2013年7月7日

和州閣

S=-1からS=-2の分光へ

永江　知文

京都大学・理学研究科

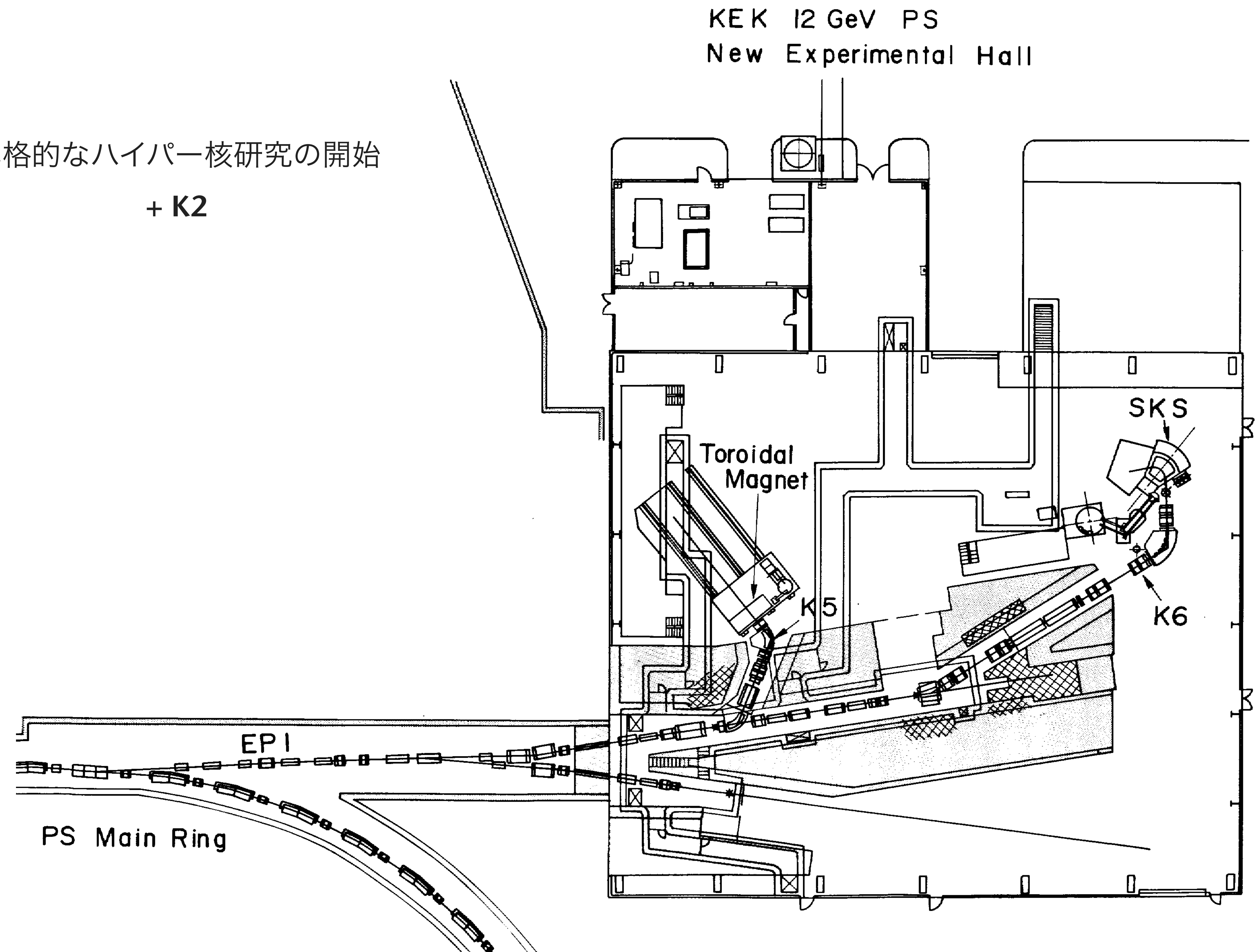
内容

- **SKS**スペクトロメーター
- **(π^+, K$^+$)**スペクトロスコピー
  - **E140a, E336, E369**
- **S-2S**の建設と**(K$^-$,K$^+$)**スペクトロスコピー

