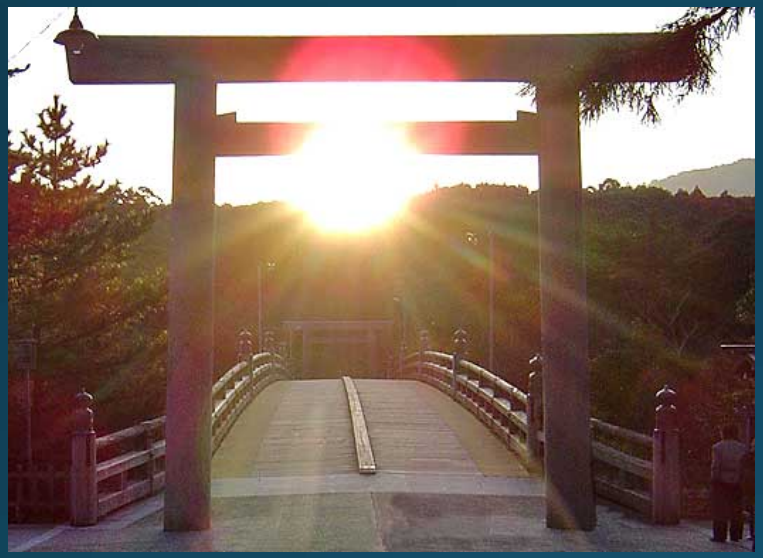
研究会「ハイパー核物理の発展と今後の展望」
2013年7月8日　和洲閣(三重県志摩市)

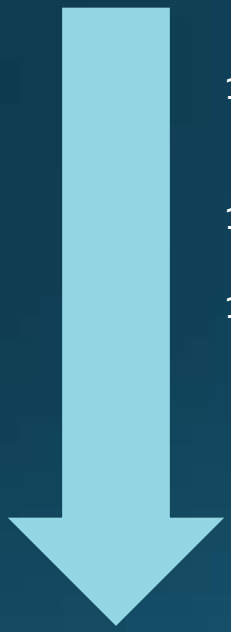


東北大学　中村　哲

電子線を用いたハイパー核分光

History of Hypernuclear Study

1953 discovery of hypernucleus (emulsion with cosmic-ray, by Danysz and Pniewski)

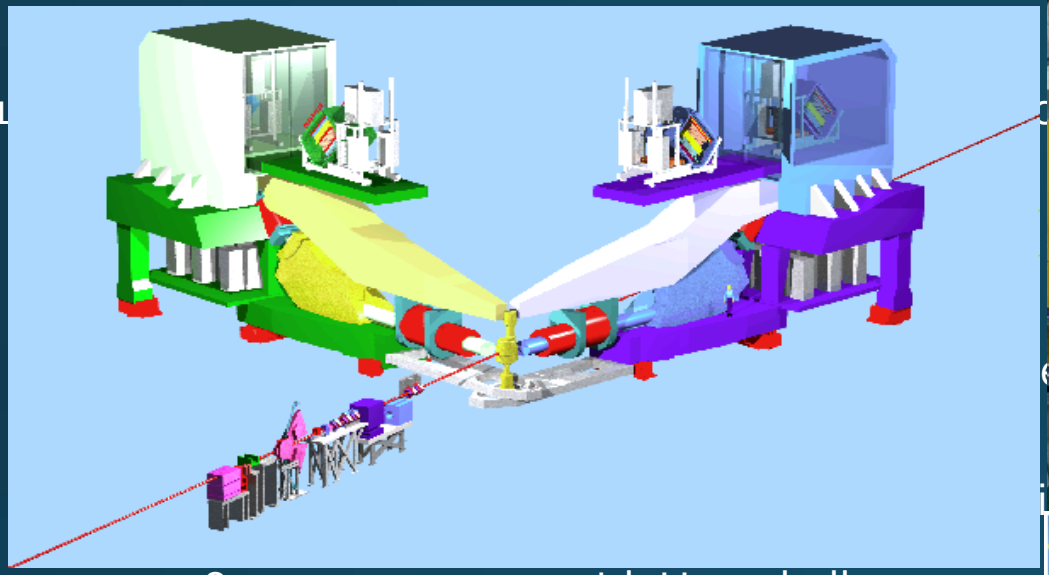


1970s CERN, BNL Counter experiments with Kaon beam

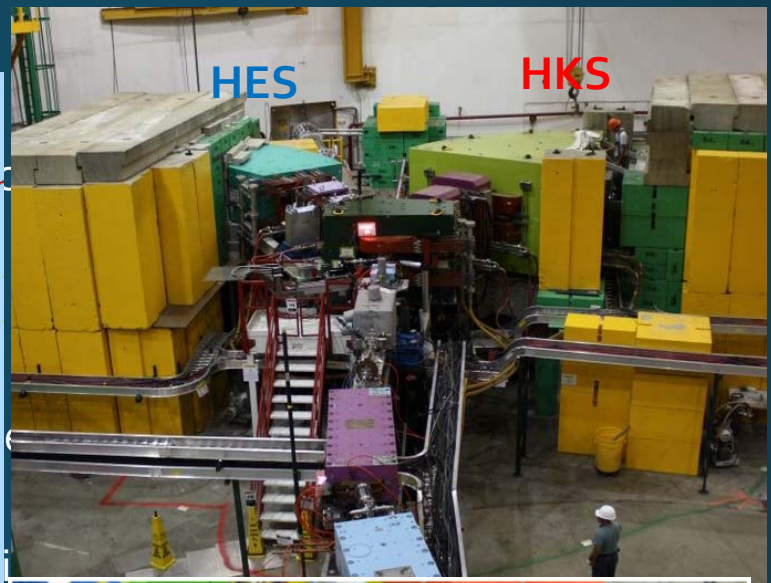
1980s BNL-AGS, KEK-PS Counter experiments with K/π beam

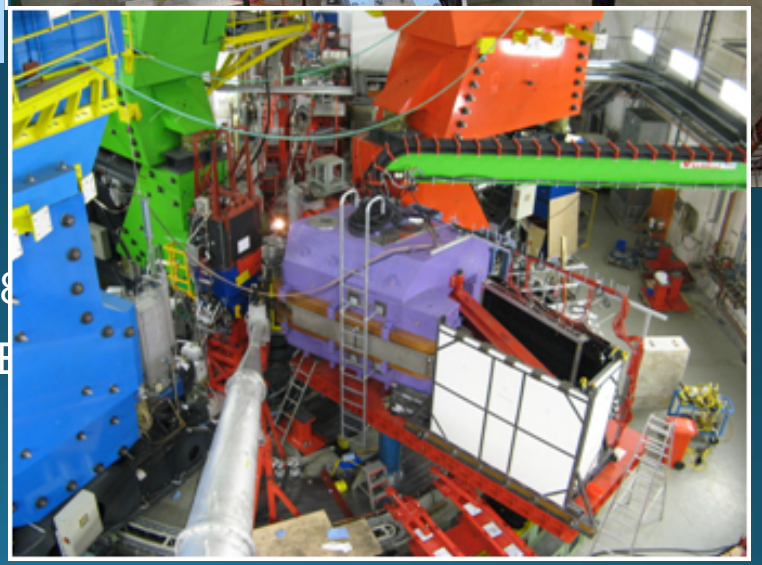
1998- γ-spectroscopy with Hyperball

History of Hypernuclear Study



1998- γ-spectroscopy with Hyperball





2000~

(e,e'K⁺) spectroscopy @ JLab

$Z(e^-,e'K^+)_\Lambda(Z-1)$ reaction

2011~ Pilot runs of decay π spectroscopy at MAMI-C

(e,e'K) ハイパー核分光の特徴

- 電磁相互作用
- 陽子をΛへ :

  (π,K), (K,π) → アイソ多重項パートナー

  Λ、 Σ^0 の質量を使った絶対エネルギー校正

  $p(e,e'K^+)\,\Lambda\,,\Sigma^0$

- 高品位電子線ビーム
  高分解能 (< 1MeV)

  同位体濃縮ターゲット

(e,e'K) 反応の困難点

- 制動放射、メラー散乱に起因する電子雑音
  信号/雑音比、検出器

- 小さな生成断面積
- (e', K^+)同時計測
  制限された統計
  連続電子線

高品位電子線ビームが必須!

(e,e'K$^+$)ハイパー核分光学創成

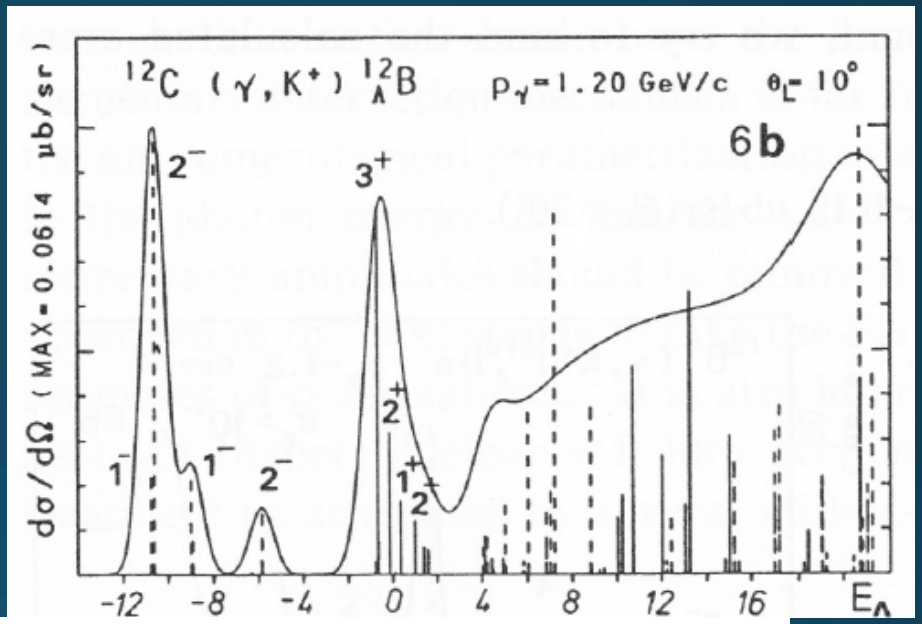
Progress of Theoretical Physics Supplement No. 117, 1994 123

