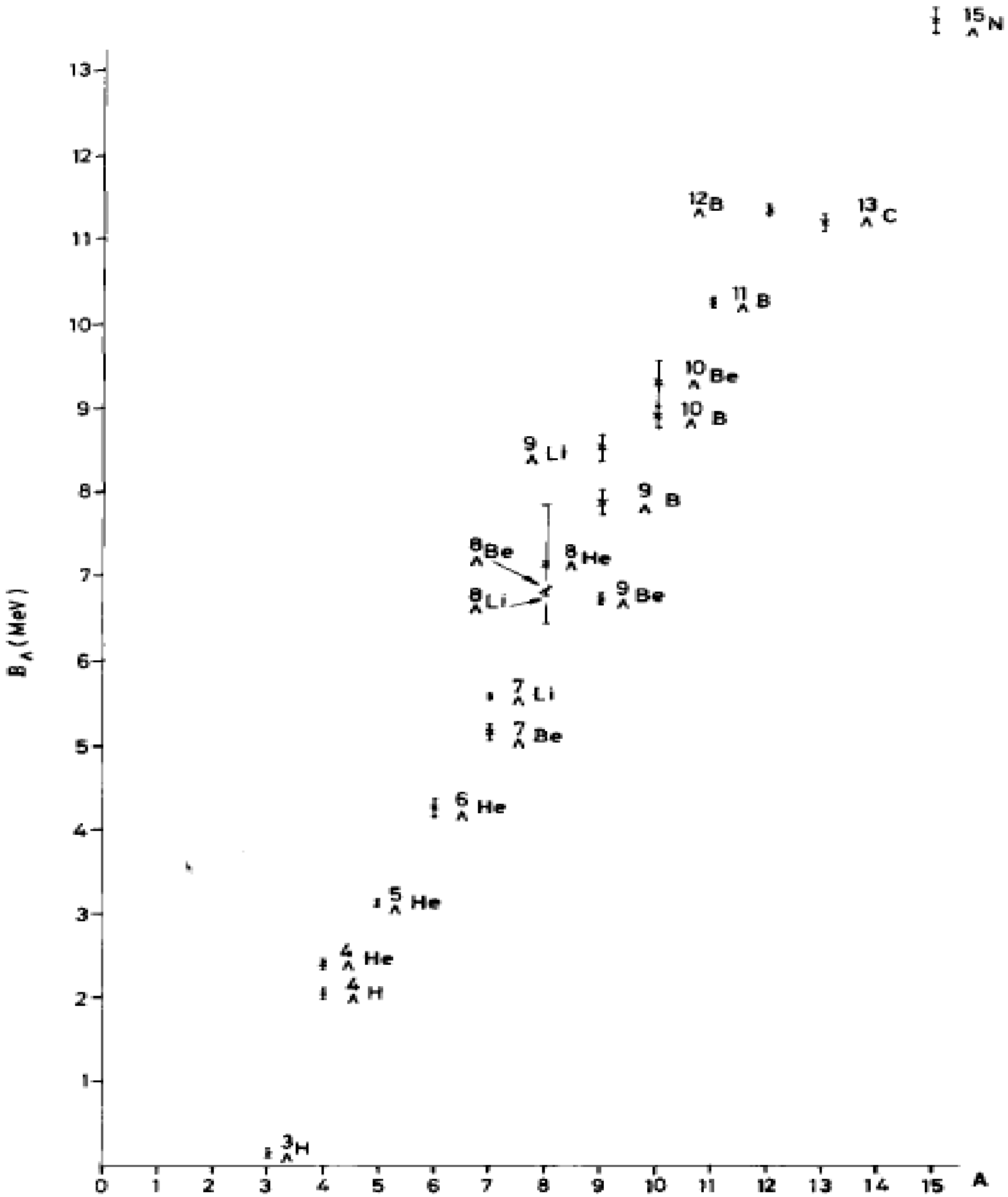
B_Λ from emulsion experiments

Hypernuclide	Number of Events	B_Λ/MeV
${}^{3}_{\Lambda}\mathrm{H}$	204	0·13 ± 0·05
${}^{4}_{\Lambda}\mathrm{H}$	155	2·04 ± 0·04
${}^{4}_{\Lambda}\mathrm{He}$	279	2·39 ± 0·03
${}^{5}_{\Lambda}\mathrm{He}$	1784	3·12 ± 0·02
${}^{6}_{\Lambda}\mathrm{He}$	31	4·18 ± 0·10
${}^{7}_{\Lambda}\mathrm{He}$	16	not averaged
${}^{7}_{\Lambda}\mathrm{Li}$	226	5·58 ± 0·03
${}^{7}_{\Lambda}\mathrm{Be}$	35	5·16 ± 0·08
${}^{8}_{\Lambda}\mathrm{He}$	6	7·16 ± 0·70
${}^{8}_{\Lambda}\mathrm{Li}$	787	6·80 ± 0·03
${}^{8}_{\Lambda}\mathrm{Be}$	68	6·84 ± 0·05
${}^{9}_{\Lambda}\mathrm{Li}$	8	8·50 ± 0·12
${}^{9}_{\Lambda}\mathrm{Be}$	222	6·71 ± 0·04
${}^{9}_{\Lambda}\mathrm{B}$	4	8·29 ± 0·18
${}^{10}_{\Lambda}\mathrm{Be}$	3	9·11 ± 0·22
${}^{10}_{\Lambda}\mathrm{B}$	10	8·89 ± 0·12
${}^{11}_{\Lambda}\mathrm{B}$	73	10·24 ± 0·05
${}^{12}_{\Lambda}\mathrm{B}$	87	11·37 ± 0·06
${}^{12}_{\Lambda}\mathrm{C}$	5	10·76 ± 0·19
${}^{13}_{\Lambda}\mathrm{C}$	6	11·69 ± 0·12
${}^{14}_{\Lambda}\mathrm{C}$	3	12·17 ± 0·33
${}^{15}_{\Lambda}\mathrm{N}$	14	13·59 ± 0·15

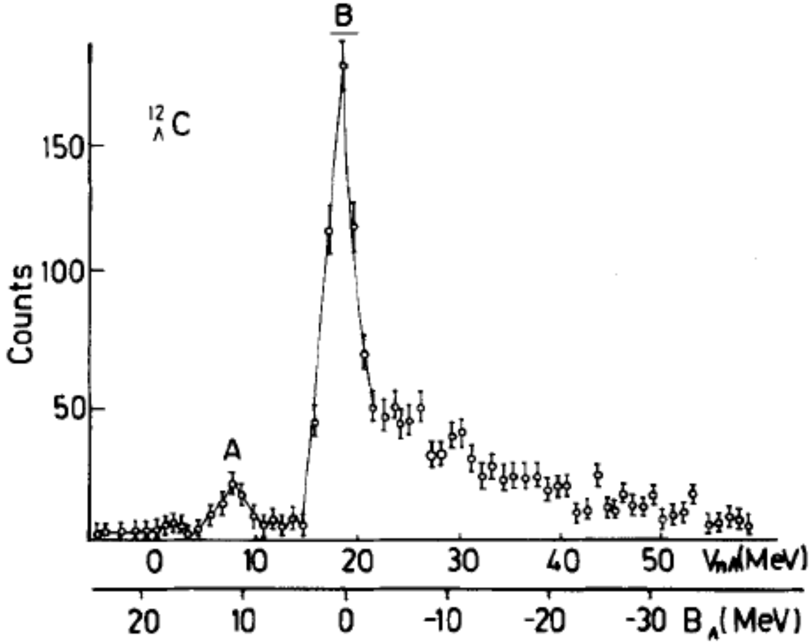
D.H.Davis (1986) C. Phys.

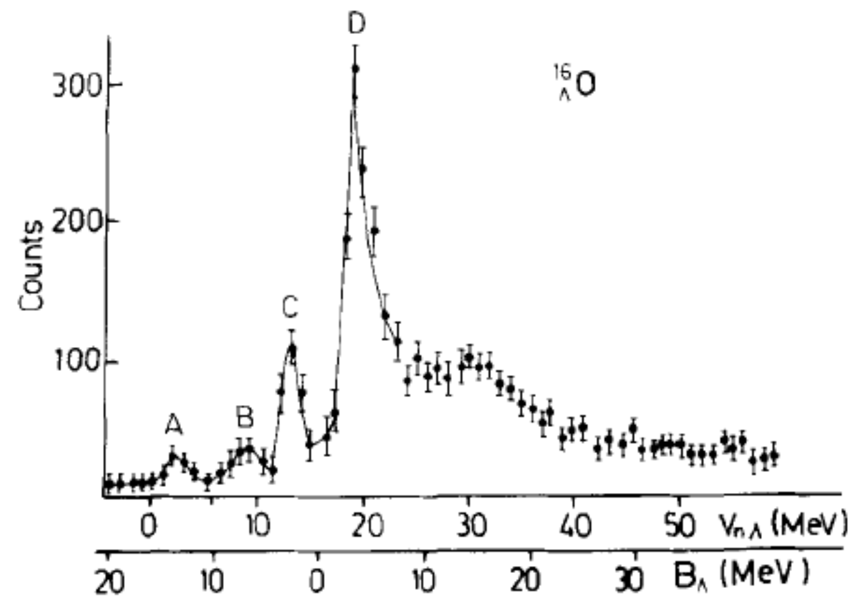
B_{Λ}(MeV) vs A

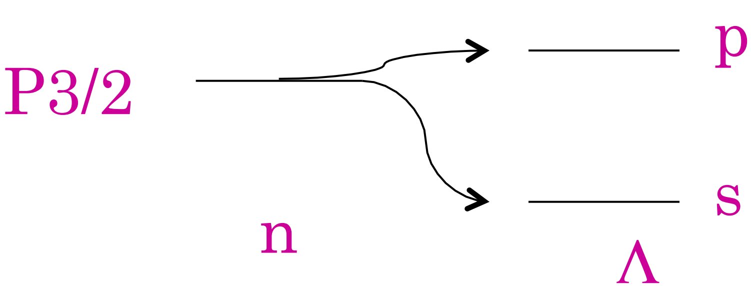
(Juric et al.)

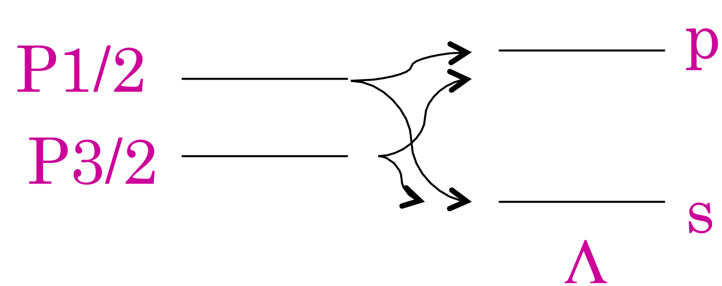


$A\,(K^-,\pi^-)\,A_\Lambda$

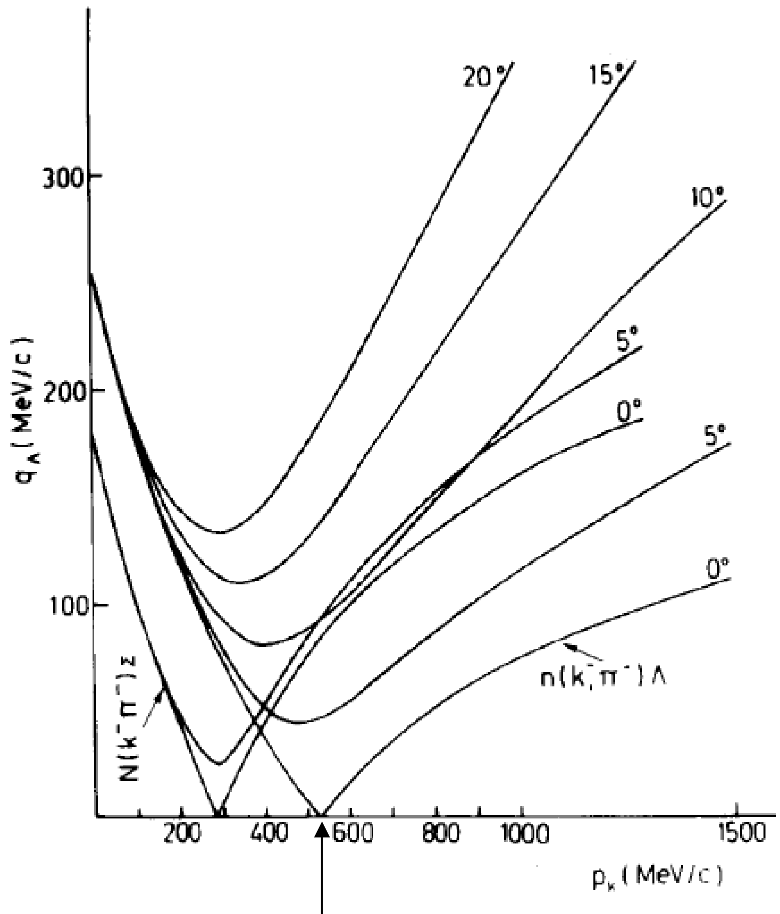




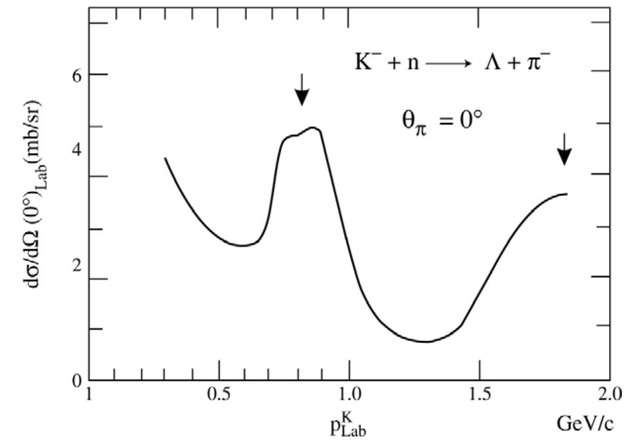


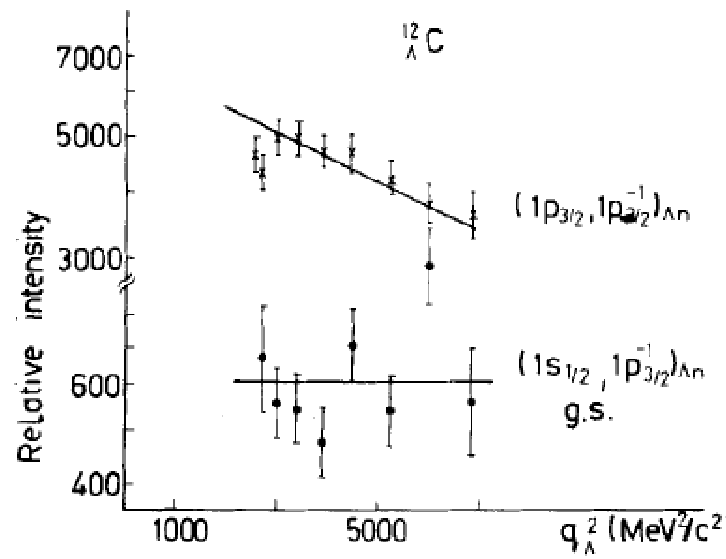


Momentum transfer q_Λ for (K-,π-) reaction



Magic momentum



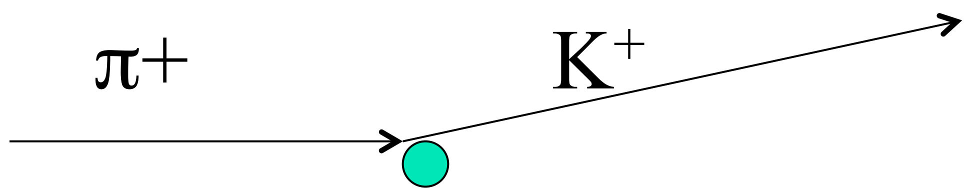


Spectroscopy with magnetic spectrometers

- Missing mass spectroscopy

$$M_{\mathrm{HYP}} = \sqrt{(E_{\pi^+} + M_A - E_{K^+})^2 - (p_{\pi^+}^2 + p_{K^+}^2 - 2p_{\pi^+}p_{K^+}\cos\theta)},$$

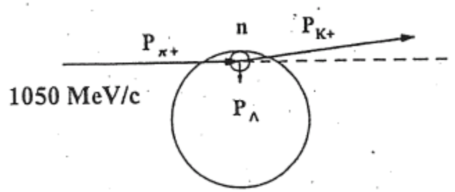
$$B_\Lambda = M_{\mathrm{core}} + M_\Lambda - M_{\mathrm{HYP}}$$

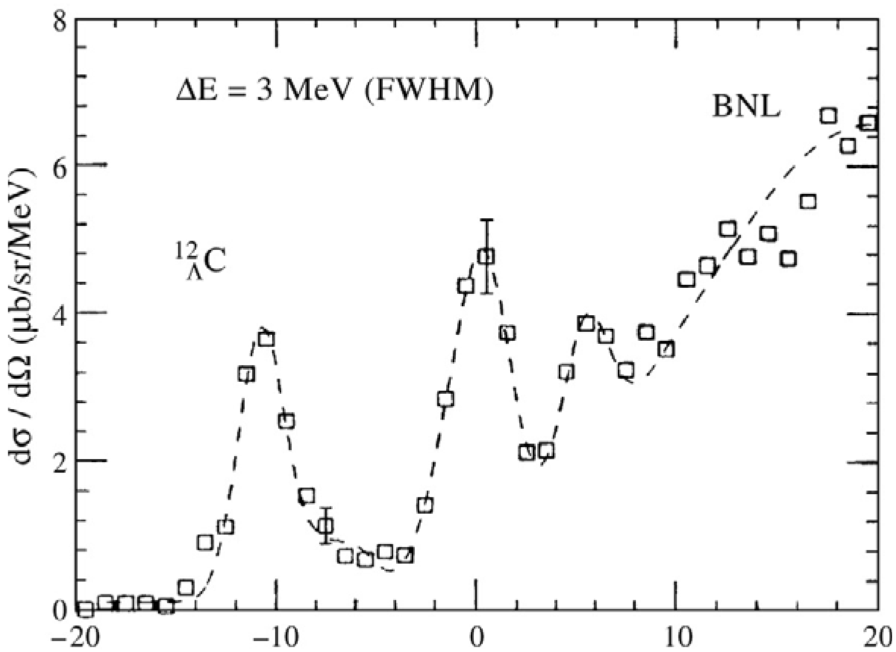


$A(\pi+,K+)\ A_\Lambda$ reaction

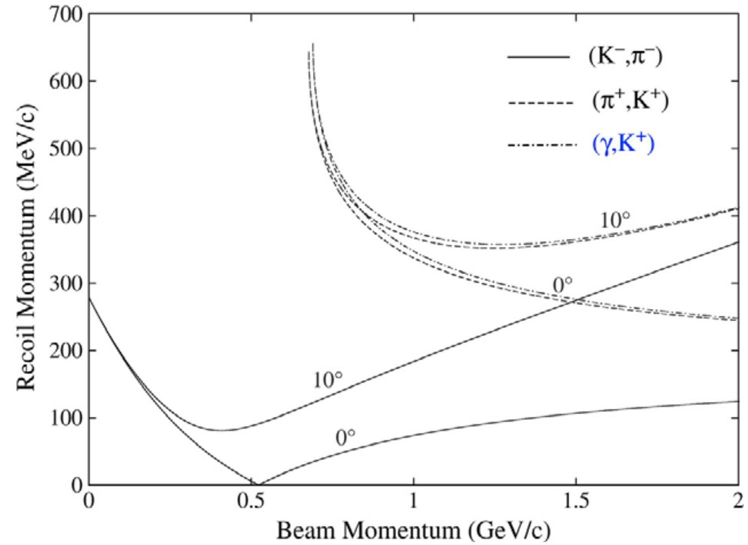
(π^+, K^+) 反応

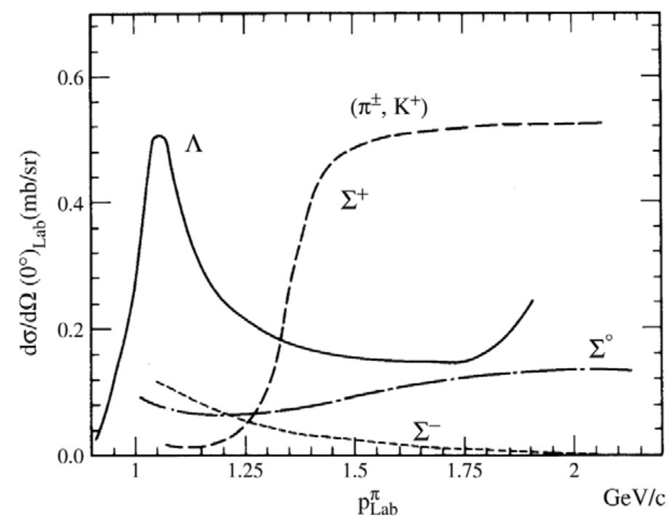
$$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+ \ (Q<0)$$



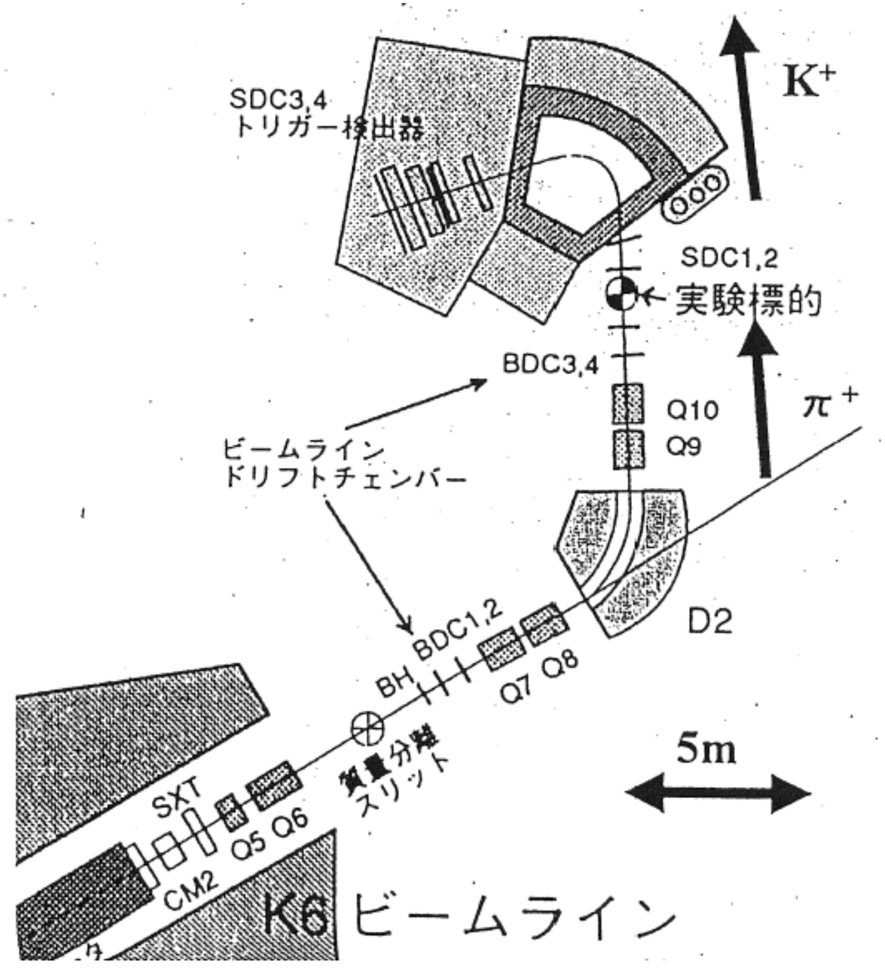


$-B_\Lambda$(MeV)

