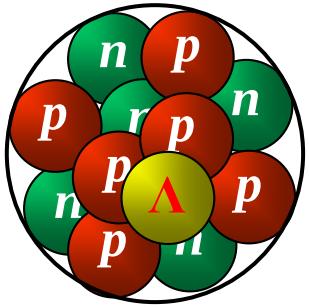
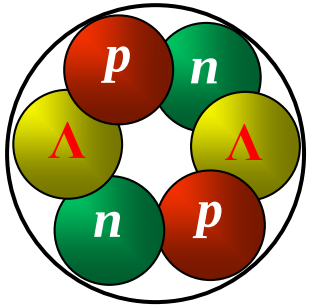
Hypernuclear physics

at



J-PARC



RIKEN

8th Japan-Italy Symposium

March 7-10, 2016, RIKEN, Tokyo, Japan

INFN Istituto Nazionale di Fisica Nucleare

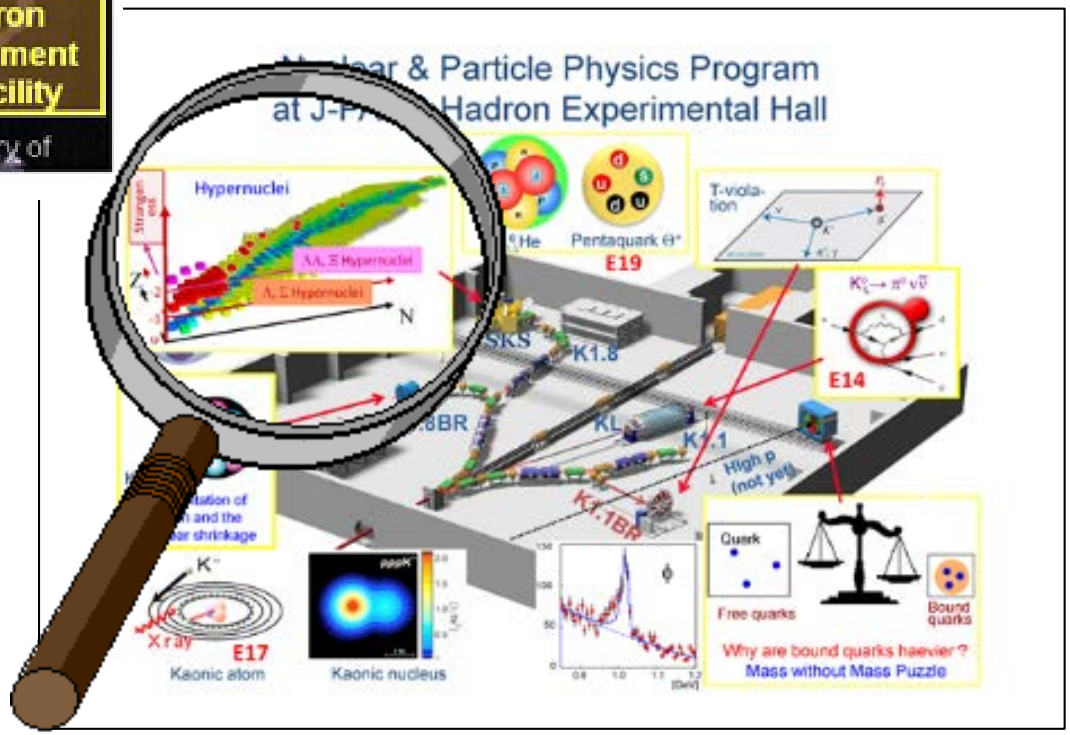
Alessandro Feliciello

I.N.F.N. - Sezione di Torino

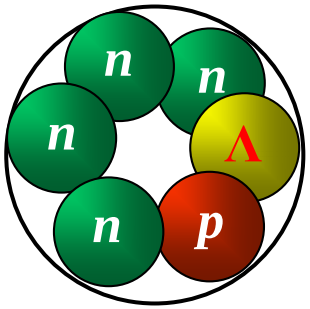
Outline

- The Experimental Hadron Facility @ J-PARC
- The INFN ULYSSES experiment
- S = -1 Λ-hypernuclei:
  - E10: search for neutron-rich Λ-hypernuclei (Dec 12 / Jan 13)
  - E13: γ-ray spectroscopy of Λ-hypernuclei (May/Jun 2015)
- S = -2 Λ-hypernuclei:
  - E05: search for Ξ-hypernuclei (Oct-Nov 2015)
- future perspectives:
  - Hydrogen hyperisotopes ($^{3}H_{\Lambda}$ and $^{4}H_{\Lambda}$) lifetime measurement
  - hypernuclear weak decay further studies (determination of some missing decay widths)

The J-PARC facilities



The E10 experiment



Proposal for J-PARC 50 GeV Proton Synchrotron

Production of Neutron-Rich Λ-Hypernuclei with the Double Charge-Exchange Reaction

(Revised from P10 "Study on Λ-Hypernuclei with the Charge-Exchange Reactions")

S. Ajimura, A. Sakaguchi[1], T. Kishimoto,
Osaka University, Toyonaka, Osaka 560-0043, Japan
H. Noumi, T. Takahashi,
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
T. Fukuda, Y. Mizoi,
Osaka Electro-communications University, Neyagawa, Osaka 572-8530, Japan
H. Bhang,
Seoul National University, Seoul 151-742, Korea
P.K. Saha,
Japan Atomic energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan
L. Busso,
Università di Torino, I-10125 Torino, Italy
D. Faso,
INFN, Sezione di Torino, I-10125 Torino, Italy
and
O. Morra
INAF-IFSI, Sezione di Torino, C.so Fiume 4, I-10125 Torino, Italy

10 December, 2006

Abstract

We propose experiments to produce neutron-rich Λ-hypernuclei by using the (π^-,K^+) double charge-exchange reaction. The neutron-rich Λ-hypernuclei ${}^{9}_{\Lambda}$He and ${}^{6}_{\Lambda}$H, which have never produced experimentally, may be produced for the first time by using the K1.8 secondary beamline and SKS in the very early stage of Day-1. The structure of the new hypernuclear species will provide us important information on the ΛN strong interaction in a neutron-rich environment.

[1]Spokesperson, e-mail: sakaguch@phys.sci.osaka-u.ac.jp, phone: +81-6-6850-5352.

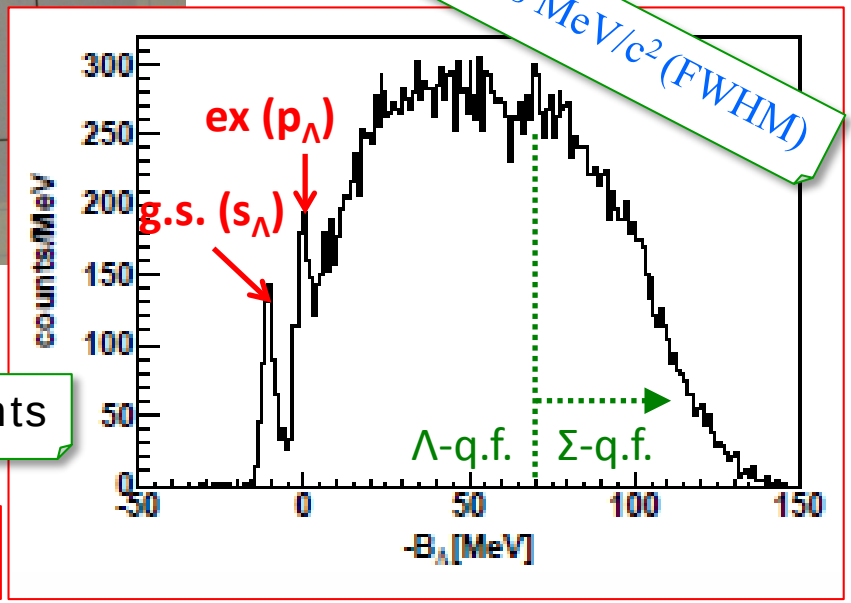
1

E10: first hypernuclei at J-PARC

$$\pi^+ + {}^{12}\mathrm{C} \rightarrow {}^{12}_{\Lambda}\mathrm{C} + K^+$$

@ 1.2 GeV/C

ΔB_Λ: 2.8 MeV/c² (FWHM)



Hadron Hall
K1.8 line

yield (g.s.): ~600 events

reaction	momentum (GeV/c)	intensity (/spill)	time (hour)
${}^{12}\mathrm{C}(\pi^+, K^+){}^{12}_{\Lambda}\mathrm{C}$	1.2	3.5×10^6	24

H. Sugimura *et al.*, *EPJ* Web of Conf. 66 (2014) 09017

Search for neutron-rich hypernuclei

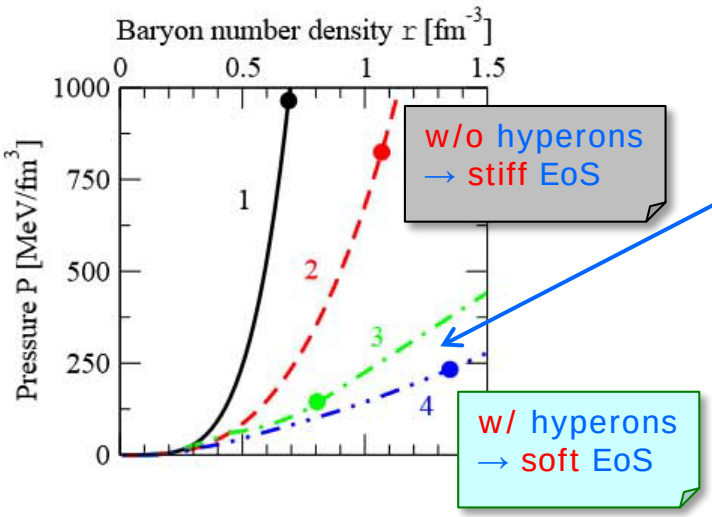
central issue in hypernuclear physics

❖ historical paper: R.H. Dalitz and R. Levi Setti, Nuovo Cimento 30 (1963) 489

1. Pauli effect not effective for Λ
2. Λ extra binding energy

⇒ existence of hypernuclei with core nucleus near (or even beyond) the neutron drip line

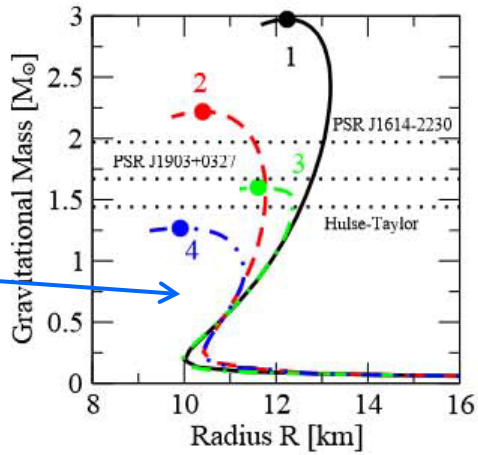
❖ unique opportunity to study:
- effect of 3-body forces (ΛNN)
- ΛN- ΣN coupling contribution to binding en.
- hyperon behaviour in n-rich environment



direct influence on neutron star EoS

prediction of neutron star main parameters

I. Vidaña *et al.*, *EPL* 94 (2011) 11002



The status of art (as of 2011)

$$K^-_{stop} + {}^A Z \rightarrow {}^A_\Lambda (Z-2) + \pi^+$$

- $K^- + p \rightarrow \pi^0 + \Lambda$, $\pi^0 + p \rightarrow \pi^+ + n$: 2-step (S-EX + C-EX)
- $K^- + p \rightarrow \bar{K}^0 + n$, $\bar{K}^0 + p \rightarrow \Lambda + \pi^+$: 2-step (C-EX + S-EX)
- $K^- + p \rightarrow \pi^+ + \Sigma^-$, $\Sigma^- + p \rightarrow \Lambda + n$: 1-step (S-EX)

experimental results

KEK

- ${}^9_\Lambda He({}^9Be) : u.l. = 2.3 \cdot 10^{-4} / K^-_{stop}$
- ${}^{12}_\Lambda Be({}^{12}C) : u.l. = 6.1 \cdot 10^{-5} / K^-_{stop}$
- ${}^{16}_\Lambda C({}^{16}O) : u.l. = 6.2 \cdot 10^{-5} / K^-_{stop}$