北カウンターホール

本格的なハイパー核研究の開始

+ **K2**



SKS建設の歴史

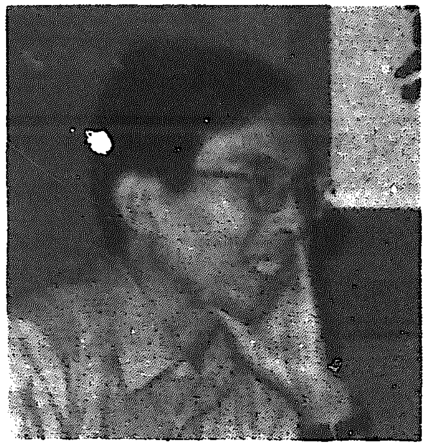
- **1987:** 建設開始
- **1990:** 超伝導磁石完成→北カウンターホールへ据え付け
- **1991:** 冷凍システム完成
- **1991.9:** **3T**励磁に成功！→磁場測定
- **1992.2: SKS+K6**ビームコミッショニング開始
- **1992.10-11: E269**実験**(π-C**弾性散乱）データ取得
- **1993.1-7: E140a**実験データ取得開始（最初の**(π,K)**実験）

２人の巨人逝く: 1990,91

T. Motoba, NPA547 (1992) 379c-392c.

In memory of professor Hiroharu Bandō, I quote a part of the note added by Žofka and myself in our recent review article [3].

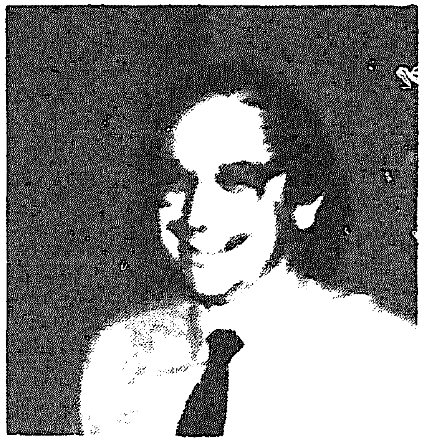
"Hiro started his scientific work at Kyoto University with an investigation on nuclear collective motion in 1961 and did many noticeable studies with more than 110 papers which are related to three groups: (i) the many-body theory of the effective interactions based on the realistic nuclear force, (ii) the cluster model of nuclei and clustering mechanism, and (iii) the theory of hypernuclear physics covering the various stages (production, structure and decay) of hypernuclei."



Dr. Hiroharu Bandō (1938–1990)

In memory of professor Jan Žofka, let me simply quote several sentences from a recent article by G. Ripka[5].

"Jan Žofka, the internationally known expert on hypernuclei, died unexpectedly last May (5th, 1991) in Prague. Žofka graduated in 1966 from the Czech Technical Faculty of Nuclear Physics and entered the Institute of Nuclear Physics in Řež near Prague, where he worked until his death. He started as a student of Professor Trlifaj and after a six month visit to the Service de Physique at CEN Saclay, France, he completed, in 1971 in Prague, his PhD on the Hartree-Fock theory applied to nuclear shape." [5]



Dr. Jan Žofka (1943 – 1991)

元場さんの支援

- 現実的な理論計算
- ハイパー核コミュニティの形成
- 若手の育成

SKS建設の歴史（続き）

- **1987:** 建設開始
- **1990:** 超伝導磁石完成→北カウンターホールへ据え付け
- **1991:** 冷凍システム完成
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- **1993.1-7: E140a**実験データ取得開始（最初の**(π,K)**実験）