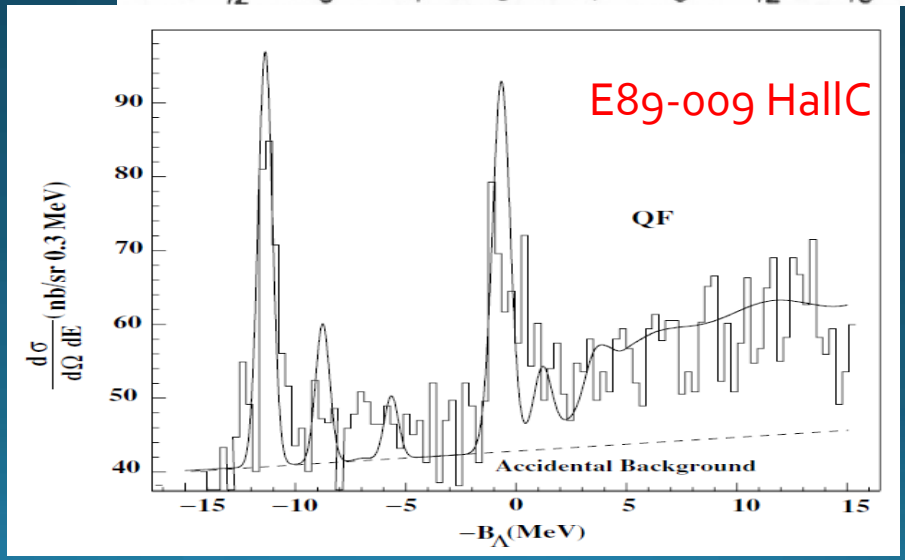
Photoproduction of Polarized Hypernuclei†)

Toshio MOTOBA, Miloslav SOTONA* and Kazunori ITONAGA**

Laboratory of Physics, Osaka Electro-Communication University, Neyagawa 572
**Nuclear Physics Institute, 250 68 Řež /Prague*
*** Laboratory of Physics, Miyazaki Medical College, Miyazaki 889-16*

元場さんの計算 1994



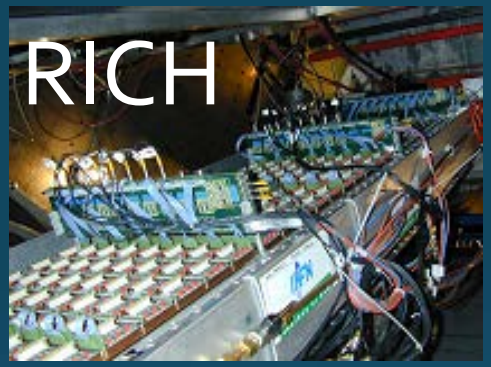


E89-009 (実験 2000年)
PRL 90 (2003) 232502.
PRC 73 (2006) 044607.

開発してきたハードウェア

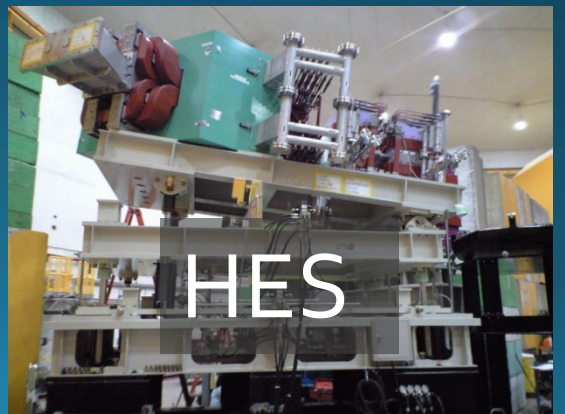
High Resolution, Large Solid Angle and Short Orbit Spectrometer (Hall-C)

RICH for good K ID (Hall-A)

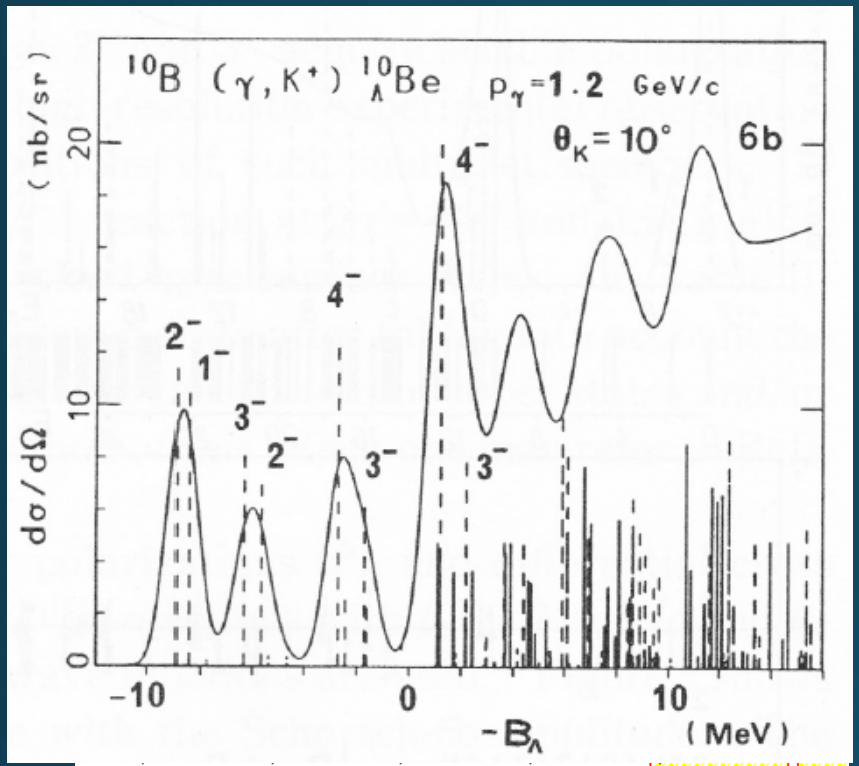


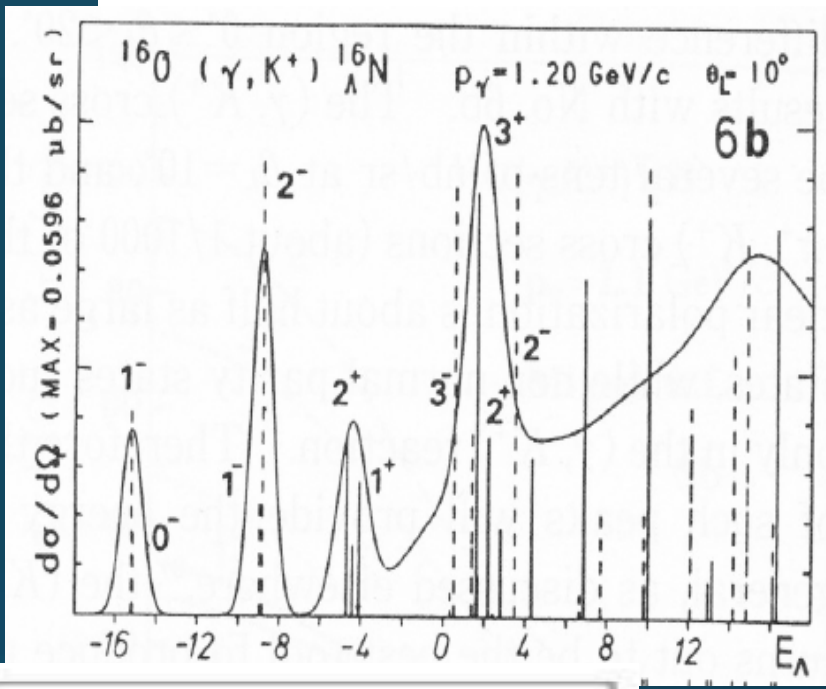
SC Septum for charge separation (Hall-A)

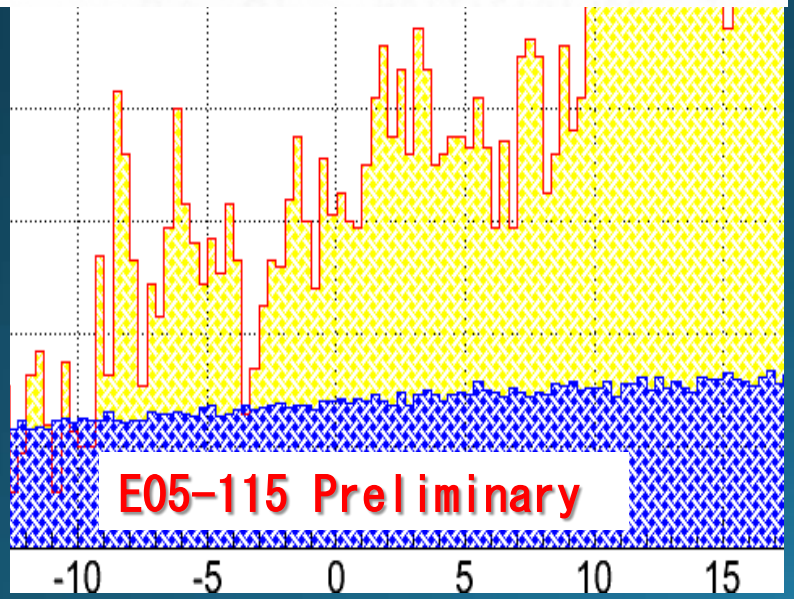
High Resolution Electron Spectrometer (Hall-C)

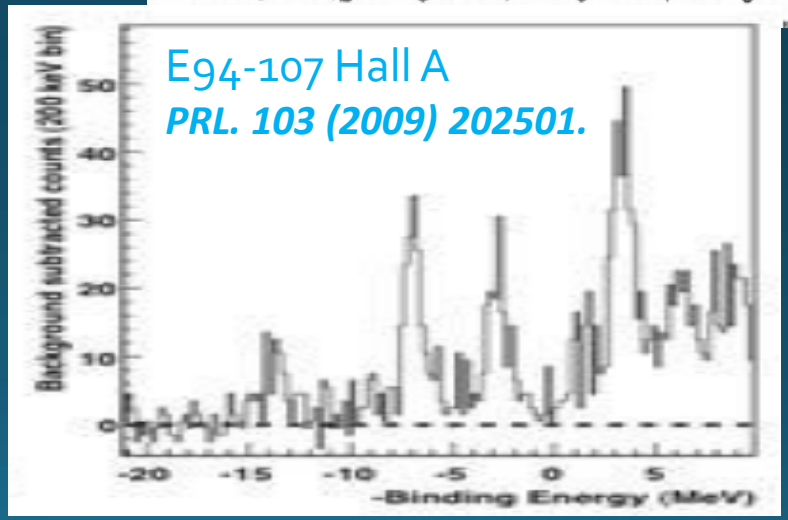


Motoba, Sotona, Itonaga (1994)