K. Kubota *et al.*, *NPA* 602 (1996) 327

INFN-LNF

- ${}^6_\Lambda H({}^6Li) : u.l. = (2.5 \pm 1.4) \cdot 10^{-5} / K^-_{stop}$
- ${}^7_\Lambda H({}^7Li) : u.l. = (4.5 \pm 1.4) \cdot 10^{-5} / K^-_{stop}$
- ${}^{12}_\Lambda Be({}^{12}C) : u.l. = (2.0 \pm 0.4) \cdot 10^{-5} / K^-_{stop}$

M. Agnello *et al.*, *PLB* 640 (2006) 145

theoretical predictions

$10^{-6} \div 10^{-7} / K^-_{stop}$

T.Y. Tretyakova *et al.*, *NPA* 691 (2001) 51c

$$\pi^- + {}^A Z \rightarrow {}^A_\Lambda (Z-2) + K^+$$

- $\pi^- + p \rightarrow \pi^0 + n$, $\pi^0 + p \rightarrow K^+ + \Lambda$: 2-step (C-EX + AP)
- $\pi^- + p \rightarrow K^0 + \Lambda$, $K^0 + p \rightarrow K^+ + n$: 2-step (AP + C-EX)
- $\pi^- + p \rightarrow K^+ + \Sigma^-$, $\Sigma^- + p \rightarrow \Lambda + n$: 1-step (AP)

experimental results

KEK

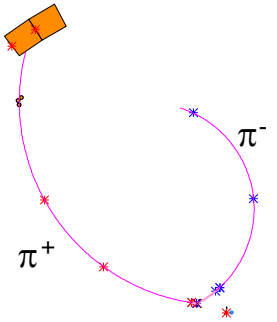
theoretical predictions

${}^{10}_\Lambda Li({}^{10}B) : d\sigma / d\Omega = 11.3 \pm 1.9 \ nb/sr$

P.K. Saha *et al.*, *PRL* 94 (2005) 052502

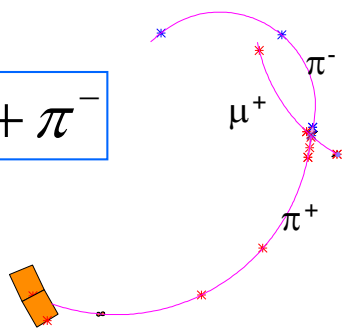
T.Y. Tretyakova *et al.*, *PAT* 66 (2003) 1681

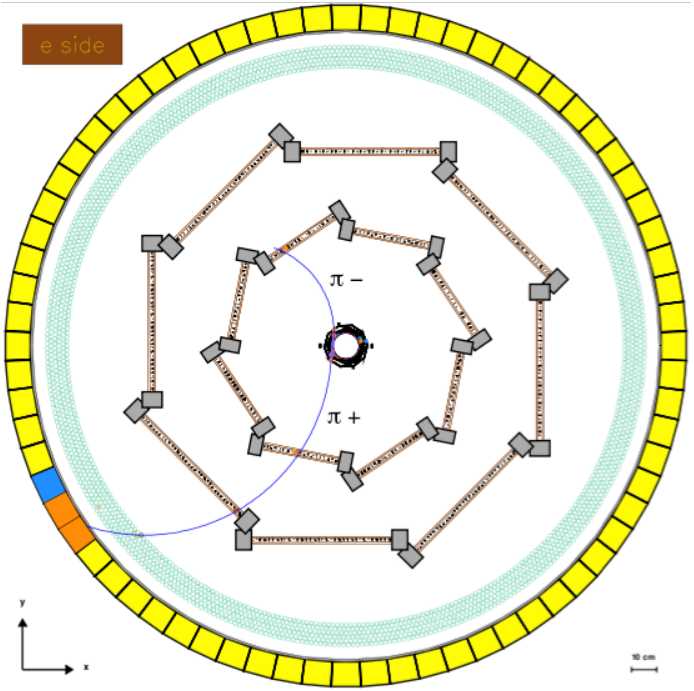
Experimental evidence for ${}^{6}_{\Lambda}H$ (2012)



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

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



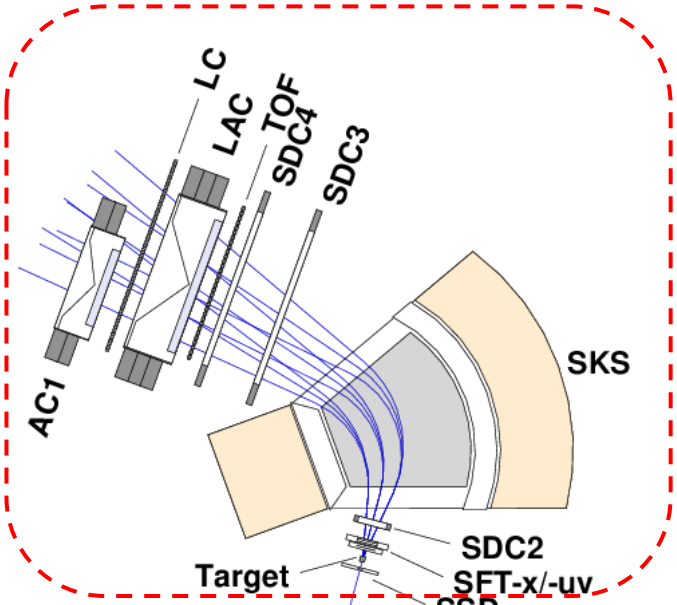


FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501
FINUDA Coll. and A. Gal, *NPA* 881 (2012) 269

E10: esperimental setup

SKS spectrometer

- central momentum: 0.9 GeV/c
- $\Delta p/p$ ~1.0 x 10^{-3}
- momentum calculated or estimated via Runge-Kutta integration SDC1,2(x,y,x',y')-SDC3,4(x,y,x',y')
- scattered *K* identified at online trigger level: TOFxLCxAC

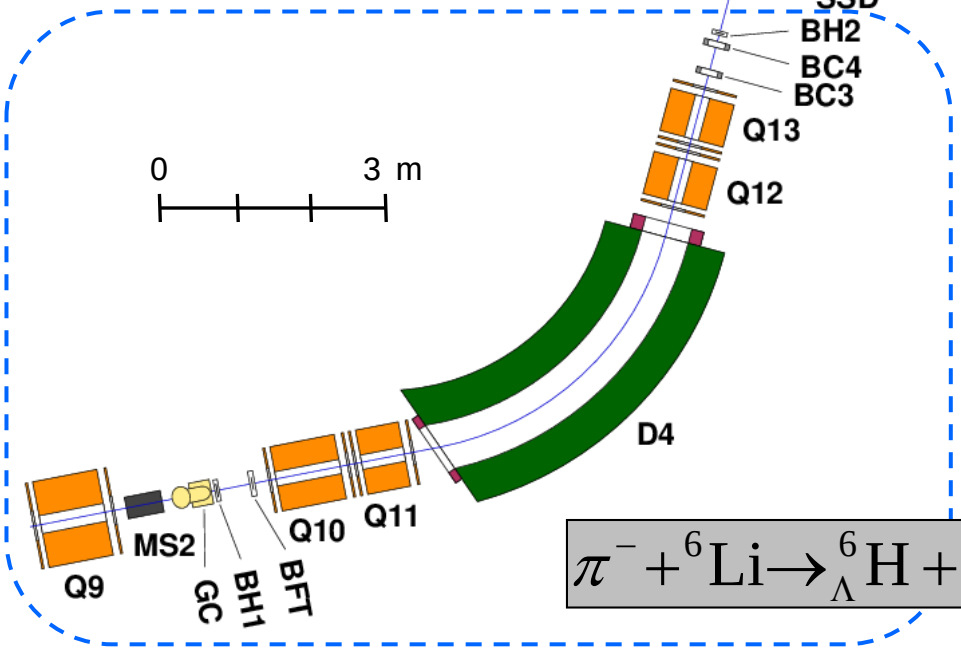


Target

- 3.5 g/cm^2 of 95.54% enriched ^{6}Li

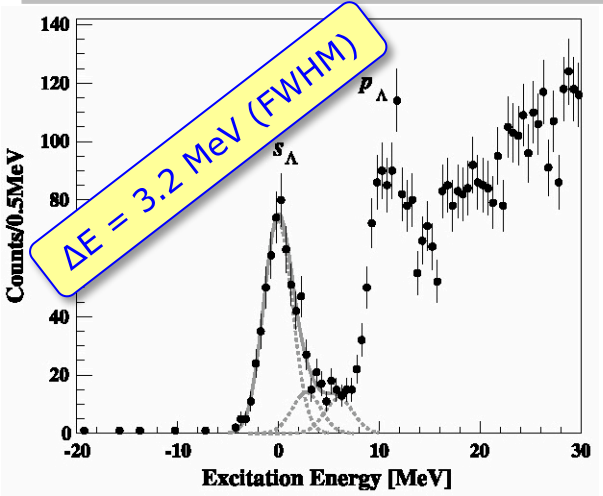
K1.8 Beamline spectrometer

- π momentum: 1.2 GeV/c
- $\Delta p/p$ ~3.3 x 10^{-4}
- 1.0-1.2x10^7 pion/spill
- spill duration 2 s
- momentum measured by Transfer Matrix BFT(x)-BC3,4(x,y,x',y')



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

E10: no evidence!?!

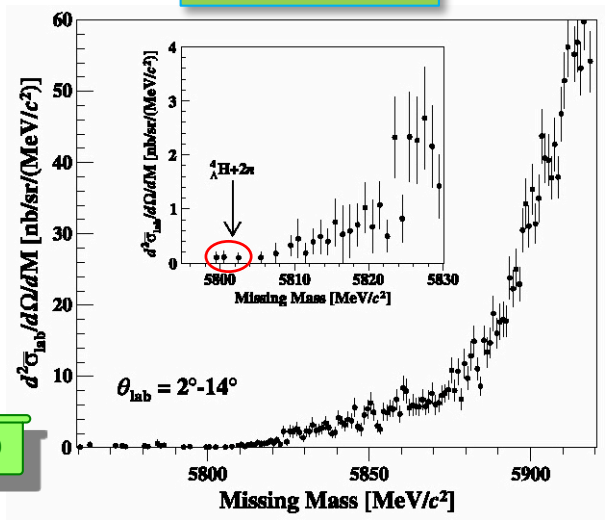


$$\pi^- + {}^6\mathrm{Li} \rightarrow {}^6_\Lambda\mathrm{H} + K^+$$

J-PARC

H. Sugimura *et al.*, *PLB* 729 (2014) 39

J-PARC E10



$$d\sigma/d\Omega \leq 1.2 \ nb/sr \ (90\% \ C.L.)$$

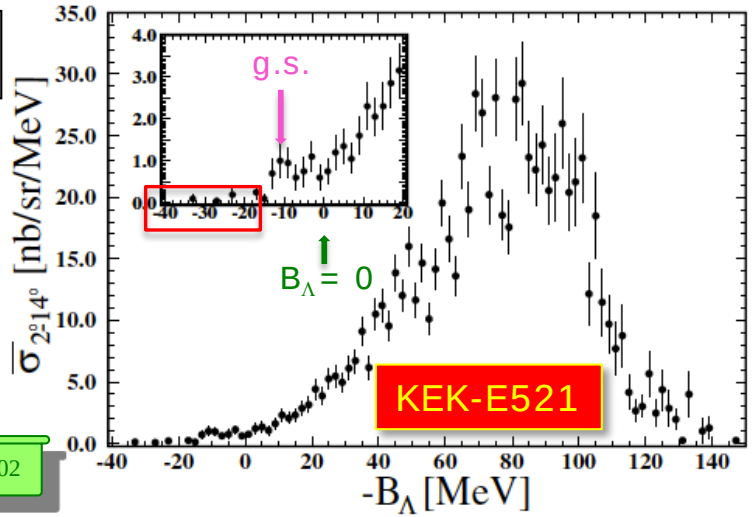
one order of magnitude lower than...

background free reactions

$$\pi^- + {}^{10}\mathrm{B} \rightarrow {}^{10}_\Lambda\mathrm{Li} + K^+$$

ΔE = 2.5 MeV (FWHM)