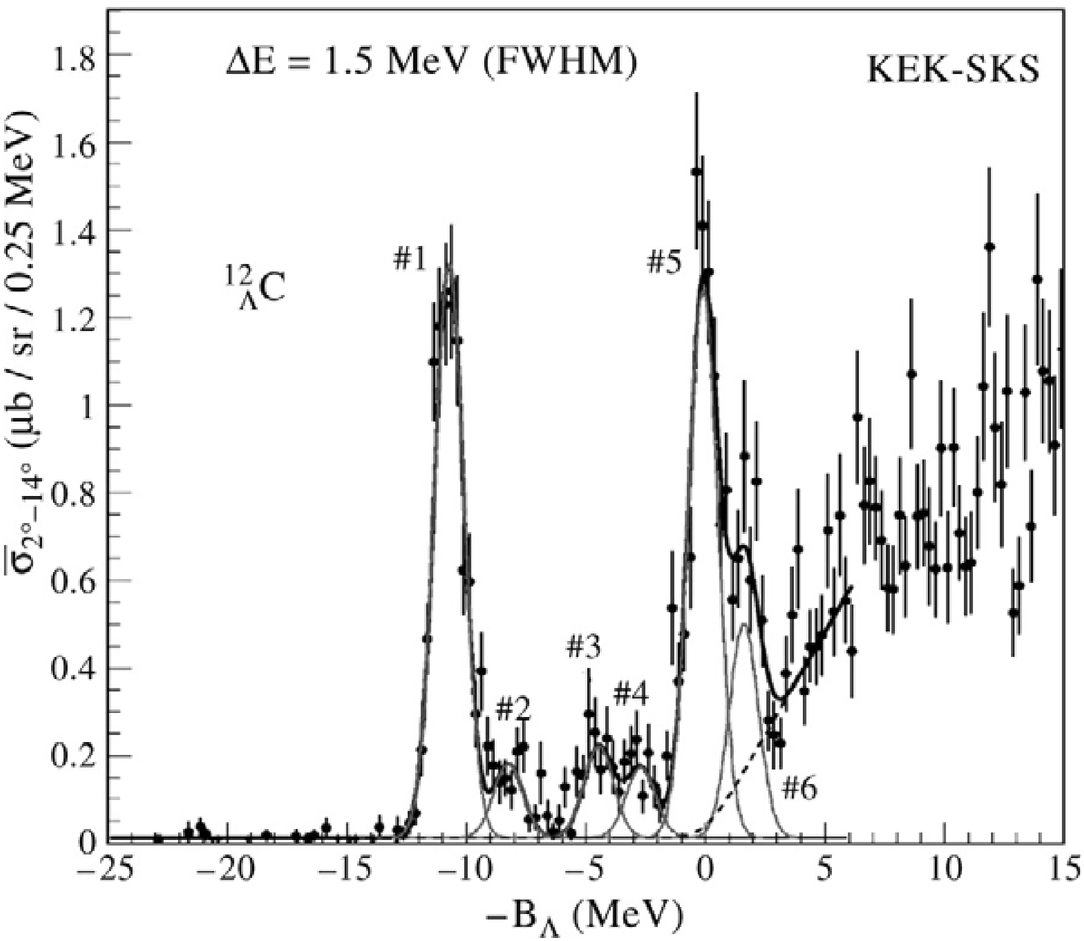


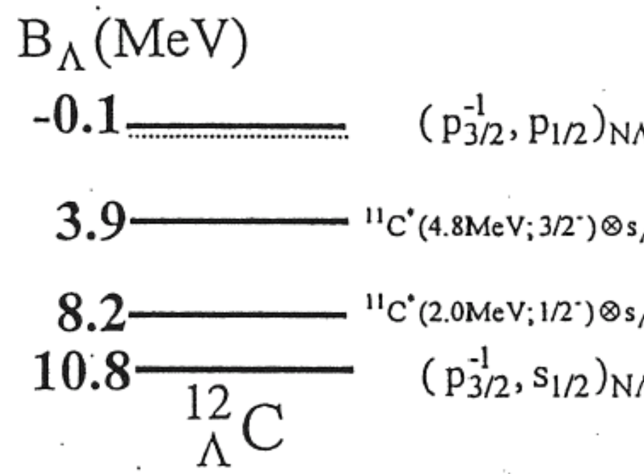


KEK-PS SKS spectrometer



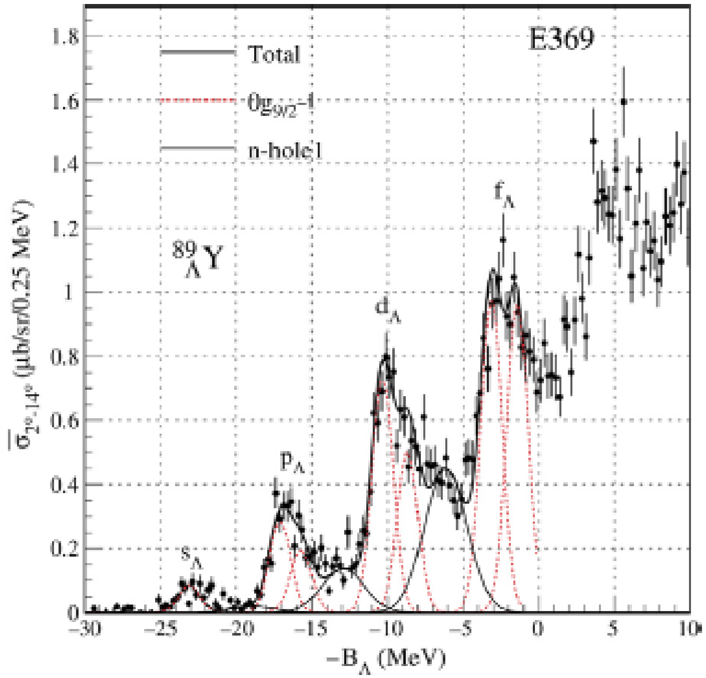
High resolution spectrum with SKS

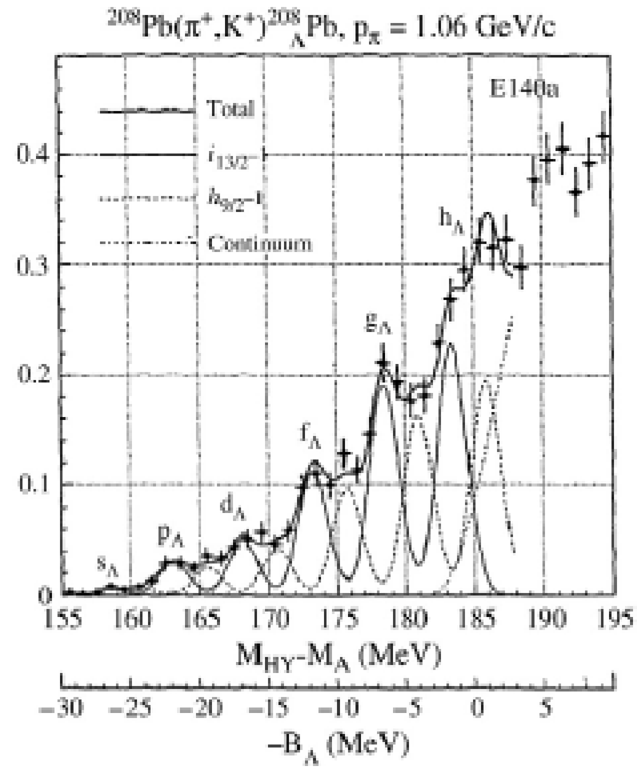




O.Hashimoto et al.,
NP A639 (1998)

(π+,K+) spectroscopy at SKS (KEK-PS)





The (π^+, K^+) experiments with the SKS spectrometer

E140a	Systematic spectroscopy of Λ hypernuclei	$^{10}_{\Lambda}$B, $^{12}_{\Lambda}$C, $^{28}_{\Lambda}$Si, $^{89}_{\Lambda}$Y, $^{139}_{\Lambda}$La, $^{208}_{\Lambda}$Pb
E336	Light Λ hypernuclear spectroscopy	$^{7}_{\Lambda}$Li, $^{9}_{\Lambda}$Be, $^{12}_{\Lambda}$C, $^{13}_{\Lambda}$C, $^{16}_{\Lambda}$O
E369	Spectroscopy of medium-heavy hypernuclei	$^{12}_{\Lambda}$C, $^{51}_{\Lambda}$V, $^{89}_{\Lambda}$Y

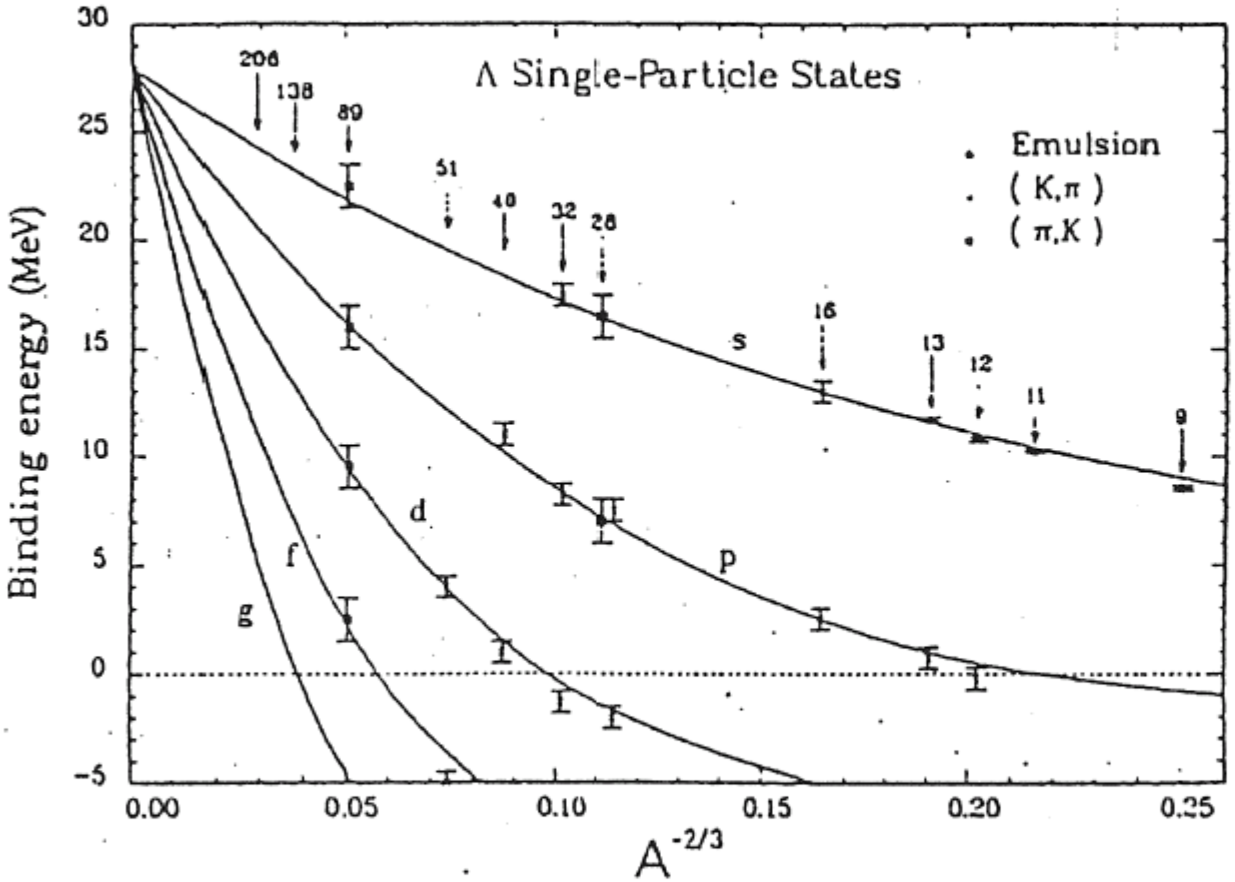
Λ single particle states

Woods - Saxon

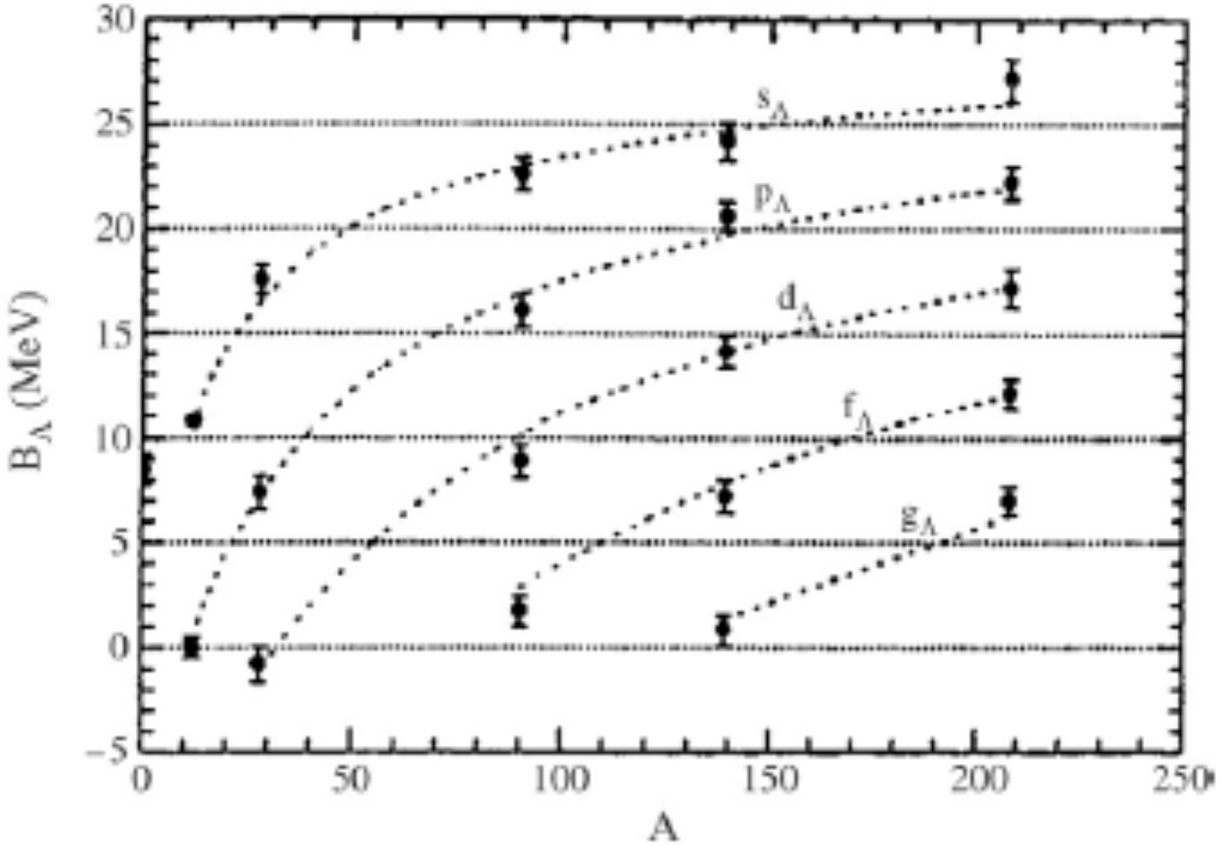
well depth ≈ 28 MeV

$r_0 = 1.128 + 0.439 A^{-2/3}$

~3/5 of nucleon



fit to heavy nuclei



$V_\Lambda \sim 30$ MeV

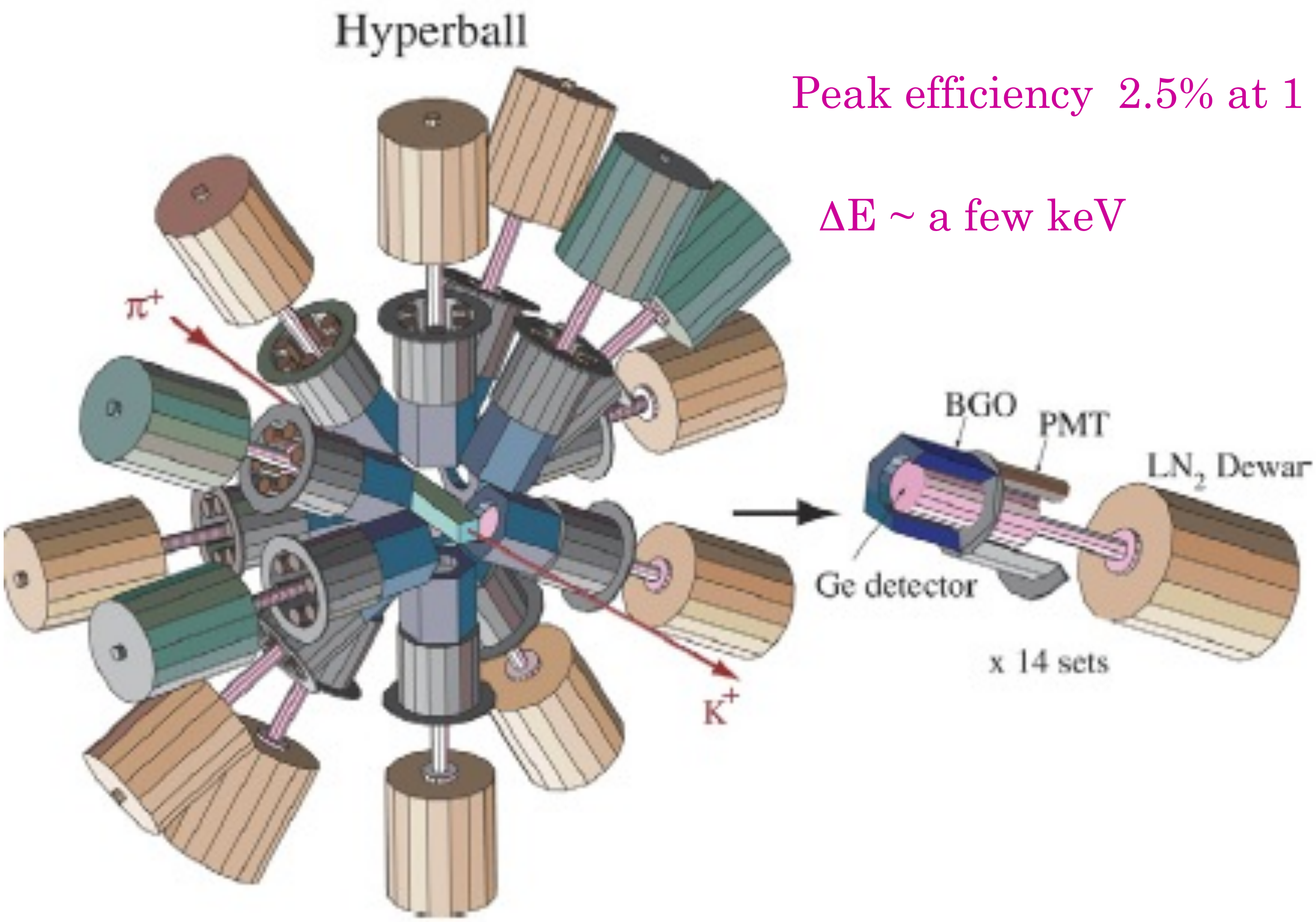
Spin dependence (fine structure)

- If a core nucleus (A) has spin I, a hypernucleus (A_Λ) has spin doublet (J+- ½) ~ <MeV

which depend on spin-dependent ΛN interactions (spin-spin, spin-orbit and tensor interactions)

→ γ spectroscopy of hypernuclei

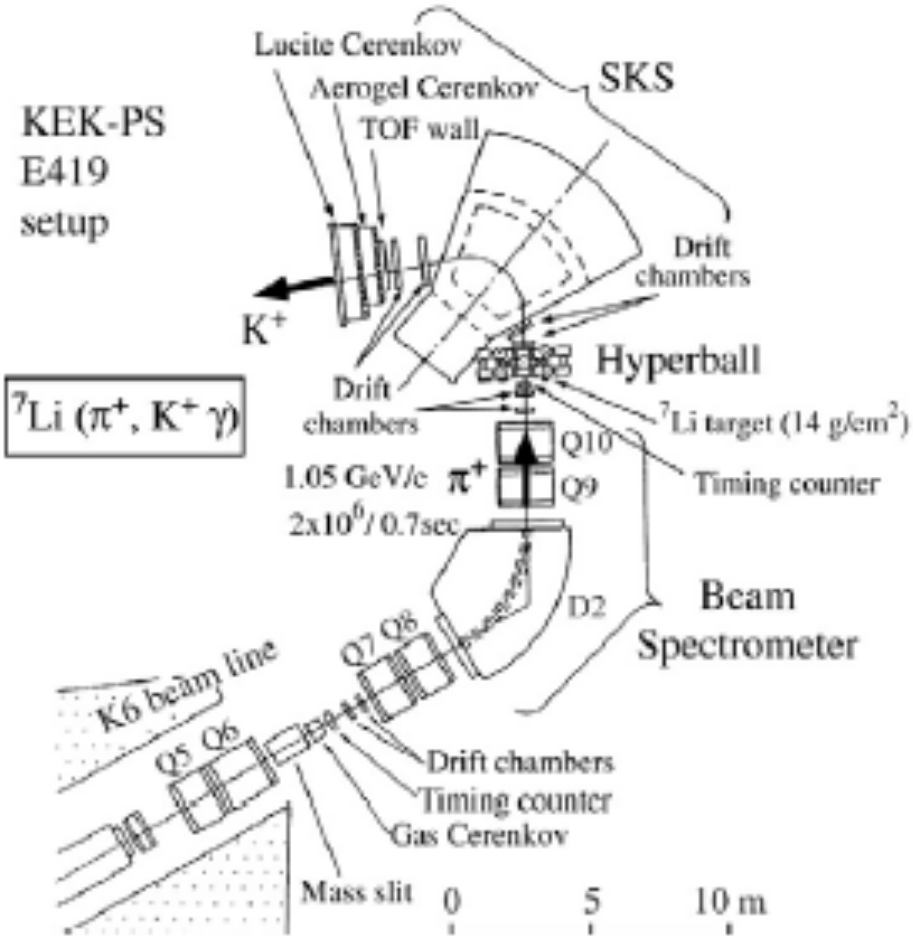
large acceptance Ge detector - Hyperball

