中性子過剰核物質中のストレンジネス（計画研究A02）

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Physics of Neutron Stars and A02 issue

- Neutron stars
  - Various types of signals and activities
    - Identify neutron stars, information by observation (C01, D01)
  - Structure: "Nuclear Matter" from low to high ($\approx 9\rho_0$) densities
    - Low density: Atmosphere, Outer-crust, Inner-crust
    - High density: Outer-core, Inner-core
- What governs the structure of neutron stars?
  - Gravity: well known (general relativity), mass of neutron stars
  - EoS of neutron matter ($n + p + e^- + \mu^-$)
    - Density dependence of symmetry energy of nucleons
    - Experimental study with accelerators, etc. (B01-B03, D01)
  - Does the inner-core have Exotic components?
    - Contributions of hyperons (Λ, Σ, Ξ, …), mesons (π, K, …), etc.
    - Experimental studies at J-PARC (A01-02, D01)

Strangeness in Neutron Stars

- Strangeness appears in high density nuclear matter

Degree of nucleons and hyperons

$n + p + e^- + \mu^-$

$\Lambda + \Sigma + \Xi$

Phenomenological BB interaction

$$V_y(\rho_x) = \underbrace{a_{xy}\rho_x}_{\text{2-body}} + \underbrace{b_{xy}t_x t_y \rho_x}_{\text{symmetry energy}} + \underbrace{c_{xy}\rho_x^{\gamma_{xy}}}_{\text{3-body}}$$

γ_{xy}: Hardness of EoS

Hyperon-nucleon interaction

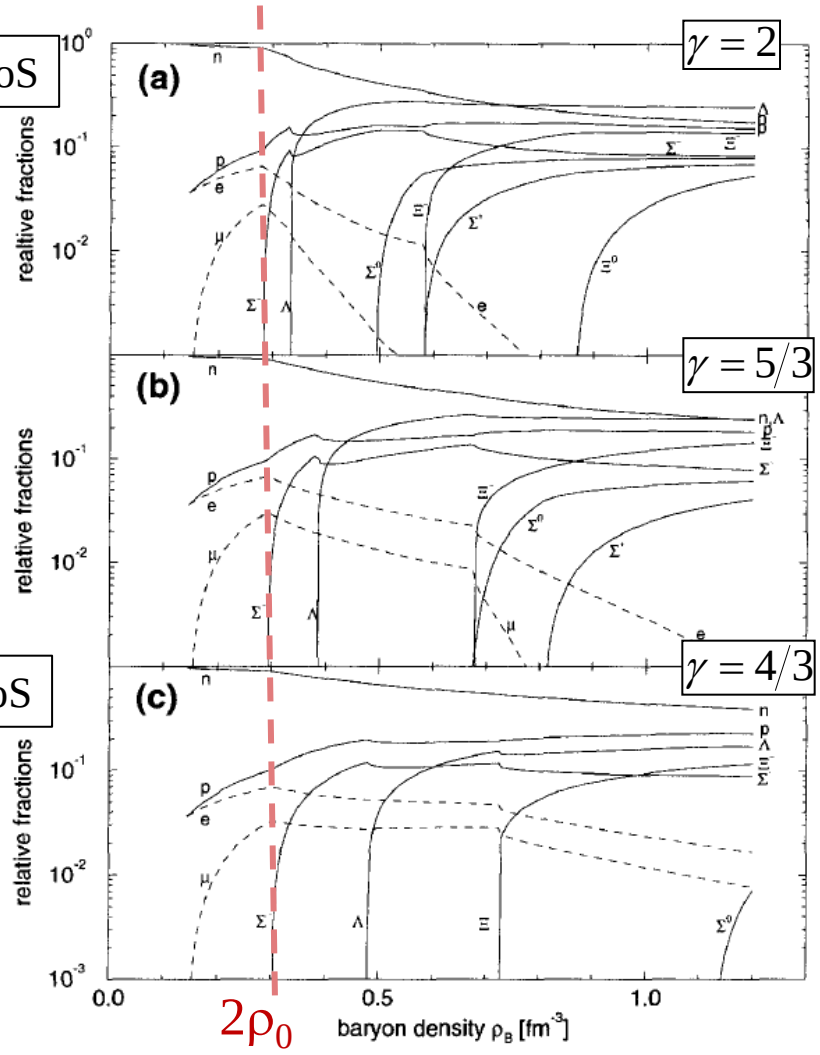
$$V_\Lambda(\rho_0) \approx \underbrace{V_\Sigma(\rho_0)}_{?} \approx V_\Xi(\rho_0) \approx -30 MeV$$

Hyperons appear around $2\rho_0$

Hyperon appearance looks robust

Hard EoS

Soft EoS



S. Balberg, A. Gal, NPA 625 (1997) 435

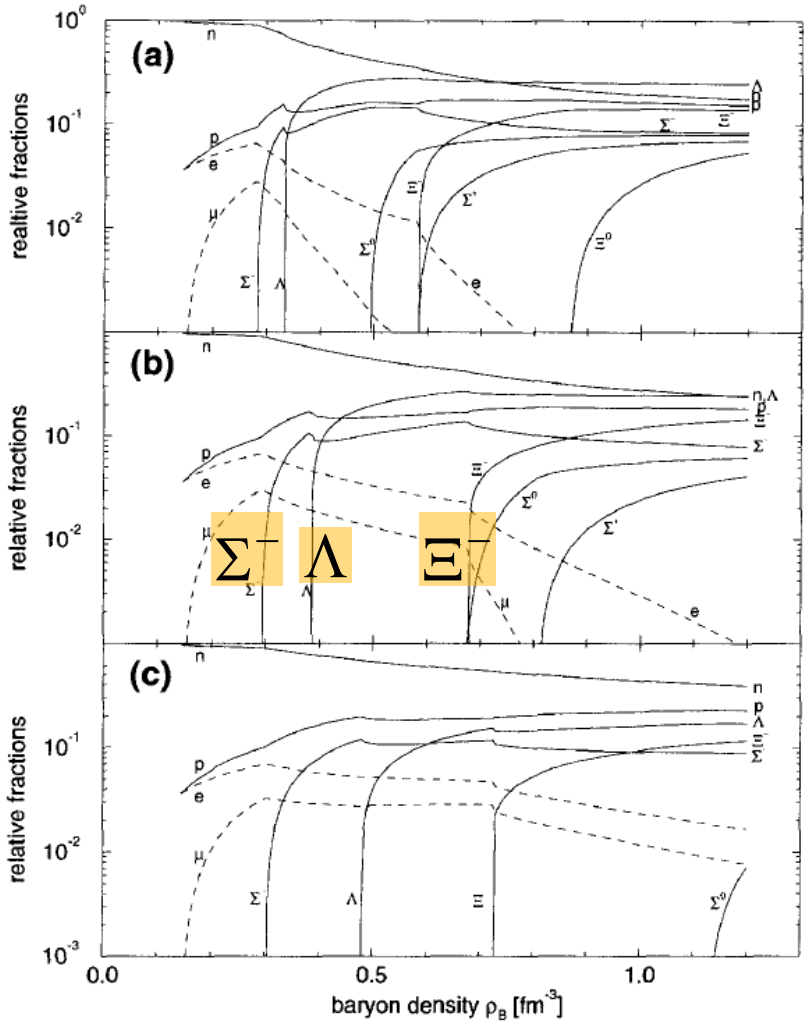
- What controls the appearance of hyperons?

well fixed

- Negative charge
  - Σ^- appears first
  - Appearance of Ξ^-
  - π^- and K^- condensation
- Mass of hyperons
  - Early appearance of Λ

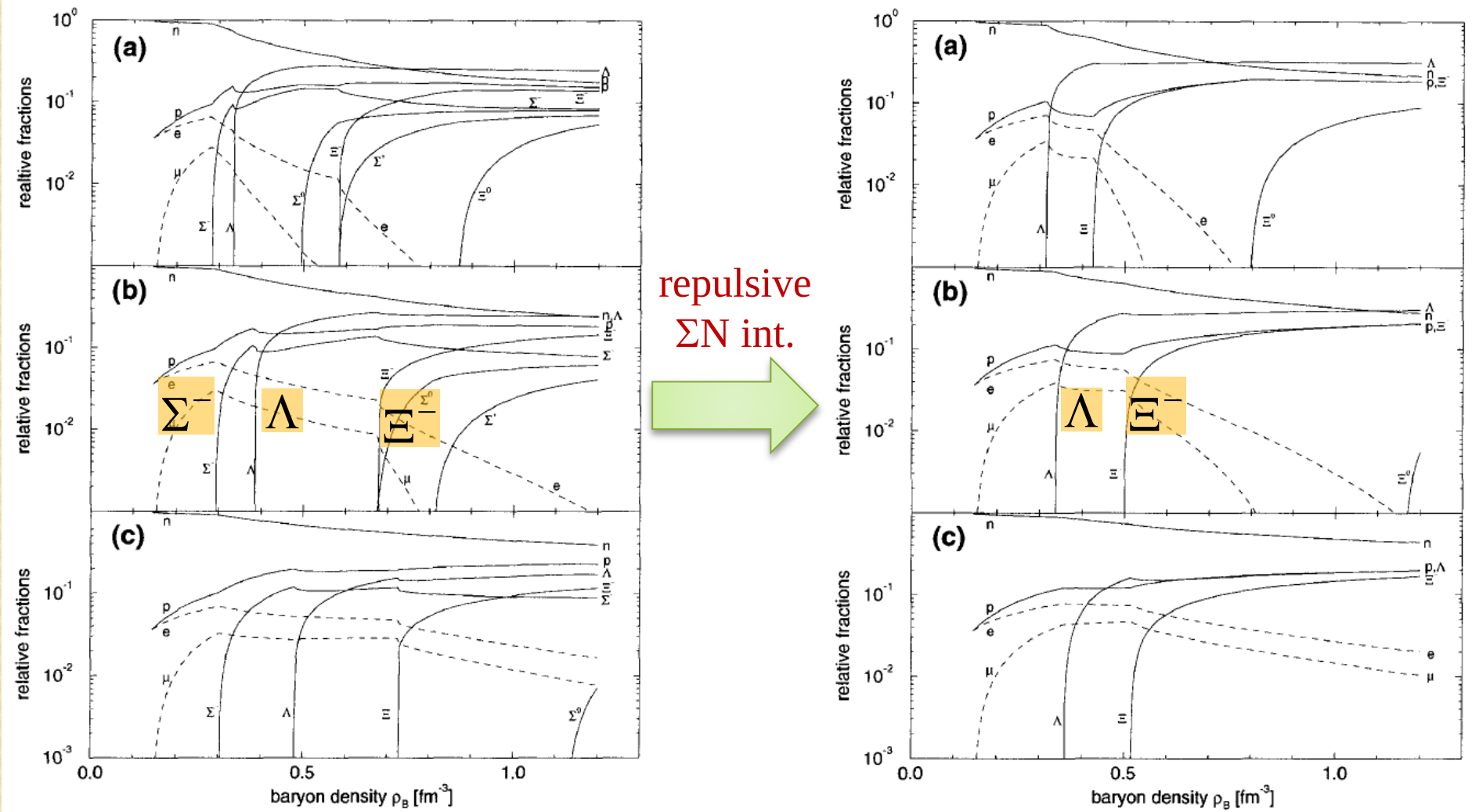
large ambiguity

- Attractive interaction
  - $V_{\Lambda n}$ is attractive
  - Σ^-n, Ξ^-n, $\Lambda\Lambda$ under study
  - π^- and K^- under study
- Symmetry energy
  - Large? for Σn (I=1)
    - Pauli blocking in quarks
  - None? for Λn (I=0)