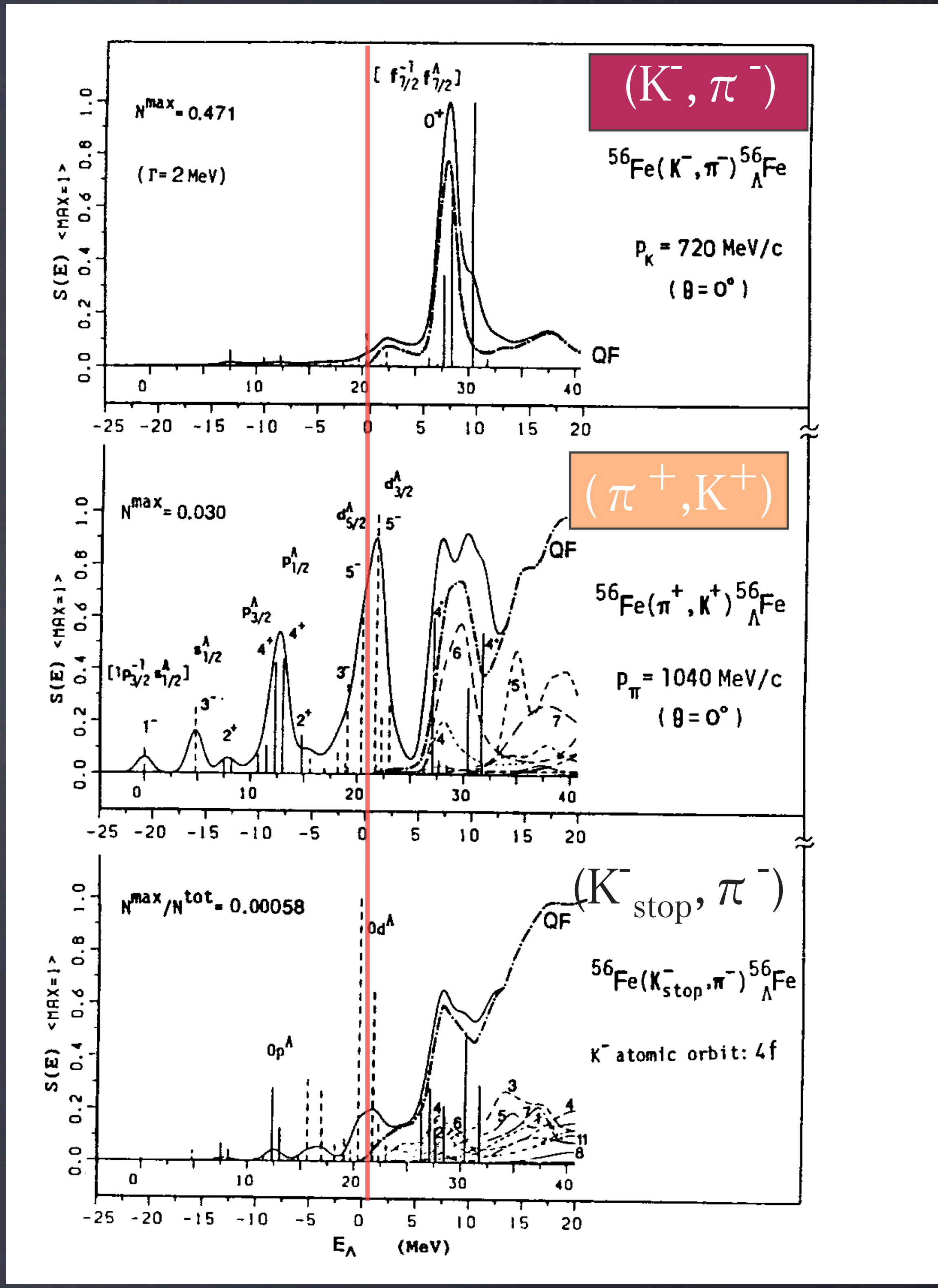
SKSでの実験のまとめ

- 実験期間：1992〜2005（14年間）
  - K2Kライン建設のため１年間シャットダウン
- 実施ビームタイム：〜1700シフト（570日）
- 実験数：１５課題
- Ph.D取得数：２０人