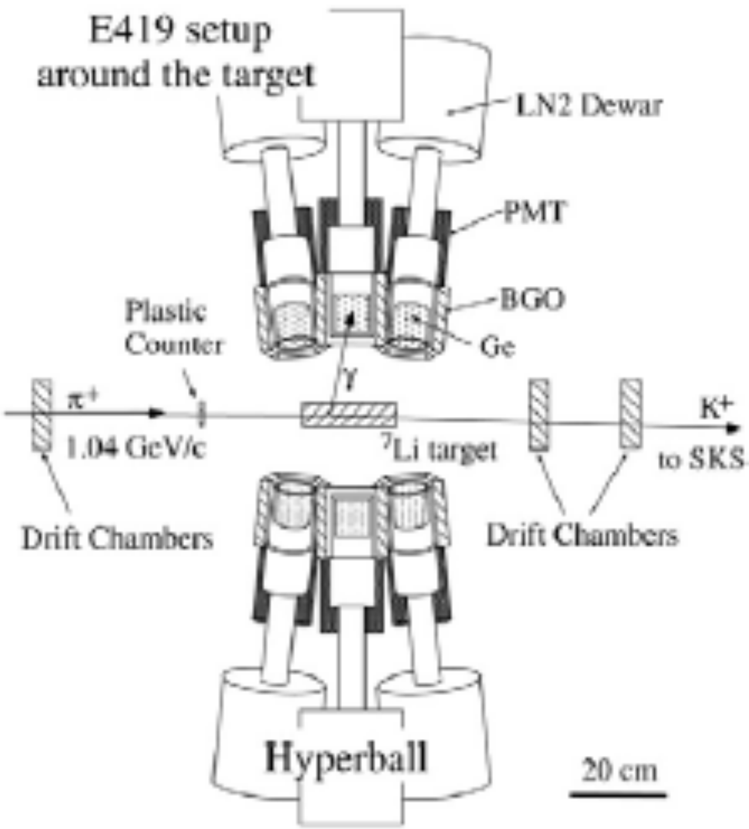


Peak efficiency 2.5% at 1 MeV

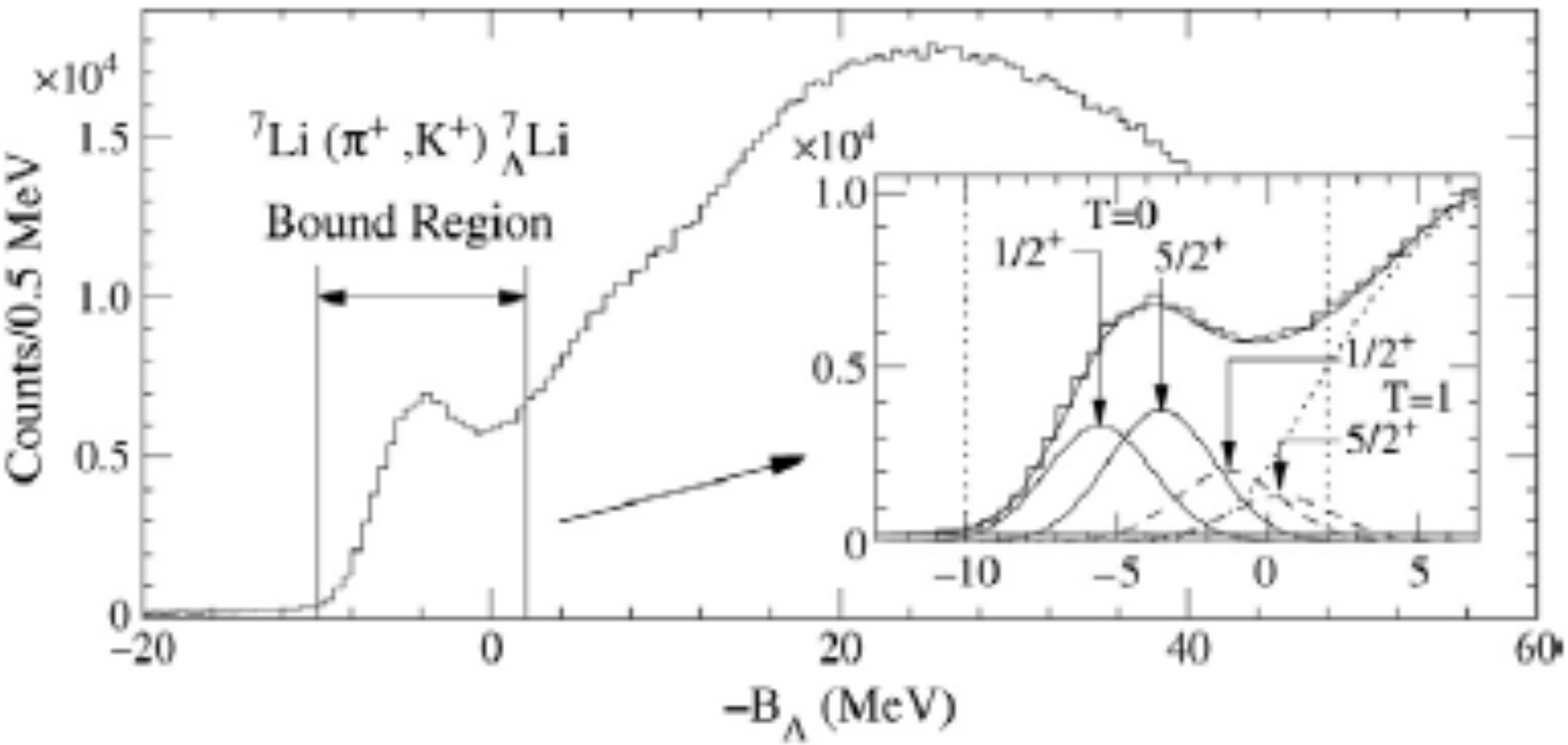
ΔE ~ a few keV

Setup of γ spectroscopy experiment at KEK (E419)

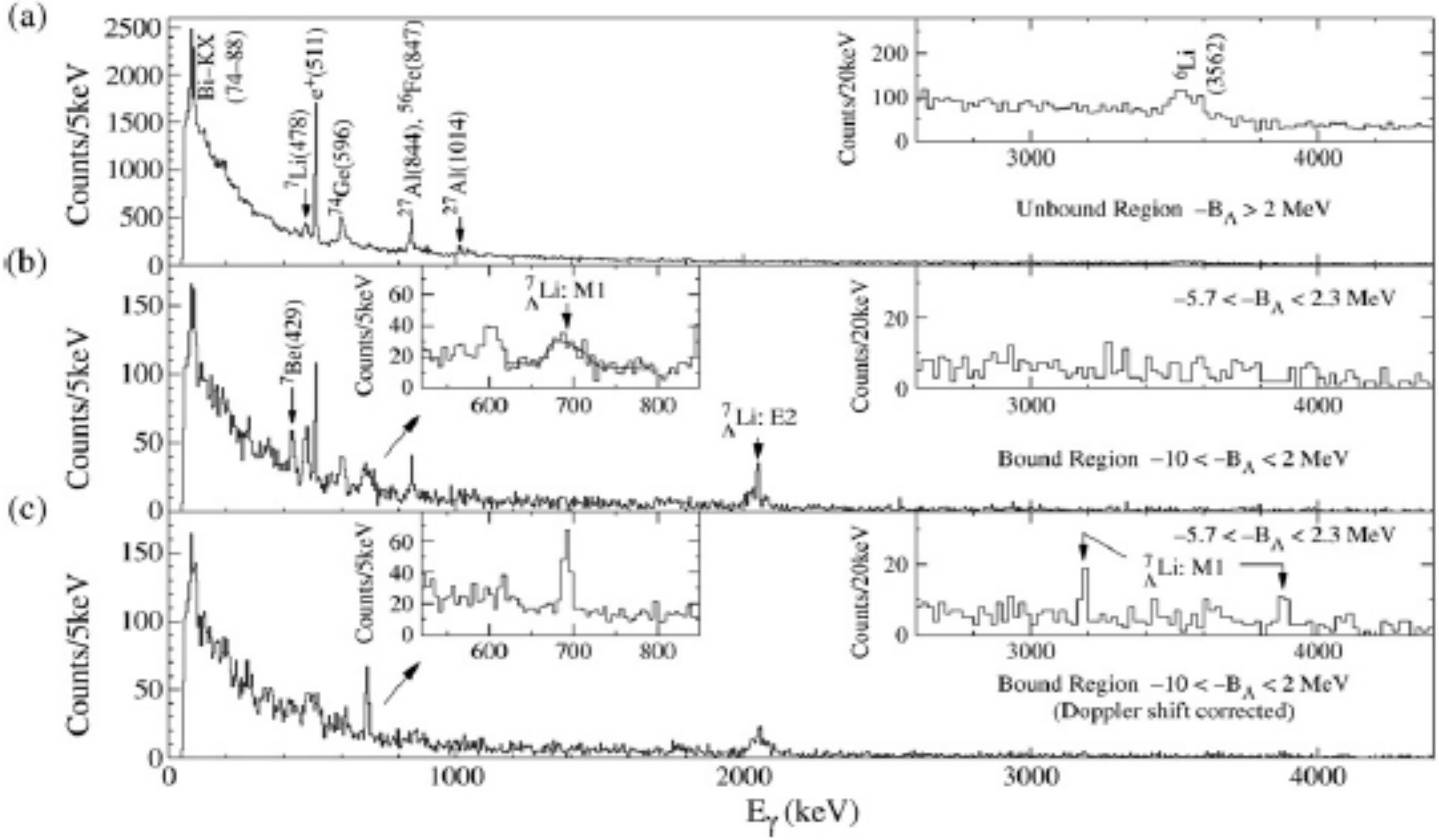




$^7Li(\pi+,K+)$ spectrum (thick target)

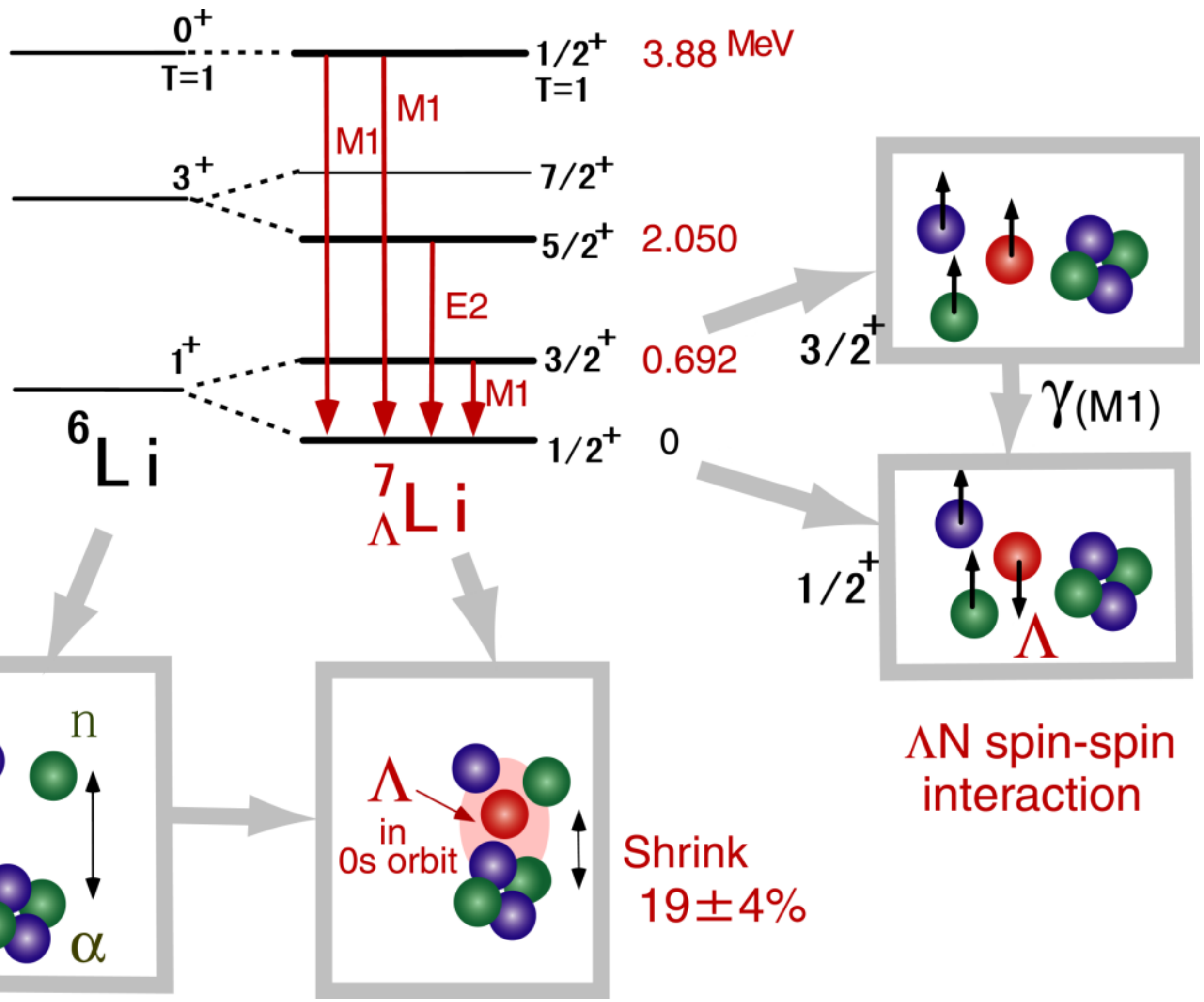


$^{7}Li(\pi^+,K^+\gamma)$ γ spectra *H.Tamura et al., PRL 84 (2000)*

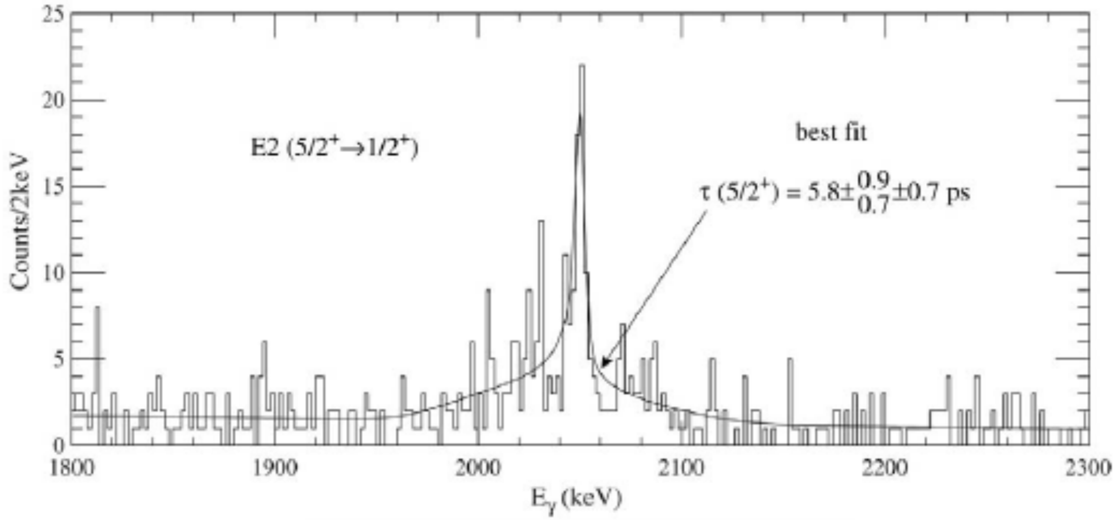


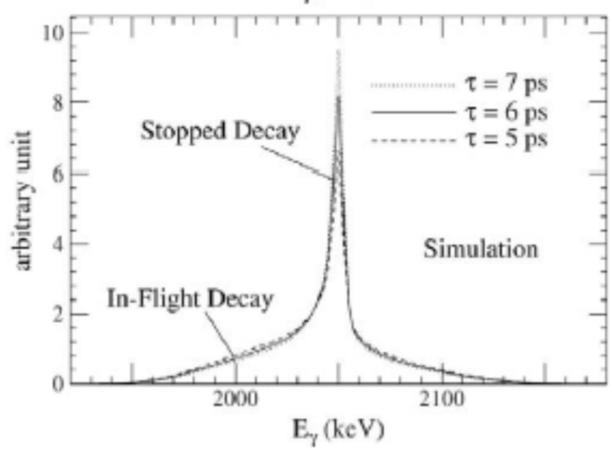
a) Unbound region b) bound region c) Doppler correction applied

level scheme of $^7Li_\Lambda$



B(E2) Doppler attenuation method





$B(E2) \sim e\mathbf{r}^2$

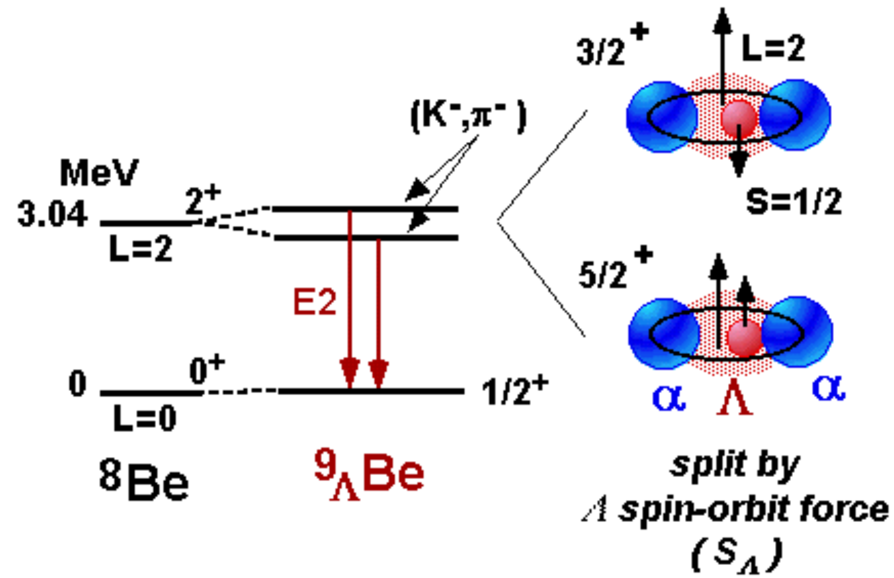
Srinkage (r): 19+-4%

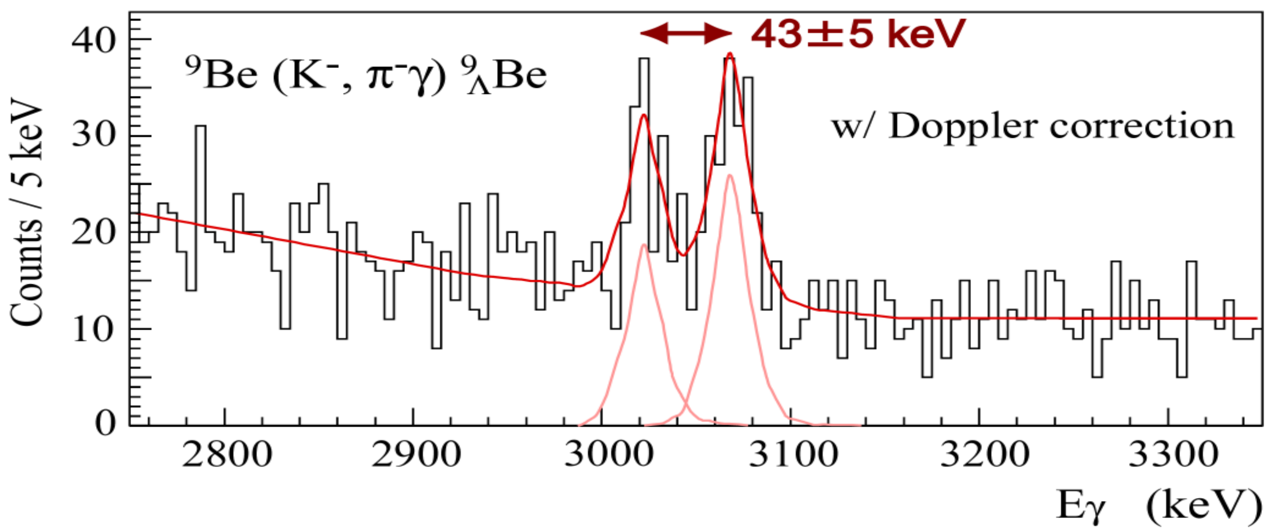
"hyper-fine" splitting of $^{9}Be_{\Lambda}$

Sensitive to ΛN spin-orbit force

~ 2 order smaller than NN !!