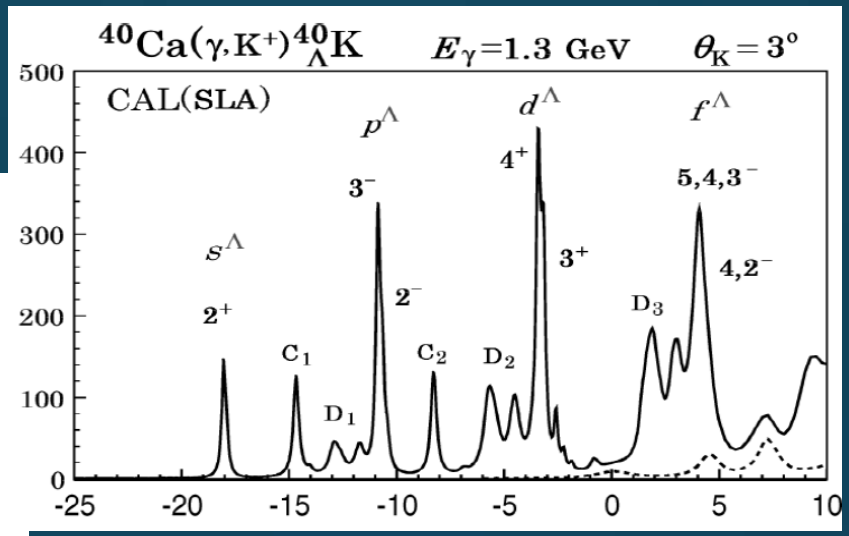


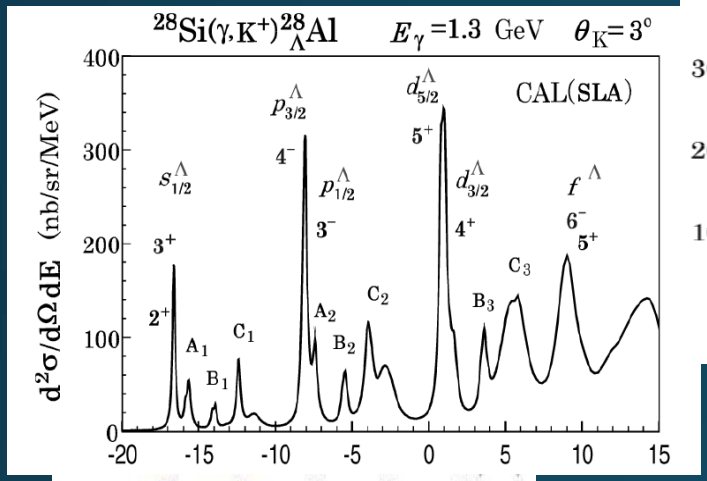


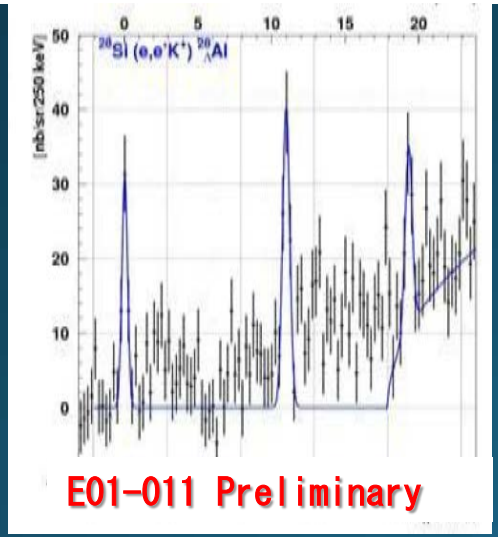


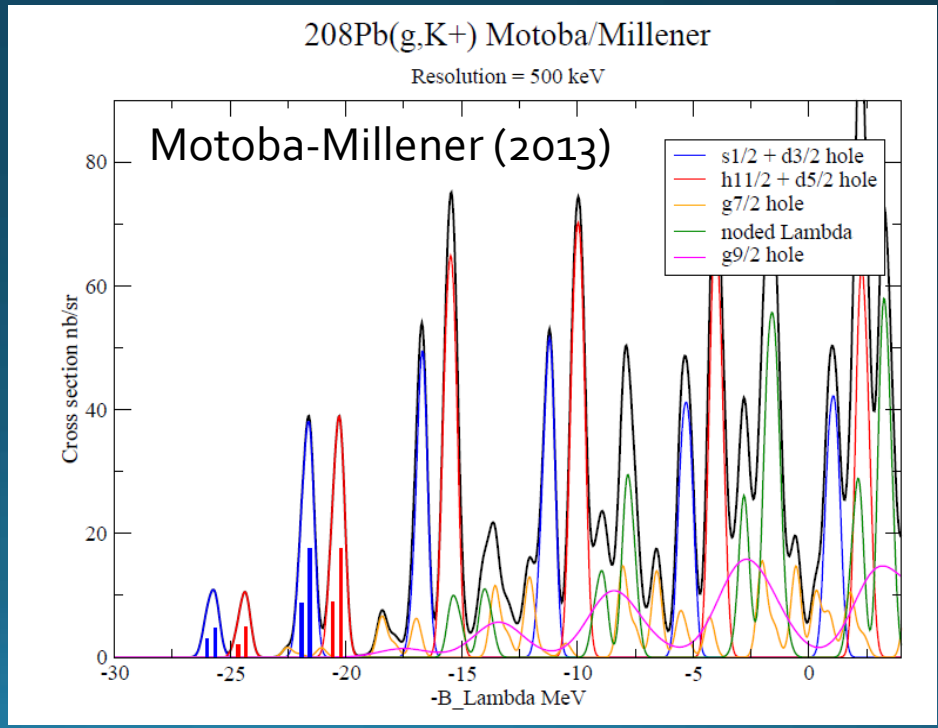


より重い核へ


^{40}Ca(γ,K$^+$)$^{40}_{\Lambda}$K
E_γ=1.3 GeV
θ_K=3°
CAL(SLA)
s^Λ
p^Λ
d^Λ
f^Λ
2$^+$
3$^-$
4$^+$
3$^+$
2$^-$
5,4,3$^-$
4,2$^-$
C$_1$
C$_2$
D$_1$
D$_2$
D$_3$
d²σ/dΩdE (nb/sr/MeV)


^{28}Si(γ,K$^+$)$^{28}_{\Lambda}$Al
E_γ=1.3 GeV
θ_K=3°
CAL(SLA)
$s^\Lambda_{1/2}$
$p^\Lambda_{3/2}$
$p^\Lambda_{1/2}$
$d^\Lambda_{5/2}$
$d^\Lambda_{3/2}$
f^Λ
3$^+$
2$^+$
4$^-$
3$^-$
5$^+$
4$^+$
6$^-$
5$^+$
A$_1$
B$_1$
C$_1$
A$_2$
B$_2$
C$_2$
B$_3$
C$_3$
d²σ/dΩdE (nb/sr/MeV)

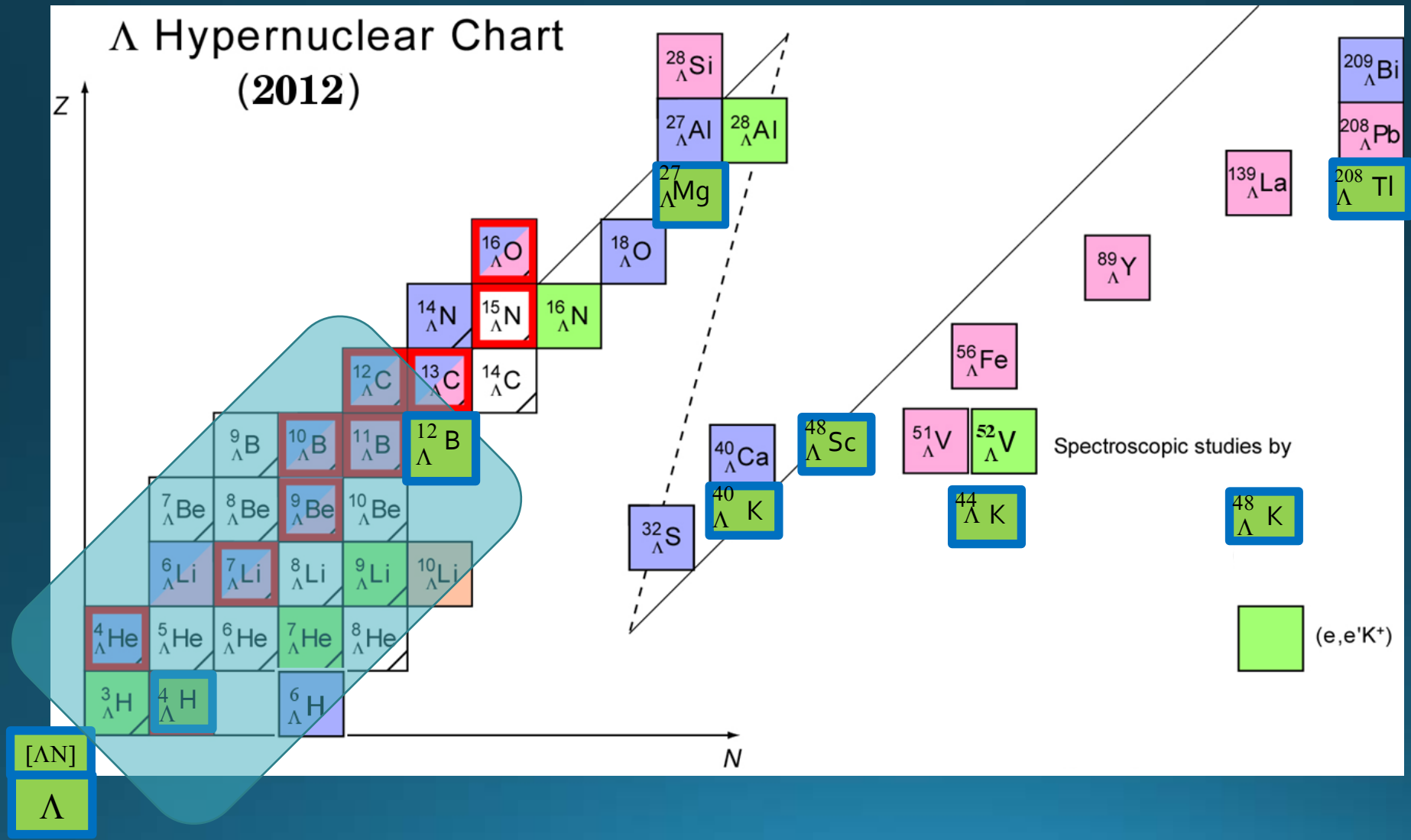

^{28}Si (e,e'K$^+$) $^{28}_{\Lambda}$Al
E01-011 Preliminary


208Pb(g,K+) Motoba/Millener
Resolution = 500 keV
Motoba-Millener (2013)
s1/2 + d3/2 hole
h11/2 + d5/2 hole
g7/2 hole
noded Lambda
g9/2 hole
Cross section nb/sr
-B_Lambda MeV