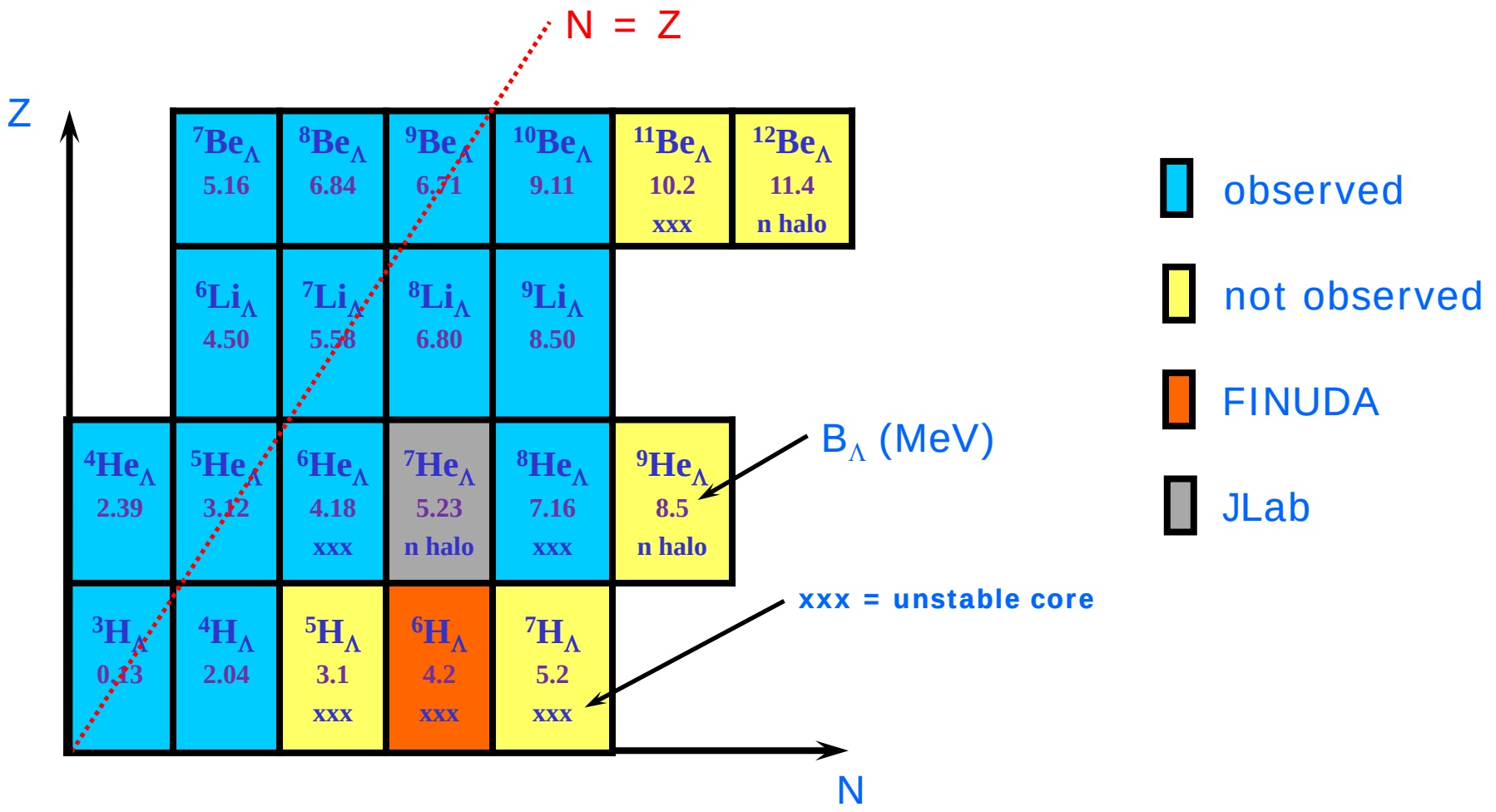
$$d\sigma/d\Omega = 11.3 \pm 1.9 \ nb/sr$$



P.K. Saha *et al.*, *PRL* 94 (2005) 052502

E10: future plans

E10 second round: search for $^{9}He_{\Lambda}$ (201X)



from: Nuclear Wallet Cards 2001, NNDC, BNL

L. Majling, *NPA* 585 (1995) 211c

The ${}^{6}H_{\Lambda}$ puzzle

T_{tot} (MeV)	$p_{\pi}+$ (MeV/c)	$p_{\pi}-$ (MeV/c)	$M({}^{6}_{\Lambda}H)$ prod. (MeV)	$M({}^{6}_{\Lambda}H)$ decay (MeV)	$M({}^{6}_{\Lambda}H)$ mean (MeV)	$\Delta M({}^{6}_{\Lambda}H)$ (MeV)
202.6 ± 1.3	251.3 ± 1.1	135.1 ± 1.2	5802.33 ± 0.96	5801.41 ± 0.84	5801.87 ± 0.96	0.92 ± 1.28
202.7 ± 1.3	250.1 ± 1.1	136.9 ± 1.2	5803.45 ± 0.96	5802.73 ± 0.84	5803.09 ± 0.96	0.72 ± 1.28
202.1 ± 1.3	253.8 ± 1.1	131.2 ± 1.2	5799.97 ± 0.96	5798.66 ± 0.84	5799.32 ± 0.96	1.31 ± 1.28

$(N+Y)/Z({}^{6}_{\Lambda}H) = 5 >> N/Z({}^{8}He) = 3$

formation mass values systematically higher than the ones from decay

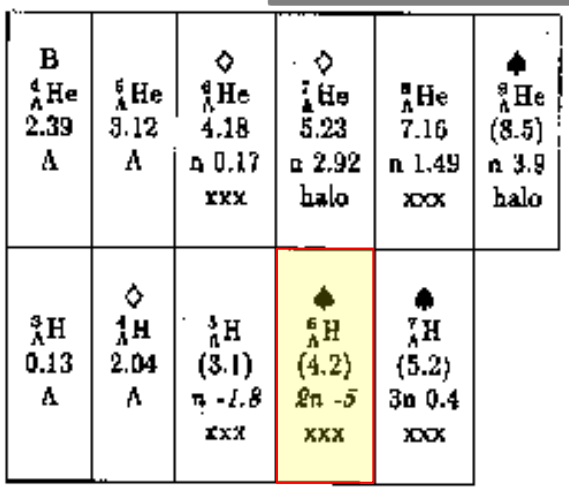
(0.98 ± 0.74) MeV

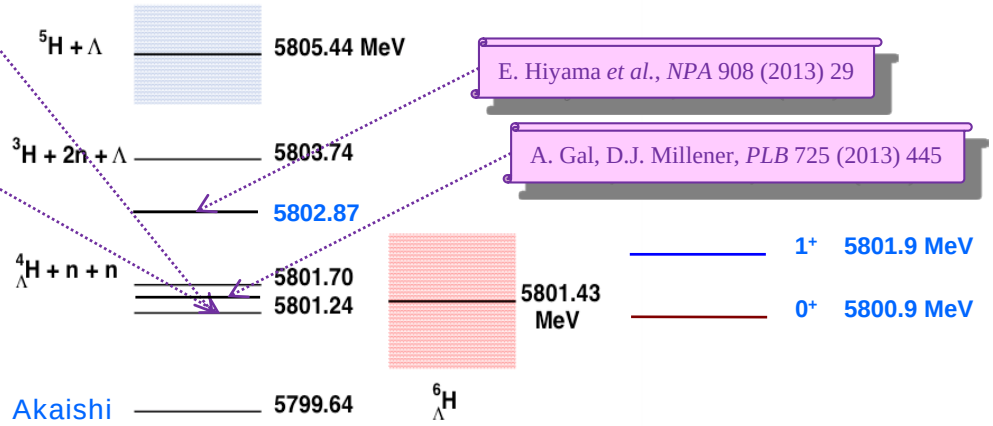
excited state production

theoretical predictions

- B_{Λ} = 4.2 MeV — R.H. Dalitz and R. Levi Setti, *NC* 30 (1963) 489
- B_{Λ} = 4.2 MeV — L. Majling, *NPA* 585 (1995) 211c

$\bar{M}$ = (5801.4 ± 1.1) MeV





E. Hiyama *et al.*, *NPA* 908 (2013) 29

A. Gal, D.J. Millener, *PLB* 725 (2013) 445

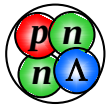
B_{Λ} = (4.0 ± 1.1) MeV ($^{5}H + \Lambda$)

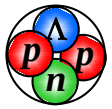
~~B_{Λ} = 5.8 MeV ($^{5}H + \Lambda$)~~
~~ΛNN force ≡ 1.4 MeV~~

FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501
FINUDA Coll. and A. Gal, *NPA* 881 (2012) 269

nrh prod. rate: ~10^{-2} hyp. prod. rate in (K^{-}_{stop}, π^{-})

The E13 experiment

$^{4}_{\Lambda}$H 

$^{4}_{\Lambda}$He 

Proposal for J-PARC 50 GeV Proton Synchrotron

Gamma-ray spectroscopy of light hypernuclei

Y. Fujii, K. Futatsukawa, O. Hashimoto, K. Hosomi, H. Kanda, M. Kaneta, T. Koike, Y. Ma, K. Maeda, A. Matsumura, M. Mimori, S.N. Nakamura, K. Nonaka, Y. Okayasu, T. Suzuki, K. Shirotori, H. Tamura(spokesperson), K. Tsukada, M. Ukai
Tohoku University, Japan

K. Aoki, Y. Kakiguchi, T. Nagae, H. Noumi, Y. Sato, M. Sekimoto, H. Takahashi, T. Takahashi, A. Toyoda
High Energy Accelerator Research Organization (KEK), Japan

P. Evtoukhovitch, V. Kalinnikov, W. Kallies, N. Kravchuk, A. Moiseenko, D. Mzhavia, V. Samoilov, Z. Tsamalaidze, O. Zaimidoroga
Joint Institute for Nuclear Research, Russia

Y.Y. Fu, C.B. Li, X.M. Li, J. Zhou, S.H. Zhou, L.H. Zhu
China Institute of Atomic Energy, China

E. V. Hungerford, A. Lan (+ a postdoc and 2 graduate students)
University of Houston, U.S.A.

T. Bressani, S. Bufalino, L. Busso, D. Faso, A. Feliciello, S. Marcello,
University of Torino and INFN, Sezione di Torino, Italy

S. Kamigaito, K. Imai, K. Miwa, K. Tanida
Kyoto University, Japan

H. Fujioka, D. Nakajima, T.N. Takahashi
University of Tokyo, Japan

P. Markowitz, J. Reinhold
Florida International University, U.S.A.

K. Nakazawa, T. Watanabe
Gifu University, Japan

S. Minami, T.R. Saito
GSI, Germany

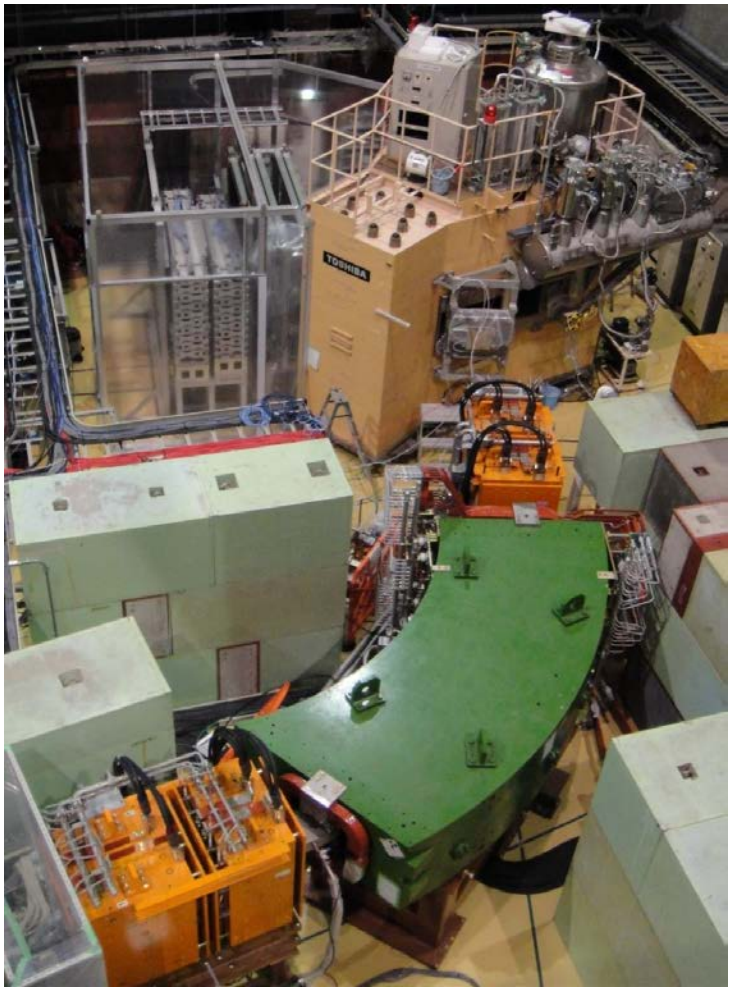
A. Krutenkova, V. Kulikov
Institute for Theoretical and Experimental Physics, Russia