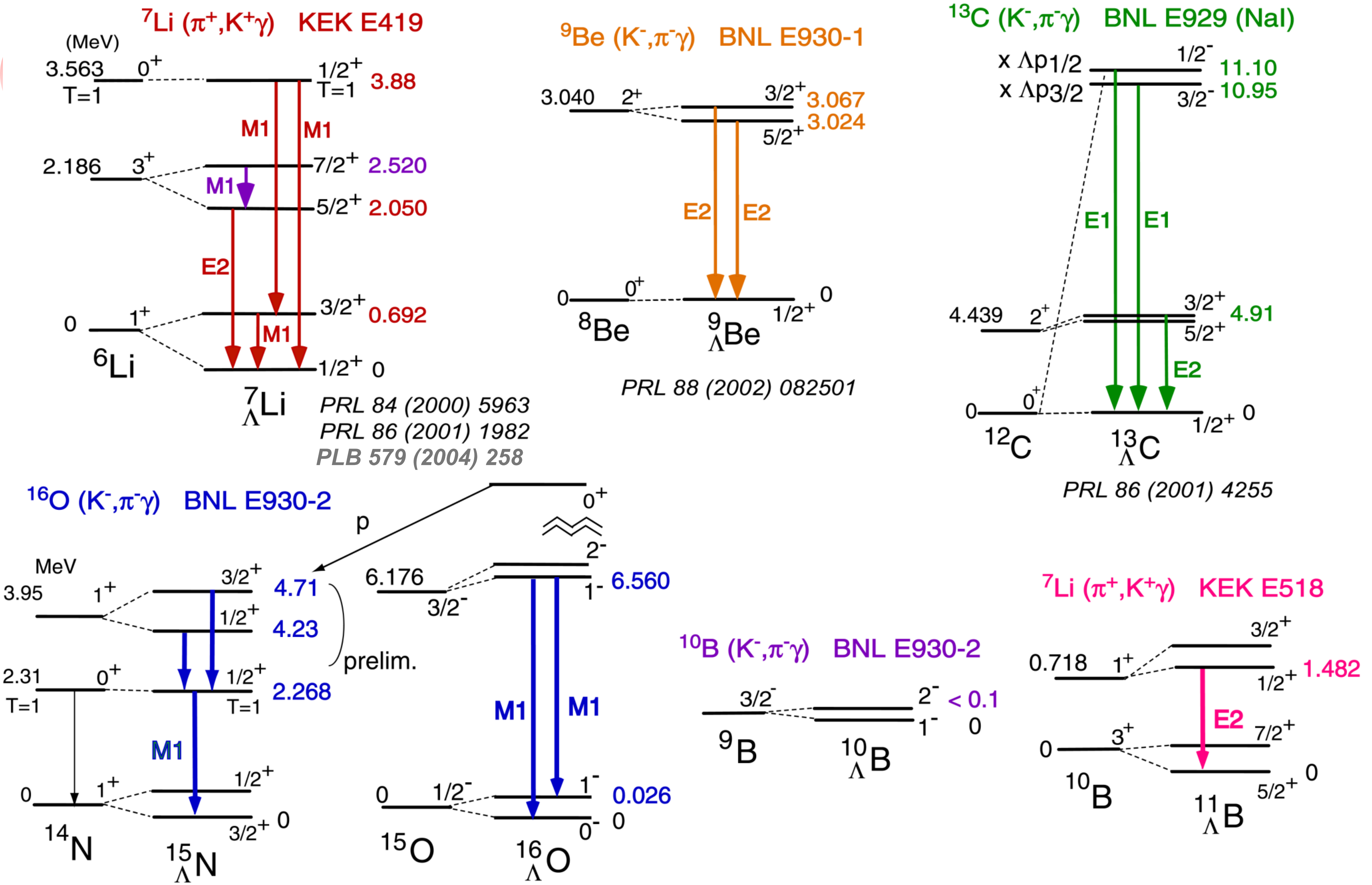
Akikawa et al., PRL 88 (2002) 82501





$^{13}C_{\Lambda}$ p2/3-1/2 splitting is consistent

Summary of observed γ



ΛN effective interaction in p-shell nuclei

Energy levels were fitted by a shell model using following effective interaction (J. Millener)

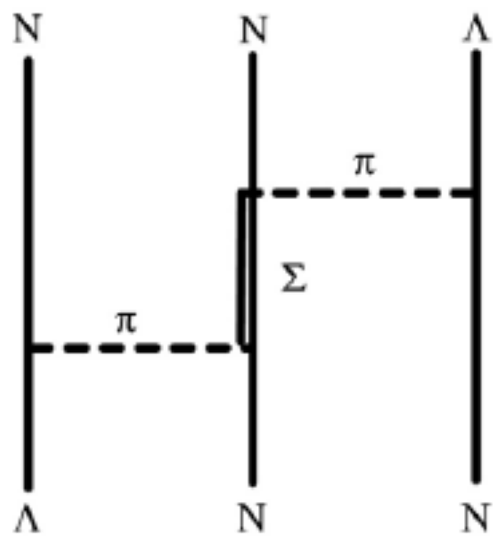
$$V_{\Lambda N}(r) = V_0(r) + V_\sigma(r)\, s_\Lambda\, s_N + V_\Lambda(r)\, l_{\Lambda N} s_\Lambda + V_N(r)\, l_{\Lambda N} s_N + V_T(r) S_{12}$$

V Δ S_Λ S_N T

Energies of the four hypernuclear level spacings that are described in terms of the spin-dependent ΛN interaction parameters obtained by Millener's shell model calculations [101]

Hypernuclear levels		Shell model calculation by Millener	$\Lambda\Sigma$ (MeV)	Exp. (MeV)
${}^{7}_{\Lambda}$Li	$E(3/2^+) - E(1/2^+)$	$1.444\Delta + 0.054S_\Lambda + 0.016S_N - 0.271T$	+0.071	0.692
${}^{7}_{\Lambda}$Li	$\overline{E(7/2+, 5/2+)}$	$-0.05\Delta + 0.07S_\Lambda + 0.70S_N - 0.08T$		1.858
	$-\overline{E(3/2+, 1/2+)}$[a]	$+\Delta E_{core}$[b]		
${}^{9}_{\Lambda}$Be	$E(3/2^+) - E(5/2^+)$	$-0.037\Delta - 2.464S_\Lambda + 0.003S_N + 0.994T$	−0.008	0.043
${}^{16}_{\Lambda}$O	$E(1^-) - E(0^-)$	$-0.382\Delta + 1.378S_\Lambda - 0.004S_N + 7.850T$	−0.014[c]	0.026

ΛΣ coupling and 3-body force



- ΛΣ mass difference (~70 MeV) is smaller than NΔ (~300 MeV)

→ more important in hypernuclei

charge symmetry breaking Λp Λn

$\Delta = 0.48\ \text{MeV}, S_{\Lambda} = -0.01\ \text{MeV}, S_N = -0.43\ \text{MeV}, T = 0.03\ \text{MeV}$

Very small Λ spin-orbit interaction and tensor interaction !!

(no pion exchange in ΛN)

Compared to Λ N potential (model) through G-matrix

boson exchange (Nijmegen)

quark cluster (Kyoto-Niigata fss)

chiral models

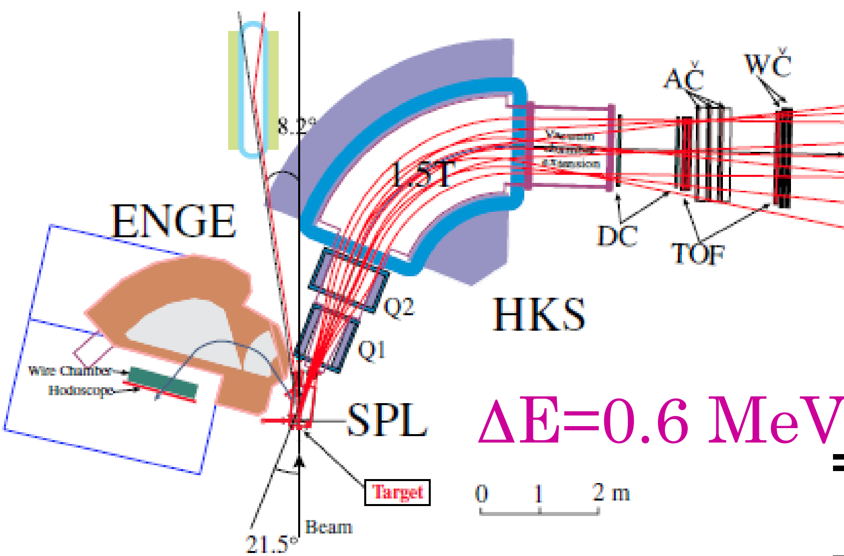
neutron rich hypernuclei 1

(e,e'K+) at Jlab (Mainz)

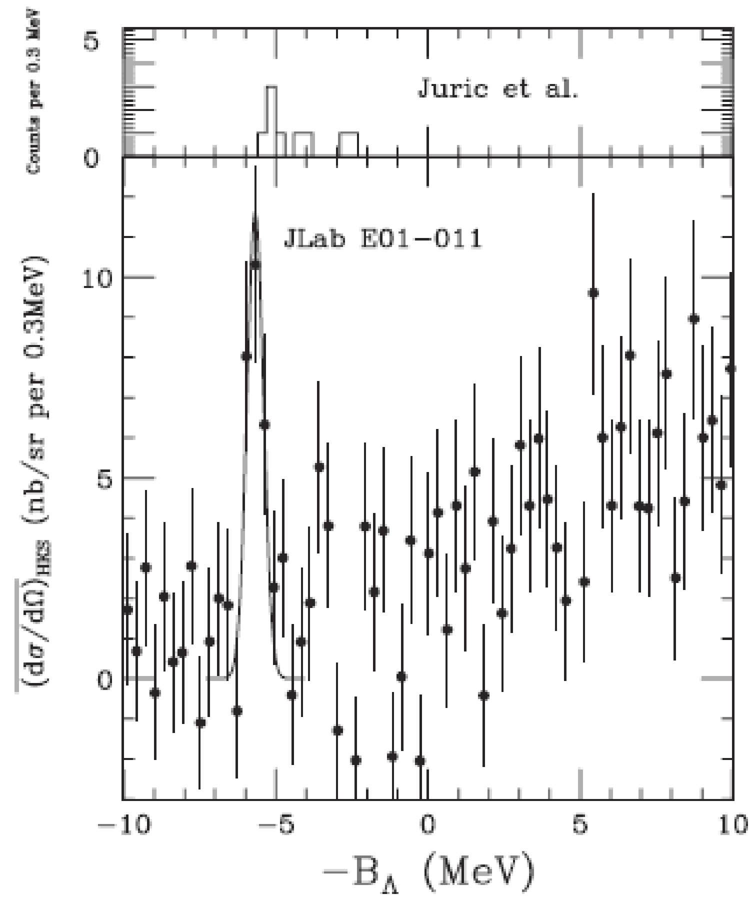
p → Λ

^{7}Li(e,e'K+)^{7}He$_\Lambda$

S.N.Nakamura et al., PRL 110 (2013)



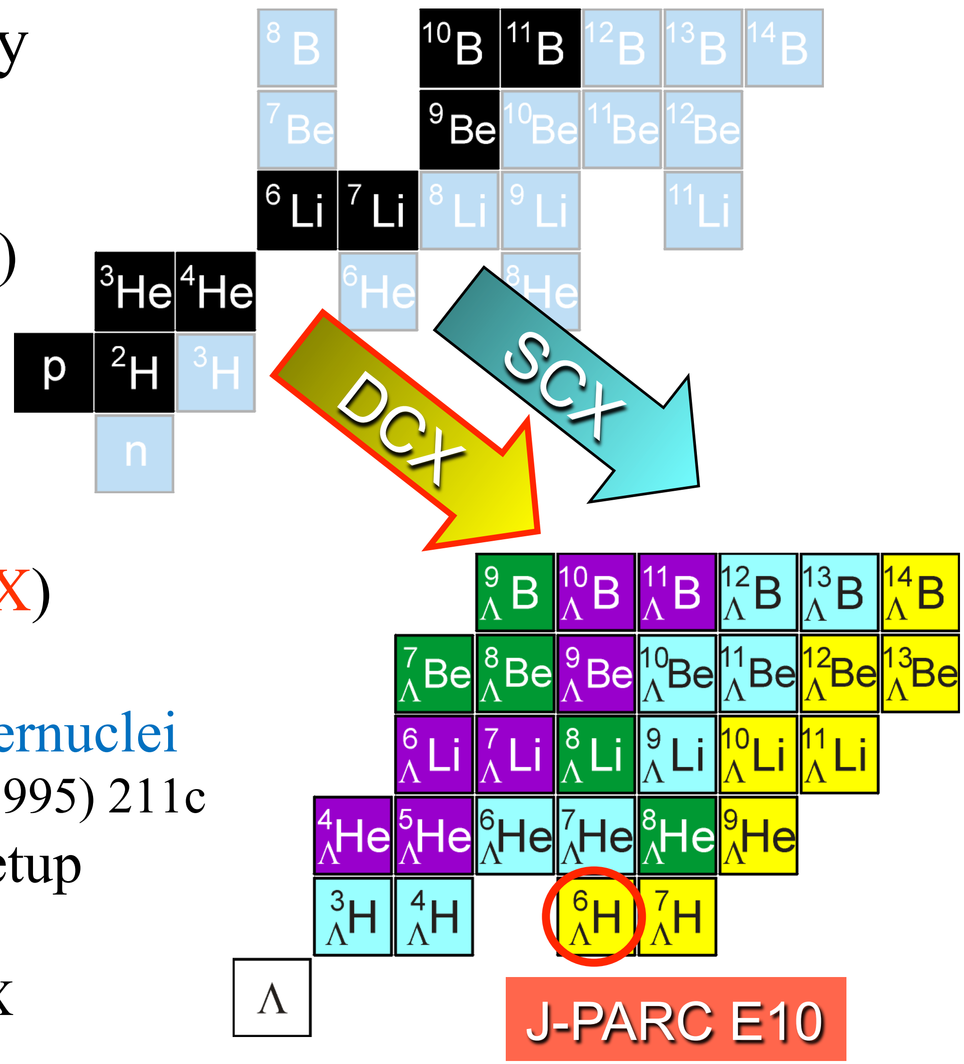
ΔE=0.6 MeV



	$^7_\Lambda$He (E01-011)	$^7_\Lambda$Li* [6,17]	$^7_\Lambda$Be [6]
B_Λ (MeV)	5.68 ± 0.03 ± 0.25	5.26 ± 0.03	5.16 ± 0.08

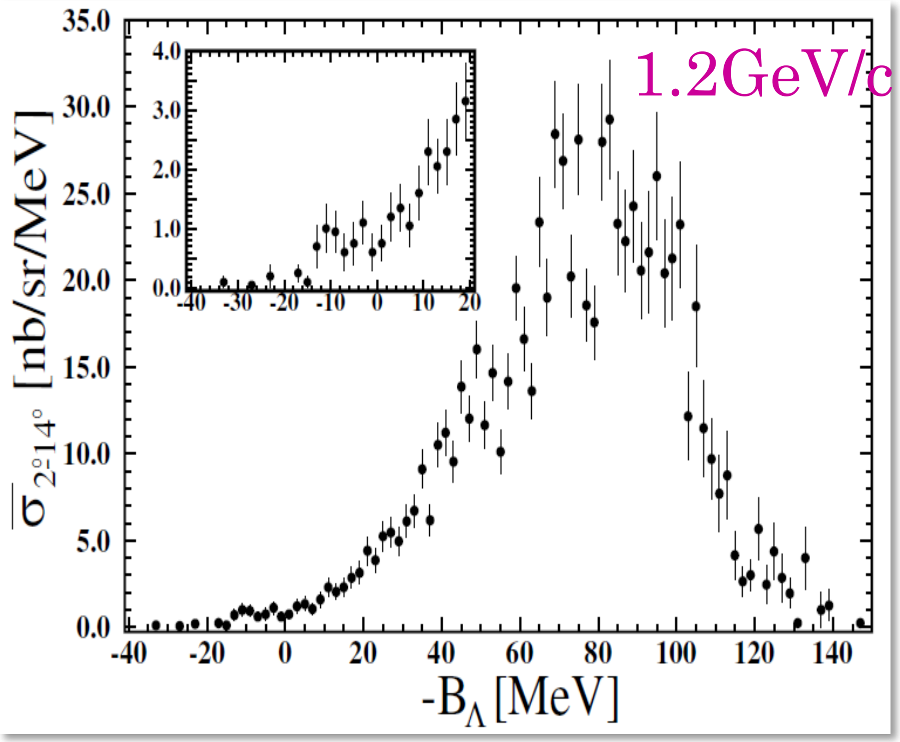
Double charge exchange (π^-,K^+), (K^-,π^+)

- Missing-mass spectroscopy
  - Non-CX reactions (NCX)
    - (K^-,π^-), (π^+,K^+)
  - Single CX reactions (SCX)
    - $(e,e'K^+)$
      - thin target
    - (K^-,π^0), (π^-,K_S)
      - Spectrometer ?
  - Double CX reactions (DCX)
    - (π^-,K^+), (K^-,π^+)
    - access neutron-rich hypernuclei
      - L. Majling NP A585 (1995) 211c
    - possible with existing setup
    - very low cross section !
      - roughly 1/1000 of NCX



Studies of neutron-rich Hypernuclei

- $^{10}B(\pi^-,K^+)^{10}{}_{\Lambda}Li$ reaction at KEK
  - P.K.Saha et al. PRL **94** (2005) 052501.
  - Pion beam momentum
    - **1.2** GeV/c → **11.3** nb/sr
  - 47 events in Λ bound region

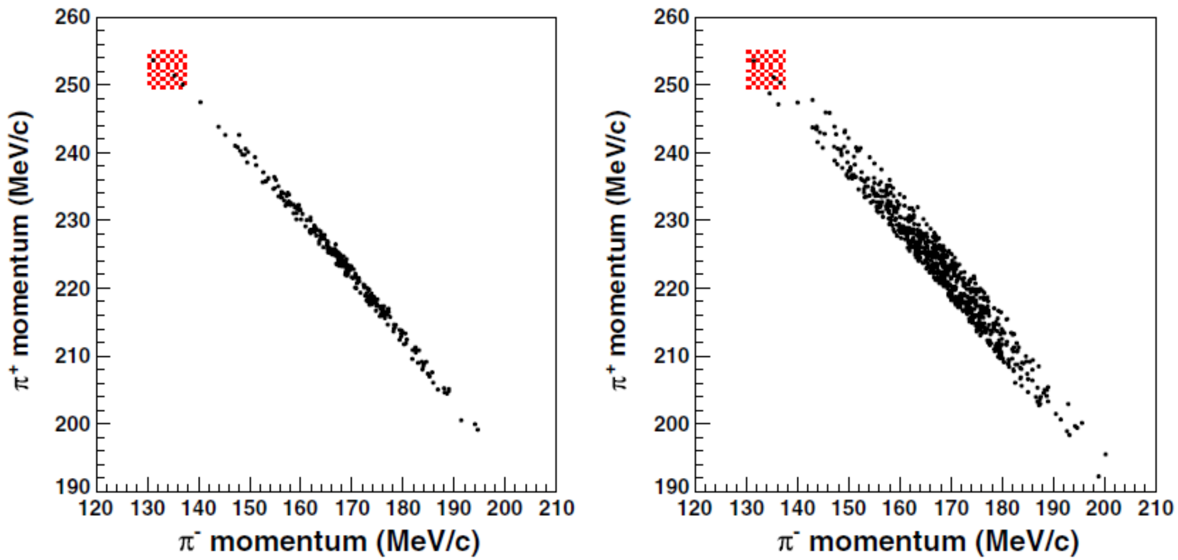


Studies of Neutron-rich Hypernuclei

- DAΦNE (FINUDA)
  - M. Agnello et al. PRL 108 (2012) 042501.
  - ^{6}Li(stopped K^-,π^+) reaction
    - measure also weak decay
    - cut on $T(\pi^+)+T(\pi^-)$
  - 3 events of candidates
    - $2.9 \pm 2.0 \times 10^{-6}$/(stopped K^-)