JLab's Hypernuclear Program To Date

Nucleus	What Have We Learned?
$H(e,e'K)\Lambda$	Very Forward, Small Q^2 Elementary Λ Cross section is important. One of proposing program. *Phys. Rev. C81 (2010) 052201(R).*
$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$	First reliable observation of $^{7}_{\Lambda}He$ w/ good statistics, **CSB of ΛN interaction** ***Phys. Rev. Lett. 110 (2013) 012502.***
$^{9}Be(e,e'K^{+})^{9}_{\Lambda}Li$	Theory doesn't reproduce observed energies and strengths. To be published soon. Preliminary result can be found in *Nucl. Phys. A804 (2008) 116.* *Nucl. Phys. A835 (2019) 129.*
$^{10}B(e,e'K^{+})^{10}_{\Lambda}Be$	**CSB** discussion with A=7, A=4 system. Analysis is in progress.
$^{12}C(e,e'K^{+})^{12}_{\Lambda}B$	A **reference nucleus**. Demonstrates **high resolution** **750 keV (FWHM)** ***Phys. Rev. Lett. 90 (2003) 232502.*** ***Phys. Rev. C73 (2006) 044607.*** *Phys. Rev. Lett 99 (2007) 052501.* *Nucl. Phys. A835 (2010) 129.*
$^{16}O(e,e'K^{+})^{16}_{\Lambda}N$	Study of **mirror hypernuclei** to $^{16}_{\Lambda}O$. *Phys. Rev. Lett. 103 (2009) 202501.* *Nucl. Phys. A835 (2010) 129.*
$^{28}Si(e,e'K^{+})^{28}_{\Lambda}Al$	First **beyond p-shell** hypernuclear spectroscopy with (e,e'K). Analysis in progress. Preliminary result can be found in ***Nucl. Phys. A804 (2008) 125.***
$^{52}Cr(e,e'K^{+})^{52}_{\Lambda}V$	First **medium heavy** hypernuclear study with (e,e'K). Analysis in progress.

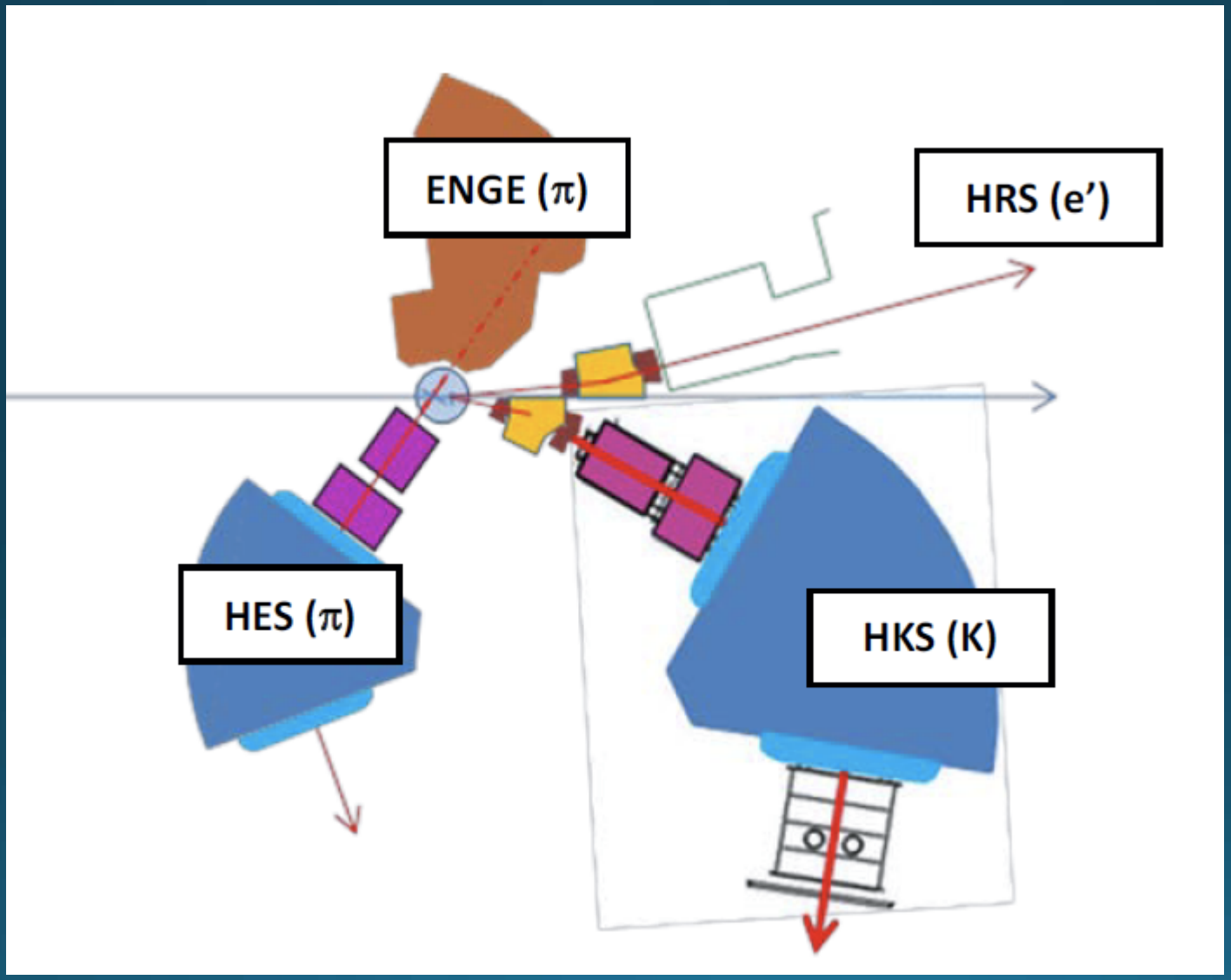
Hypernuclear Chart



Hall-A setup vs. Hall-C setup

	Hall-A (E94-107)	Hall-C (E05-115)	PR12-13-002 New Experiment In Hall-A
Beam Energy	3.7 GeV Low Brems. e' BG.	2.3 GeV	**4.5 GeV** **Lower Brems BG.**
Virtual Photon	$E\gamma$ = 2.3 GeV	$E\gamma$ = 1.5 GeV Larger σ_Λ	**$E\gamma$ = 1.5 GeV** **Larger σ_Λ**
Charge Separation	SC septum Easier calib.	Splitter Larger S.A.	**SC + New Septa** Easier calib., Opt. SA
K Spectrometer	HRS (2.0 GeV/c)	HKS (1.2GeV/c) Larger S.A., Easier PID	**HKS (1.2GeV/c)** Larger S.A., Easier PID
e' Spectrometer	HRS (1.4 GeV/c) Higher momentum	HES (0.8 GeV/c) Low momentum High res., Short Orb.	**HRS (3.0 GeV/c)**
Decay π Spectroscopy			**HES + ENGE** **(90-140 MeV/c)**

JLab New Experiment Setup in 12GeV Era



K(HKS) x HRS (e') + K(HKS) x {ENGE (π) + HRS (π)}

Proposing Programs

1. Elementary Λ, Σ^0

   Reliable data ^{1}H(e,e'K$^+$)Λ, Σ^0 in low Q^2

2. Few-body

   ^{2}D(e,e'K$^+$) [ΛN] Exotic bound state, ΛN int.