1

E13: physics motivations

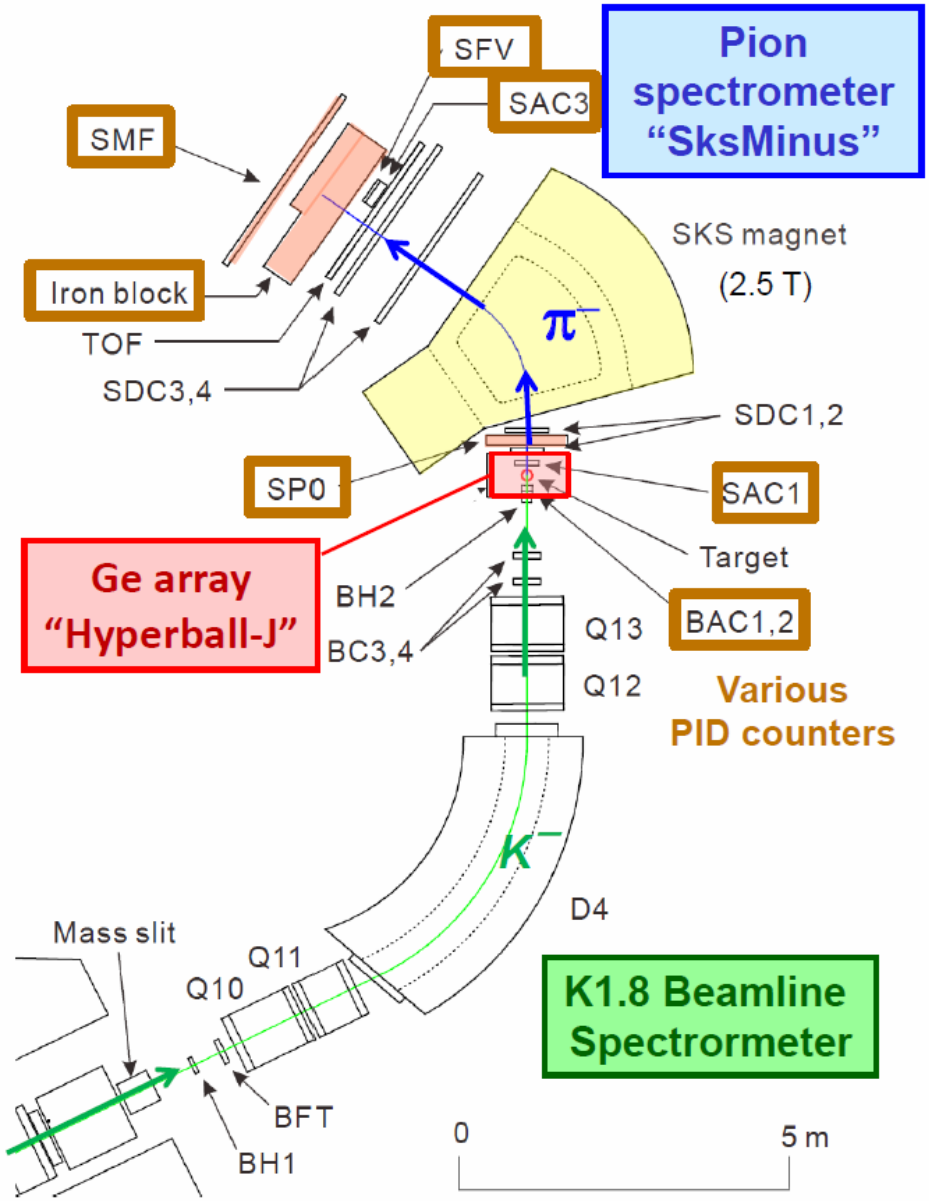
- to explore the *s*-shell Λ–hypernuclei ($^{4}He_{\Lambda}$)
  - doorway to investigate the CSB effect in $A = 4$ systems
- to explore the *sd*-shell Λ–hypernuclei ($^{19}F_{\Lambda}$)
  - study of radial dependence of Λ*N* interaction
- to measure B(M1) in order to evaluate g_{Λ} in nuclear matter

E13: experimental setup



$$^{A}_{\ }Z\,(K^-,\pi^-)\,^{A}_{\Lambda}Z^{*}$$

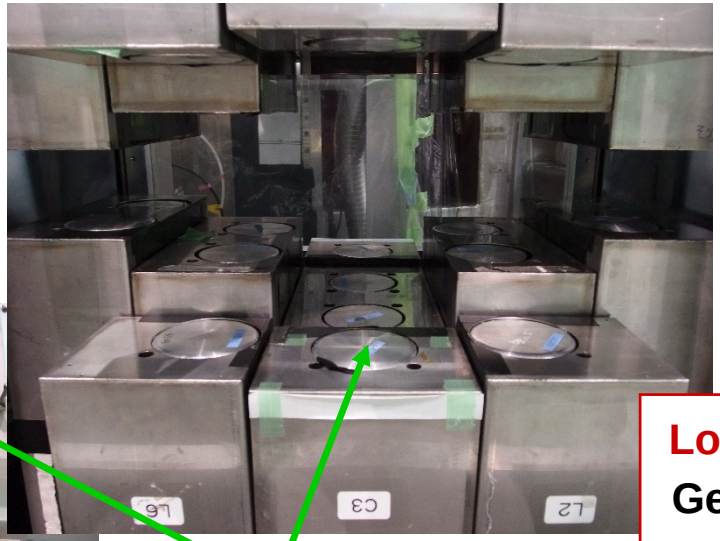
$$\rightarrow\ ^{A}_{\Lambda}Z+\gamma$$

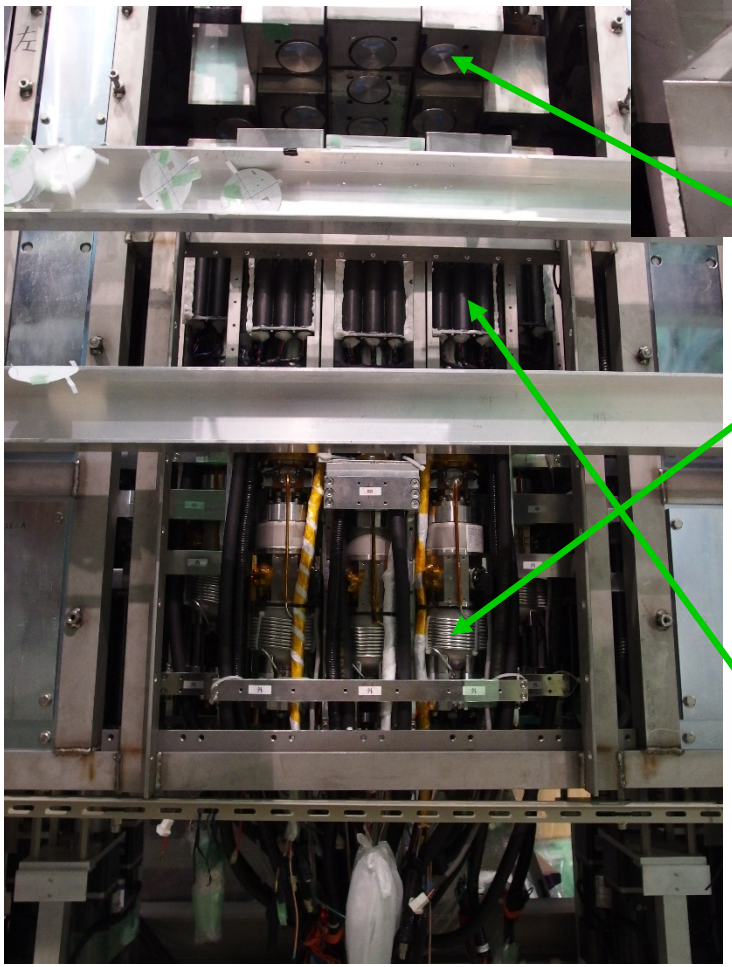


New generation γ–ray detector array

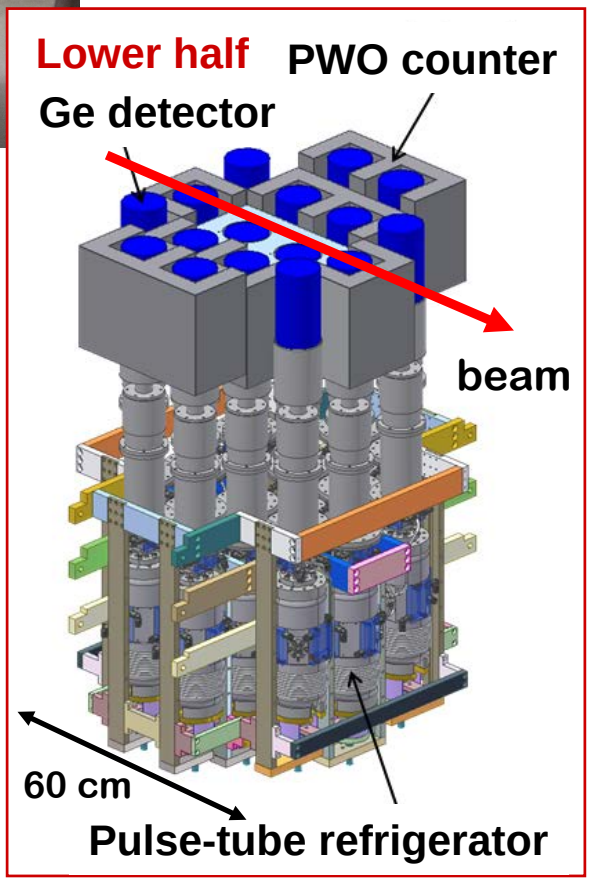
Hyperball-J:

32-crystal array
compact assembly

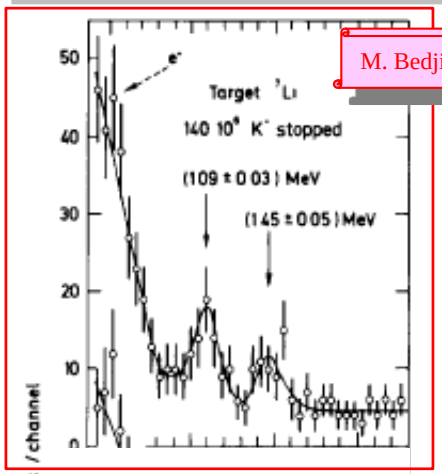




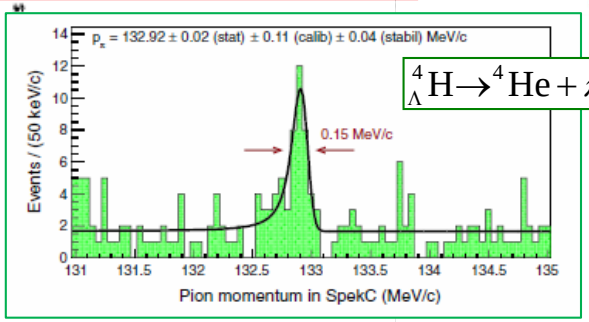
- Ge crystals cooled down to ~70 K by pulse-tube refrigerator → radiation damage reduction (92 K w/ LN_2)
- fast(er) background suppression with PWO counters
- ΔE = 3.1(1) keV at 1.33 MeV
- eff. = 5.4% at 1 MeV