S. Balberg, A. Gal, NPA 625 (1997) 435

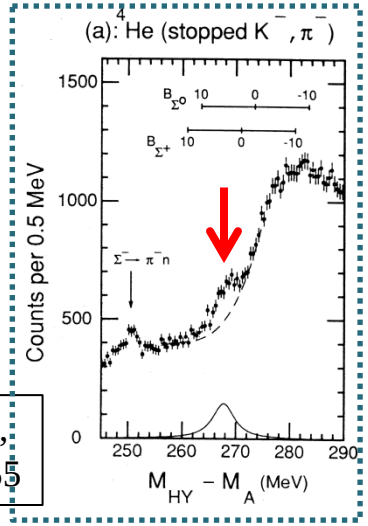
- Example of effect of YN interaction

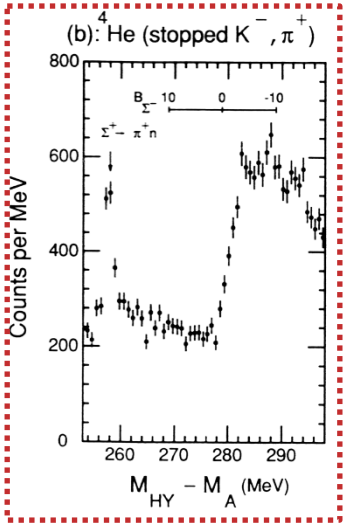


S. Balberg, A. Gal, NPA 625 (1997) 435

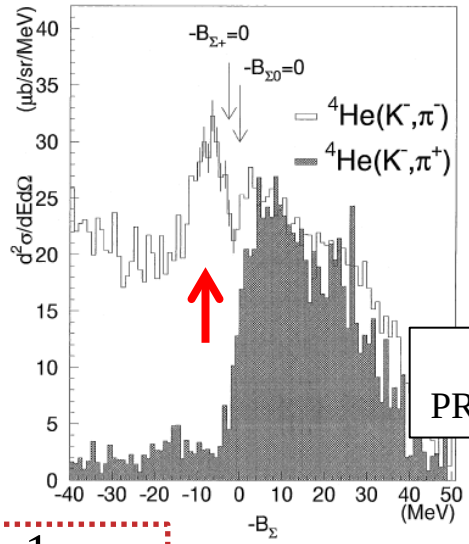
ΣN interaction (J-PARC E40)

- Sources of information on ΣN interaction
  - Σ hypernuclei
    - Clear bound state was observed in ^{4}He(K$^-$,π$^-$) reactions
    - Large decay width: strong ΣN-ΛN conversion in nuclei
    - No clear Σ bound state was observed in other hypernuclei

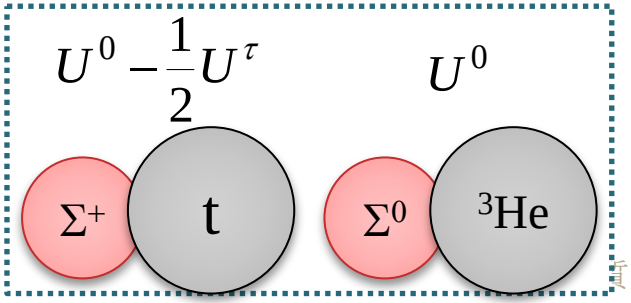




R.S. Hayano et al., PLB 231 (1989) 355



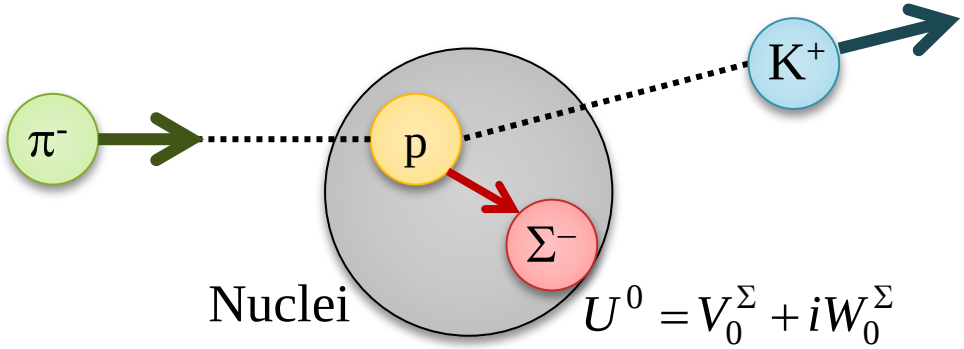
T. Nagae et al., PRL 80 (1998) 1605



$U^\tau \propto \tau_\Sigma \cdot \tau_A$

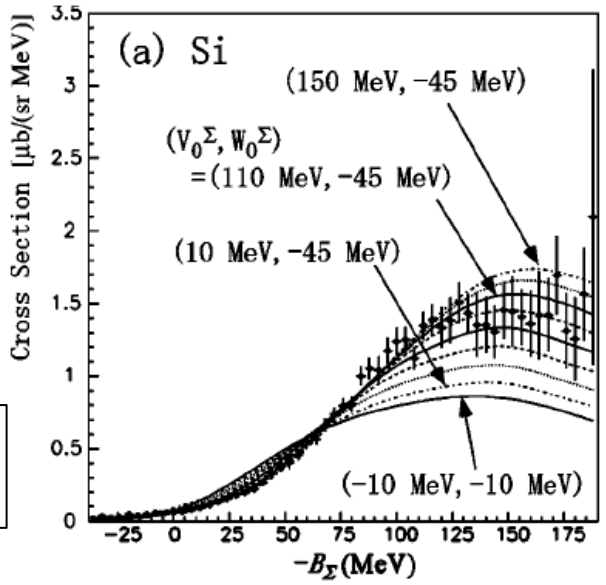
Lane term repulsive

- Quasi free Σ production off nuclei
  - Use quasi-free process to estimate ΣN interaction



Analysis with Green's function method

  - Quasi-free $p(\pi^-,K^+)\Sigma^-$ reaction off C, Si, Ni, In and Bi



$U^\tau \propto A^{-1}$ negligible

U^0 isoscalar potential

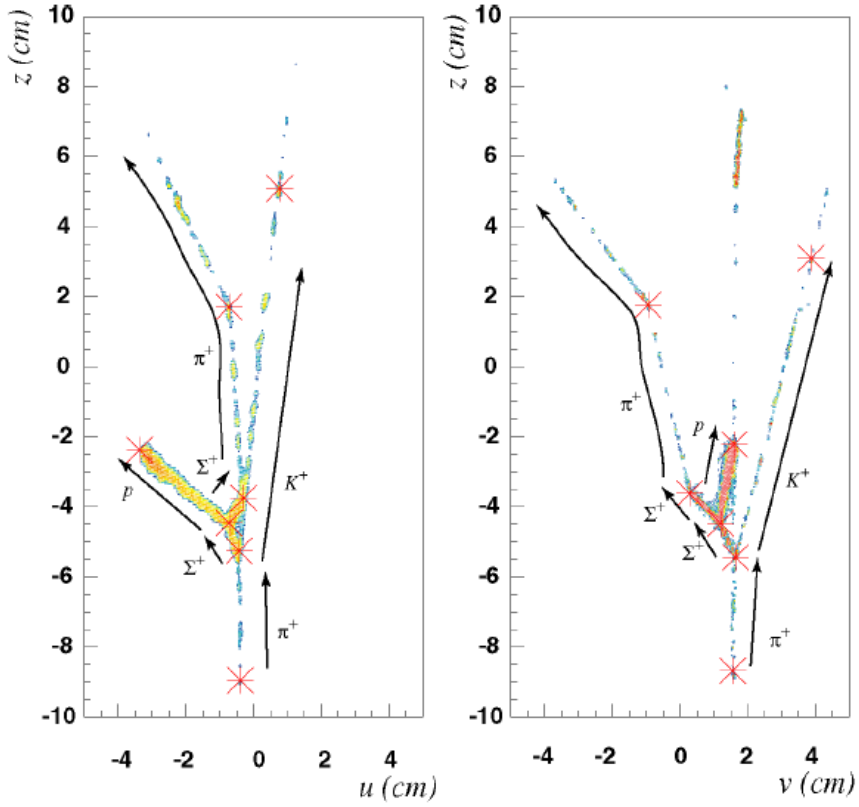
V_0^Σ: (strong) repulsive is favored

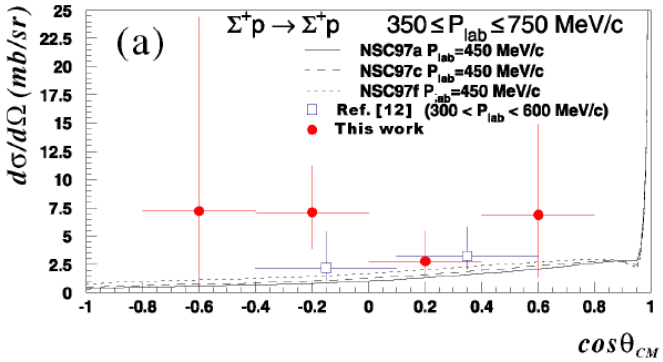
P.K. Saha, H. Noumi et al., PRC 70 (2004) 044613

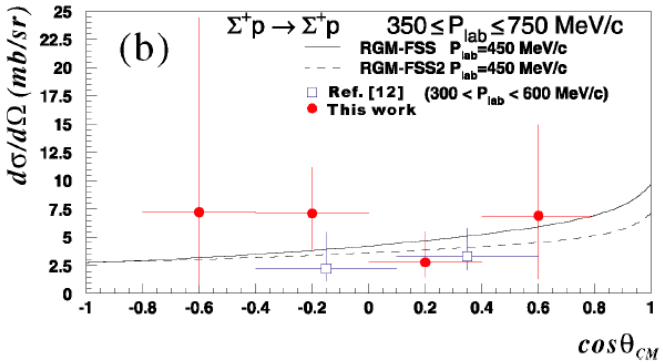
- ΣN elastic scattering
  - Most straight forward method to know ΣN interaction
  - Technically quote difficult (event selection and statistics)

$$\pi^+ + p \to K^+ + \Sigma^+$$
$$\Sigma^+ + p \to \Sigma^+ + p, \quad \Sigma^+ \to \pi^+ + n$$

$$U_{\Sigma^+ p} \approx U_{\Sigma^- n}$$



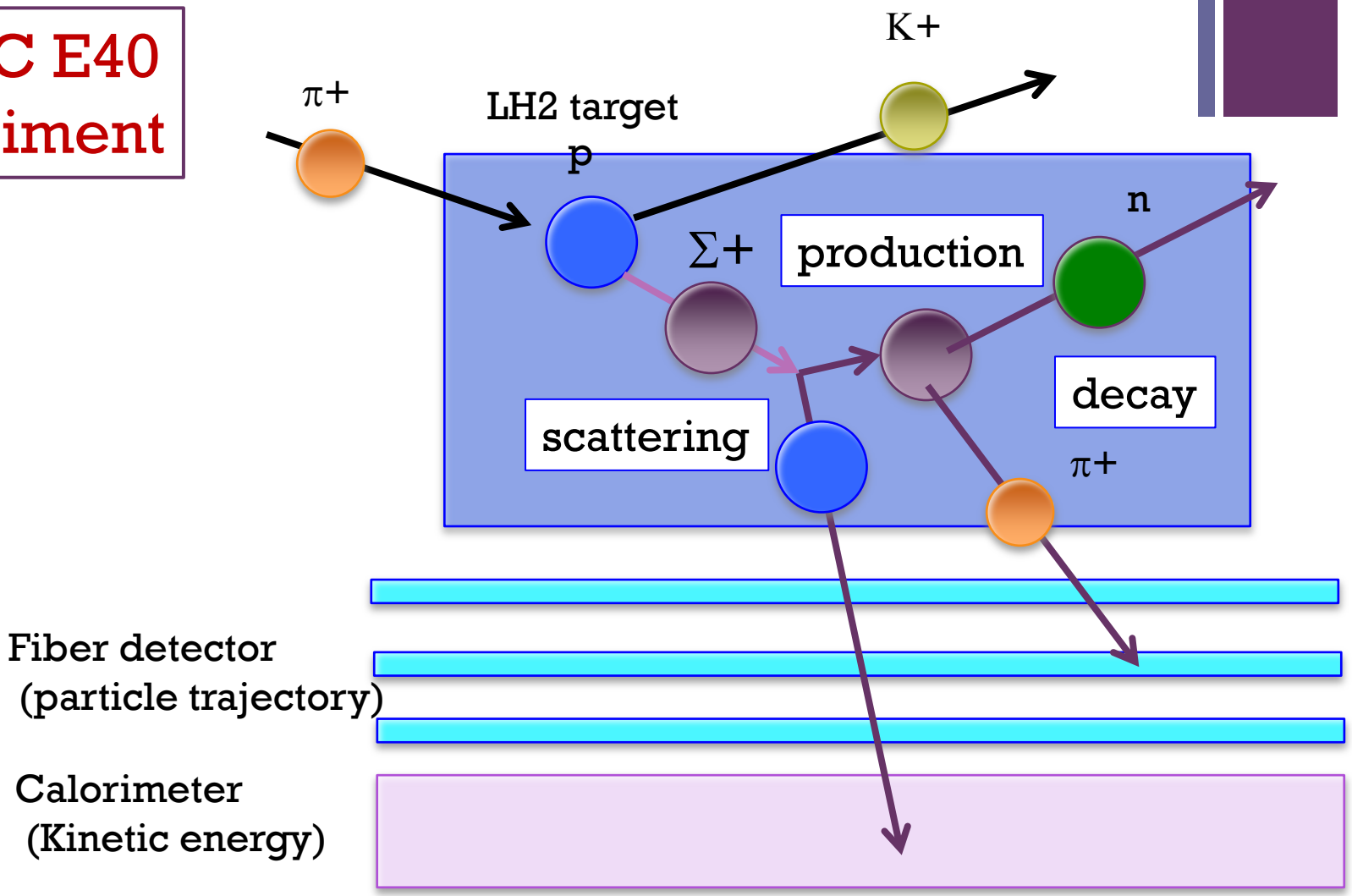




J.K. Ahn et al., NPA 761 (2005) 41

Principal of Σp scattering

J-PARC E40 experiment



Experimental setup at K1.8 beamline

- Σ beam spectrometer

  --- Σ beam part ---

  - $\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$ reaction
    - K1.8 spectrometer
    - SKS spectrometer