   ^{4}He(e,e'K$^+$)$^4_\Lambda$H ΛN CSB

3. Medium-heavy

   ^{40,44,48}Ca(e,e'K$^+$) $^{40,44,48}_\Lambda$K Λ's S.E., iso-spin

   ^{27}Al(e,e'K$^+$) $^{27}_\Lambda$Mg Tri-axial deformation

   ^{48}Ti(e,e'K$^+$) $^{48}_\Lambda$Sc Level inv. due to Λ

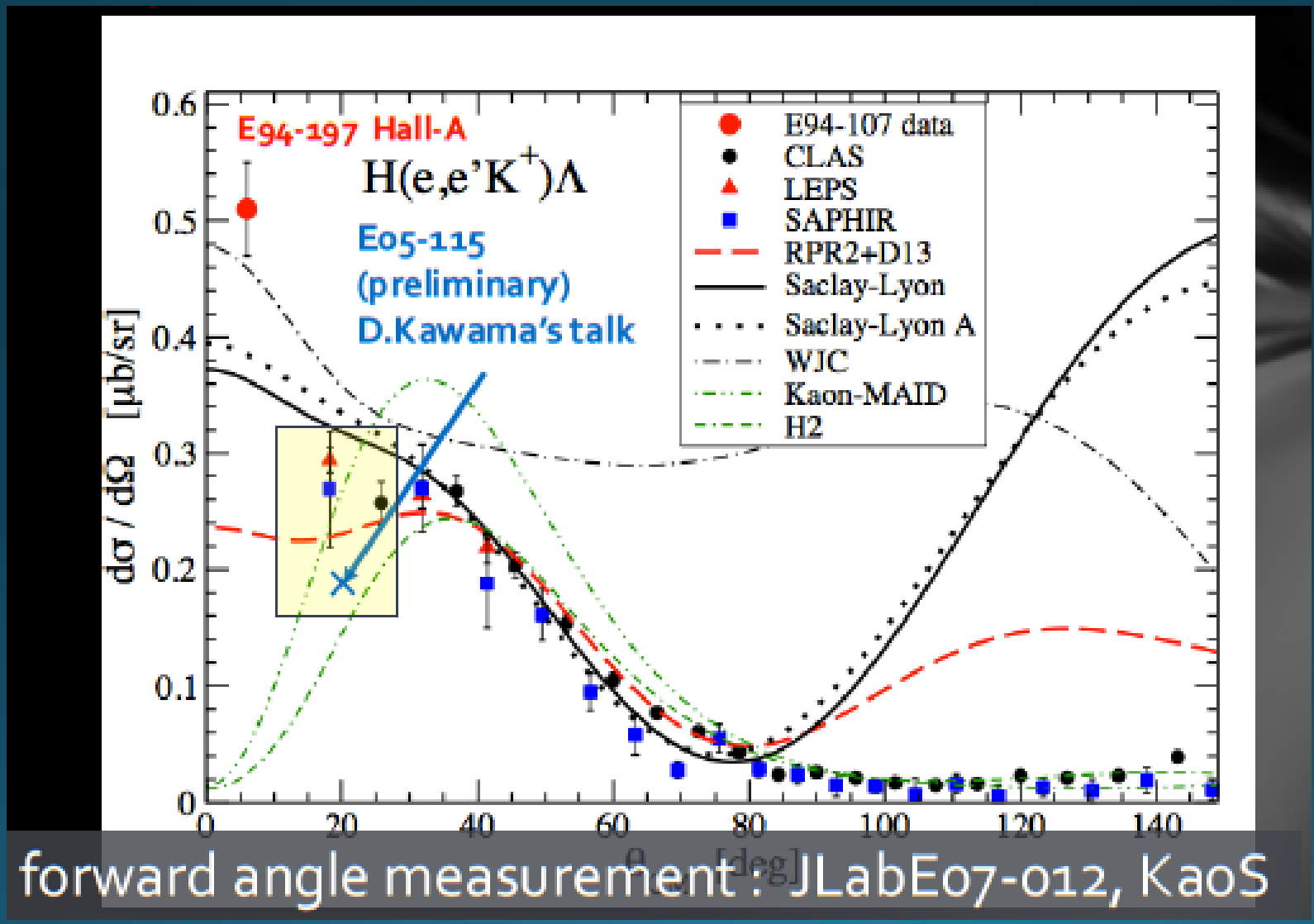
4. Heavy

   ^{208}Pb(e,e'K$^+$) $^{208}_\Lambda$Tl Λ in heaviest nucleus

5. Decay π

   Weak decay of light hyper-fragments

Electro-production of strangeness



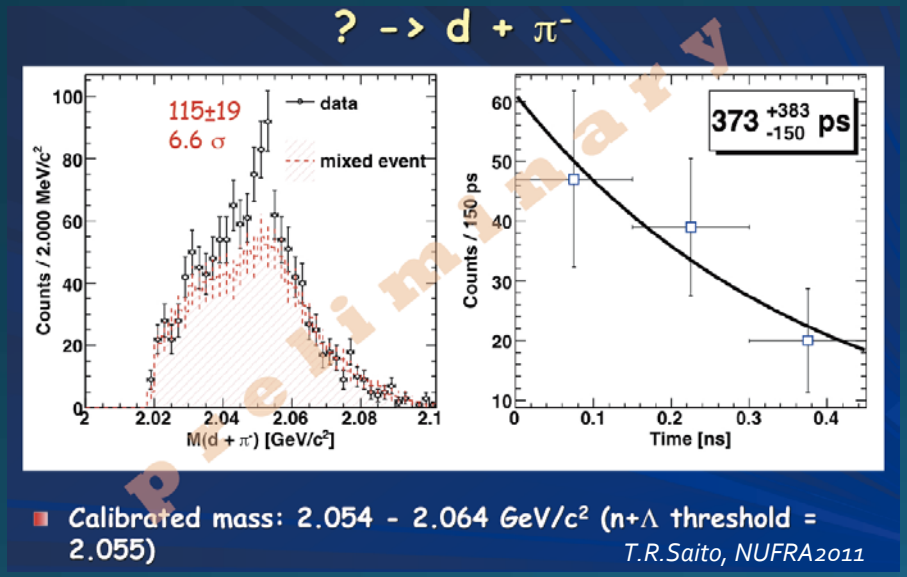
forward angle measurement : JLabE07-012, KaoS

Few-body physics with strangeness

1. Search of [nΛ] bound state and study of n-Λ interaction through FSI.

Established lightest hypernyclei = ${}^{3}_{\Lambda}$H

Hyp-HI experiment at GSI a structure in d + π^- invariant mass



Indication of a nΛ bound state ?

²d(e,e'K⁺)[nΛ]

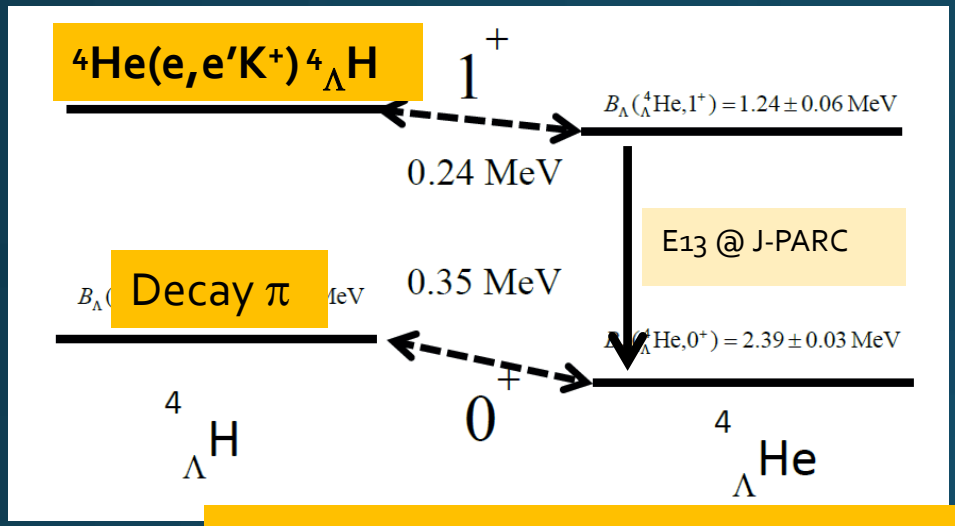
Direct method
to search or set upper limit
on this exotic system.
(charge 0, S=-1 nuclei)

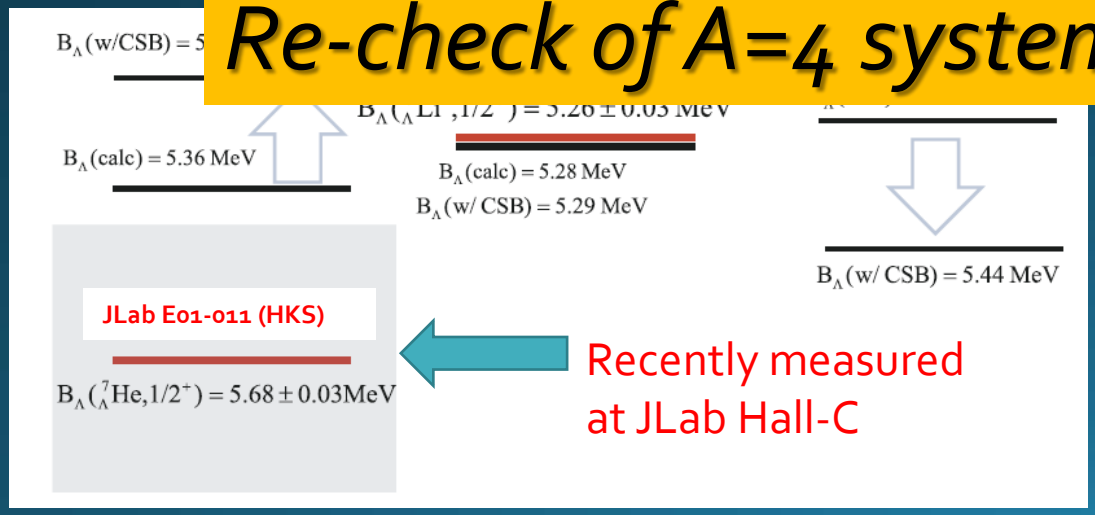
Electro-production data of ²d(e,e'K⁺) provide also information of n-Λ interaction through FSI.
(not very sensitive to deuteron W.F. and basic production mech.)

R.A.Adelseck & L.E.wright
PRC 39(1989) 580.

Few-body physics with strangeness

2. Charge Symmetry Breaking of ΛN interaction





Re-check of A=4 system

A=4,iso-doublet hypernuclei

Introduced to explain A=4.