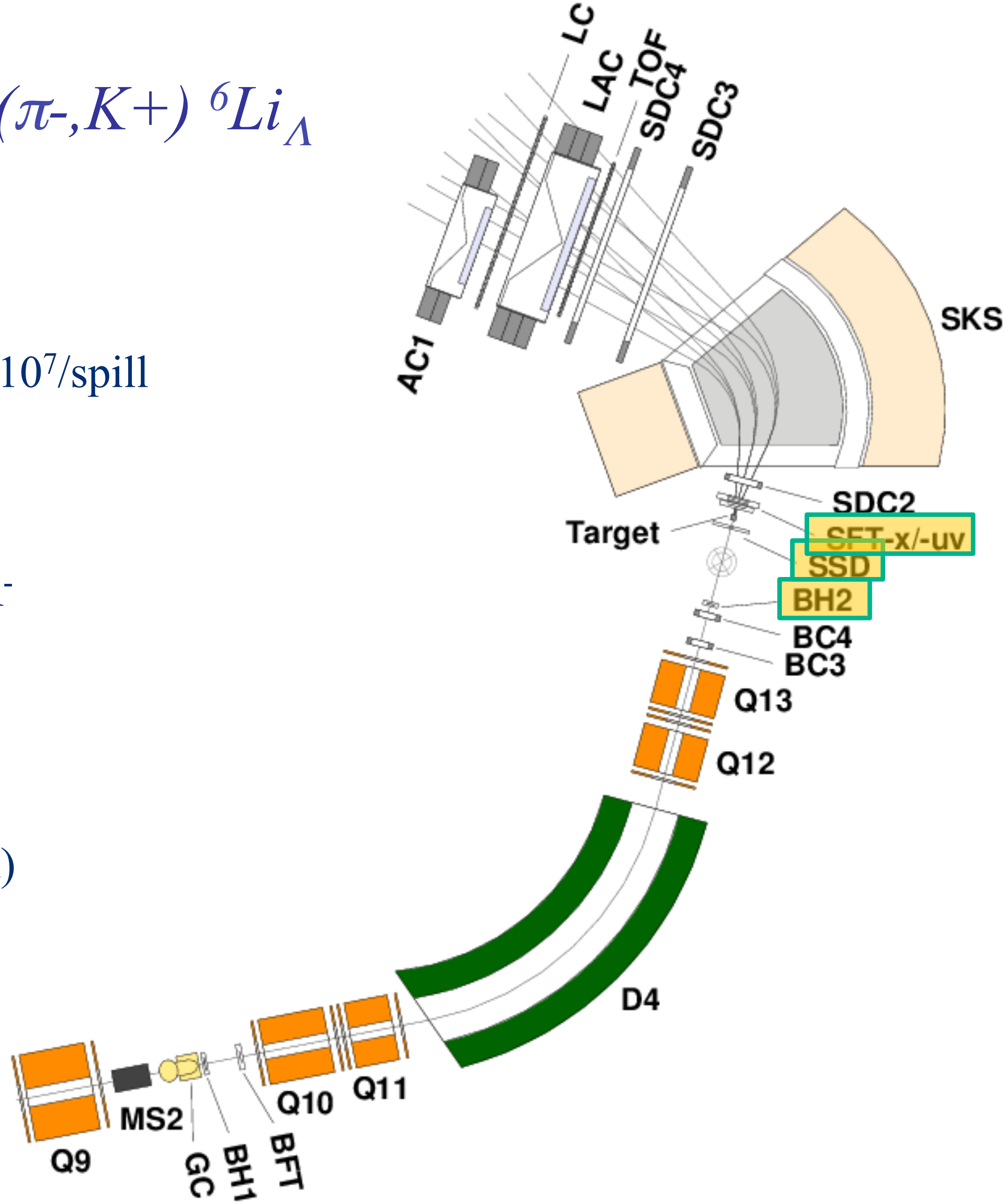
$$K^- + {}^{6}Li \rightarrow \underline{\pi^+} + {}^{6}_{\Lambda}H$$

$${}^{6}_{\Lambda}H \rightarrow \underline{\pi^-} + {}^{6}He$$

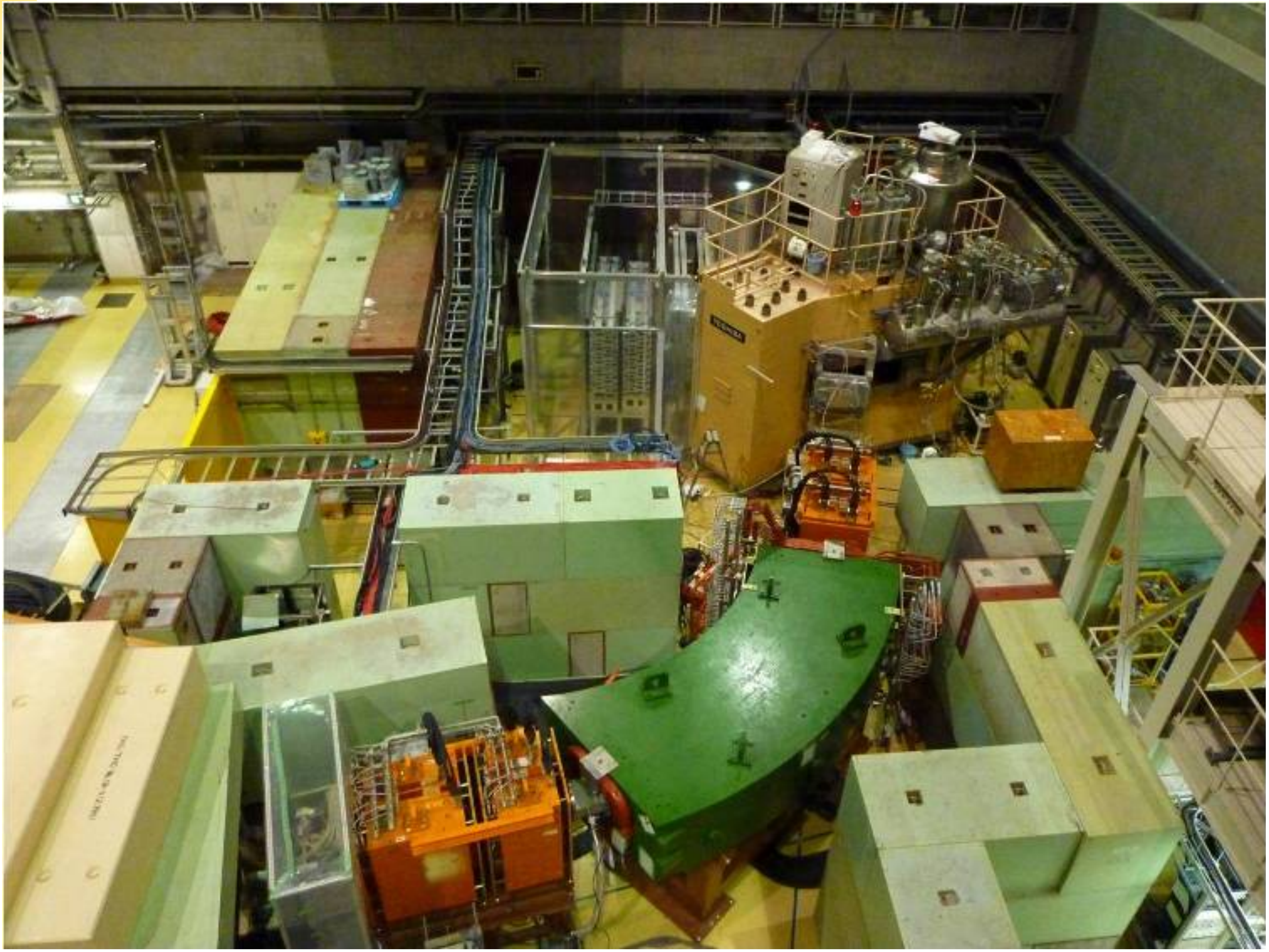


J-PARC E10 $^{6}Li(\pi^-,K^+)\ ^{6}Li_{\Lambda}$

- K1.8 Beam Analyzer
  - ✓ -1.2GeV/c π^- Beam 10^7/spill
  - ✓ $\Delta p/p \sim 3.3\times10^{-4}$
- SKS Spectrometer
  - ✓ 0.9GeV/c scattered K^-
  - ✓ $\Delta p/p \sim 1.0\times10^{-3}$
  - ✓ $d\Omega$ = 120 msr
- Target
  - ✓ ^{6}Li (95.54% enriched)
  - ✓ C and $(CH_2)_n$



K1.8 and SKS spectrometer at J-PARC



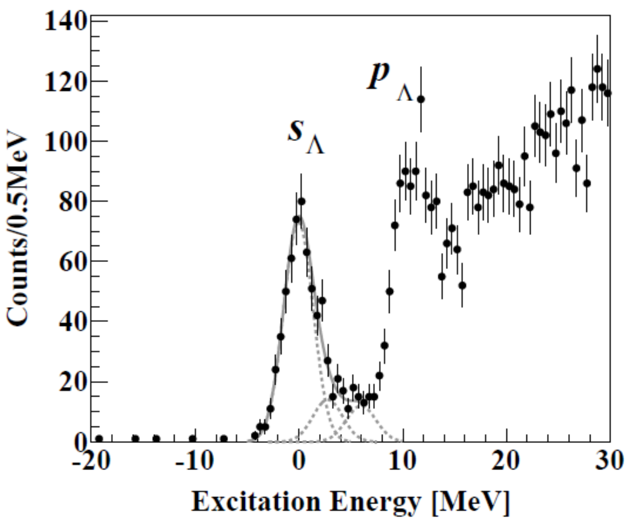
K1.8 and SKS at J-PARC

E10 result

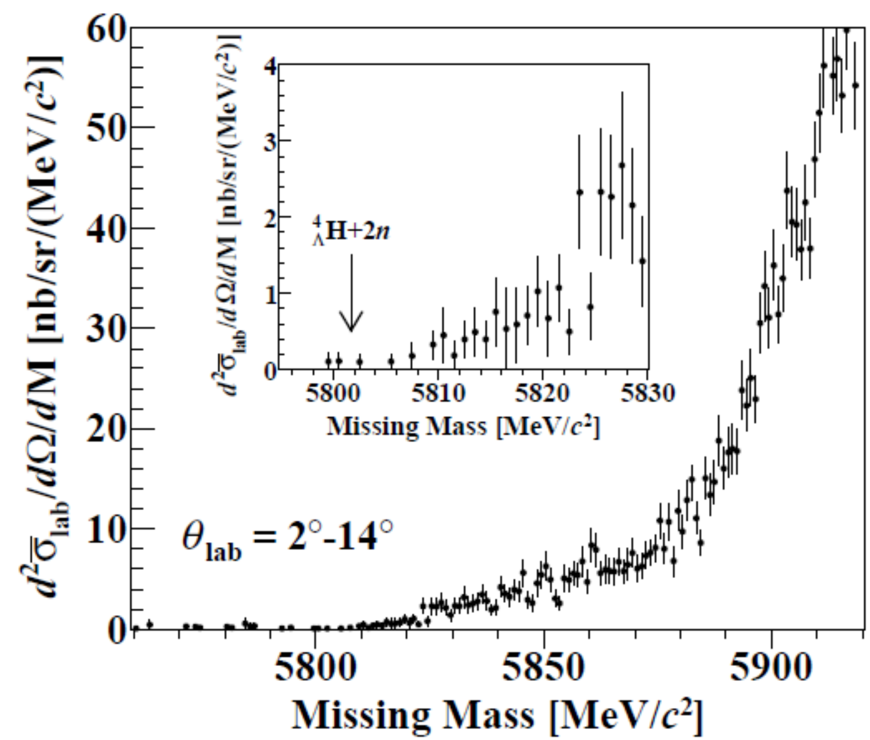
$^{12}C_{\Lambda}$ peaks look reasonable （Spectrometers OK ）

Almost no events in bound region（<nb/str）！

H.Sugimura et al., Phys. Lett. B724 (2014)



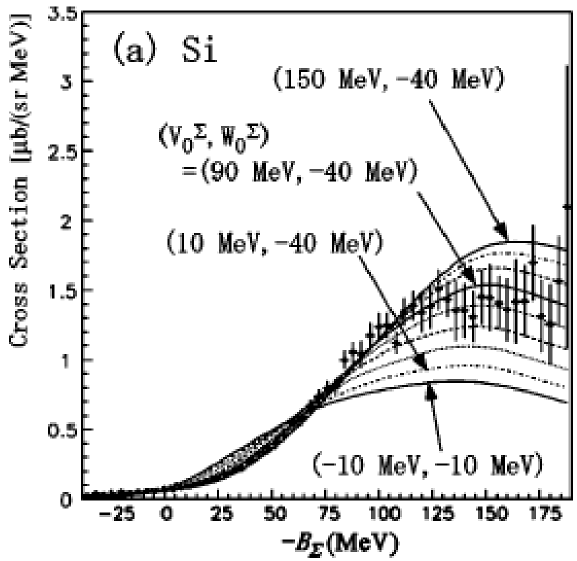
$^{12}C_{\Lambda}$

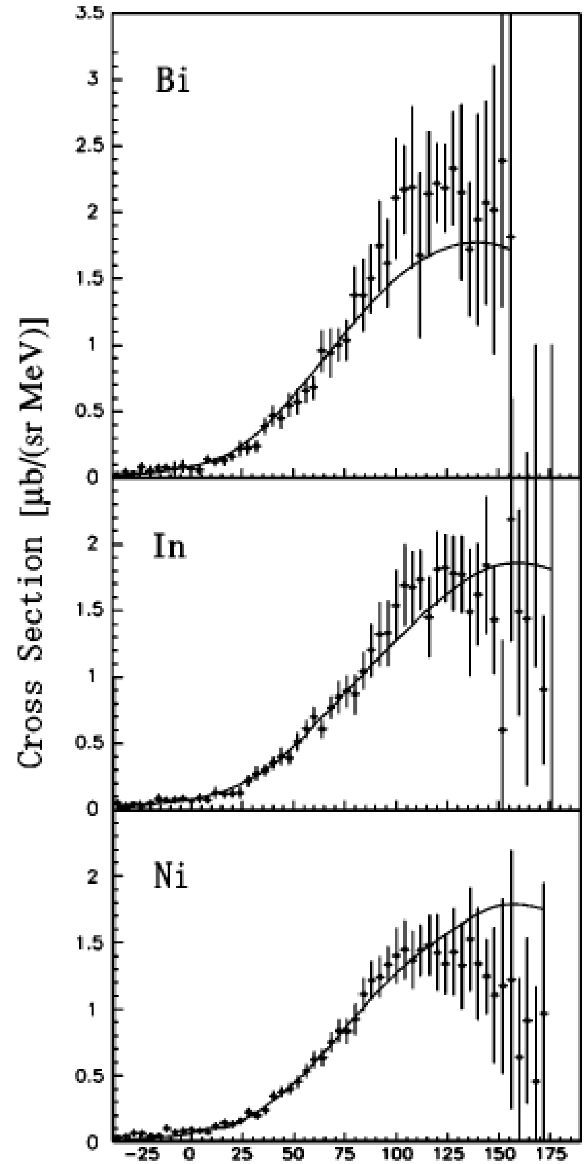


Σ-nuclei

No bound state except $^4He_\Sigma$ (T=1/2)

A(π-,K+) A(Σ^-) quasi-free spectra





DWIA fit gives repulsive Σ potential (~90 MeV)

Saha et al., PRC 70 (2004)

Double-strangeness Nuclei

Introduction

- Nuclei with s=-2

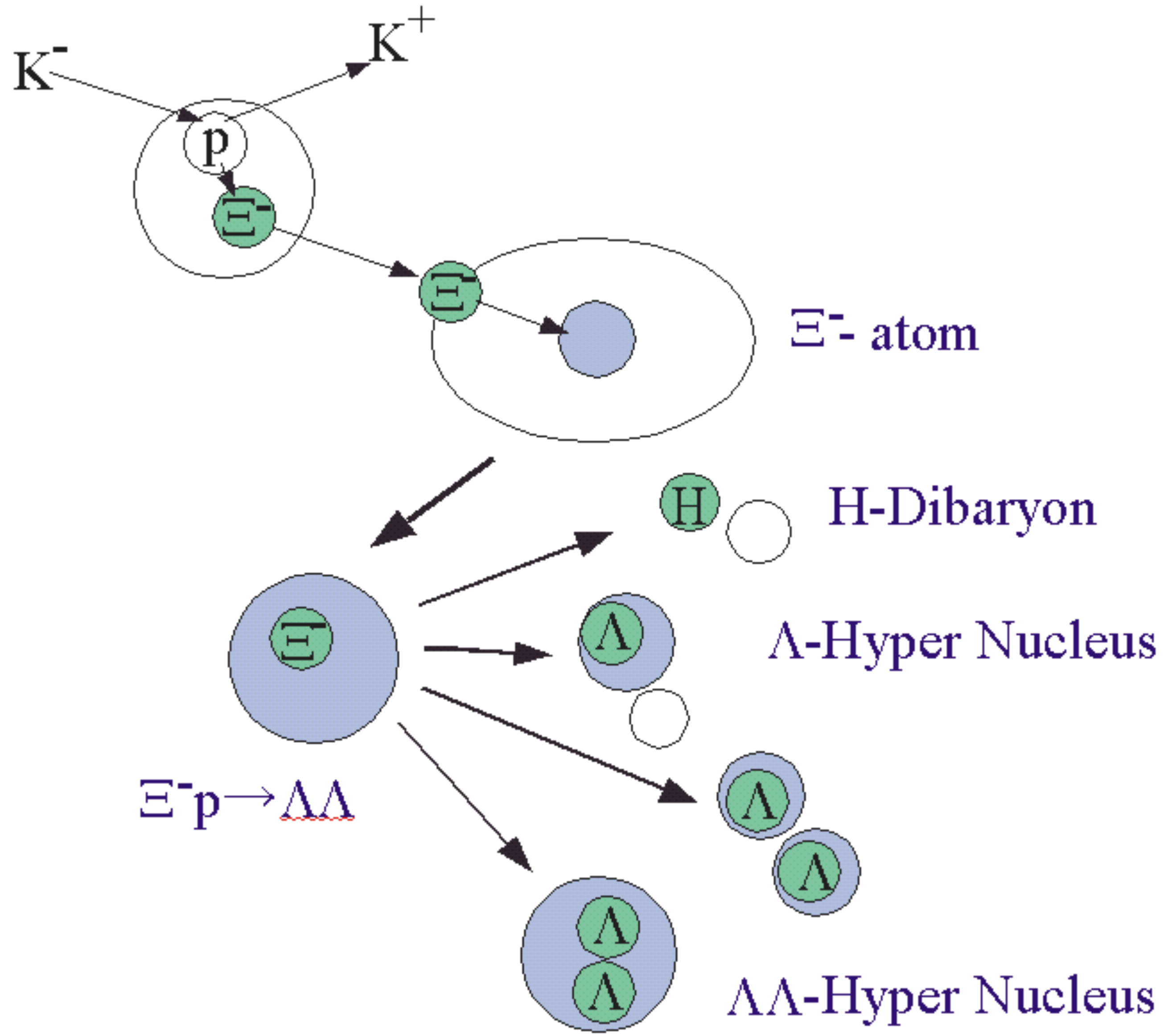
  (ΛΛ, H, ΞN) (KΛN, KΣN, KKNN)

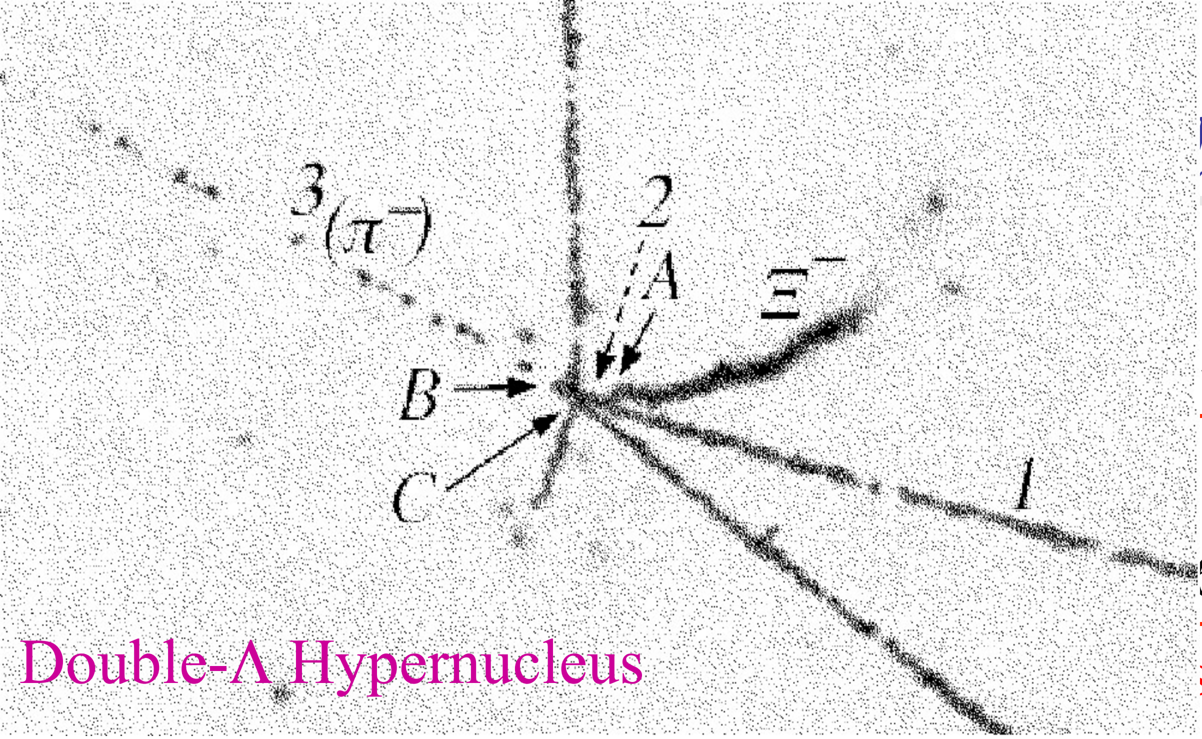
  Masses of ΛΛ, H, ΞN are close. ~28MeV

  What are well defined states with s=-2 ?

- Double Λ hypernuclei $^{6}He_{\Lambda\Lambda}$ (Nagara)
- Ξ-hypernuclei ?
- H and H-nuclei ?

Production of S=−2 Systems





'e hypernuclei

vents with emulsion

(1963)29.

66)782.

ss Ξ stop expected

Problem of "unique interpretation".