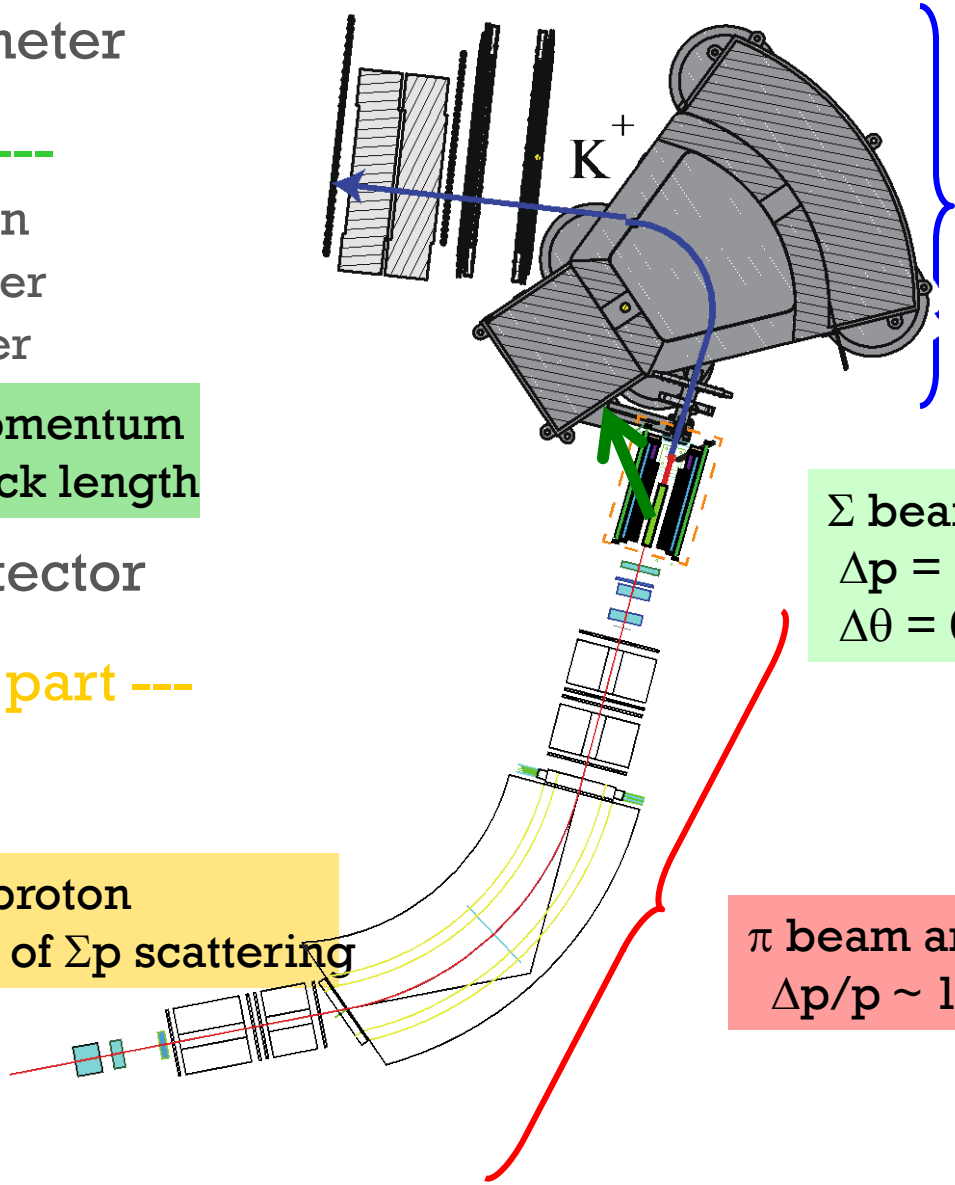
  Σ beam momentum
  Σ beam track length

- Σp scattering detector

  --- Σp scattering part ---

  - Σp→Σ" p"
  - ↳n" π"

  Detection of proton
  Identification of Σp scattering



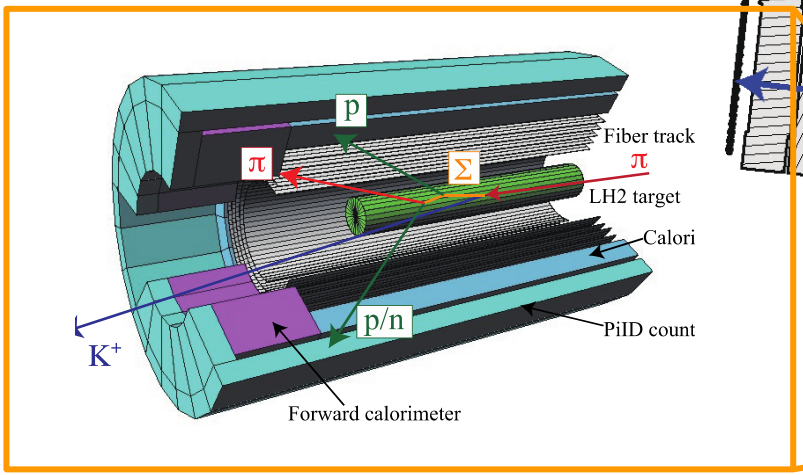
K^{+} analysis
$\Delta p/p \sim 10^{-3}$

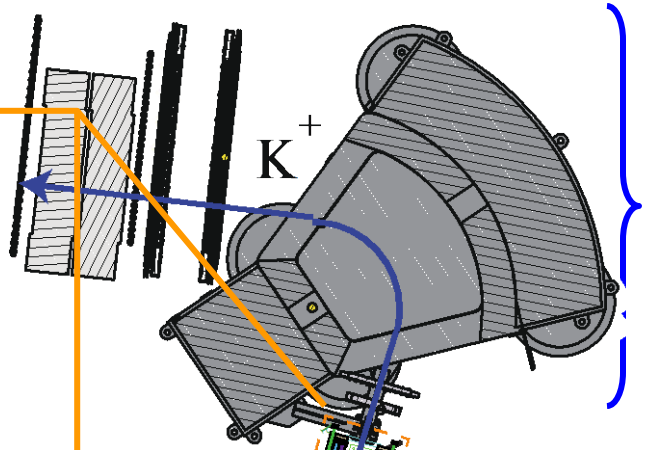
Σ beam tagging
Δp = 6.1 MeV/c (σ)
$\Delta\theta$ = 0.37 deg (σ)

π beam analysis
$\Delta p/p \sim 10^{-4}$

Experimental setup at K1.8 beamline

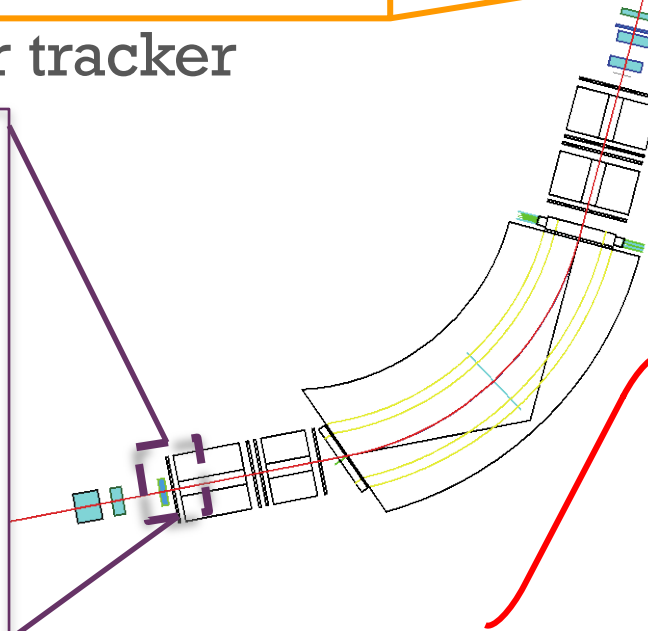
- Scattered proton detector





K^+ analysis
$\Delta p/p \sim 10^{-3}$

- Beamline fiber tracker



Σ beam tagging
$\Delta p = 6.1$ MeV/c (σ)
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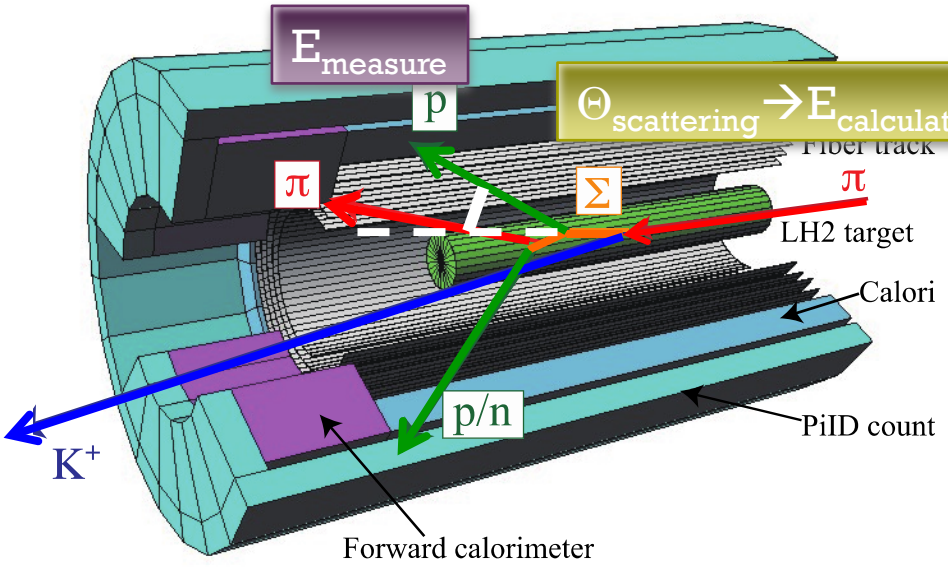
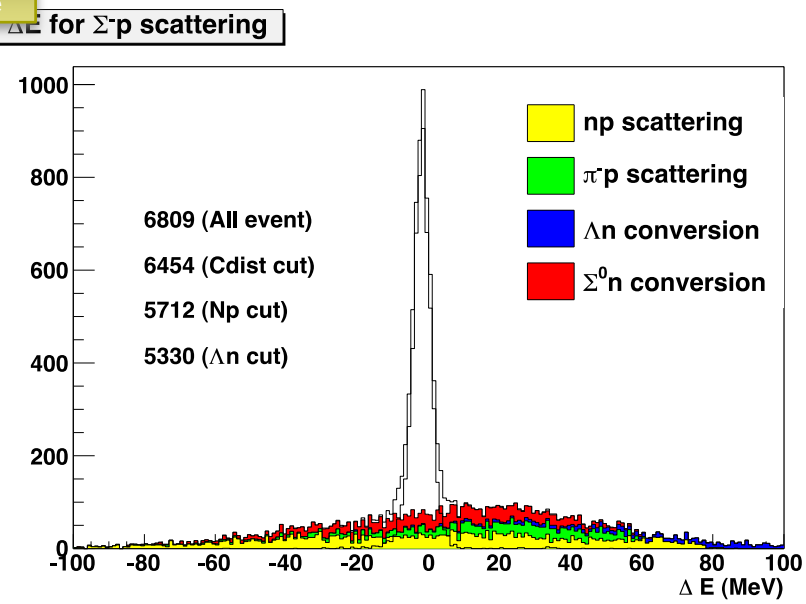
π beam analysis
$\Delta p/p \sim 10^{-4}$