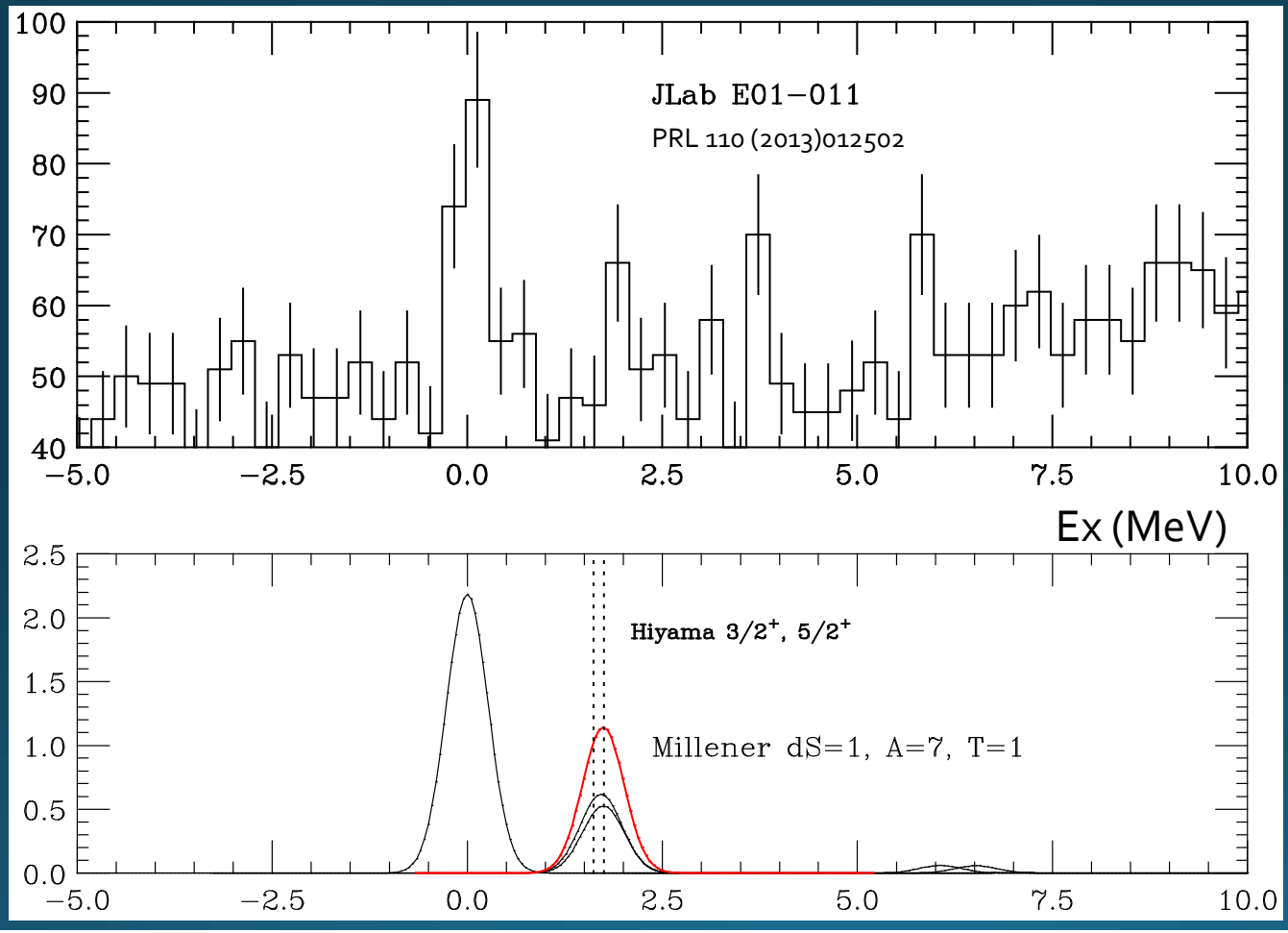
Phenomenological CSB potential

NOT becessary for A=7.

Recently measured
at JLab Hall-C

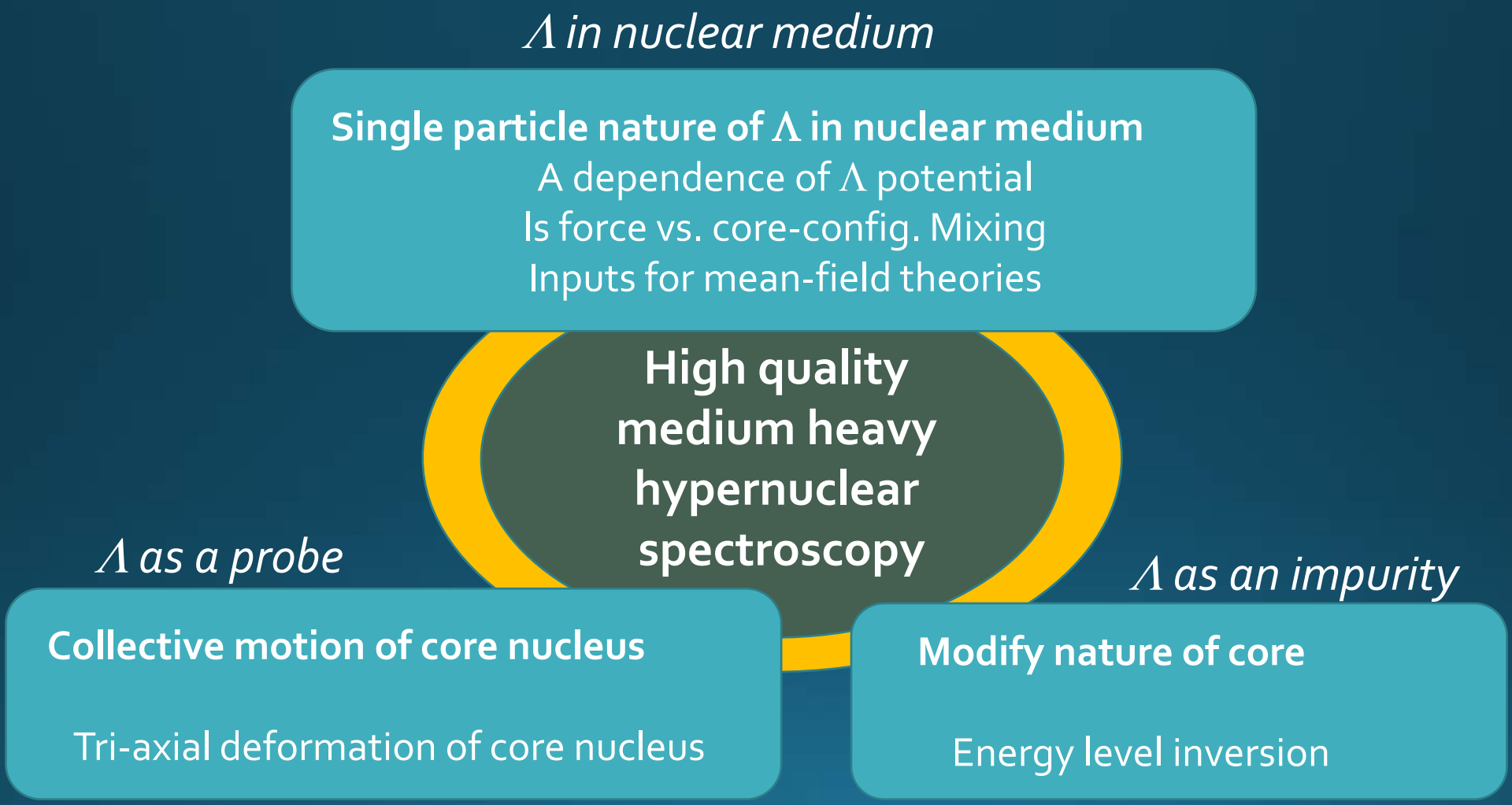
A=7,iso-triplet hypernuclei

${}^{7}_{\Lambda}\mathrm{He}$: Ground & Excited states ($3/2^{+}$, $5/2^{+}$)

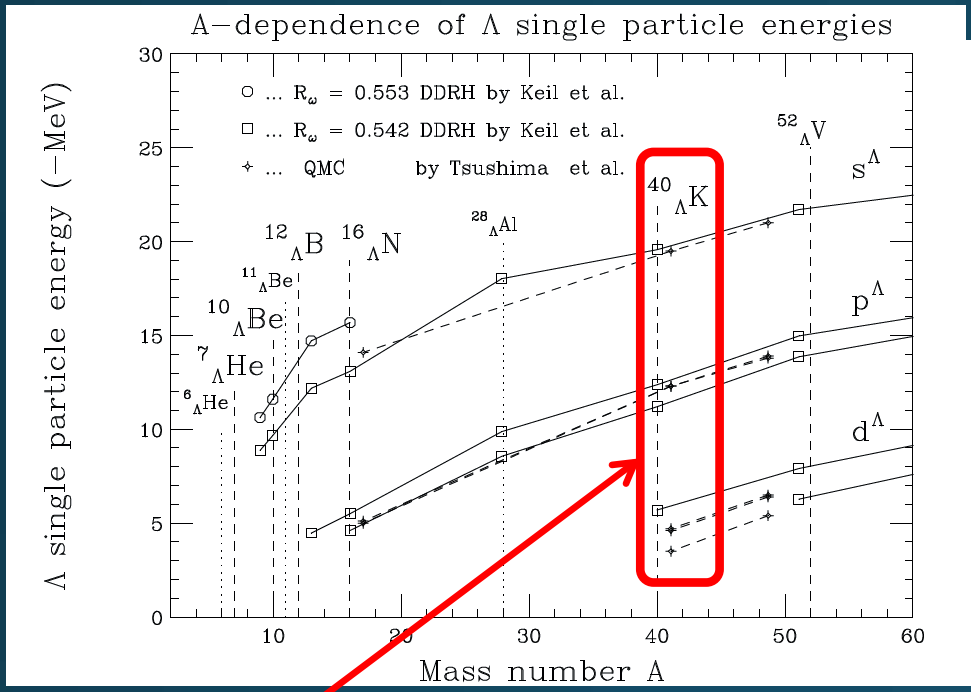


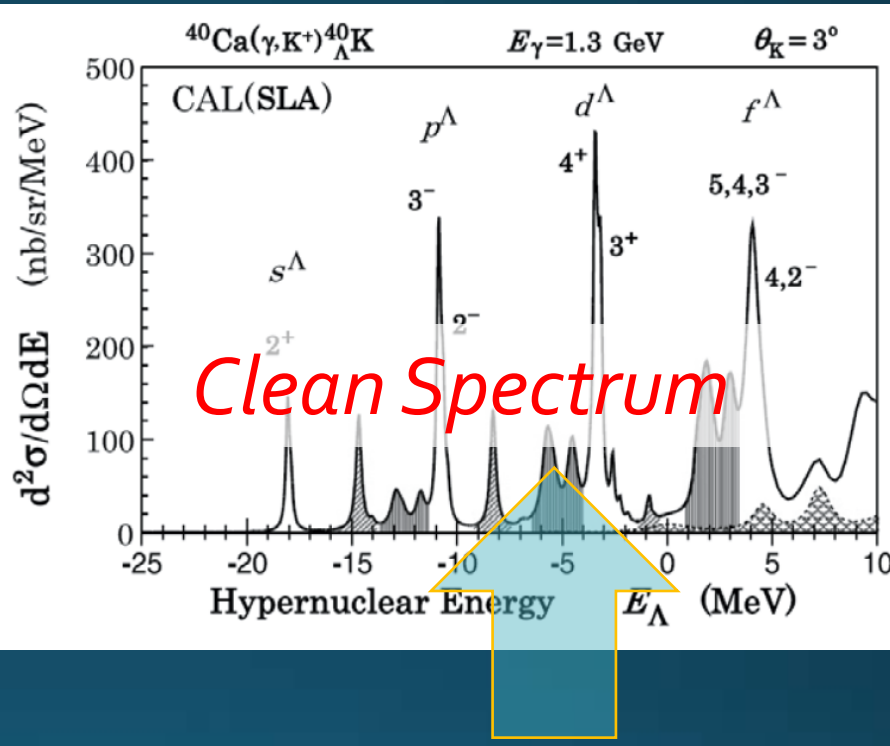
Transition amplitude for spin-flip states (J.Millener private comm.)