KEK-PS E176 **Hybrid-Emulsion Experiment**

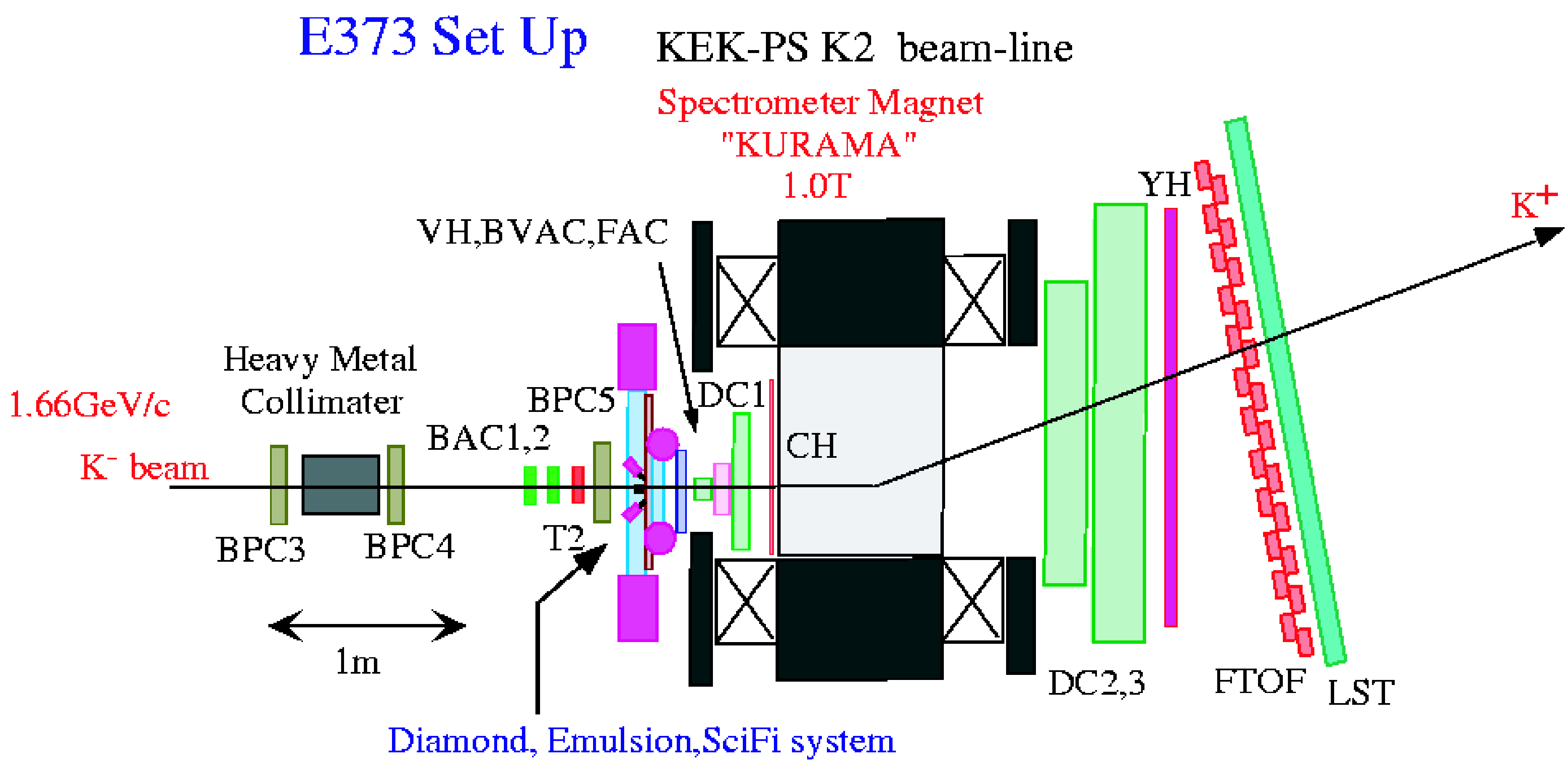
～80 Ξ^- stop events

One event ($^{10}_{\Lambda\Lambda}\mathrm{Be}$ or $^{13}_{\Lambda\Lambda}\mathrm{B}$) and Two twin-hypernuclei events

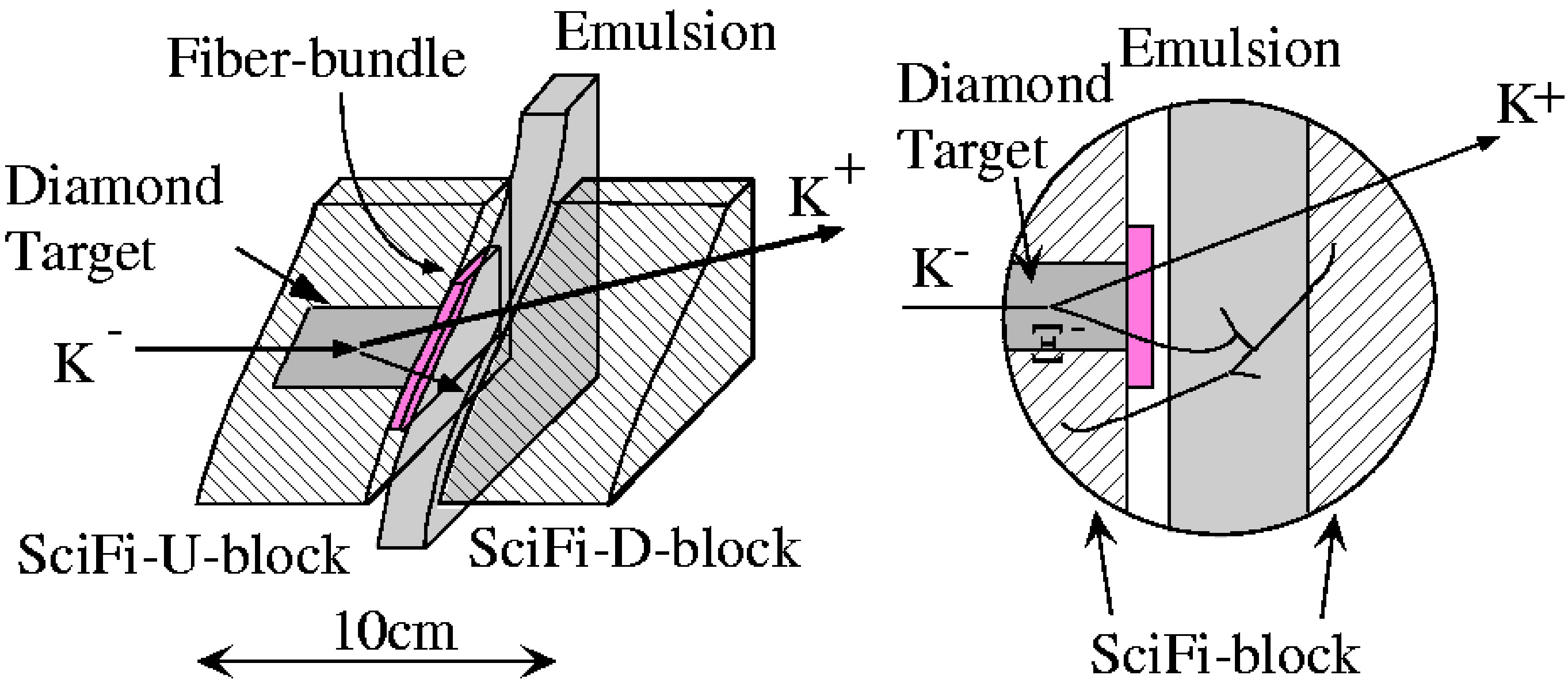
C *KEK-PS E373*

New Hybrid-Emulsion Experiment to obtain ～1000 Ξ^- stops

E373 Set up -Top View-



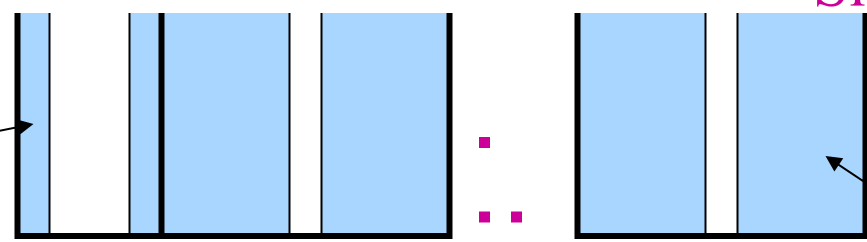
Setup around target



A. Ichikawa *et al.* Nucl. Instr. Meth. A417, 220(1998)

H. Takahashi *et al*. Nulc. Instr. Meth. In press.

Nuclear Emulsion

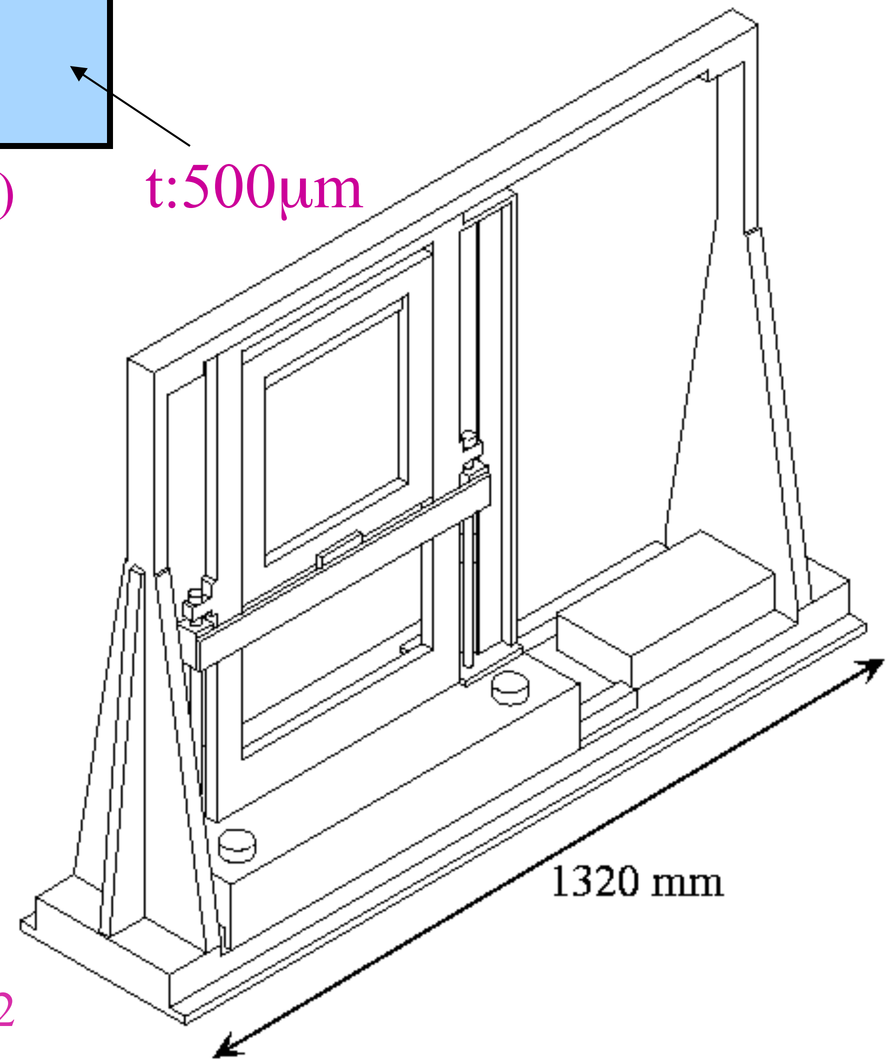


Area : 24.5×25.0 cm^2

Packed in vacuum chamber

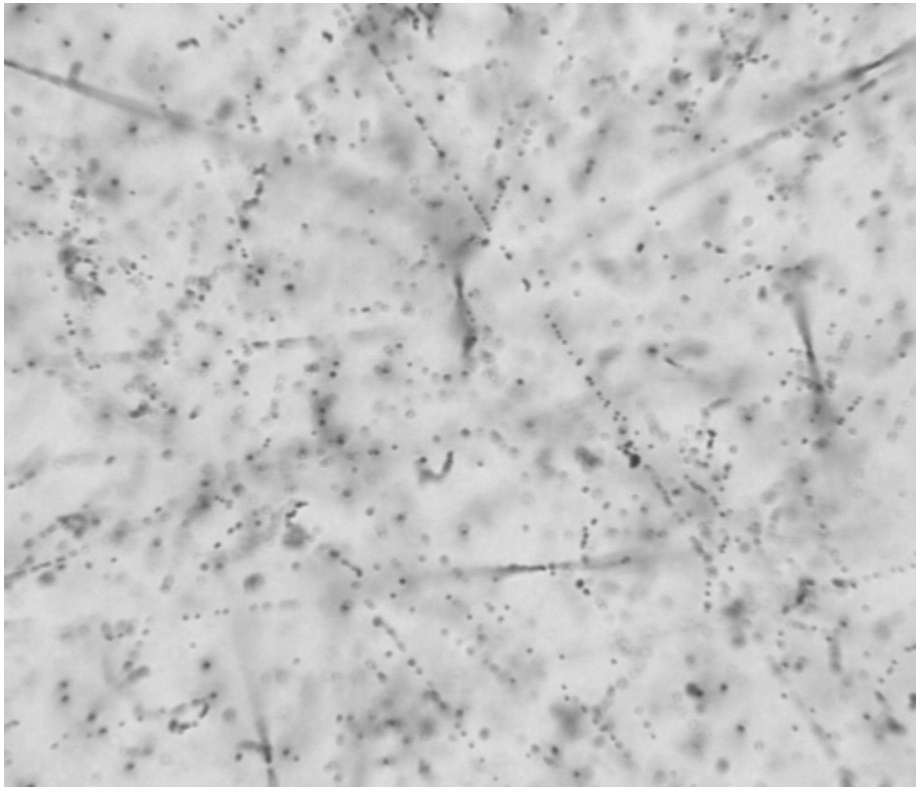
Emulsion Mover

- Controlled with PC
- Move emulsion during spills
- Keep track density to $1\times10^6/cm^2$

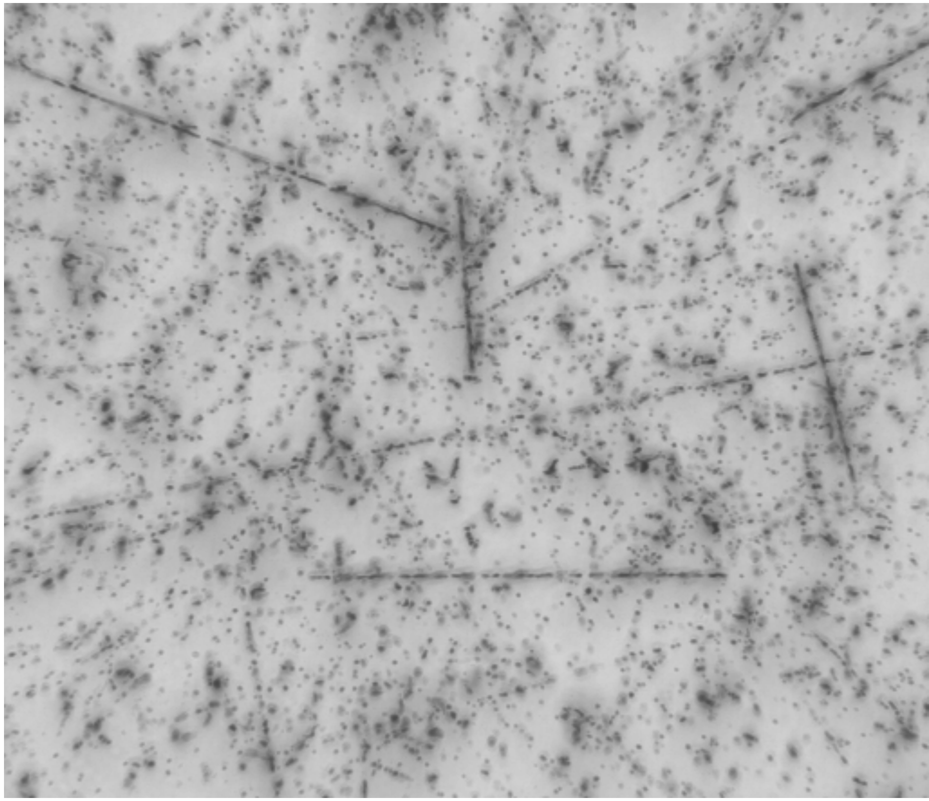


Example of Emulsion Image

Raw Image



Overlap Image

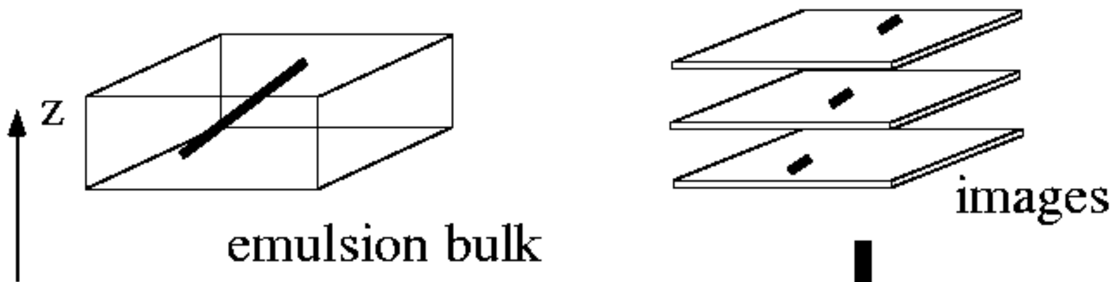


～100μm

Automatic Scanning

Track Finding Algorism (A. Ichikawa)

Take pictures at different z(focusing) position.
(z : pependicular to the emulsion plate)



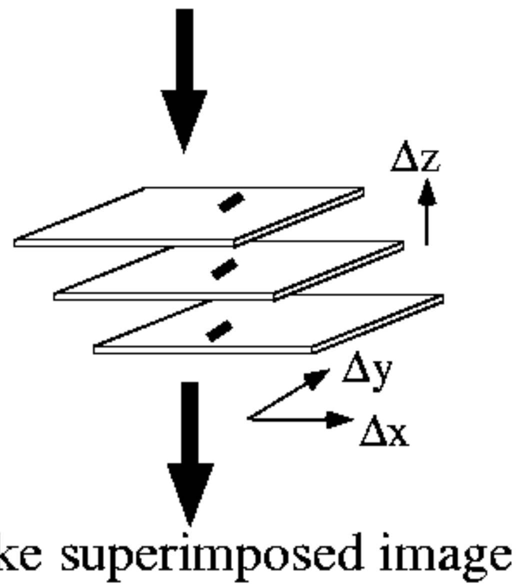
shift each image by ($-\Delta x$,$-\Delta y$)

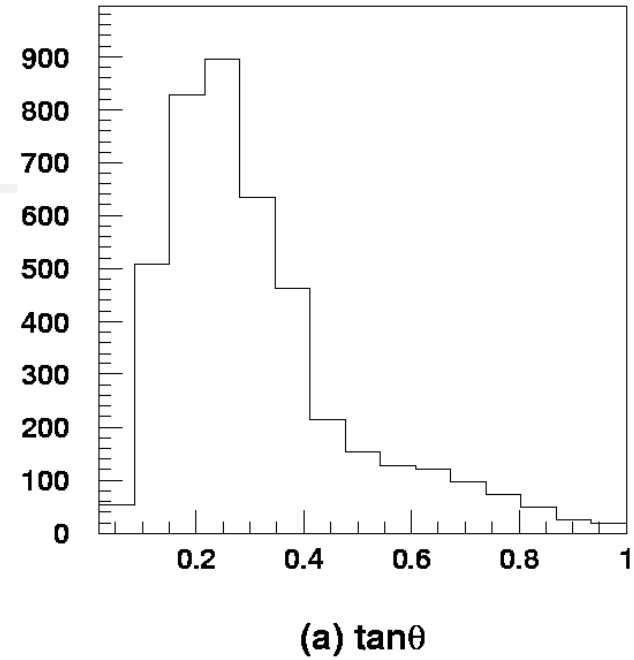
$\Delta x = dx/dz \times \Delta z$

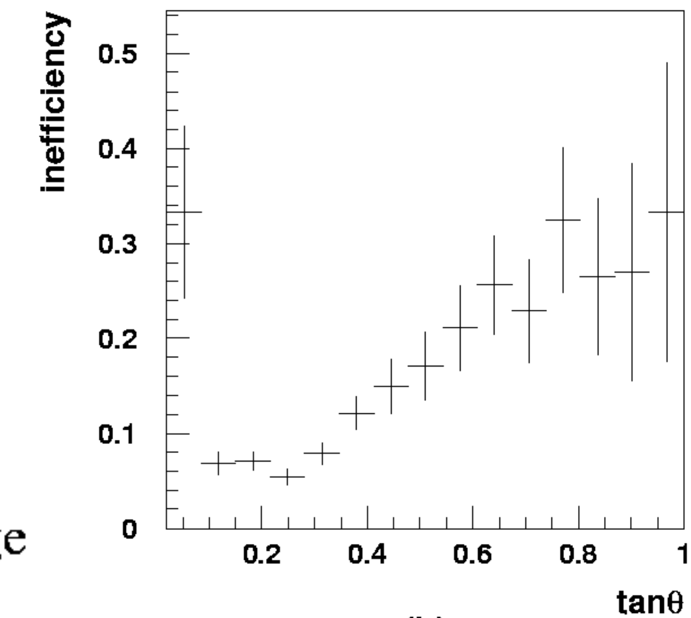
$\Delta y = dy/dz \times \Delta z$

dx/dz,dy/dz : predicted value

Δz : step size of z position



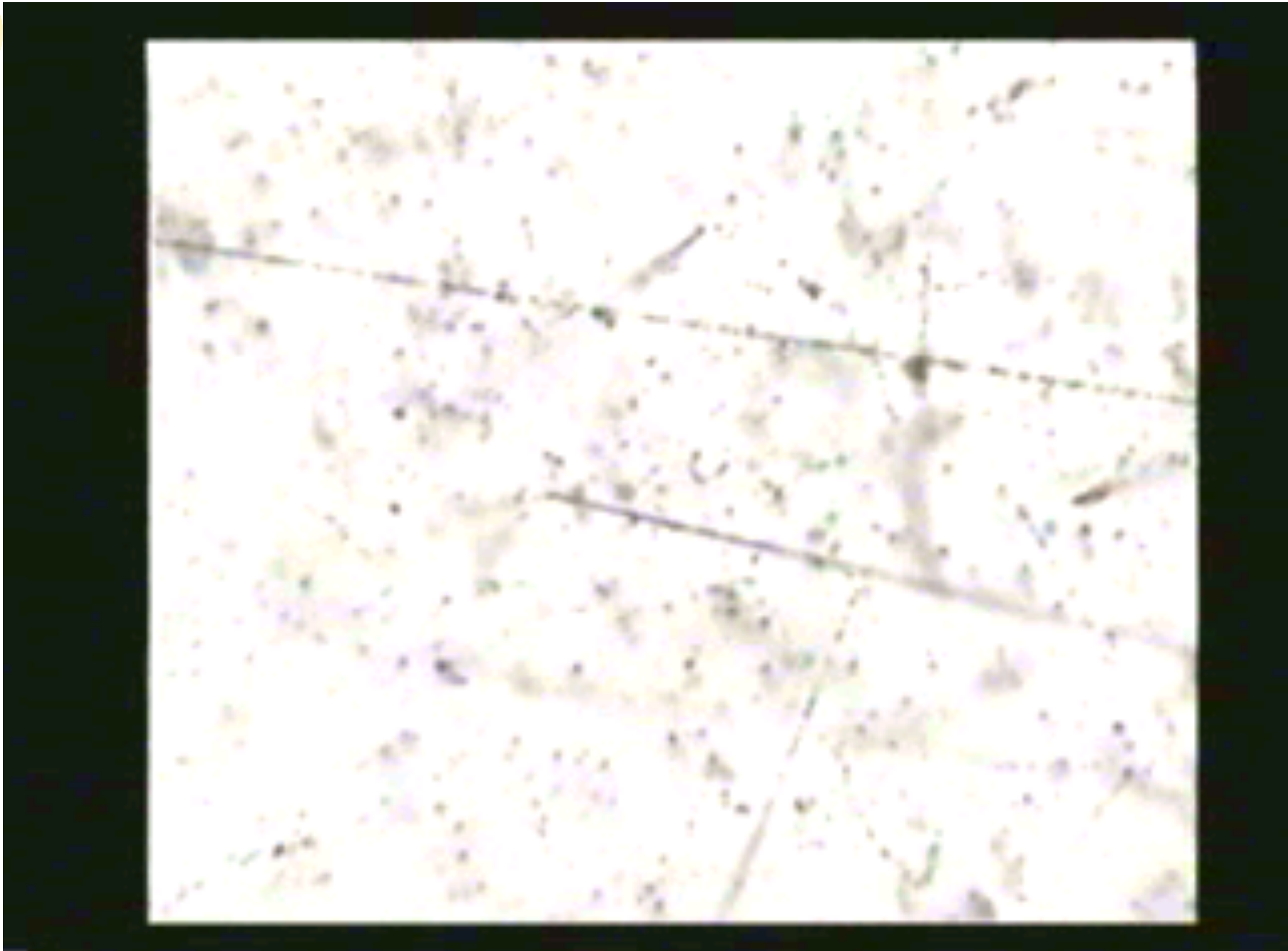




~0.7 sec per one view

Finding inefficiency

Automatic Scanning (video)