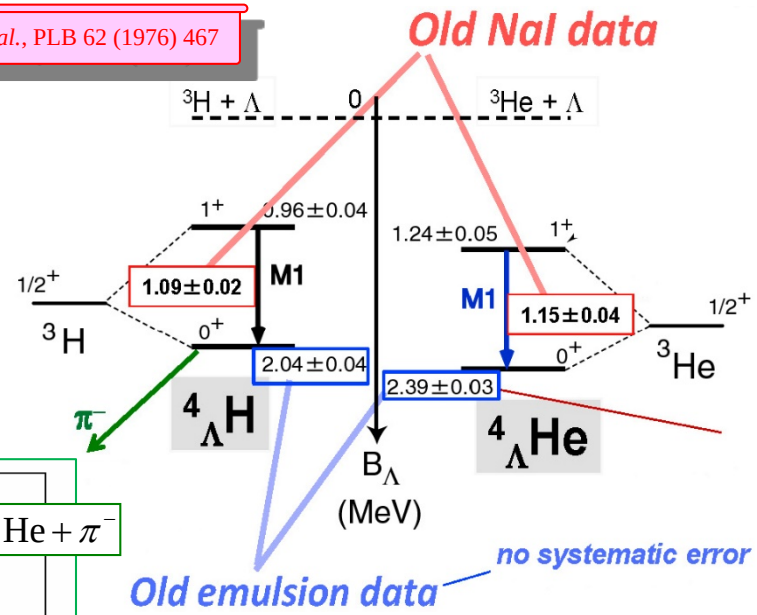
CSB in A = 4 systems



M. Bedjidian *et al.*, PLB 62 (1976) 467



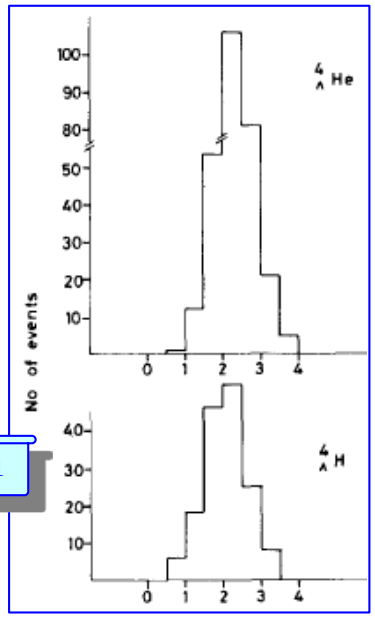
A. Esser *et al.*, PRL 114 (2015) 12501



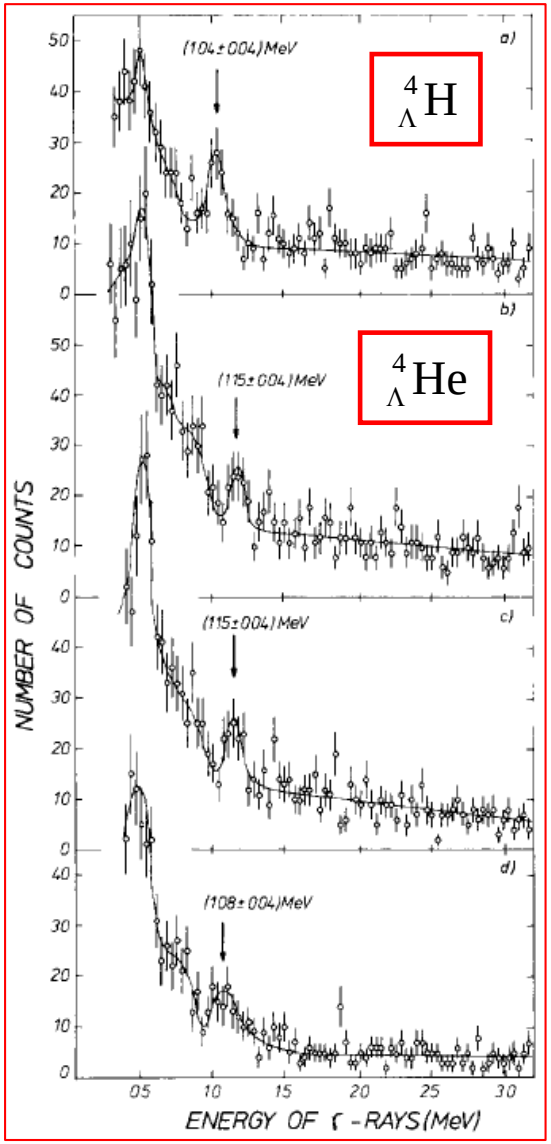
B_Λ = (2.12 ± 0.01 ± 0.09) MeV

origin:
- ???

possible explanations:
- ΛΣ mixing
- ΛN-ΣN coupling

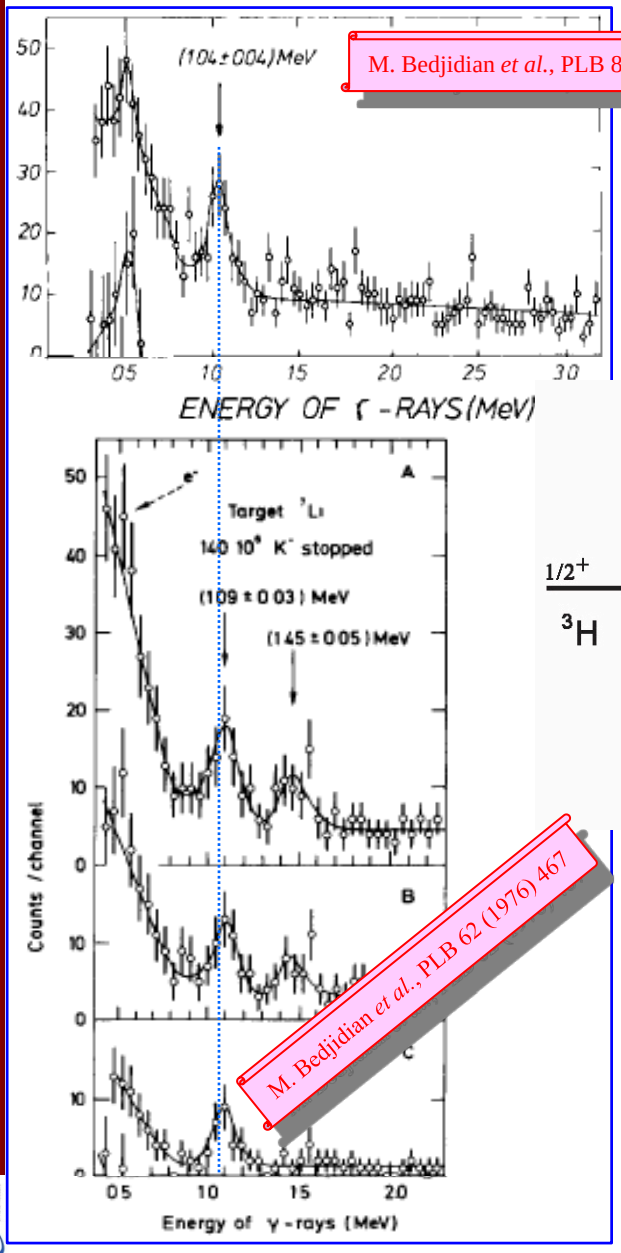


M. Jurić *et al.*, NPB 52 (1973) 1



M. Bedjidian *et al.*, PLB 83 (1979) 252

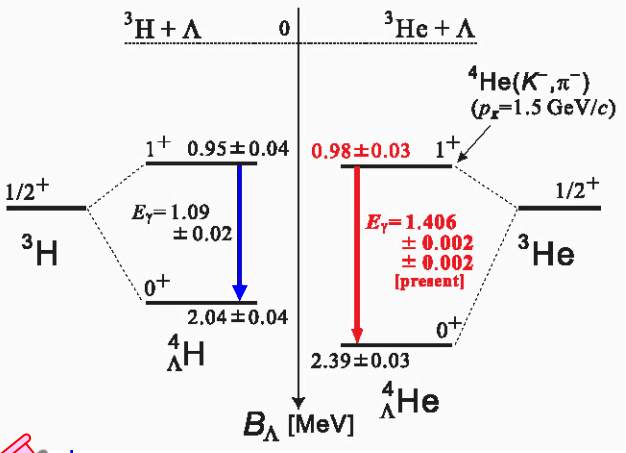
E13: experimental results on $^{4}_{\Lambda}$He

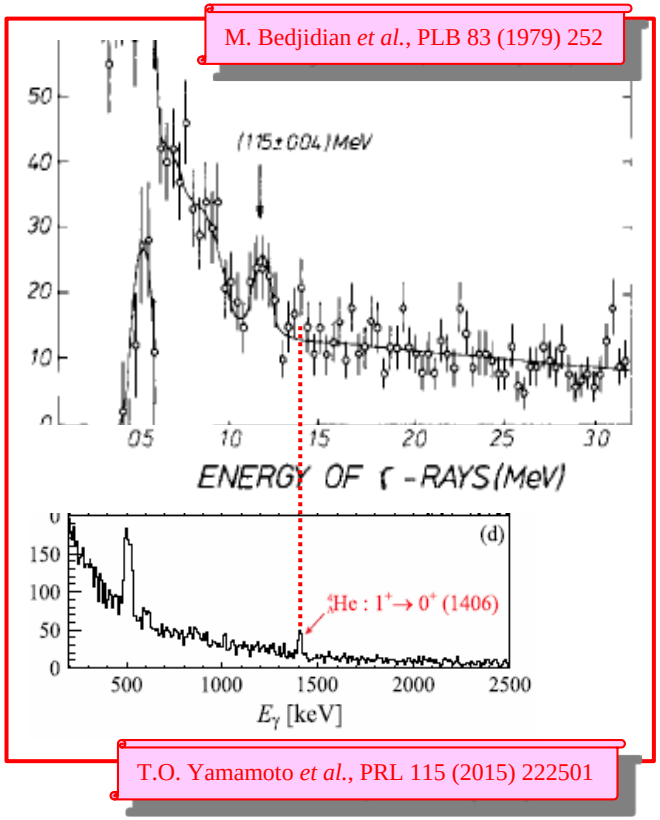


M. Bedjidian *et al.*, PLB 83 (1979) 252

M. Bedjidian *et al.*, PLB 62 (1976) 467

$$^{4}\mathrm{He}(K^{-},\pi^{-})^{4}_{\Lambda}\mathrm{He}$$





M. Bedjidian *et al.*, PLB 83 (1979) 252

T.O. Yamamoto *et al.*, PRL 115 (2015) 222501

$\Delta B_{\Lambda}(1^{+})$ = (0.03 ± 0.05) MeV

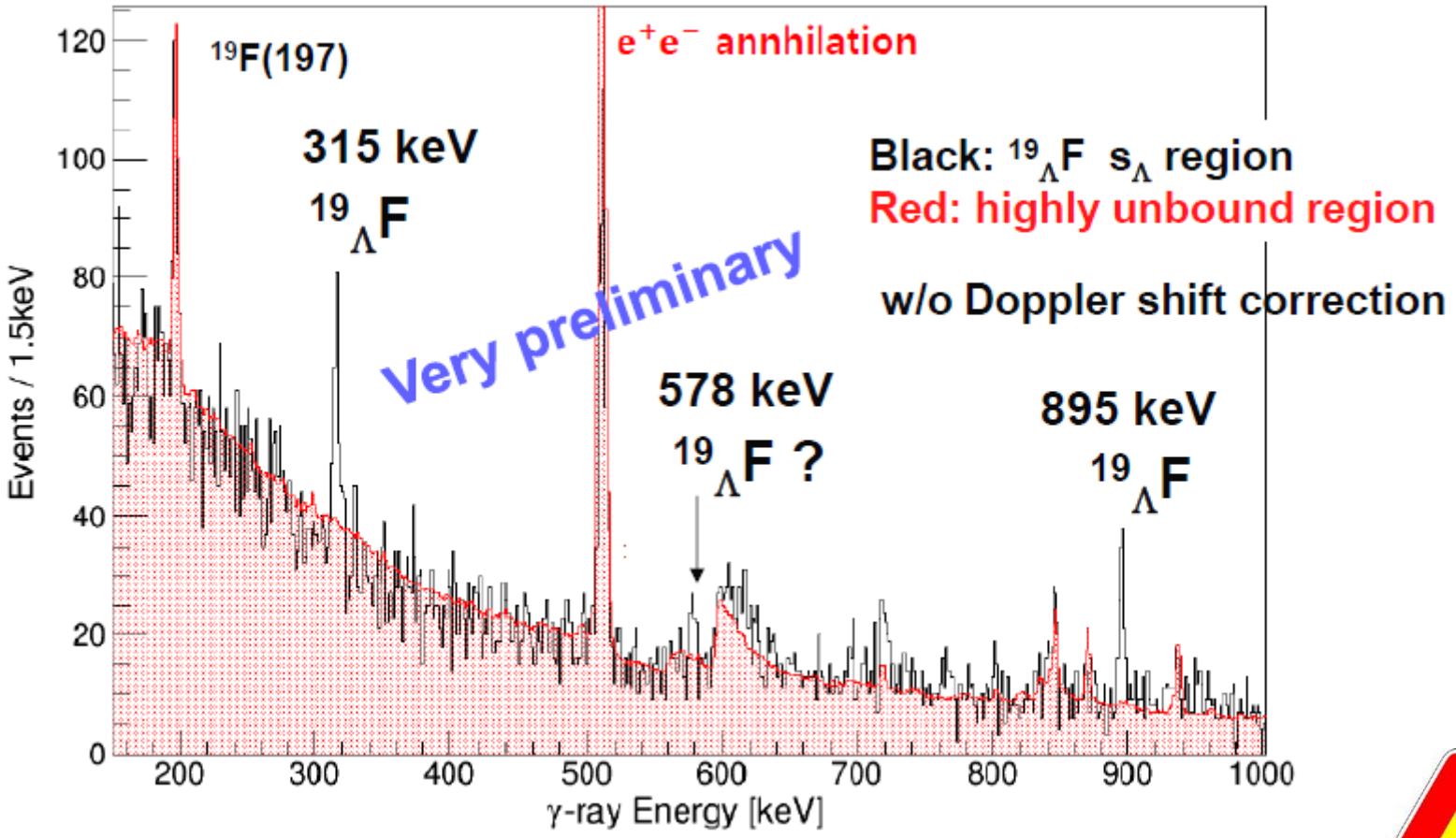
$\Delta B_{\Lambda}(0^{+})$ = (0.35 ± 0.05) MeV