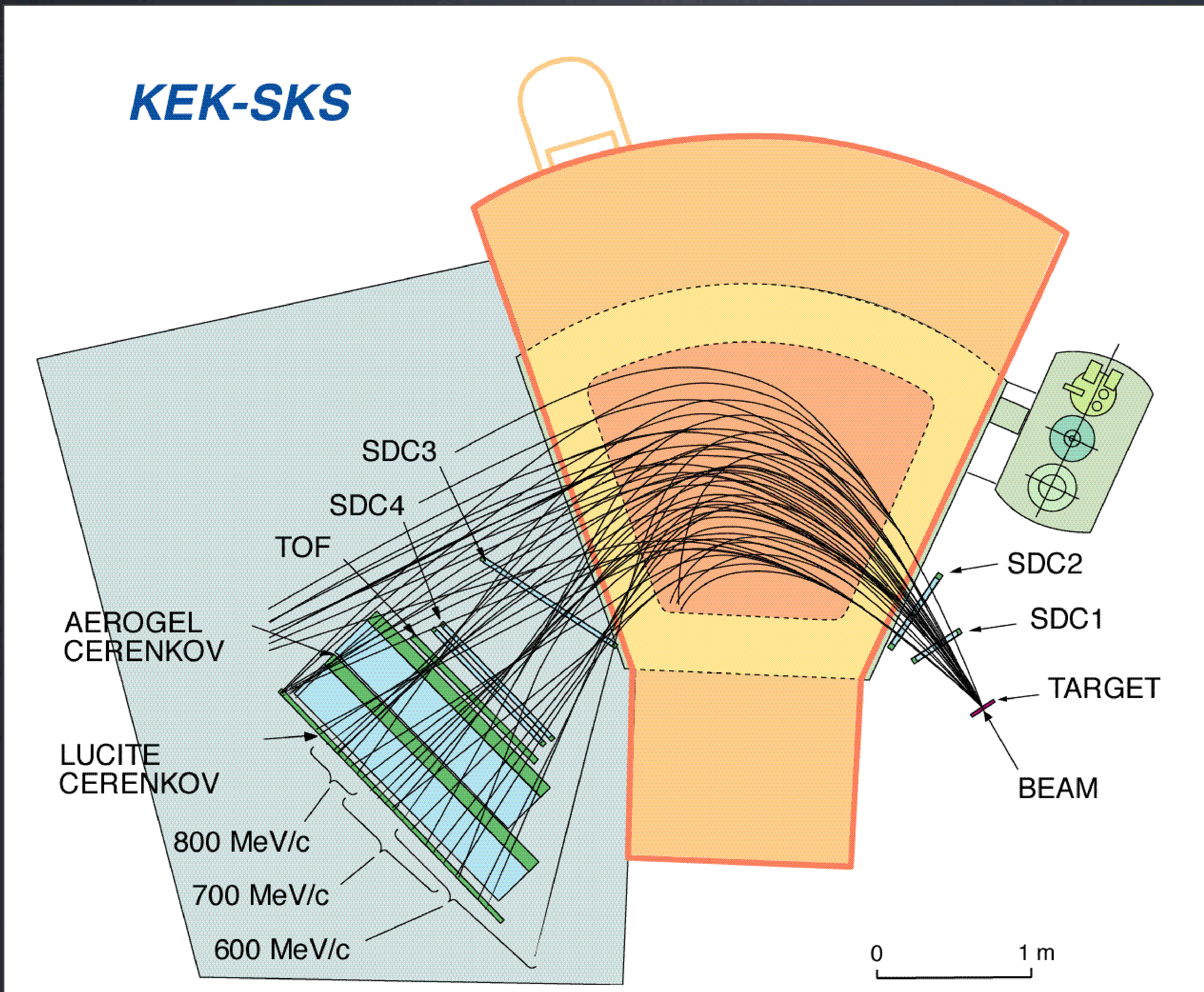
(π^+, K^+) スペクトロスコピー

(π^+,K+) Spectroscopy

- Merits
  - Large momentum transfer q~350 MeV/c
  - Efficiently produces deeply-bound states
  - Low backgrouds: γ , n
- Demerits
  - No difference in angular distributions