Identification of Σp scattering

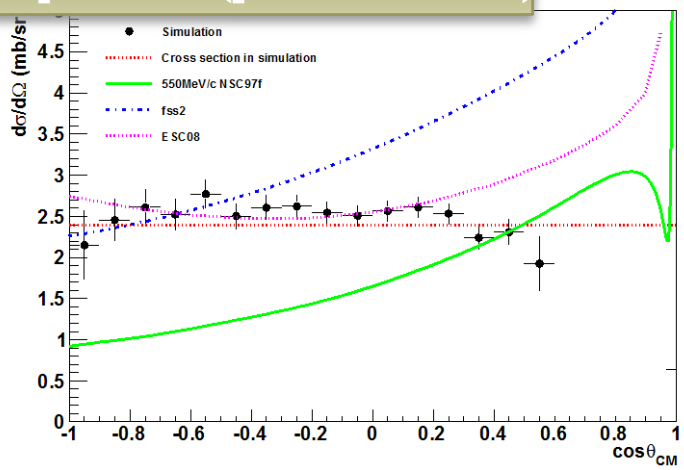




- Kinematics check
  - $E_{calulate}$ (determined from θ assuming $\Sigma^- p$ scattering)
  - $E_{measure}$ (measured by Calorimeter)
  - $\Delta E = E_{measure} - E_{calculate}$
    - ΔE should be 0 for $\Sigma^- p$ event.
    - Due to the kinematically overlapped region, there is a contamination of background around ΔE~0

Systematic study of ΣN interaction

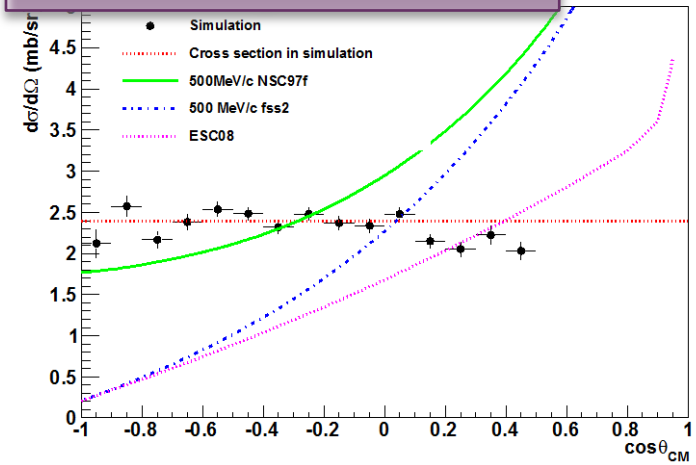
$\Sigma^+ p$ $d\sigma/d\Omega$ (p = 550 MeV/c)



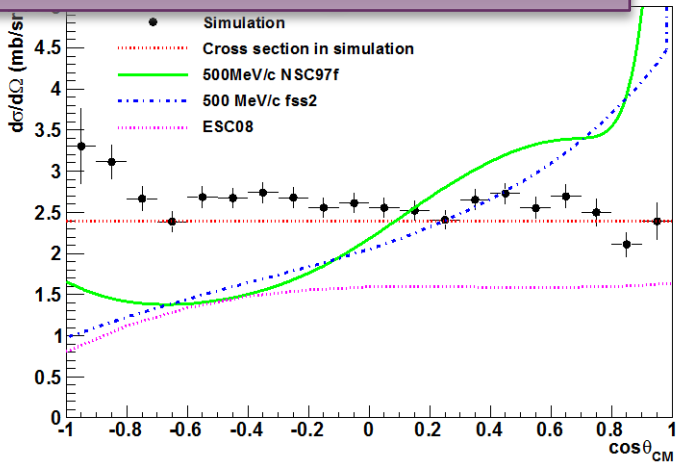
Enough acceptance to test framework
higher wave contribution
long range region (meson picture)

- We will measure the angular dependence of $d\sigma/d\Omega$ with 0.2 mb/sr precision.

$\Sigma^- p$ $d\sigma/d\Omega$ (p = 500 MeV/c)

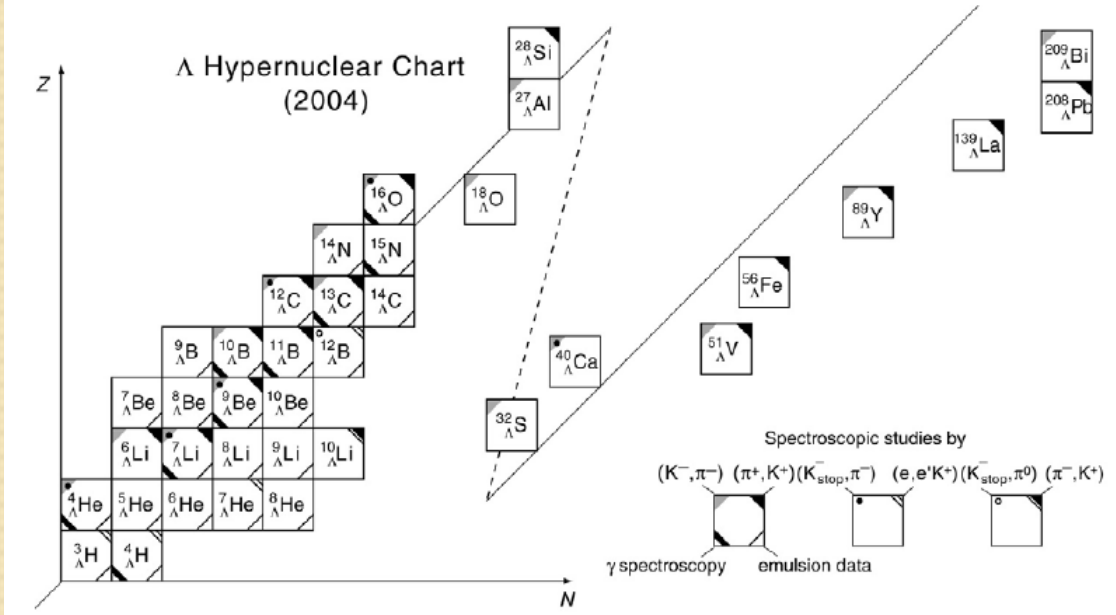


$\Sigma^- p \rightarrow \Lambda n$ $d\sigma/d\Omega$ (p = 500 MeV/c)

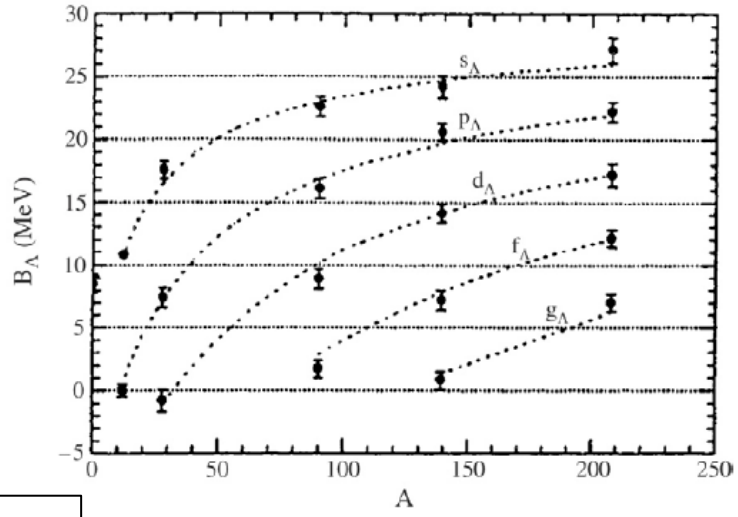


ΛN interaction (J-PARC E13/E10)

- Information on ΛN interaction from Λ hypernuclei
  - Light Λ hypernuclei
    - (K^-,π^-) and (π,K^+) reactions, and emulsion experiments
  - Medium to heavy Λ hypernuclei close to stability line
    - (K^-,π^-) and (π^+,K^+) reactions



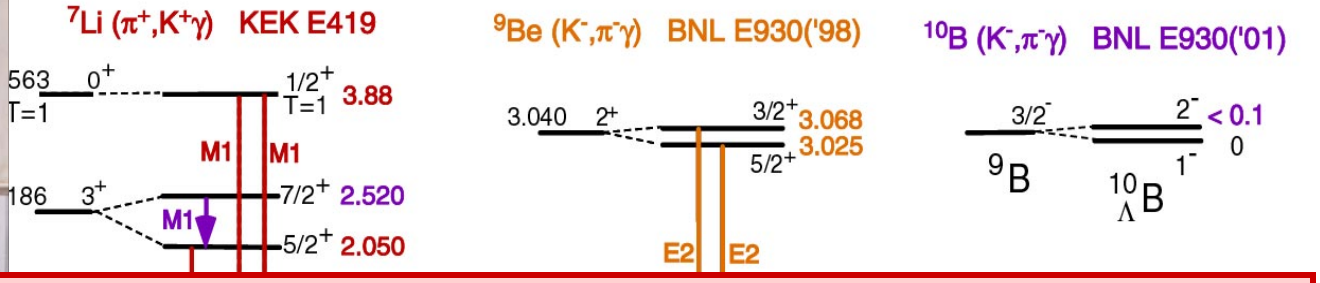
$$V_0^{\Lambda} \approx -30 MeV$$



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

Hyperball

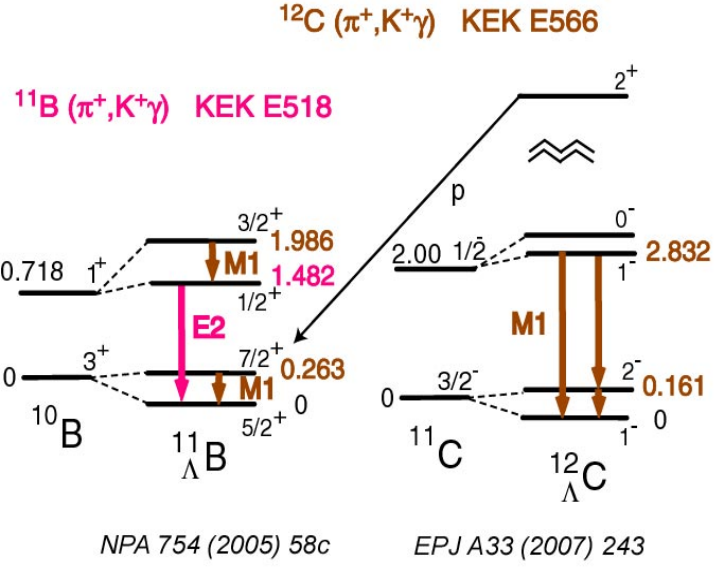
ハイパー核のガンマ線分光

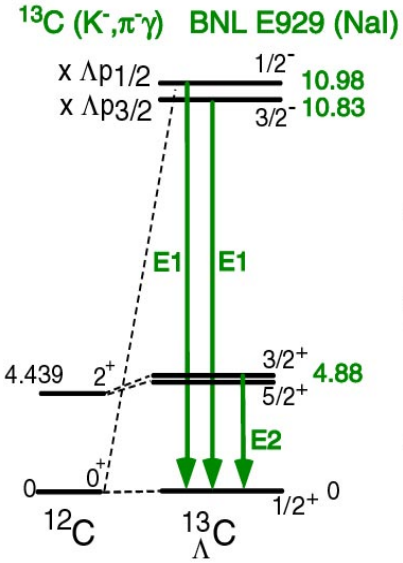


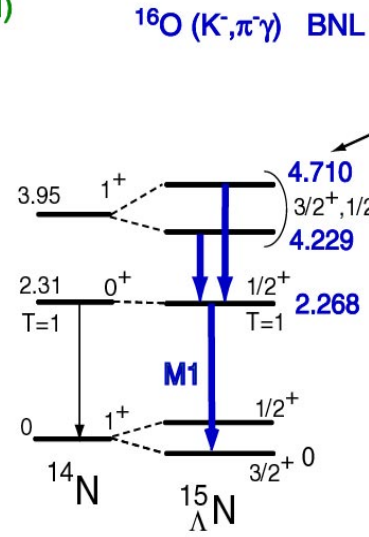
ΛN スピン依存相互作用を決定した

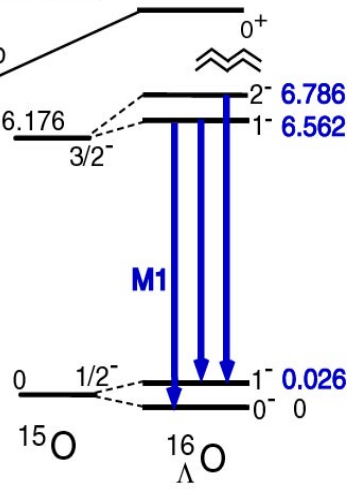
Δ = 0.3~0.4, S_Λ = -0.01, S_N = -0.4, T =0.03 MeV