Medium heavy hypernuclei



1. Ca (e,e'K$^+$) $_\Lambda$K



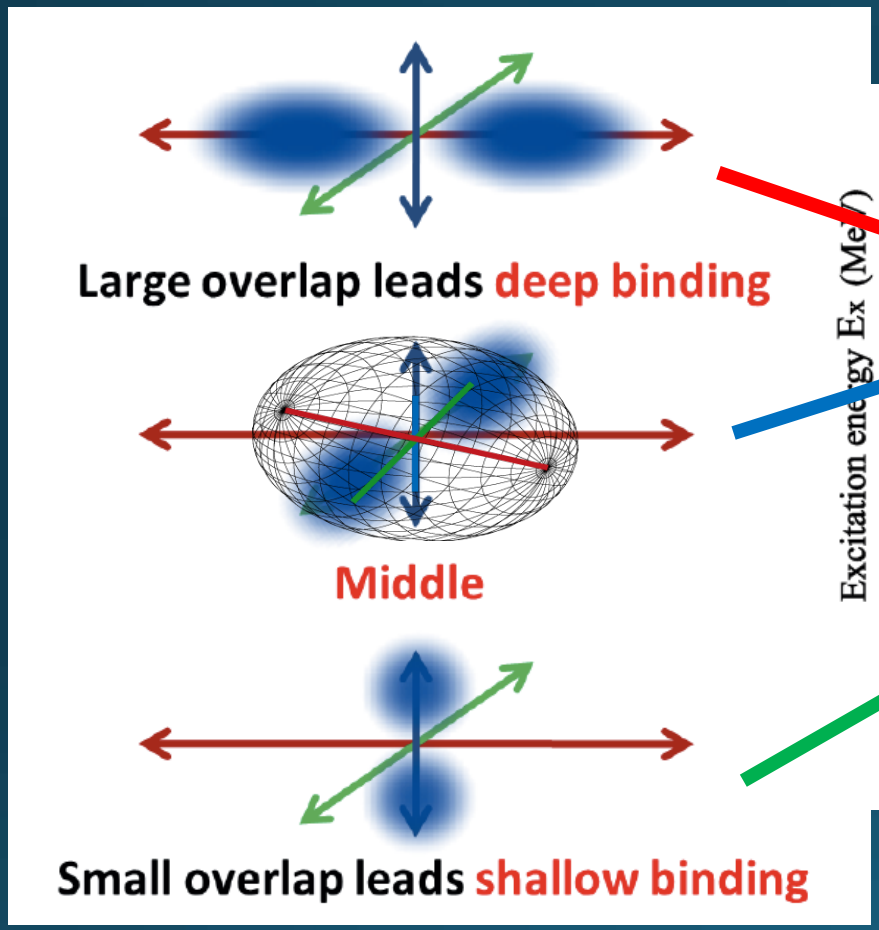


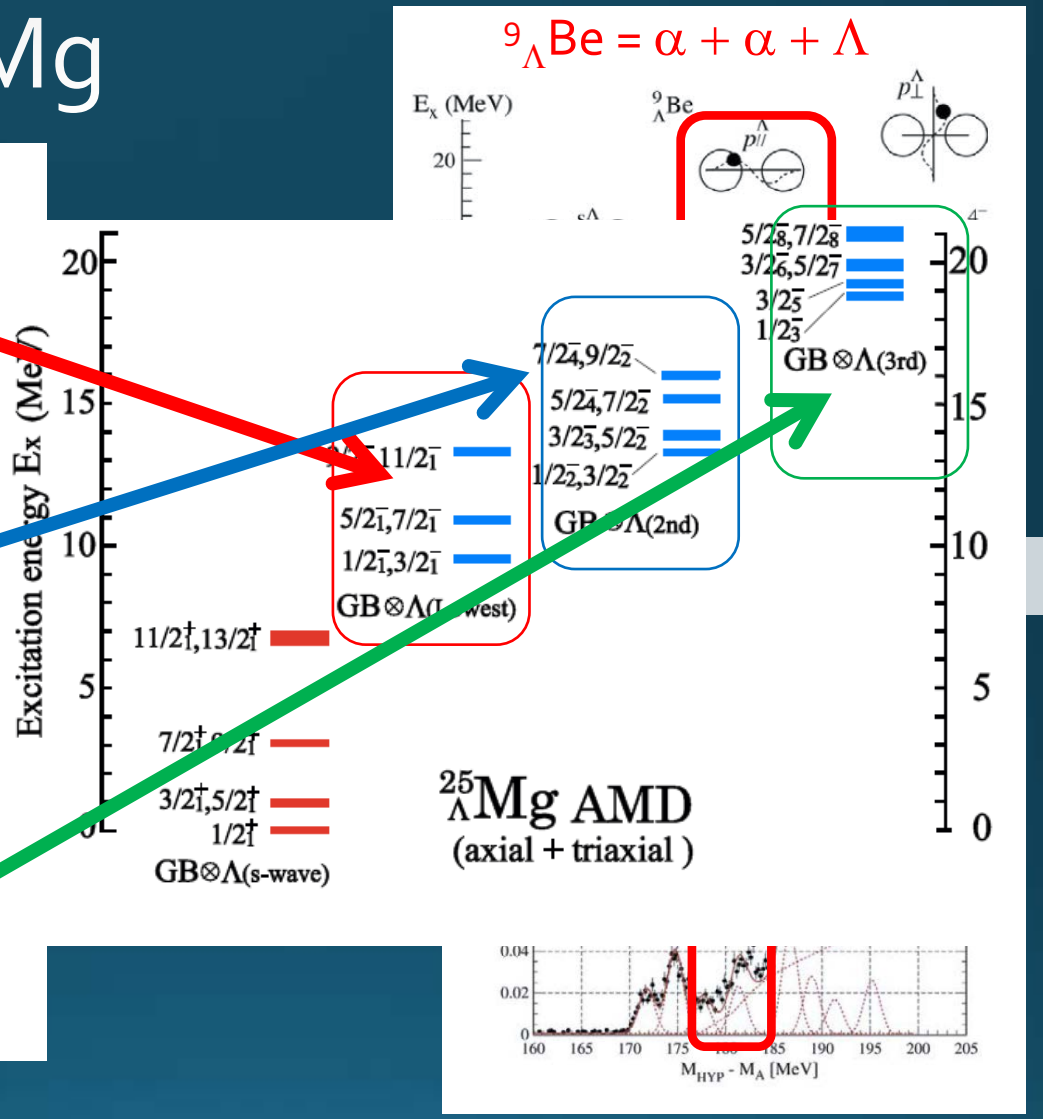
Missing in (e,e'K) data
Complete A dependence of Λ S.P.Energy

Doubly LS closed ^{40}Ca target

Systematic study of isotope effect of core nuclei: ^{40}Ca, ^{44}Ca (, ^{48}Ca) targets

2. ^{27}Al (e,e'K$^+$) $^{27}_{\Lambda}$Mg

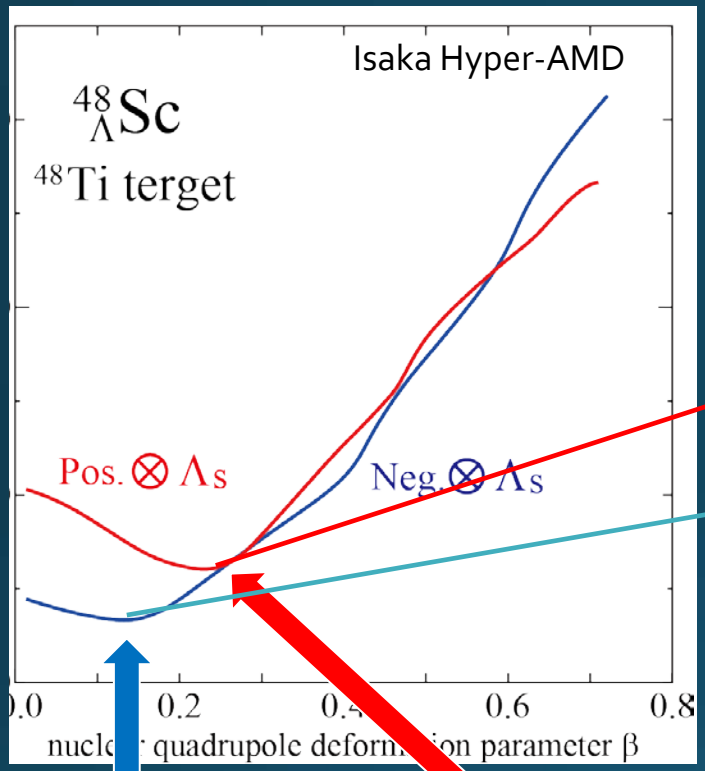


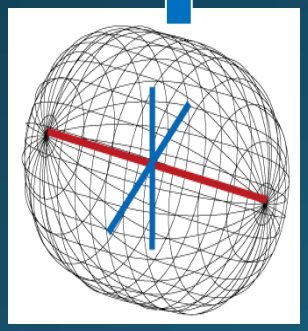


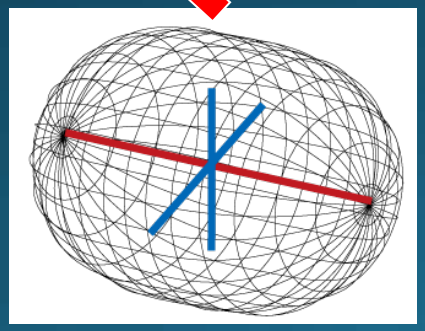
Tri-axially deformed ^{26}Mg core + Λ in p-shell