Discovery of Lambdpha

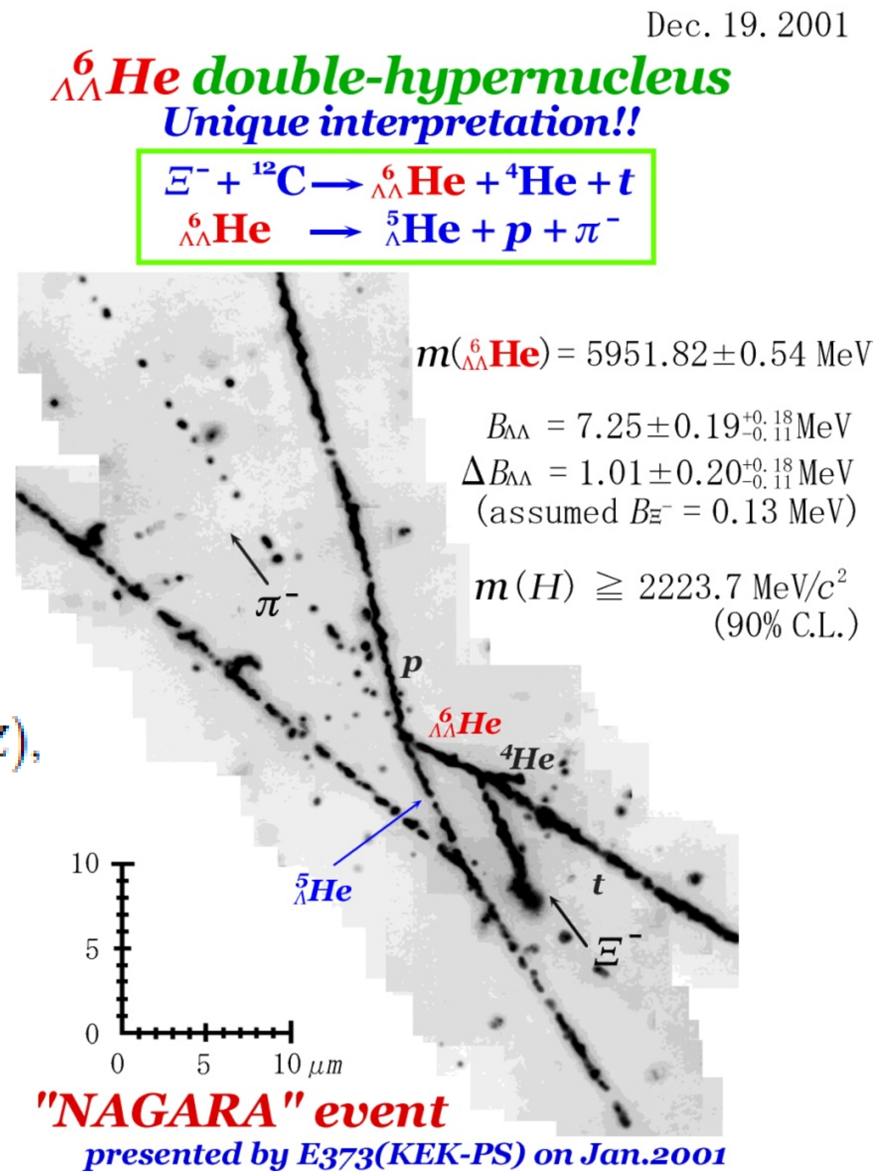
Nagara: uniquely identified among 6 candidates of DH event

H.Takahashi et al.,Phys. Rev. Lett. 87 (2001) 212502

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$
$$= 2M({}^{A-1}_{\Lambda}Z) - M({}^{A-2}Z) - M({}^{A}_{\Lambda\Lambda}Z),$$

Revised value
$\Delta B_{\Lambda\Lambda}$ = 0.67 +- 0.17 MeV
J.K.Ahn et al., PRC 88 (2013)

ΛΛ is weakly attractive



Reconstruction and $\Delta B_{\Lambda\Lambda}$

by Y.S. Iwata & H. Takahashi

Production

Target	#1	#3	#4		$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
^{12}C	${}^{\ 6}_{\Lambda\Lambda}$He	^{4}He	p	$2n$	> 16.9	> 10.6
^{12}C	${}^{\ 6}_{\Lambda\Lambda}$He	^{4}He	d	$1n$	14.5 ± 0.7	8.2 ± 0.7
^{12}C	${}^{\ 6}_{\Lambda\Lambda}$He	^{4}He	t		7.3 ± 0.2	1.1 ± 0.2
^{12}C	${}^{\ 7}_{\Lambda\Lambda}$He	^{4}He	p	$1n$	21.6 ± 1.3	13.3 ± 1.3
^{14}N	${}^{\ 6}_{\Lambda\Lambda}$He	^{7}Li	p	$1n$	24.4 ± 2.1	18.2 ± 2.1
^{14}N	${}^{\ 6}_{\Lambda\Lambda}$He	^{6}Li	d	$1n$	25.8 ± 1.3	19.6 ± 1.3
^{14}N	${}^{\ 6}_{\Lambda\Lambda}$He	^{4}He	^{4}He	$1n$	17.9 ± 1.5	11.7 ± 1.5
^{14}N	${}^{\ 7}_{\Lambda\Lambda}$Li	^{4}He	t	$1n$	26.2 ± 0.9	17.2 ± 0.9
^{14}N	${}^{\ 9}_{\Lambda\Lambda}$Li	p	^{4}He	$1n$	31.5 ± 1.8	17.9 ± 1.8
^{16}O	${}^{\ 8}_{\Lambda\Lambda}$Li	^{4}He	^{4}He	$1n$	31.1 ± 0.9	19.9 ± 0.9

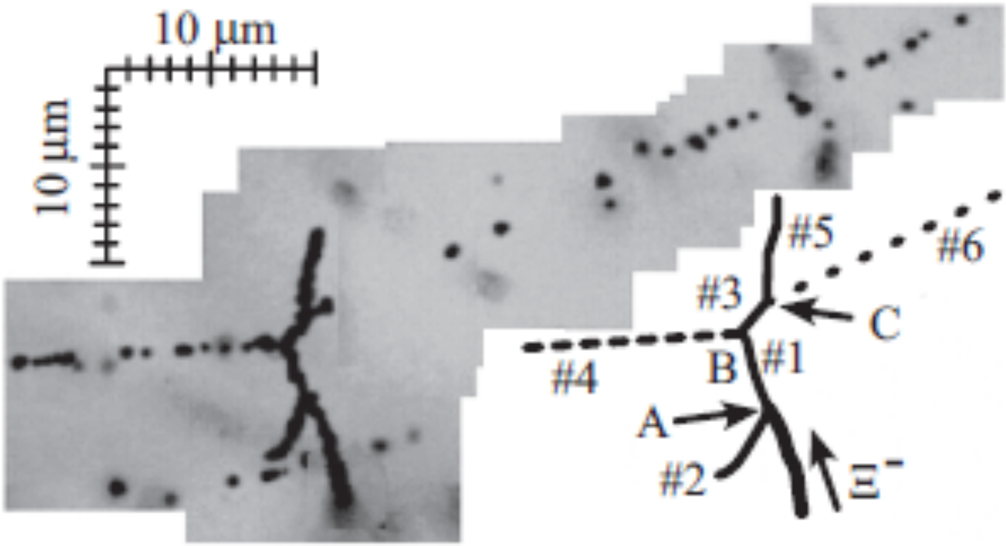
($\Delta B_{\Lambda\Lambda}$<20MeV)

Decay

double-hyp.	#2	#5	#6		$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
${}^{\ 5}_{\Lambda\Lambda}$He	${}^{4}_{\Lambda}$He	p	π^-		7.1 ± 0.5	2.4 ± 0.5
${}^{\ 6}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-		6.9 ± 0.6	0.6 ± 0.6
${}^{\ 7}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-	$1n$	< 8.6	< 0.3
${}^{\ 7}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	p	π^-		6.3 ± 0.7	-2.0 ± 0.7
${}^{\ 8}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-	$2n$	< 6.8	< -7.2
${}^{\ 8}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	d	π^-	$1n$	< 7.4	< -6.6
${}^{\ 8}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	p	π^-	$1n$	< 6.6	< -7.4
${}^{\ 8}_{\Lambda\Lambda}$He	${}^{7}_{\Lambda}$He^{a}	p	π^-		7.7 ± 0.8	-6.3 ± 0.8
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-	$3n$	< 7.2	< -7.1
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	d	π^-	$2n$	< 8.2	< -6.1
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	t	π^-	$1n$	< 11.2	< -3.1
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	p	π^-	$2n$	< 7.2	< -7.1
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	d	π^-	$1n$	< 8.4	< -5.9
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{7}_{\Lambda}$He^{a}	p	π^-	$1n$	< 11.2	< -3.1
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{7}_{\Lambda}$He^{a}	d	π^-		13.4 ± 0.5	-0.9 ± 0.5
${}^{\ 9}_{\Lambda\Lambda}$He	${}^{8}_{\Lambda}$He	p	π^-		6.4 ± 0.8	-7.9 ± 0.8

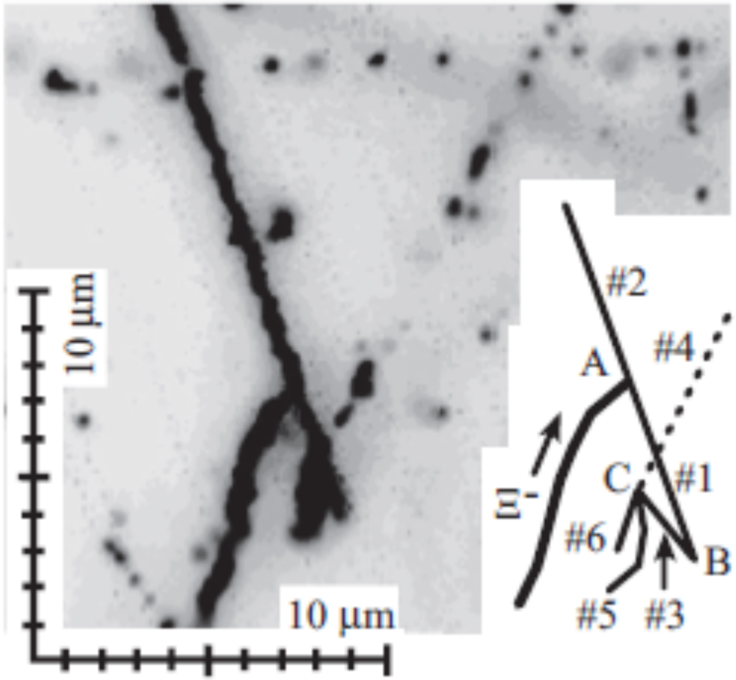
($\Delta B_{\Lambda\Lambda}$>−20MeV)

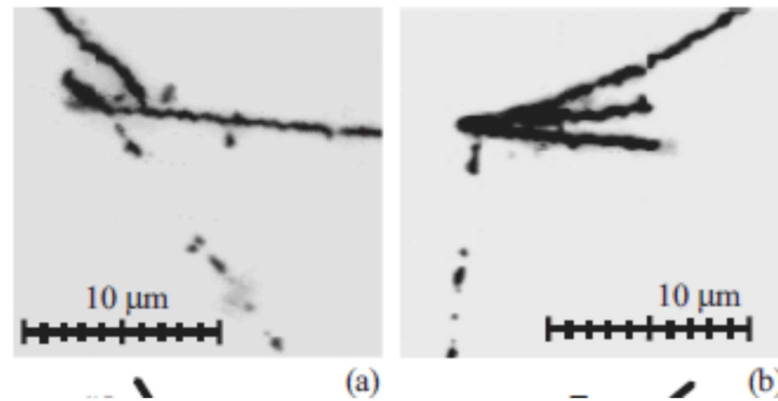
Mikage event



$$^{12}\mathrm{C} + \Xi^- \to {}^{\;6}_{\Lambda\Lambda}\mathrm{He} + {}^{6}\mathrm{Li} + n$$
$$\hookrightarrow {}^{3}_{\Lambda}\mathrm{H} + p + 2n \quad (1),$$
$$^{12}\mathrm{C} + \Xi^- \to {}^{\;11}_{\Lambda\Lambda}\mathrm{Be} + p + n$$
$$\hookrightarrow {}^{9}_{\Lambda}\mathrm{Li} + p + n \quad (2),$$
$$^{14}\mathrm{N} + \Xi^- \to {}^{\;11}_{\Lambda\Lambda}\mathrm{Be} + {}^{3}\mathrm{He} + n$$
$$\hookrightarrow {}^{9}_{\Lambda}\mathrm{Li} + p + n \quad (3).$$

Demachiyanagi event



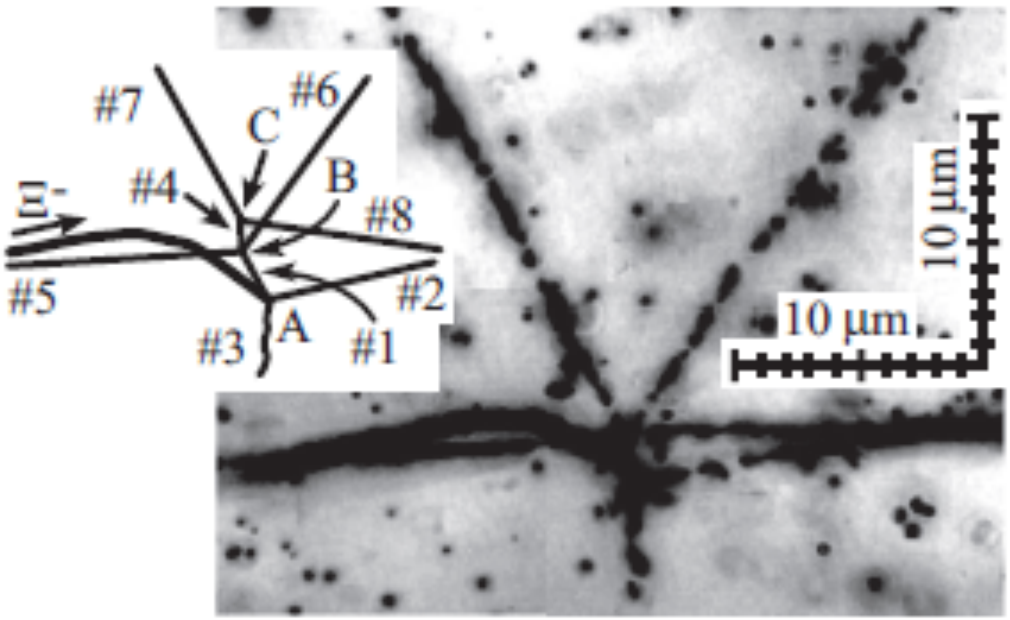


$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{10}_{\Lambda\Lambda}\mathrm{Be} + t \qquad (1),$$

$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}\mathrm{Be} + p + n \qquad (2),$$

$$^{14}\mathrm{N} + \Xi^- \rightarrow {}^{13}_{\Lambda\Lambda}\mathrm{B} + p + n \qquad (3).$$

Hida event

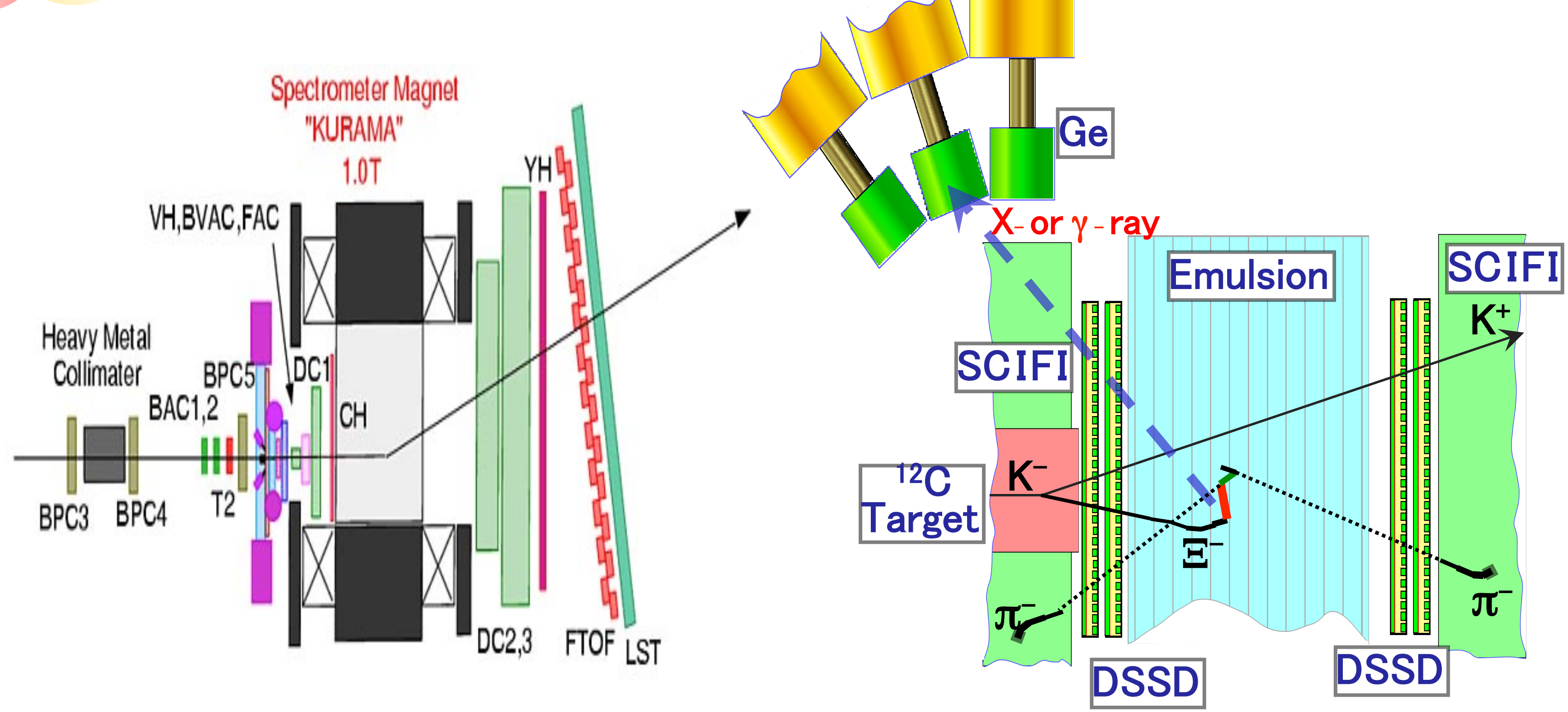


$$^{14}\mathrm{N} + \Xi^- \rightarrow {}^{12}_{\Lambda\Lambda}\mathrm{Be} + p + p + n \quad (1),$$

$$^{16}\mathrm{O} + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}\mathrm{Be} + p + {}^{4}\mathrm{He} + n \quad (2).$$

J-PARC E07 (K.Nakazawa, K.I, H.Tamura)