バリオン間力の理論模型に強い制限を与え、模型が改良された

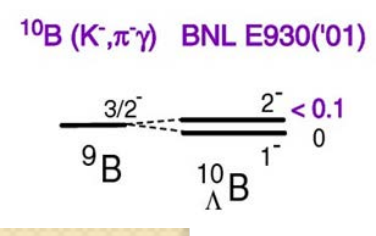


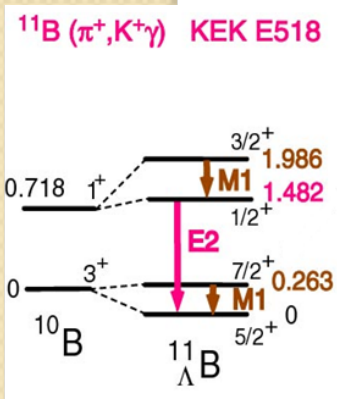






- Anomalies and missing information in ΛN interaction

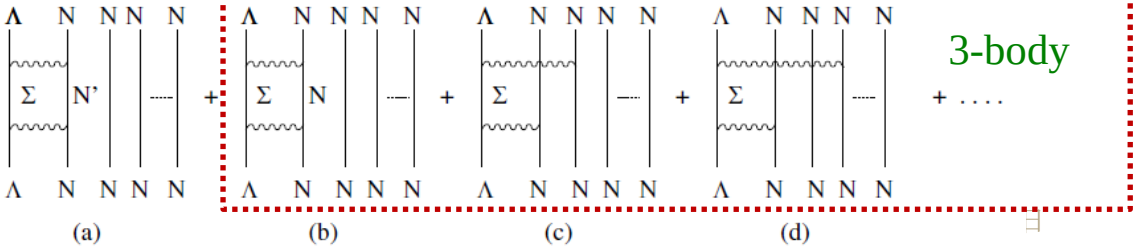




- γ-ray spectroscopy and shell-model parameterization were quite successful, but there are some anomalies
  - Quite small (<100keV) 1^- and 2^- splitting or level inversion in $^{10}_{\Lambda}$B hypernucleus
  - Measured $5/2^+$ and $1/2^+$ splitting in $^{11}_{\Lambda}$B hypernucleus is far from theoretical estimation (1020 keV)
  - One possible explanation is large ΛN-ΣN mixing contribution
- Many Λ hypernuclei were studied but only close to stability-line
  - We don't know ΛN interaction in neither neutron-rich environment nor proton-rich environment
  - ΛN-ΣN mixing may induce strong effects of neutron- and proton-rich environments

added coherently

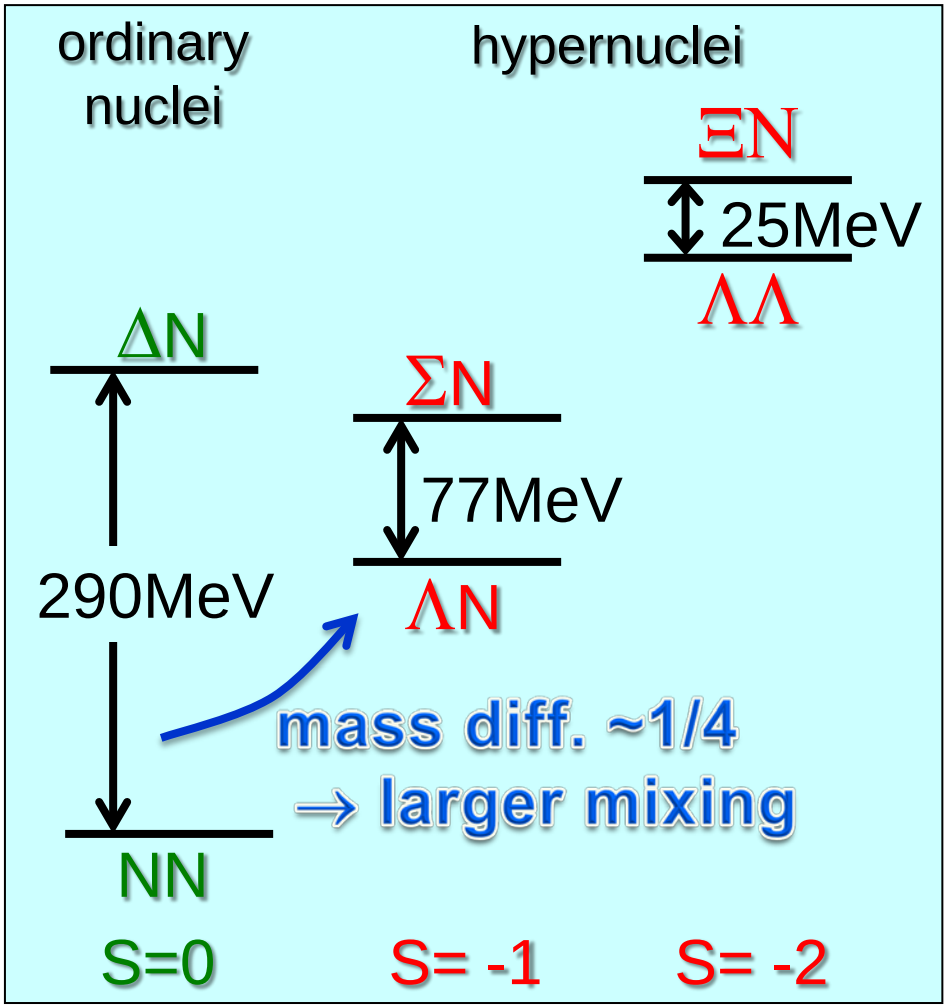
2-body

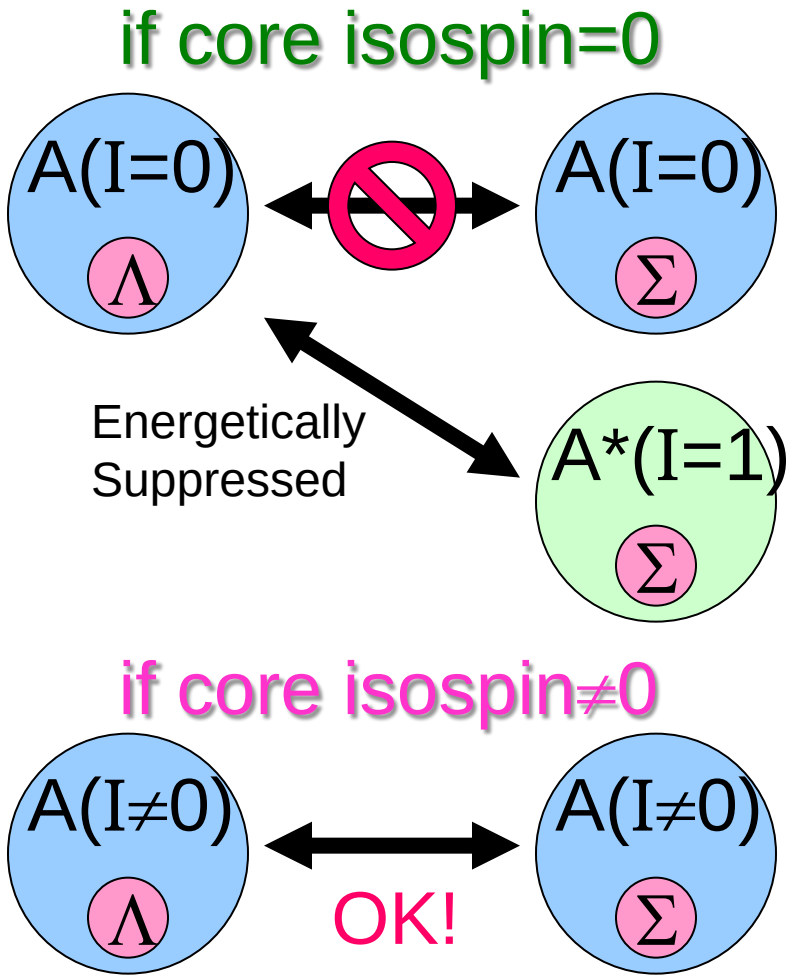


S. Shinmura et al.,
J. Phys. G 28 (2002) L1

ΛN-ΣN Mixing in Λ Hypernuclei

- B.F. Gibson et al. PR C6 (1998) 433c

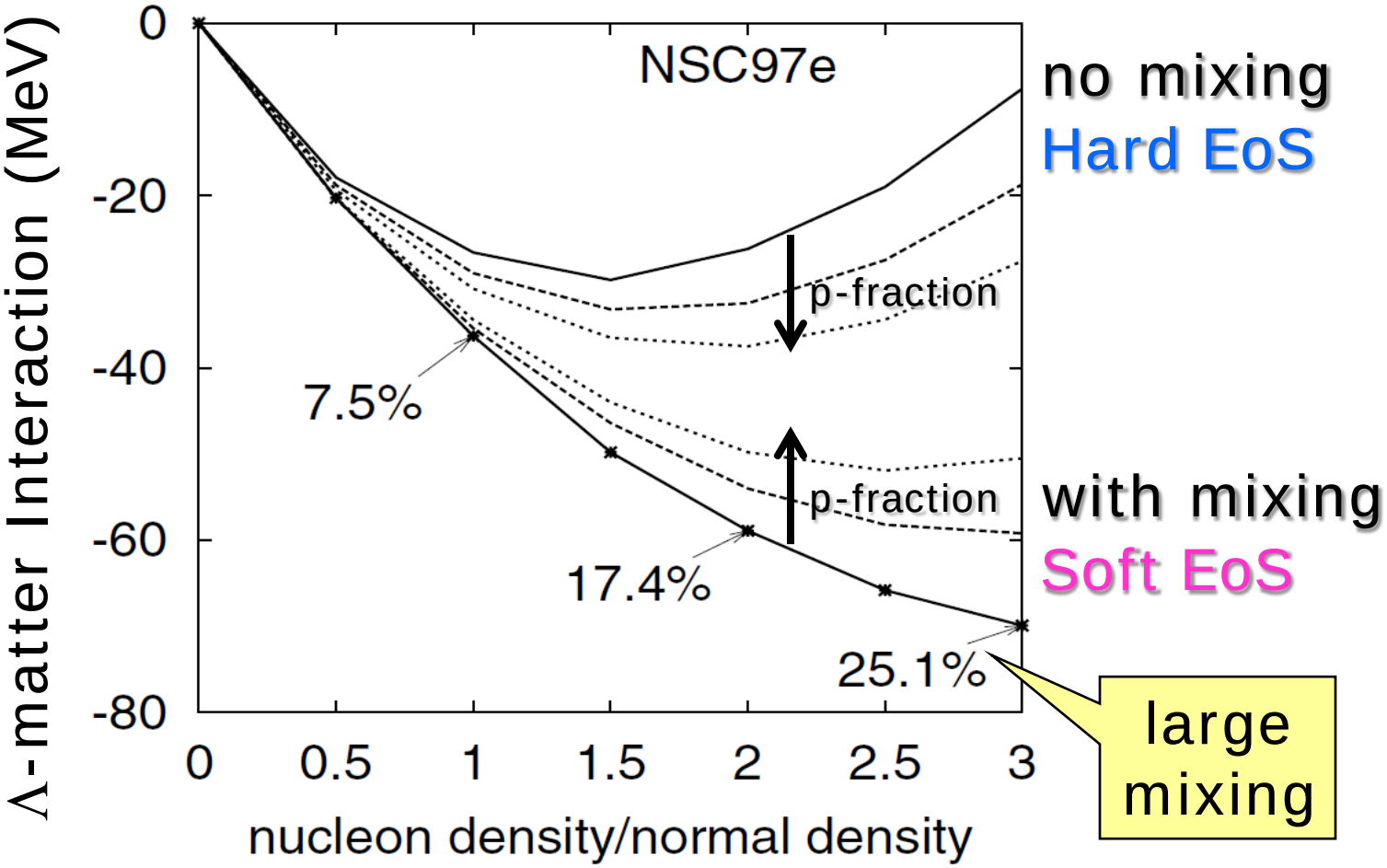




important in neutron-rich Λ-hypernuclei (large isospin)