by combining E13 results with emulsion data

strong spin dependence

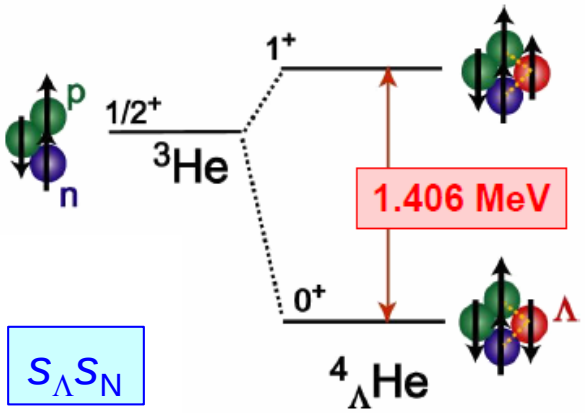
E13: $^{19}F_\Lambda$ experimental spectrum

$$CF_4(K^-,\pi^-)^{19}_{\Lambda}F$$



signal at 315 keV: most likely it could be assigned to M1 transition $^{19}F_\Lambda(3/2^+ \rightarrow 1/2^+)$

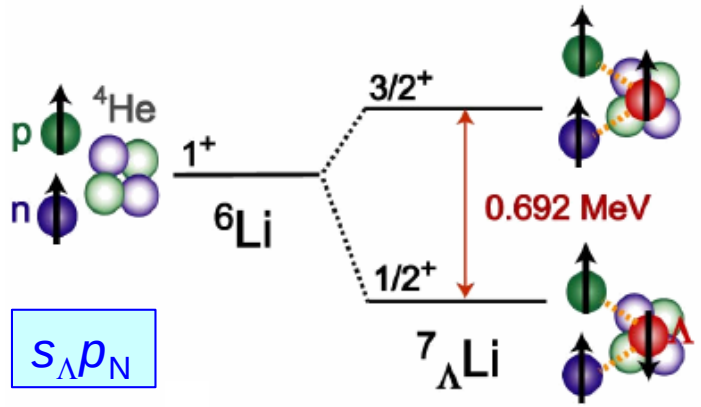
A-dependence of the ΛN interaction strenght



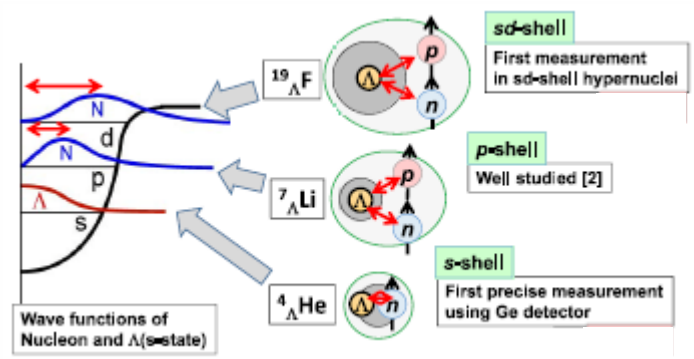
$s_\Lambda s_N$

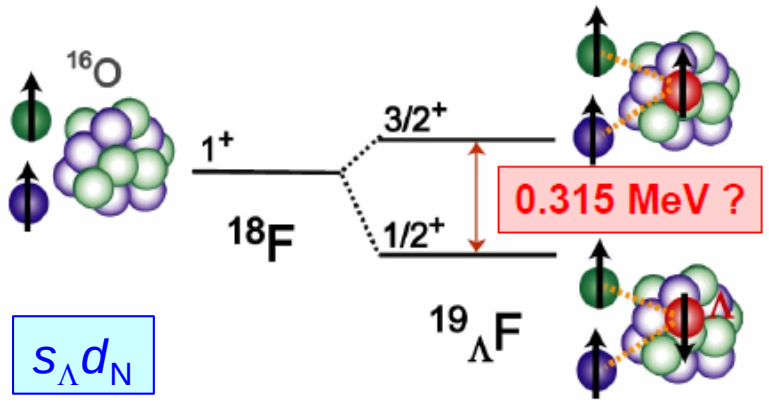
→ information on wave functions and interaction range

→ confirm short-range nature of ΛN interaction



$s_\Lambda p_N$





$s_\Lambda d_N$

$$\bar{r}(s_\Lambda - d_N) > \bar{r}(s_\Lambda - p_N) > \bar{r}(s_\Lambda - s_N)$$

E13: future plans

- light Λ-hypernuclei:

  $^{4}H_{\Lambda}$ ($\rightarrow$ CSB), $^{3}H^{*}(1^{+})$

- spin-flip B(M1) and in-medium g_{Λ}:

  $^{7}Li_{\Lambda}$ and heavier

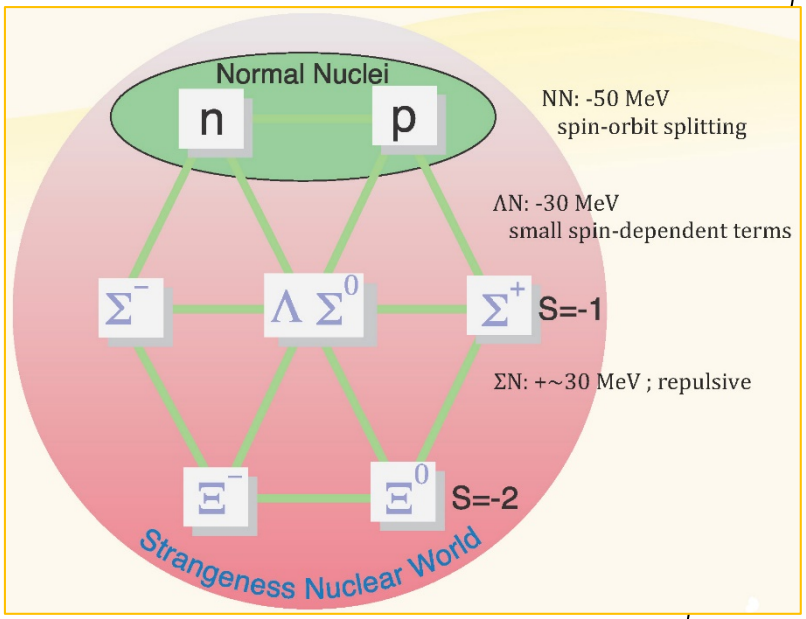
- E1($p_{\Lambda} \rightarrow s_{\Lambda}$):
  B_{Λ} ($\rightarrow$ ΛNN force) and LS splitting

- impurity effects:
  (change of deformation/clustering):

  $^{25}Mg_{\Lambda}$, $^{28}Si_{\Lambda}$, $^{20}Ne_{\Lambda}$

The E05 experiment

AXiS with SKS+



Proposal for J-PARC 50 GeV Proton Synchrotron

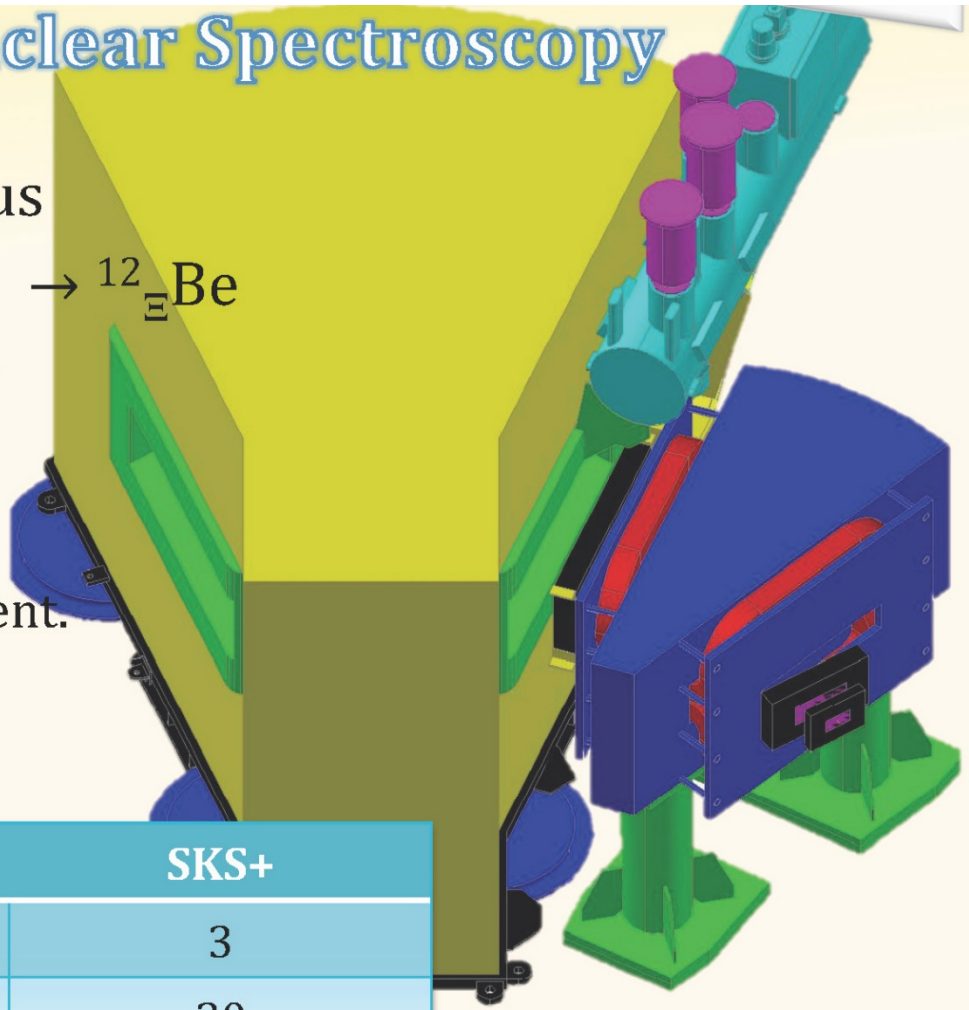
Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}$Be, via the ^{12}C(K^-, K^+) Reaction

K. Aoki, M. Ieiri, T. Maruta, T. Nagae (Spokesperson), H. Noumi, Y. Sato, S. Sawada, M. Sekimoto, H. Takahashi, T. Takahashi, A. Toyada
High Energy Accelerator Research Organization (KEK), Japan
Y. Fujii, O. Hashimoto, T. Ishikawa, H. Kanda, M. Kaneta, T. Koike, Y. Ma, K. Maeda, K. Shirotori, S. N. Nakamura, H. Tamura, M. Ukai, H. Yamazaki
Tohoku University, Japan
P. K. Saha
Japan Atomic Energy Agency (JAEA), Japan
H. Fujioka, D. Nakajima, T. N. Takahashi
University of Tokyo, Japan
K. Nakazawa, T. Watanabe
Gifu University, Japan
K. Imai, K. Miwa, K. Tanida
Kyoto University, Japan
S. Ajimura, T. Kishimoto, A. Sakaguchi
Osaka University, Japan
M. Yosoi
Research Center for Nuclear Physics (RCNP), Osaka University, Japan
T. Fukuda
Osaka Electro-Communication University, Japan
P. Evtoukhovitch, V. Kalinnikov, W. Kallies, N. Kravchuk, A. Moiseenko, D. Mzhavia, V. Samoilov, Z. Tsamalaidze, O. Zaimidoroga
Joint Institute for Nuclear Research (JINR), Russia
J. K. Ahn, B. H. Choi
Pusan National University, Korea
Y. Fu, C. Li, X. Li, C. Zhou, S. H. Zhou, L. H. Zhu
China Institute of Atomic Energy (CIAE), China
R. E. Chrien
Brookhaven National Laboratory (BNL), USA
B. Bassalleck
University of New Mexico, USA