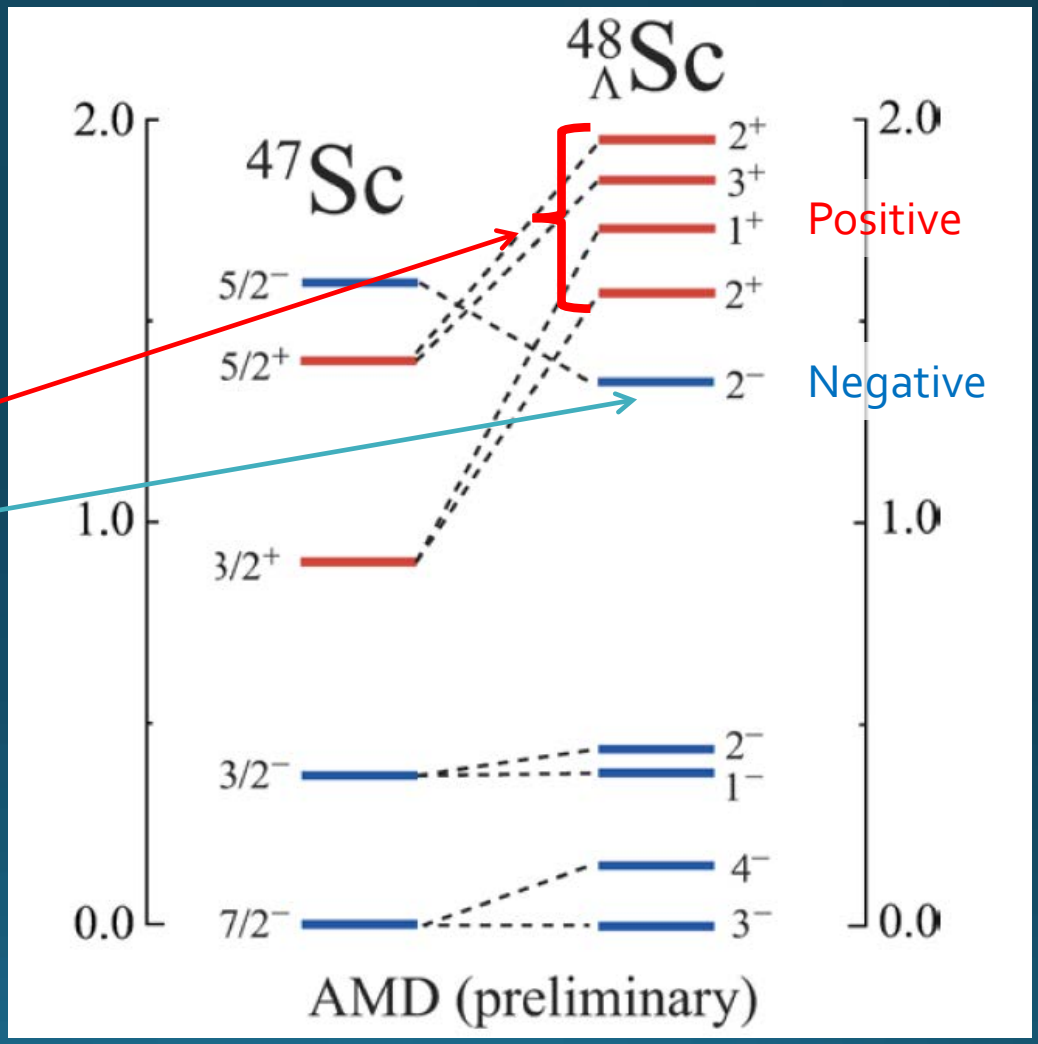
Totally new method to study shape of nucleus with Λ!

3. ^{48}Ti (e,e'K$^+$) $^{48}_{\Lambda}$Sc





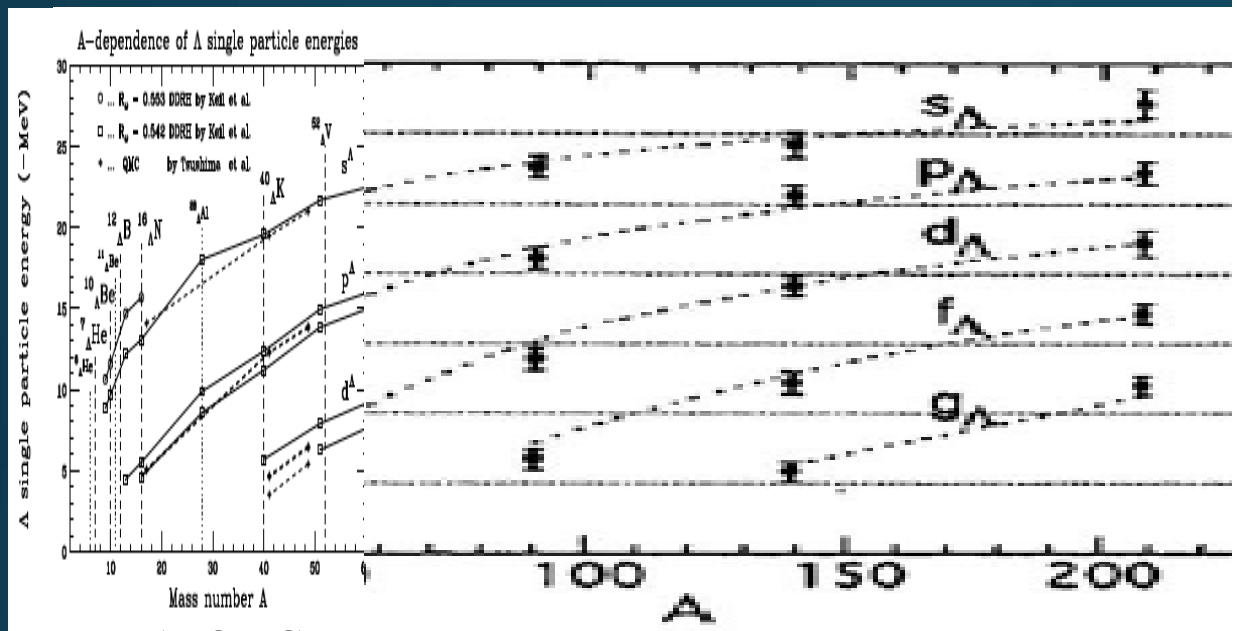


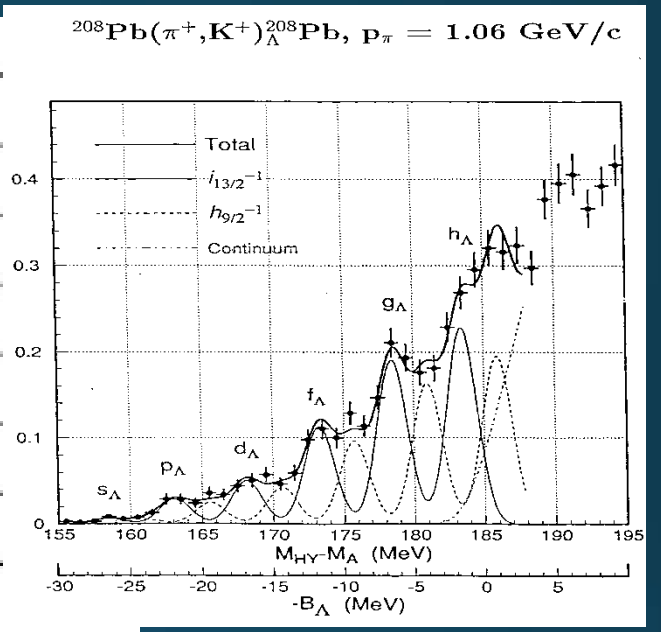


Λ impurity causes energy level inversion !

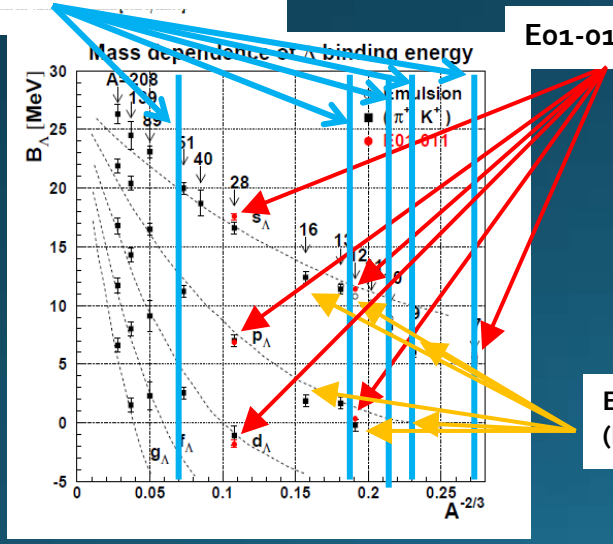
Hyperon in heavier nuclei – $^{208}(e,e'K^+)^{208}{}_{\Lambda}Ti$

Hasegawa et. al., PRC 53 (1996)1210





E05-115 (HKS-HES)

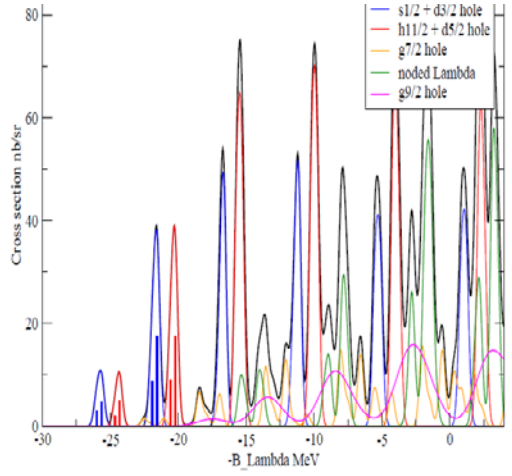


E01-011(HKS)

E94-107 (Hall A HY)

Motoba-Millener (2013)

$^{208}Pb(\gamma,K^+)^{208}{}_{\Lambda}Tl$



Summary

@Dubrovnik (2010)

電子線を用いたハイパー核

２０世紀からその重要性は理解

元場さん、Sotonaさん達の理論的サポート

Jlab E89-009による原理実証

HKS＋HES in Hall C
E01-011, E05-115

HRS＋HRS in Hall A
E94-017

MAMI-Cにおいて実験が可能に

12GeV Era におけるJlab 新実験へ

元場さん、これからもよろしくお願いします。