Mixing and EoS in Neutron Stars

- Hyperon content in core of neutron stars
  - Degree of ΛN-Σ^0N mixing and EoS



S. Shinmura et al. J.Phys G28 (2002) L1

Purpose of E13 experiment

Approved as DAY1, Second priority

ΛN interaction

Using (K^-,π^-) reaction at p_K= 1.5 (or 1.1) GeV/c

(1) Charge symmetry breaking in ΛN interaction and spin-flip property in hypernuclear production

$^{4}_{\Lambda}$He : Largest CSB is suggested but previous data is suspicious.
Easiest (100 hrs)

(2) Radial dependence of ΛN interaction from sd-shell hypernuclei

$^{19}_{\Lambda}$F : The first sd-shell hypernuclei (100 hrs)

(3) Study ΛN–ΣN coupling force

$^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B: (100+200 hrs)

Inconsistency exist but previous data not enough.
Few-body approach as well as shell model possible.

g-factor of Λ in nucleus

(4) Spin-flip B(M1) measurement and g_Λ in a nucleus

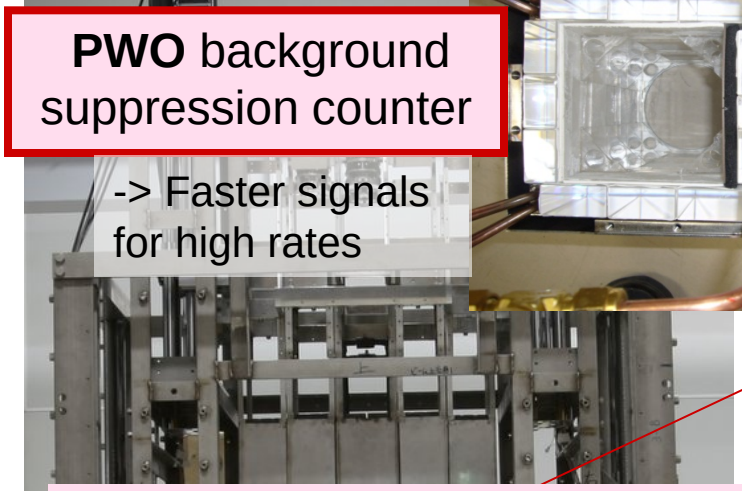
$^{7}_{\Lambda}$Li : Least ambiguities exist and most reliable. (500 hrs)

Hyperball-J

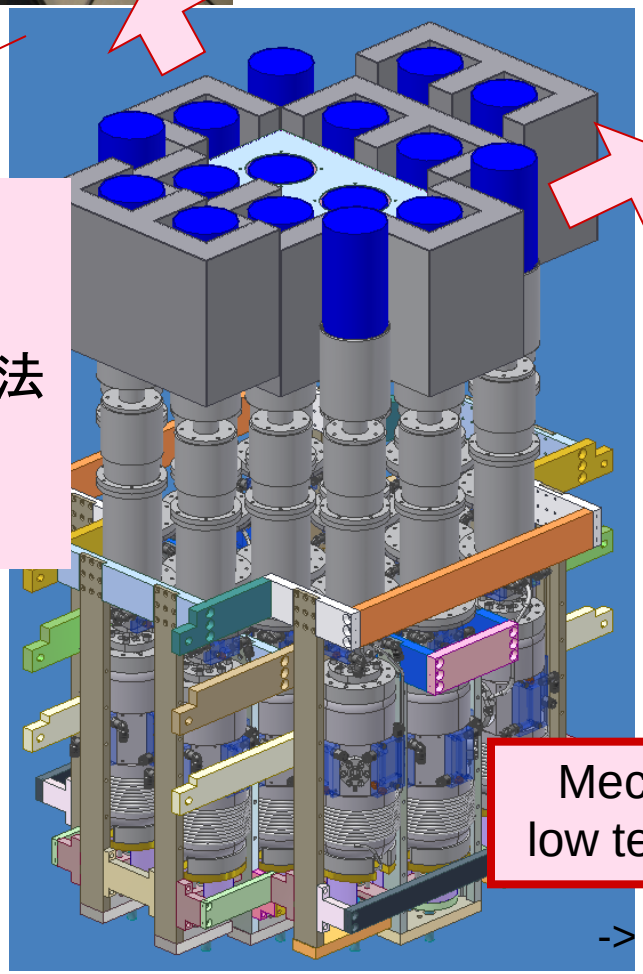
New generation Ge array

PWO background suppression counter

-> Faster signals for high rates



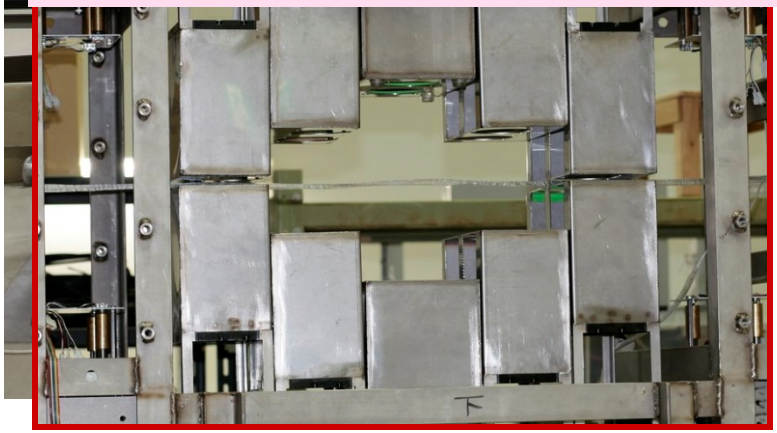
Lower half



Hyperball-Jに対するupgrade:

- 最下流部のさらなる高計数率化
- 波形解析による超高速読み出し法の開発・導入

が必要

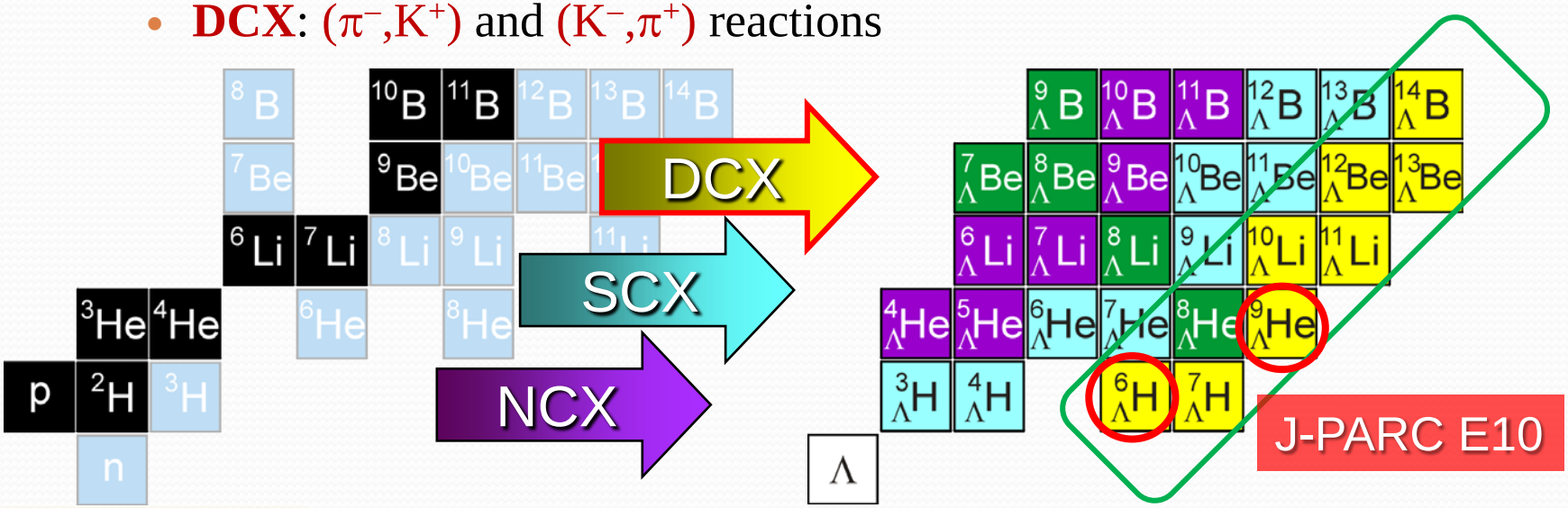


Mechanically-cooled low temp. **Ge detector**

-> Suppress effects from radiation damage

E10: Produce neutron-rich hypernuclei

- Use double charge-exchange (DCX) reactions
  - Category of reactions to produce Λ hypernuclei
    - **NCX**: (π^+,K^+) and (K^-,π^-) reactions
    - **SCX**: $(e,e'K^+)$, (π^-,K_S), (K^-,π^0) reactions, etc.
    - **DCX**: (π^-,K^+) and (K^-,π^+) reactions

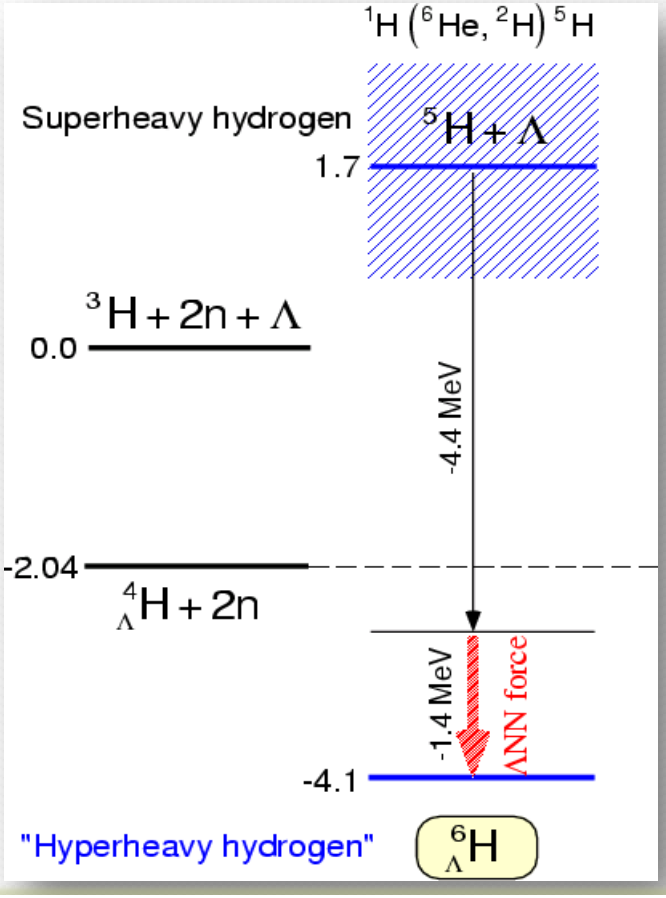


DCX reaction

$$\pi^- + p + p \rightarrow K^+ + \Lambda + n$$

the reaction has two-step nature
tiny cross section, ~1/1000 of NCX

- Investigation of ΛN-ΣN mixing
  - Precise measurement of binding energy of ${}^{6}_{\Lambda}H$