E05: esperimental setup

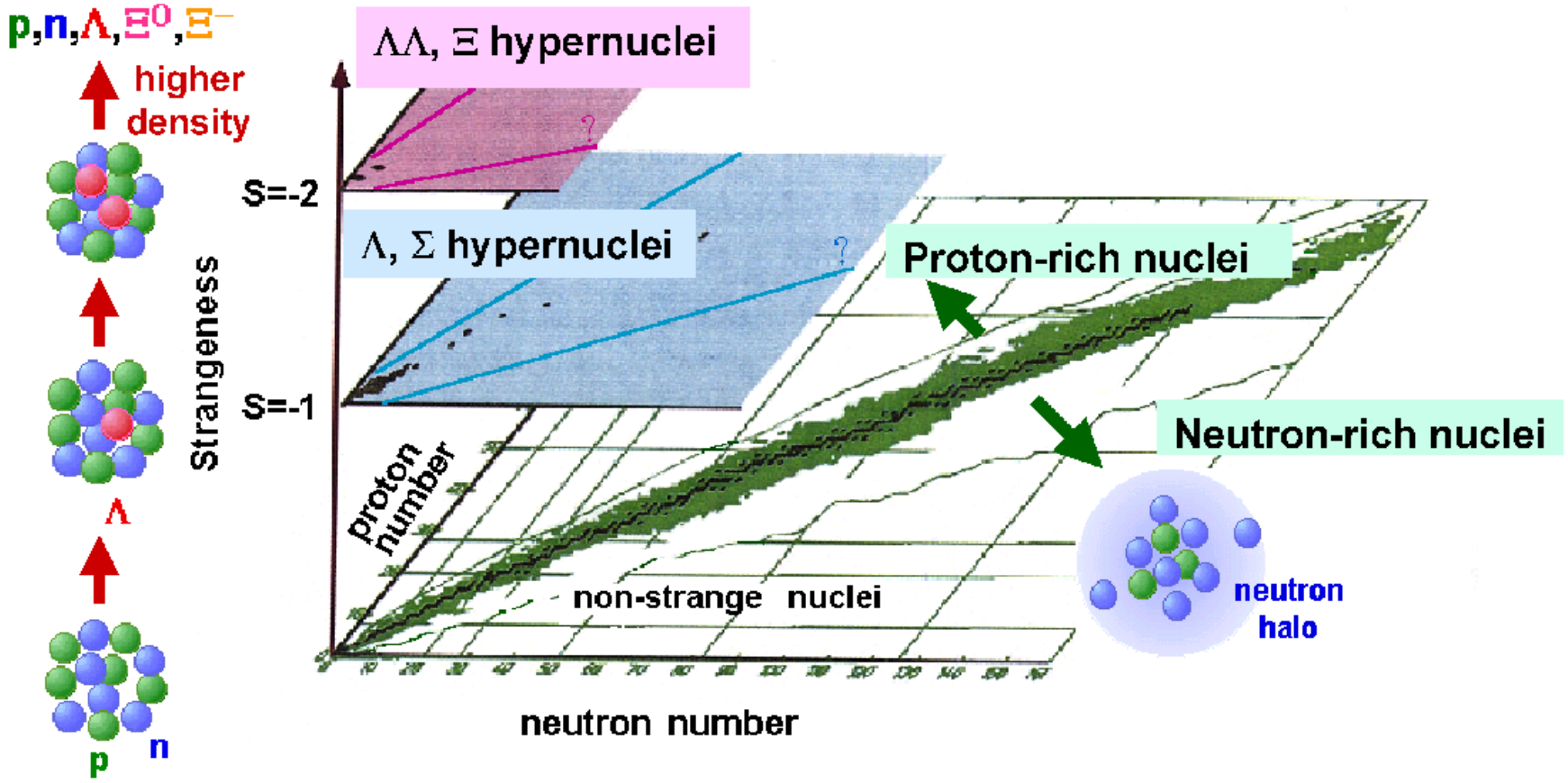
J-PARC E05: Ξ-Hypernuclear Spectroscopy

- Discovery of Ξ-hypernucleus
- using $^{12}C(K^-, K^+)$ reaction ; → $^{12}_{\Xi}Be$
- Missing mass spectroscopy
  - **high-resolution (~3MeV)**
  - **good statistics**
- Only J-PARC can do this experiment.
  - 1.4 x 10^6 K^-/spill @ 270kW



	BNL (48D48)	SKS+
ΔM (MeV)	14	3
ΔΩ (msr)	20	30

Hypernuclei's chart



courtesy of H. Tamura

The status of art for Ξ-hypernuclei

previous experiment: BNL-E885

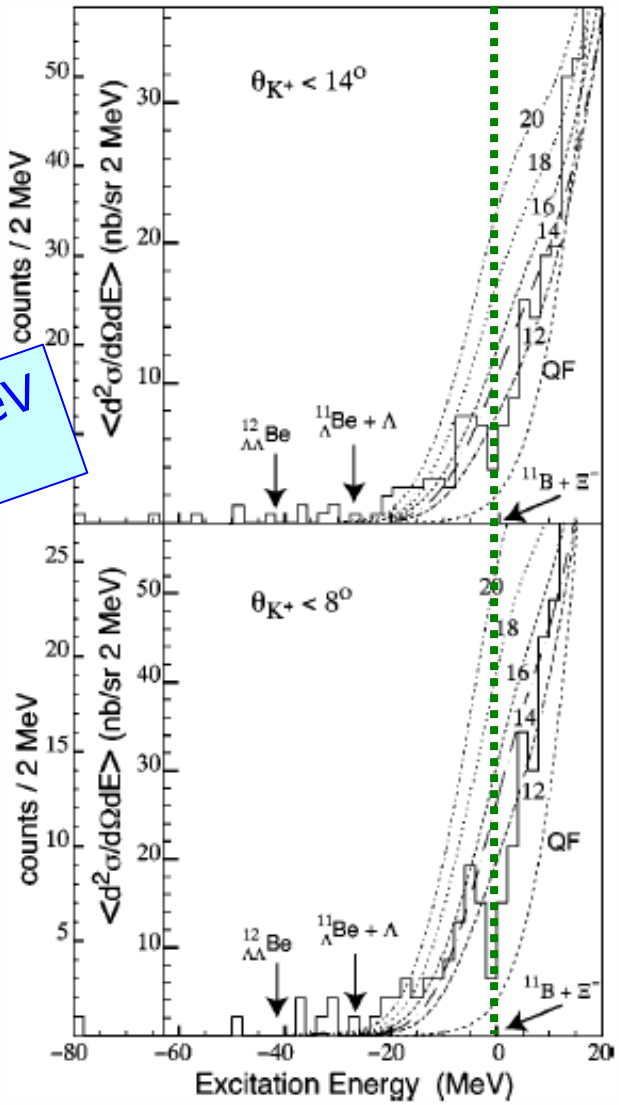
$$^{12}\mathrm{C}(K^-,K^+)\mathrm{X}$$

- evidence for Ξ-hypernuclear bound state (not definitive because of limited mass resolution)

ΔM_{exp} = 14 MeV (FWHM)

- signal shape analysys and counts in bound region, compared with DWIA calculations, suggest a weakly actractive ΞN potential ~-14 MeV deep

- production cross section:
  - dσ/dΩ = 89 ± 14 nb/sr (< 8 deg.)
  - dσ/dΩ = 42 ± 5 nb/sr (< 14 deg.)

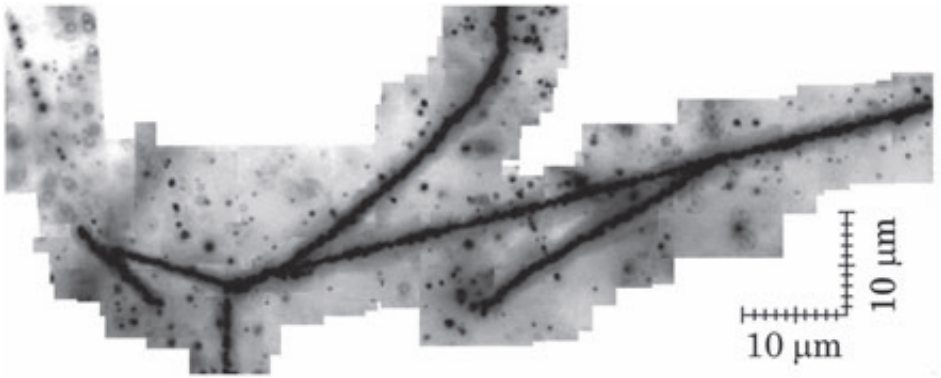


P. Khaustov *et al.*, PRC 61 (2000) 054603

The status of art for Ξ-hypernuclei

The "KISO" event

K. Nakazawa *et al.*, PTEP (2015) 033D02



observation of a bound state of the Ξ^--^{14}N system

- $\Xi^- + {}^{14}N \rightarrow {}^{10}Be_\Lambda + {}^{5}He_\Lambda$
- B_Ξ = (4.38 ± 0.25) ÷ (1.11 ± 0.25) MeV

well beyond the atomic binding of 0.17 MeV!

☛ Ξ-hypernuclei do exist!

measurement of:

? $Re(V_\Xi)$

? $\Gamma_{\Xi N-\Lambda\Lambda}$

E05: physics motivations

- First spectroscopic study of S = -2 systems via the (K^-,K^+) reaction
  - Ξ-hypernuclei ($\Rightarrow$ double $\Lambda\Lambda$-hypernuclei)
  - Ξp-$\Lambda\Lambda$ mixing
  - first step for multistrangeness baryon systems

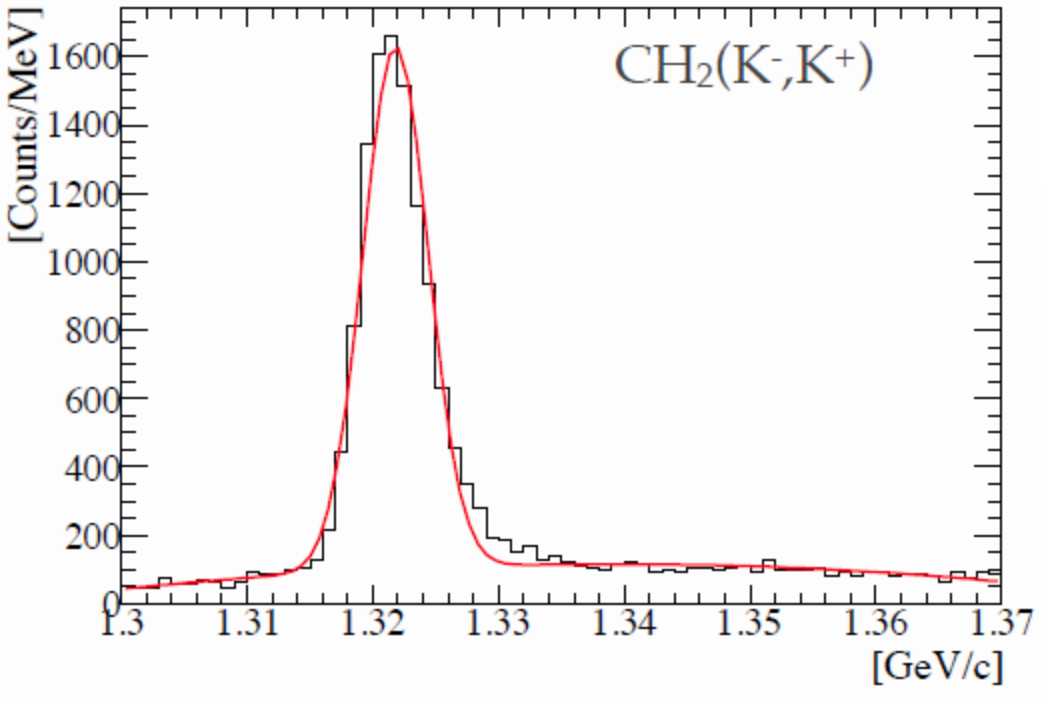
- ΞN interactions: essentially no information
  - actractive or repulsive? $\Rightarrow$ potential depth
  - Ξp-$\Lambda\Lambda$ conversion? $\Rightarrow$ conversion width
  - isospin dependence? $\Rightarrow$ Lane term ($\tau_\Xi \cdot \tau_C / A_C$)