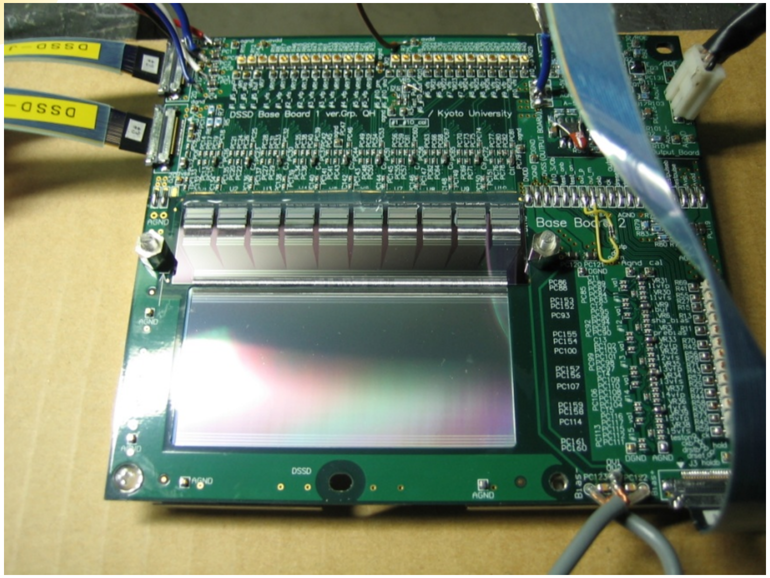
BNL-AGS E964



10 times statistics ~100 DH ~10 clean DH mini-chart

Key: 10times faster automatic scanning

For E07

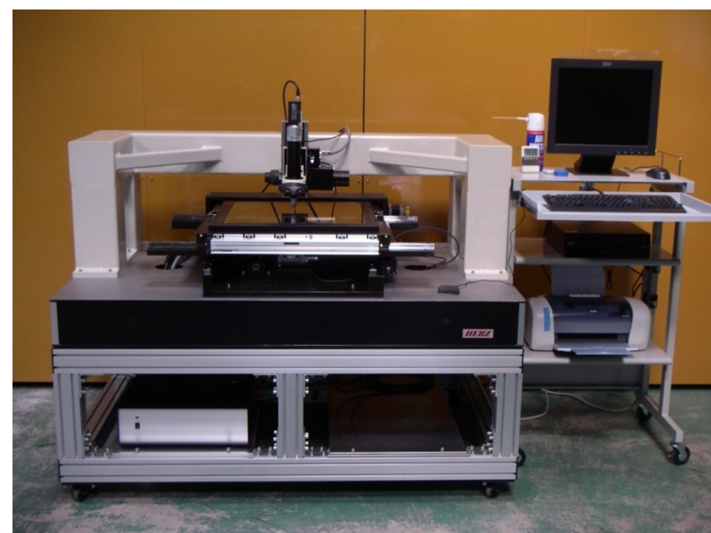


DSSD
Double sided silicon strip
50μm strip pitch -> 16μm resolution

New hybrid system was tested successfully

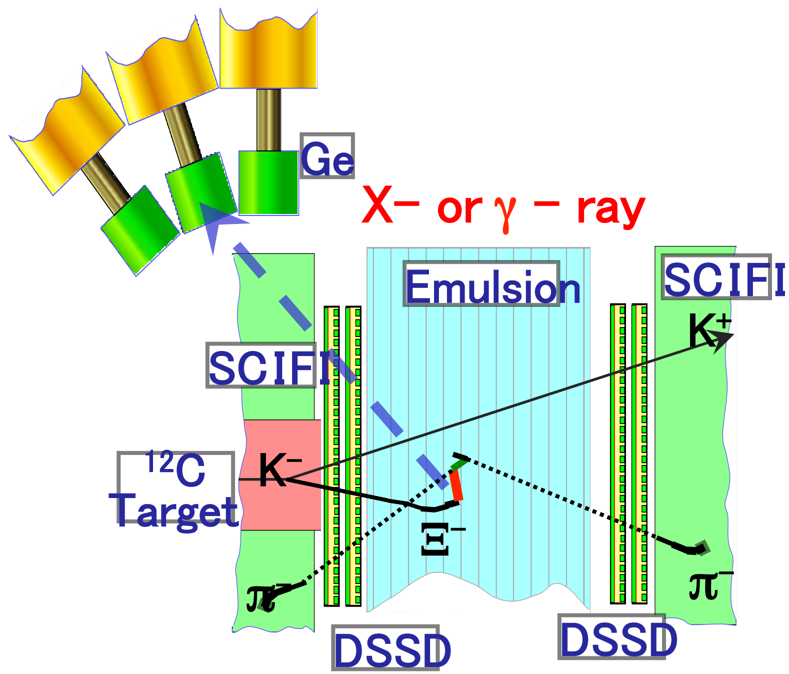
<u>New Automatic Scanning System</u>

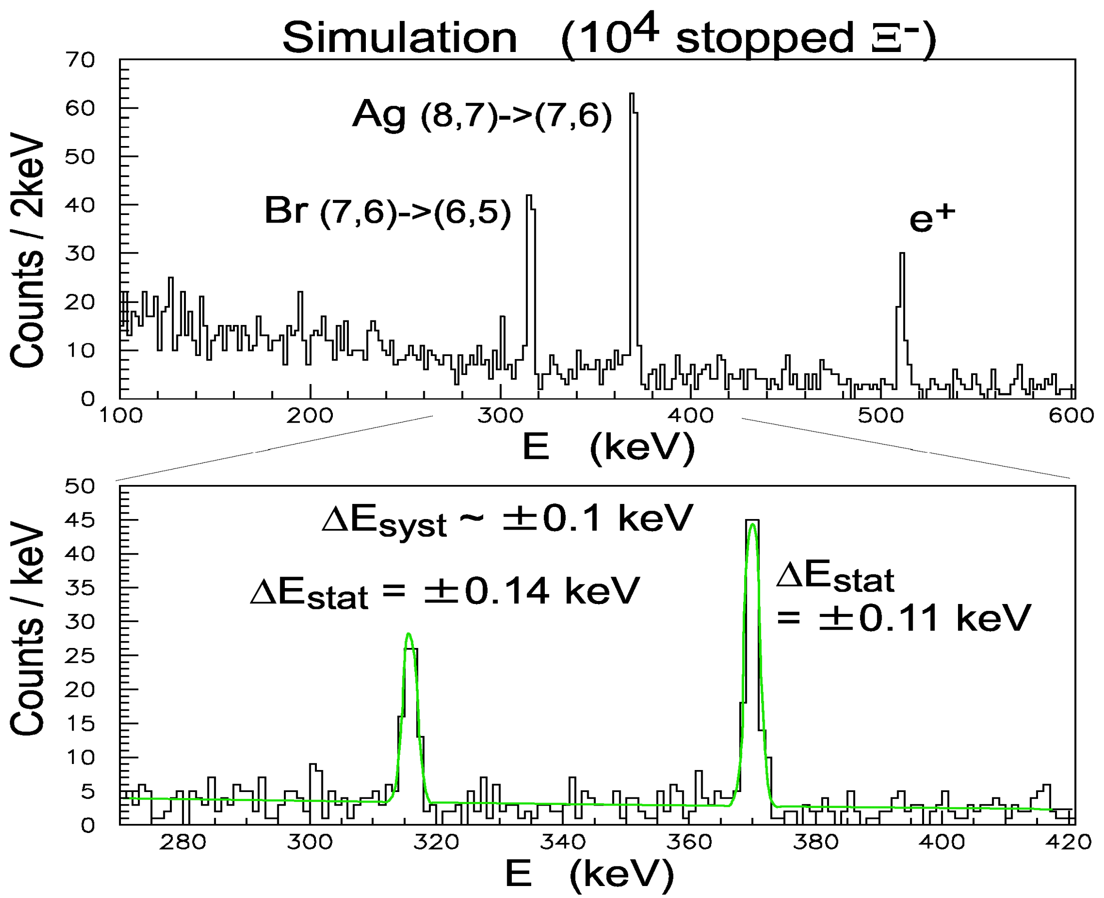
High speed and large area 40x40cm



Ξ-atom X-ray to study Ξ-nucleus potential

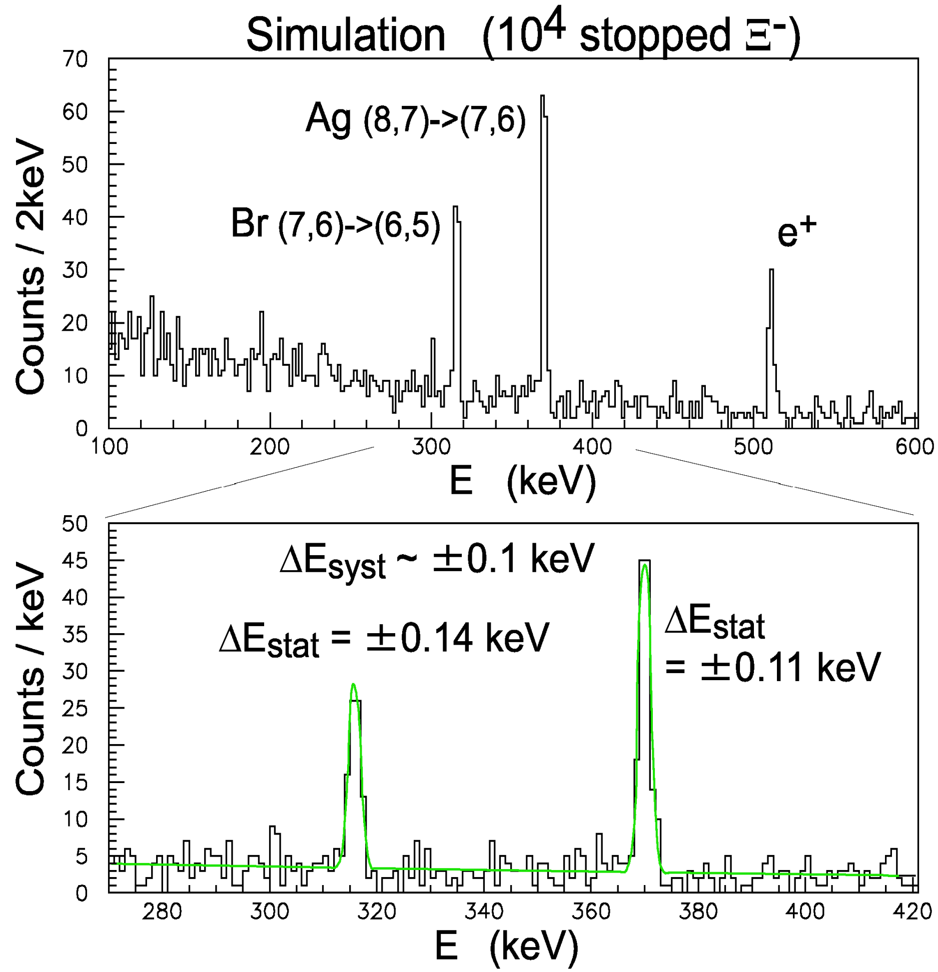
Shift and width -> Ξ-nucleus potential (real, imaginary)





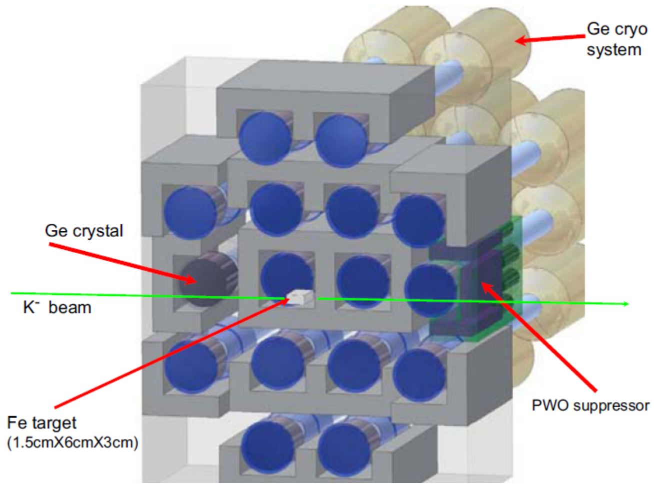
Ξ- atomic X-ray 10^4 Ξ- atoms

Energy shift ΔE depends on Ξ-nucleus potential.

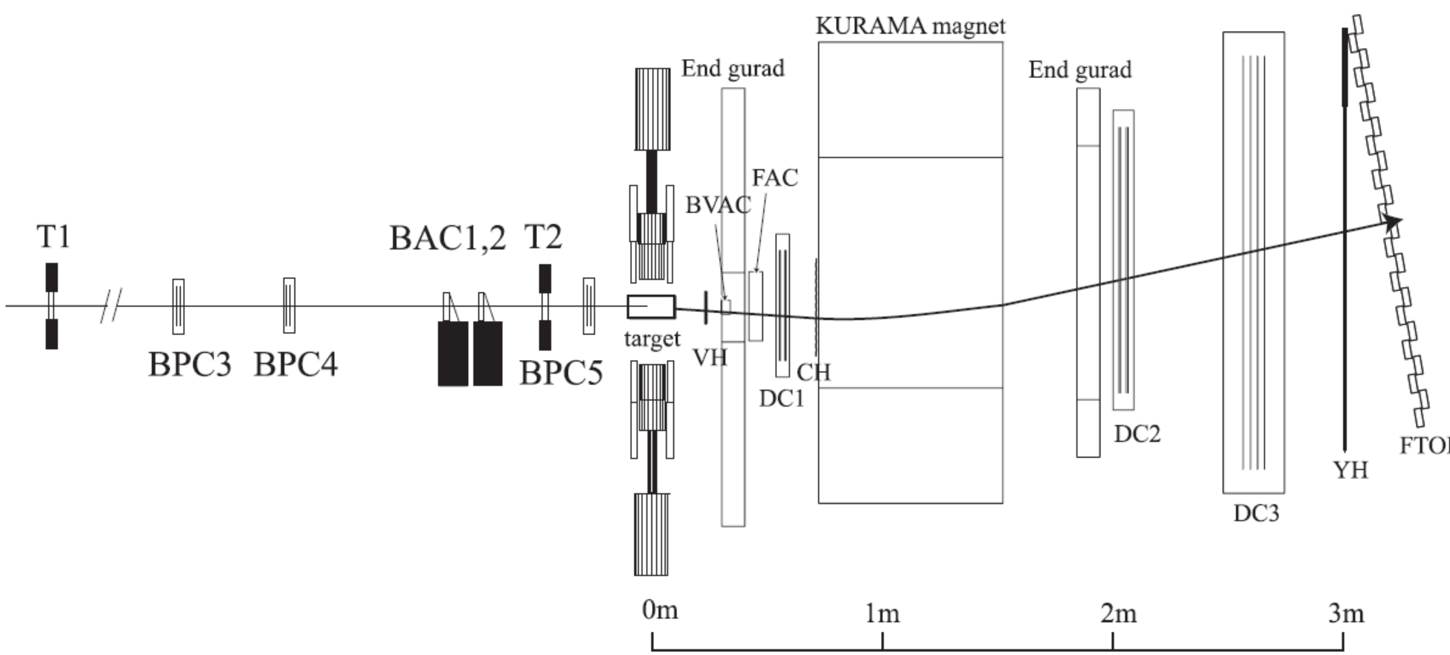


J-PARC E03 dedicated Ξ-atom X-ray

K.Tanida



Fe(K-,K+) Ξ- , Ξ- Fe atom
X-rays detected with Hyperball

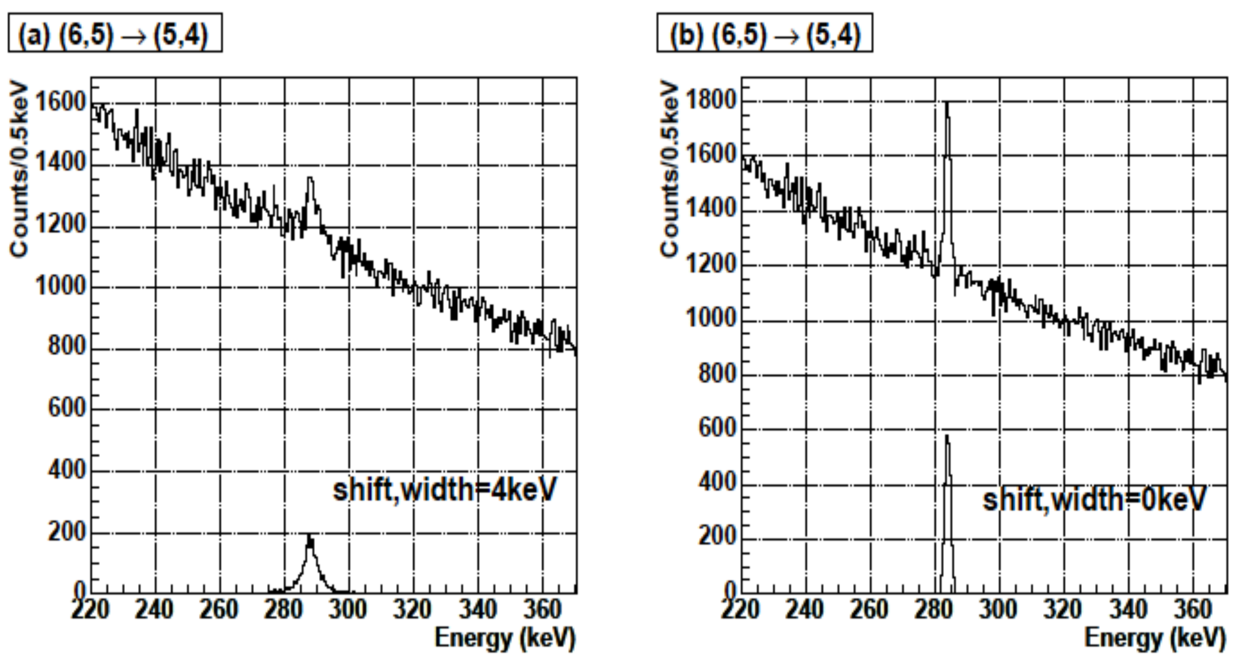


Dedicated Ξ-atom X-ray experiment

high intensity K-, large acceptance -> high statistics

if no shift for Fe, -> other appropriate elements

- 7.5×10^5 Ξ-atoms **shift: ΔE=0.05 keV, width: ΔE=1 keV**



Ξ-hypernuclei ?

Missing mass spectroscopy

BNL E885 $^{12}C(K^-,K^+)$

potential ~14MeV

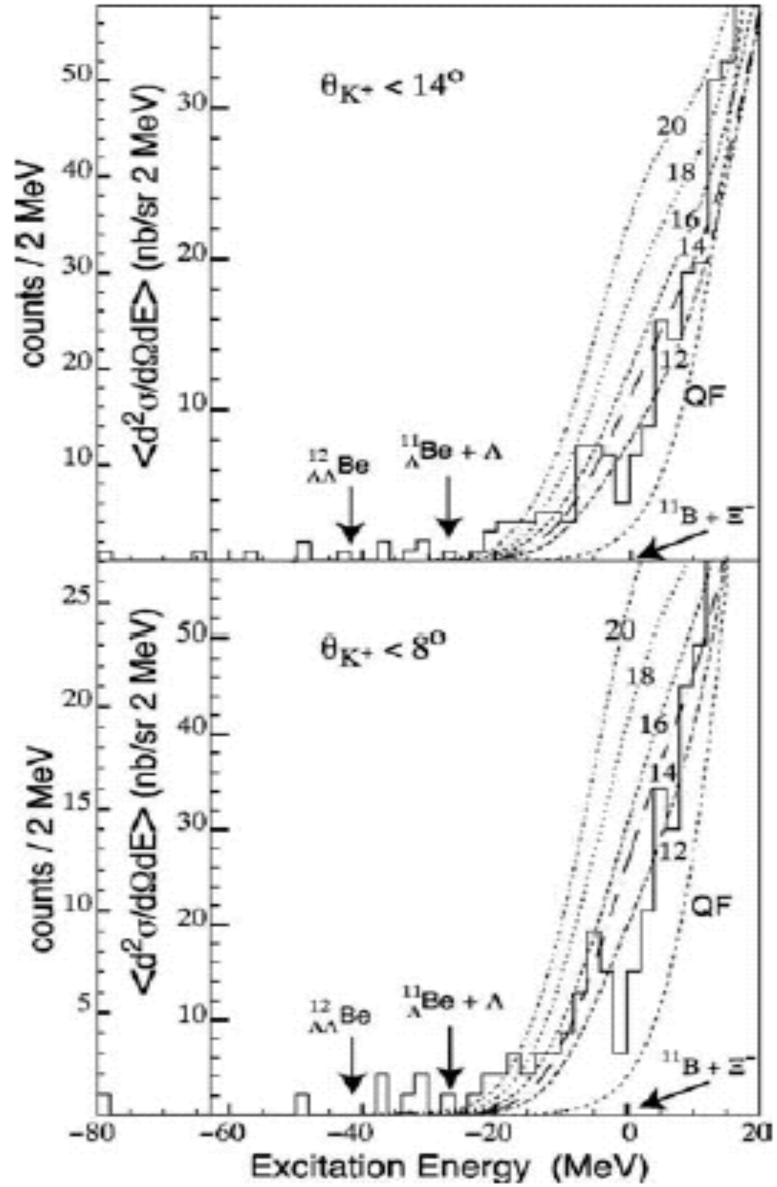
J-PARC E05 (T.Nagae)

high resolution spectroscopy

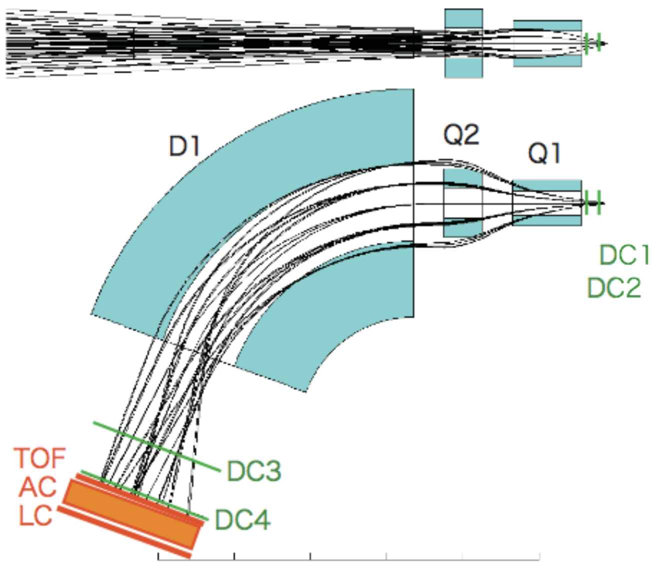
K1.8 and new S2S

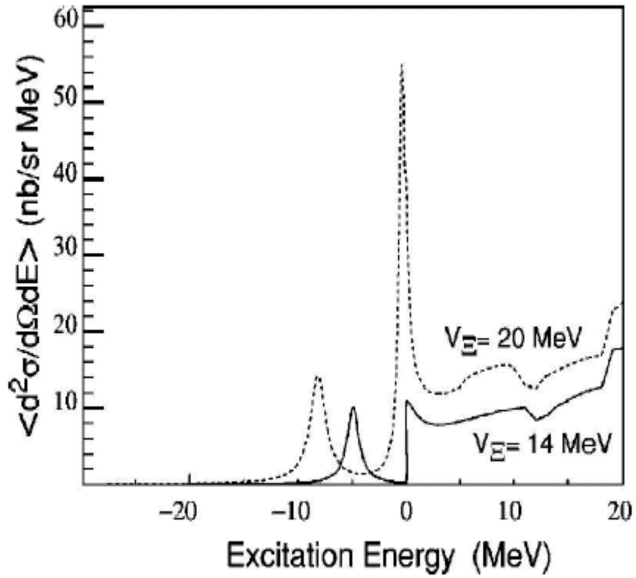
$^{12}C(K^-,K^+)$ ΔM~2MeV

E885 (BNL)



S-2S spectrometer (QQD)



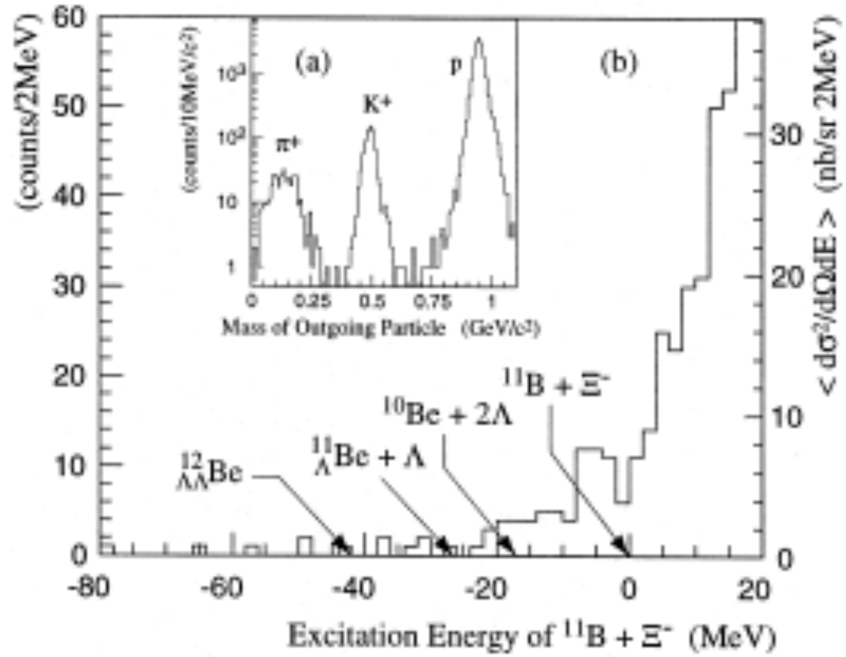


-> New S-2S spectrometer
(T.Nagae)

$\Delta p/p<5x10^{-4}$, >60 mstr.

Spectroscopy of s=-2 nuclei

- Mixing of ΛΛ and Ξ states and H?
  small mass difference of ΛΛ and ΞN ~28 MeV
- Excited states of ΛΛ states?
- Heavier nuclei



BNL-E886 K.Yamamoto et al., P.L. B478 (2000) 401.

Back up