Suggestion of the calculation

Normal ΛN interaction

B_Λ ~ 4.4 MeV

Coherent ΛN-ΣN mixing

B_Λ ~ 4.4 **+ 1.4 MeV**

Difference is considerably large experimentally accessible

Our basic idea

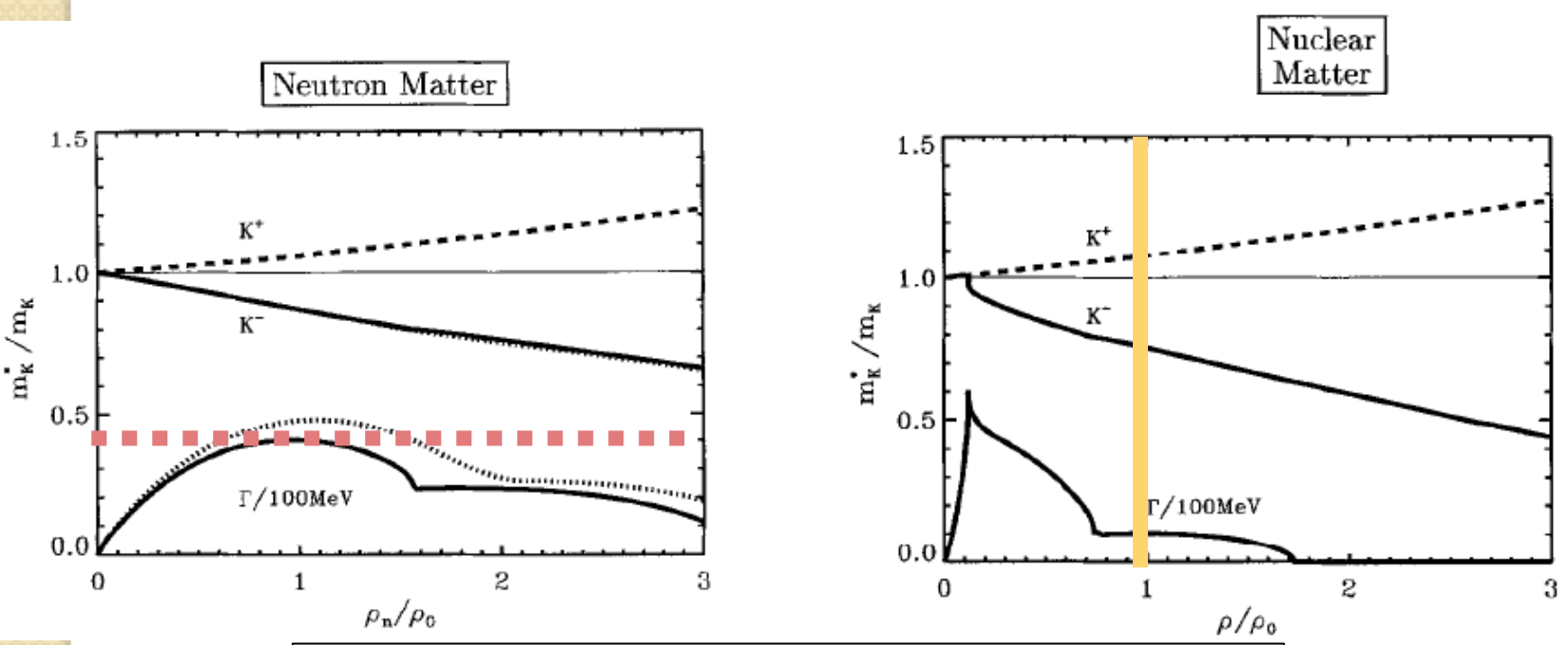
Precise measurement of B.E.

→ estimate mixing effect

Y. Akaishi et al. Frascati Phys. Ser. XVI (1999) 59

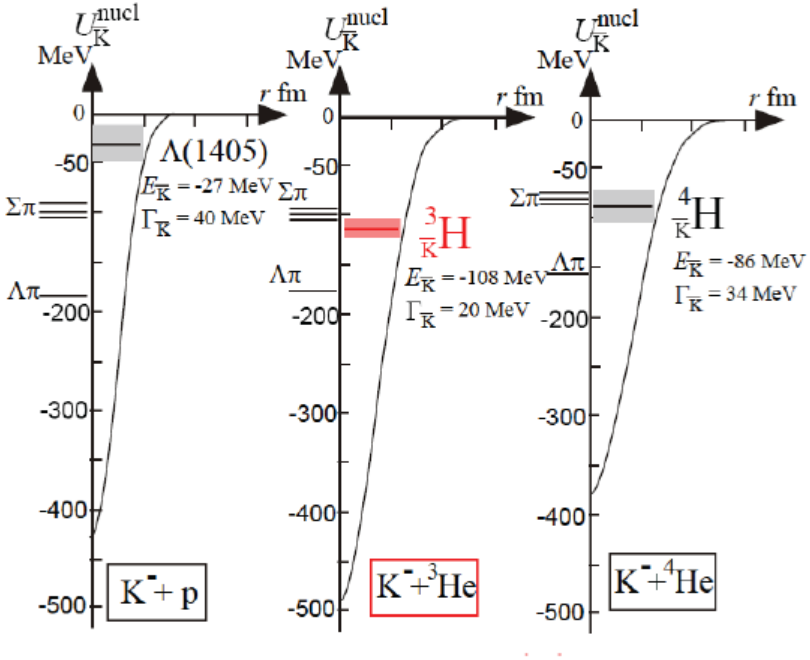
KN interaction (J-PARC E15/E17/E31)

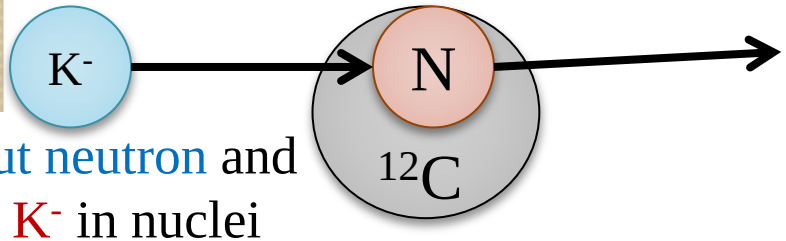
- Anti-kaon in high density nuclear matter
  - Decrease of effective mass m_K^*
    - K^- in Neutron Matter: threshold of condensation ≈ 200MeV/c^2
    - in (Symmetric) Nuclear Matter: similar drop of m_K^*
  - Considerable drop (>100MeV/c^2) even at ρ_0
    - May be observed as strong attractive force in nuclei



T. Waas, N. Kaiser, W. Wise, Phys. Lett. B379 (1996) 34

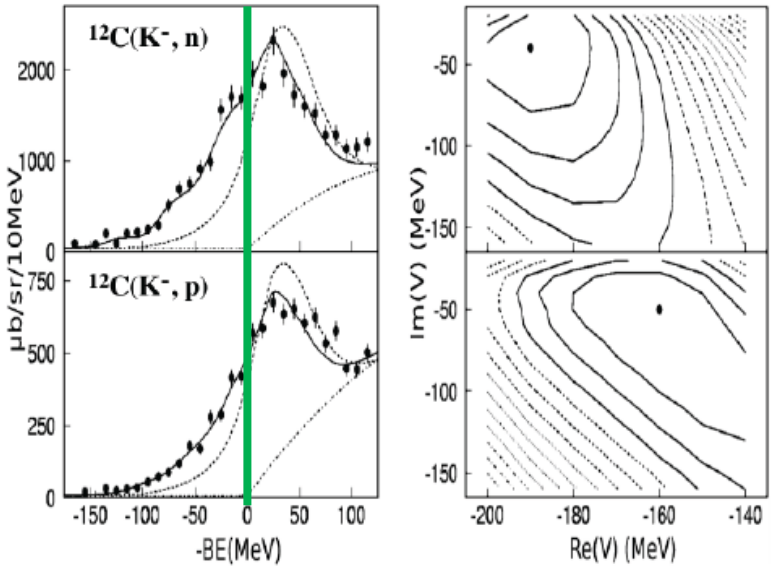
- KN interaction and property of Λ(1405)
  - Λ(1405): S=-1, I=0 and $J^{\pi}=1/2^{-}$ resonance
    - Mass is considerably lower than quark model prediction
    - Large fraction of KN hybrid (bound system)?
  - If Λ(1405) is KN hybrid, it means strong KN attraction
  - Possible production of K-nucleus bound state





Knockout neutron and
embed K^- in nuclei

in-flight (K^-, n) reaction @ 1 GeV/c



fit = Green's function

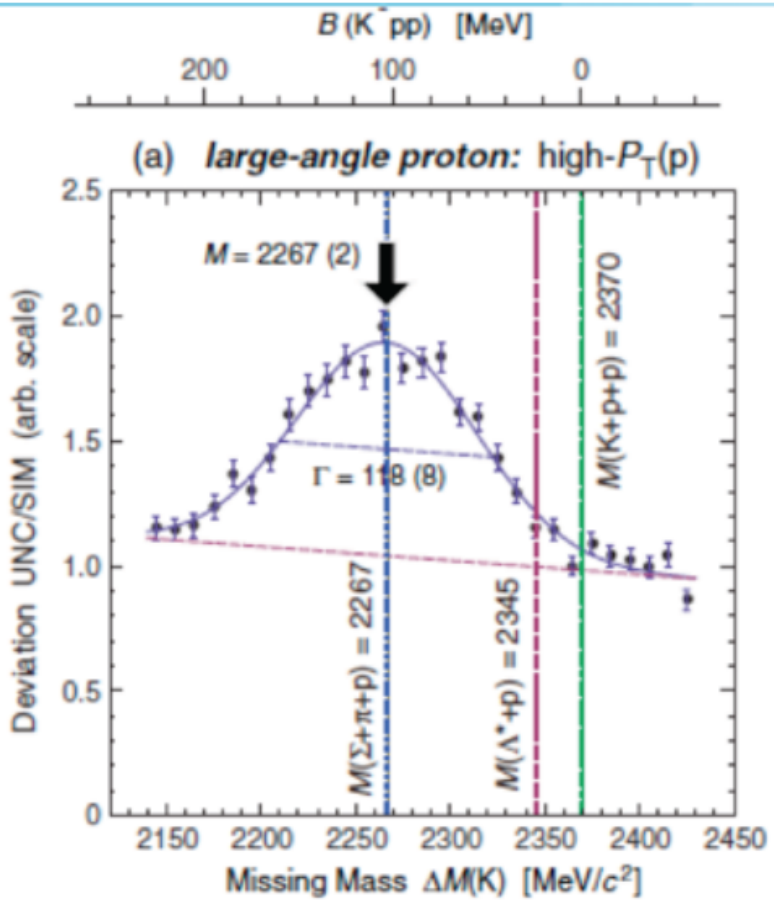
T. Kishimoto et al., Prog. Theor. Phys. 118 (2007) 18

indicating very deep potential

- deep & wide KN pot.
Re(V) ~ 180 MeV
Im(V) ~ 50 MeV

- lower background
in-flight ensures ...
2N process suppressed

p (p, K^+) X @ T = 2.85 GeV

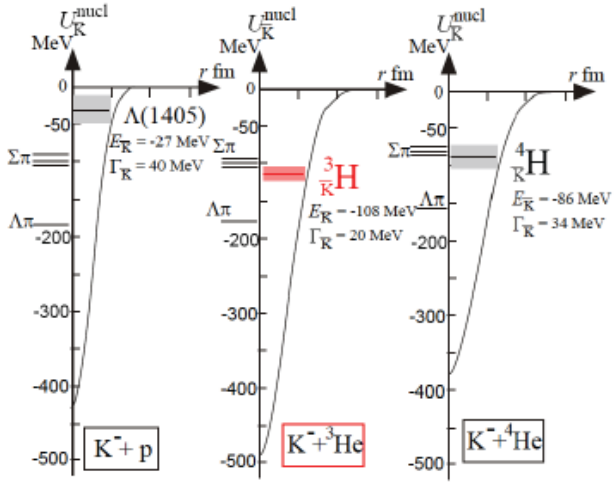


T.Yamazaki et al., PRL104(2010)132502

Kpp state? at

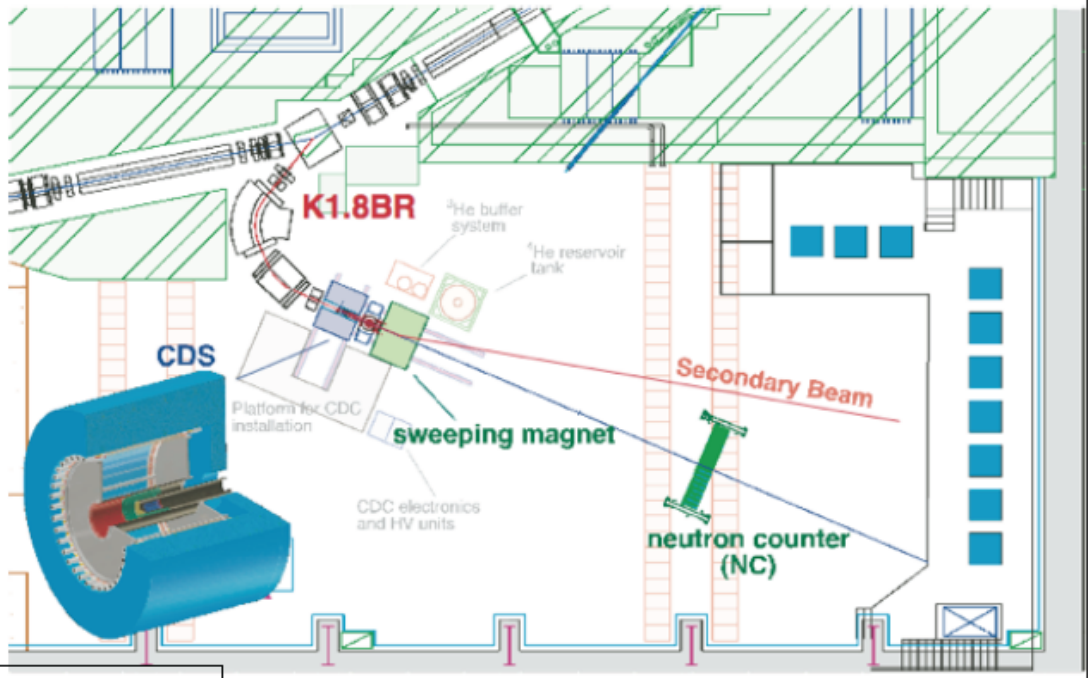
M_x=2267±3±5 MeV !
Γ_x=118±8±10 MeV !