S = -2 systems study is not just a simple extension of what has been done for S = -1 system

Birthday of S = -2 physics at J-PARC

Ξ production at J-PARC

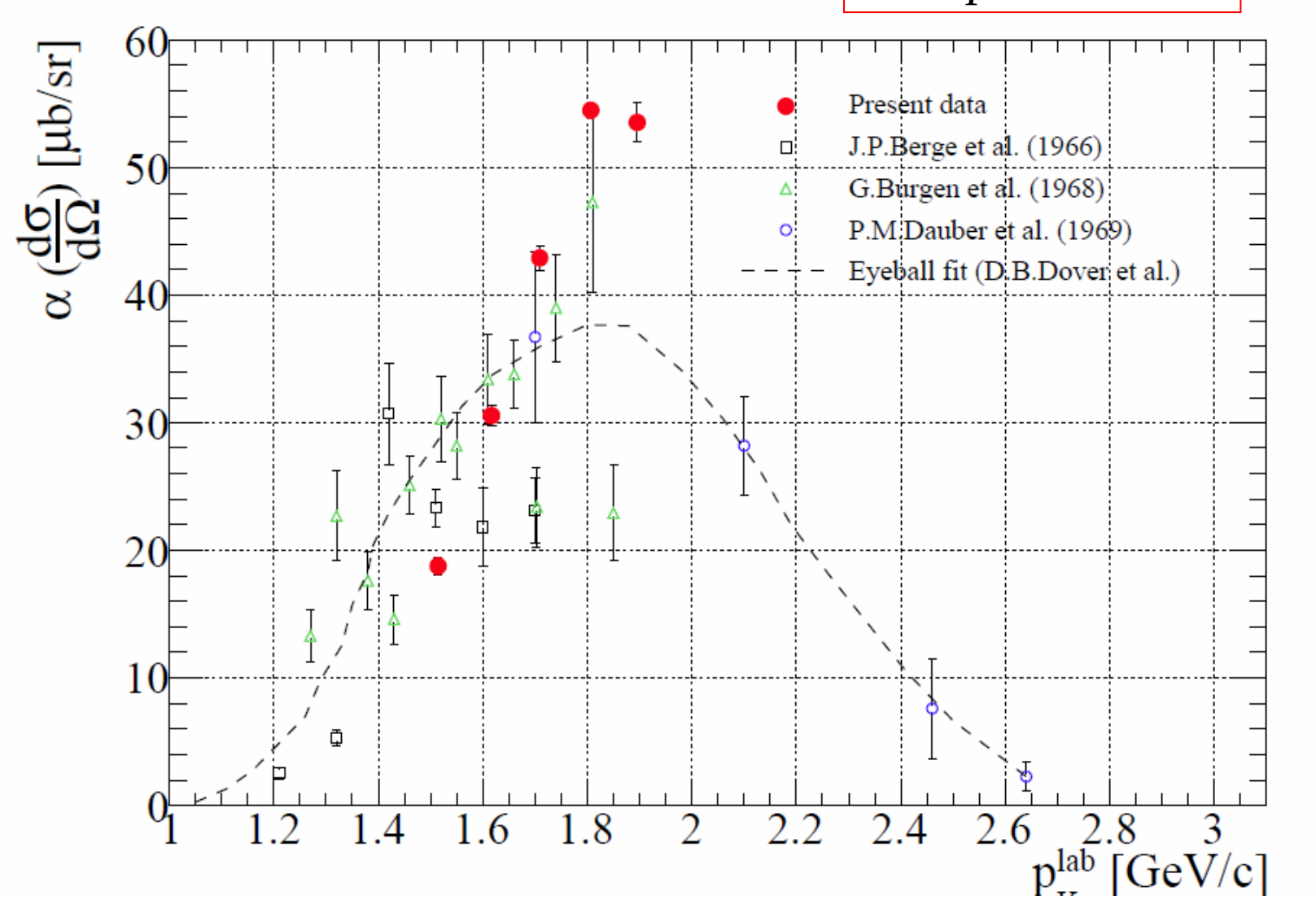
yield: ~6000 Ξ / day



ΔE ~6 MeV (FWHM)

Momentum scan

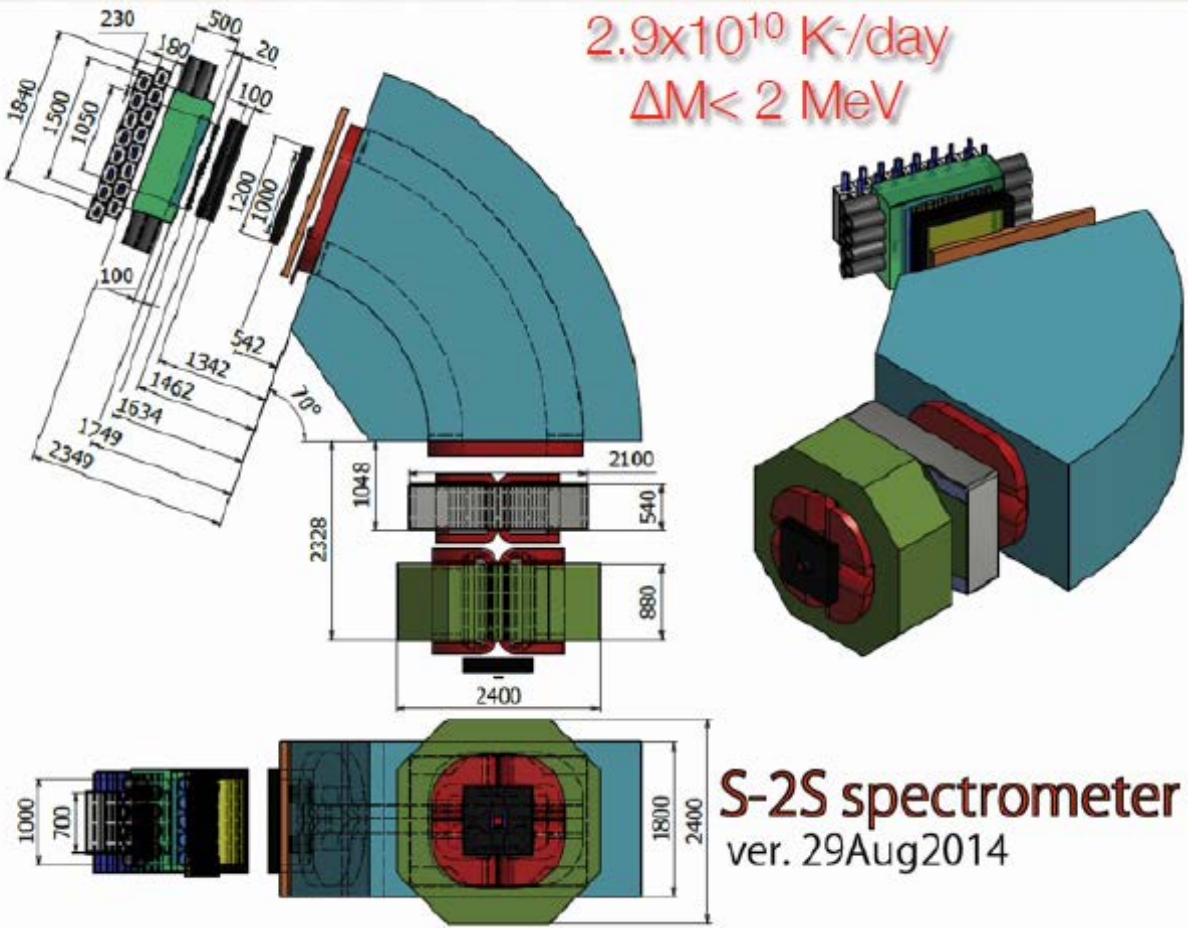
$$K^- + p \rightarrow K^+ + \Xi^-$$



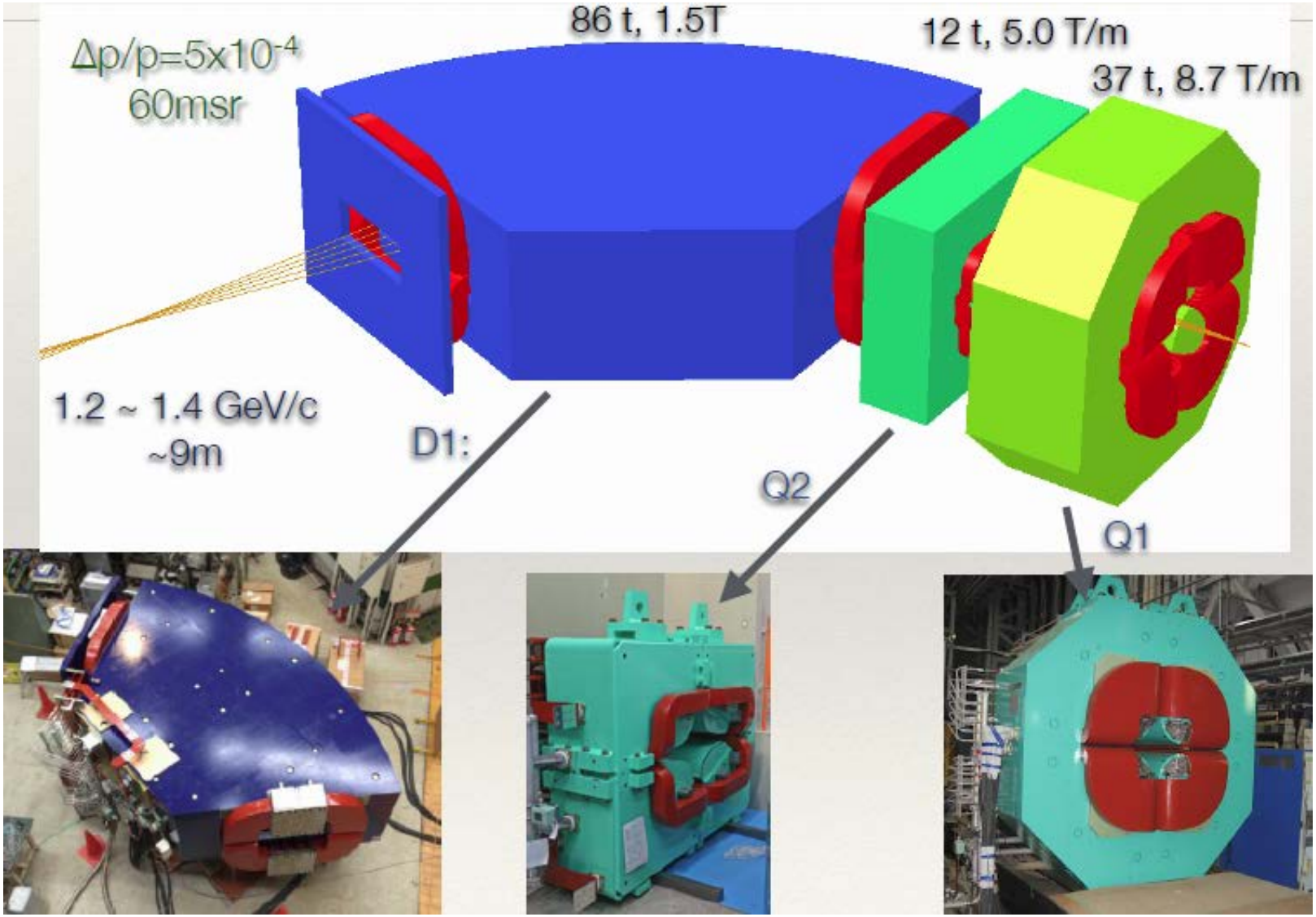
normalized data: $d\sigma/d\Omega$ = 35 μb/sr @ 1.65 GeV/*c*

E05: future plans

- Grant-In-Aid for Specially promoted research: 2011 – 2015, Total ~$3M
- 60 msr, $\Delta p/p$=0.05% → ΔM=1.5 MeV
- Construction of S-2S(QQD): ~3 years
  - ★ Installation in 2016
  - ★ Data taking in 2017 with > 50 kW !!



E05: future plans



~~Conclusions~~

The starting point!

- experimental activity on hypernuclear physics has definitively started at J-PARC
- interesting results have already been achieved
- perspectives look promising
- active and entusiastic physicists' community
  - extension of the Hadron Experimental Facility
  - call for new ideas and proposals to exploit the rich discovery potential of the field
- long and fruitful collaboration betwen Japanese and Italian Groups

Thank you!

どうも　ありがとう