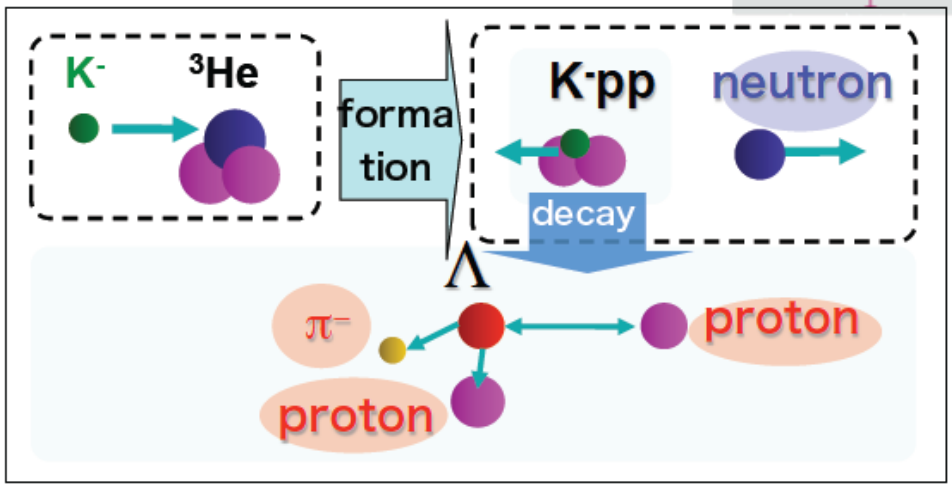
E15: $\bar{K}N$ interaction study by nuclear bound state

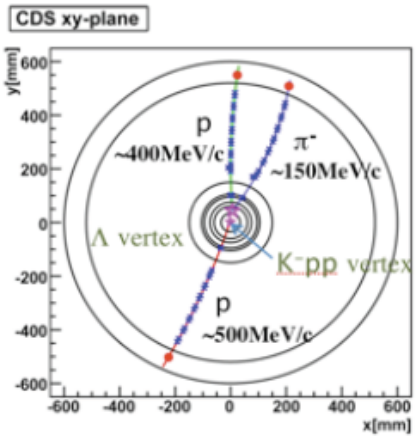


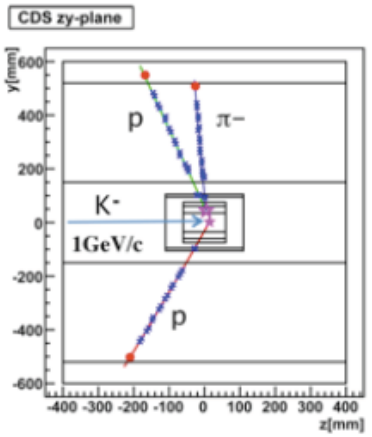
K^- ^{3}He -> "pp K^-" + n

at 1 GeV/c by both missing & invariant mass

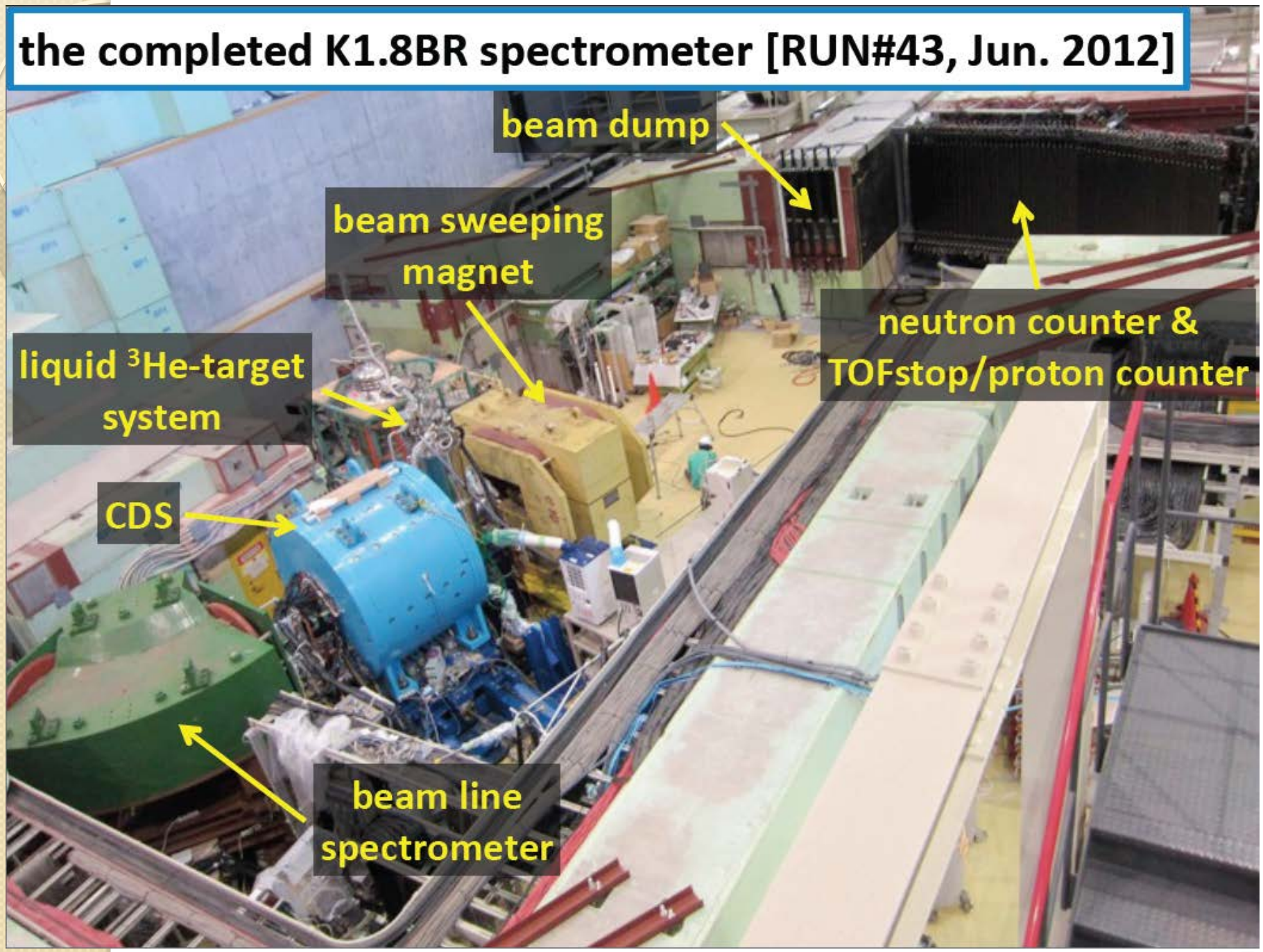








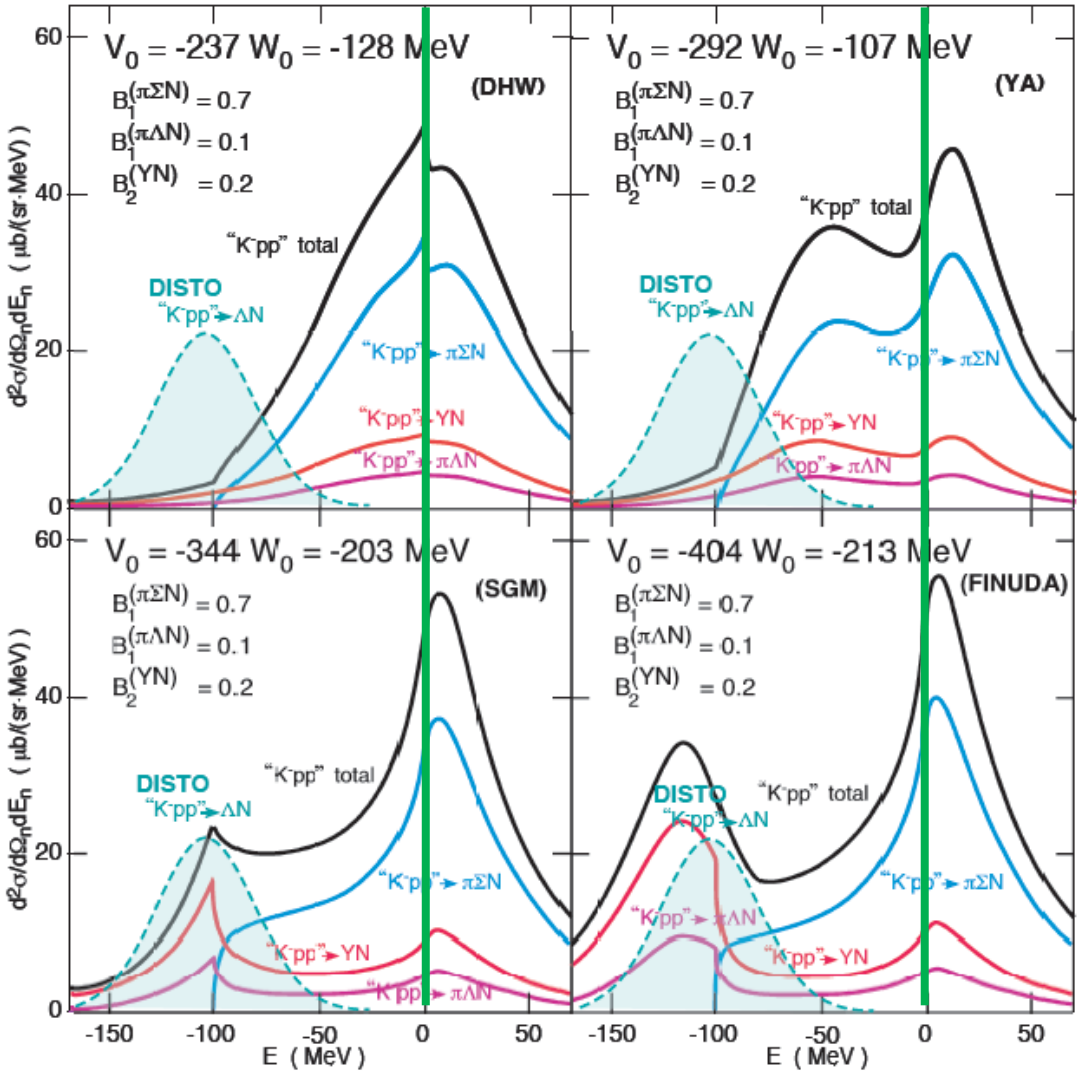
the completed K1.8BR spectrometer [RUN#43, Jun. 2012]



Koike-Harada vs DISTO

DISTO

B_K~100MeV and Γ_K~100MeV



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Phys. Lett. B535, 70 (2002);
Proc. Jpn. Academy, Series B 83, 144 (2007)

SGM: N.V. Shevchenko, A. Gal, and J. Mares,
Phys. Rev. Lett. 98, 082301 (2007);
N.V. Shevchenko, A. Gal, J. Mares, and J. Revai,
Phys. Rev. C76, 044004 (2007).

FINUDA: M. Agnello et al.,
Phys. Rev. Lett. 94, 212303 (2005).

DISTO

B_K~100MeV and Γ_K~100MeV

- only for Λp decay ch.

private communication

- does not fit in KH scheme

easy to observe,
if dσ/dΩ ≳1mb/sr

Summary

- Does the inner-core have Exotic components?
  - One of important factors to determine structure of neutron stars
  - Candidates of Exotic components are Hyperons and Kaons
  - Negative charge, mass, attractive interaction and symmetry energy control appearance
- J-PARC is the best laboratory for the investigation
  - Several experiments are in progress and in preparation
  - E40: high statics measurements of ΣN elastic scattering
  - E13: investigation of ΛN-ΣN mixing by precise γ-ray spectroscopy
  - E10: ΛN interaction in neutron-rich environment and ΛN-ΣN mixing
  - E15: search for Kpp bound state and strongly attractive KN interaction