SKS Spectrometer at KEK-PS



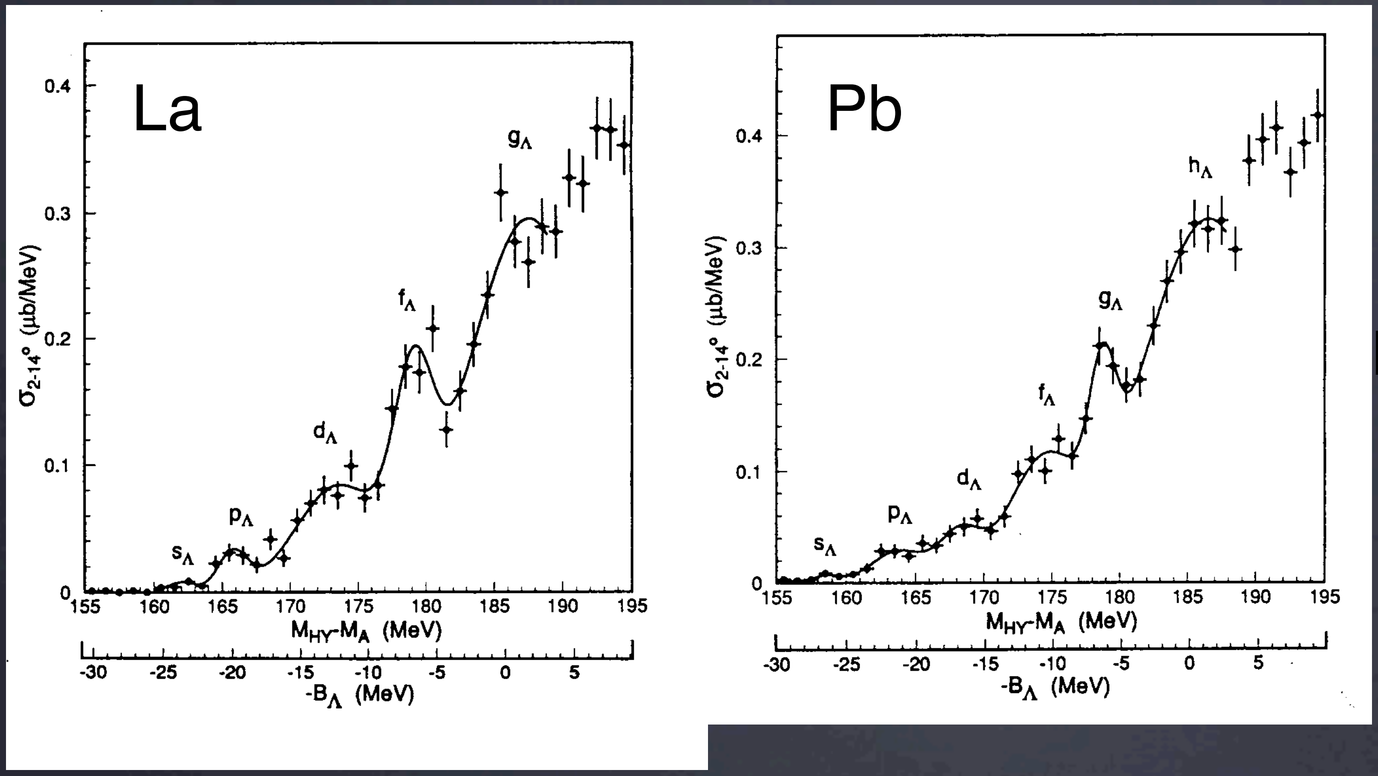
- Superconducting Kaon Spectrometer for the (π^+,K^+) reactions
- Constructed by INS, Univ. of Tokyo, from 1987 to 1990
- In operation since 1992
- B_{max}=3T(500A)
- Pole Gap=50 cm
- 10.6 MJ stored
- Cold Mass ~4.5 t
- ~280 tons

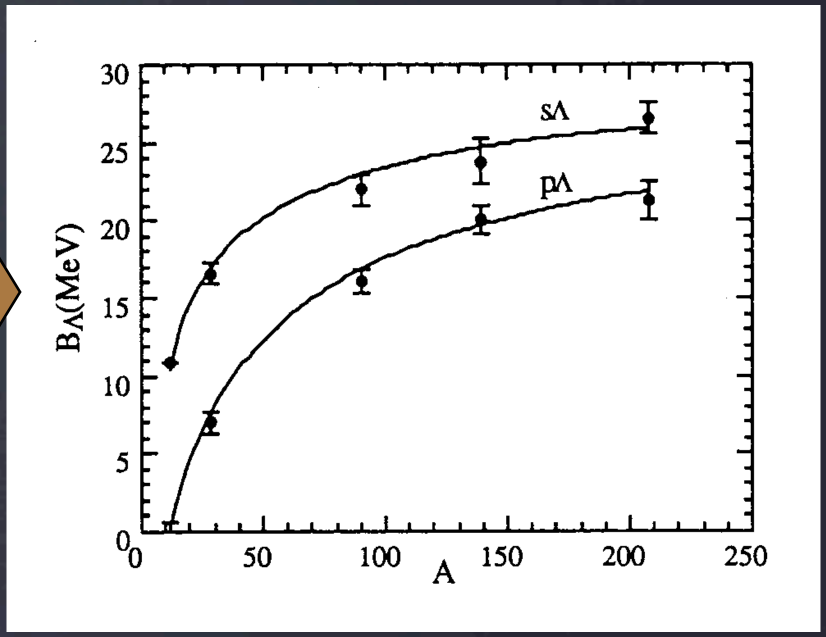
(π,K^+) experiments with SKS

- E140a: ^{10}B, ^{12}C, ^{28}Si, ^{89}Y, ^{139}La, ^{208}Pb
  - Phys. Rev. C 53 (1996) 1210.
- E336: ^{7}Li, ^{9}Be, ^{13}C, ^{16}O
  - Nucl. Phys. A 639 (1998) 93c, Nucl. Phys. A 691 (2001) 123c.
  - Prog. Part. and Nucl. Phys. 57 (2006) 564.
- E369: ^{89}Y, ^{51}V, ^{12}C in high-resolution
  - Phys. Rev. C 64 (2001) 044302.
- E521: $^{10}B(\pi^-, K^+)$
  - Phys. Rev. Lett. 94 (2005) 052502.

E140a:
First (π^+,K^+) exp. with the SKS

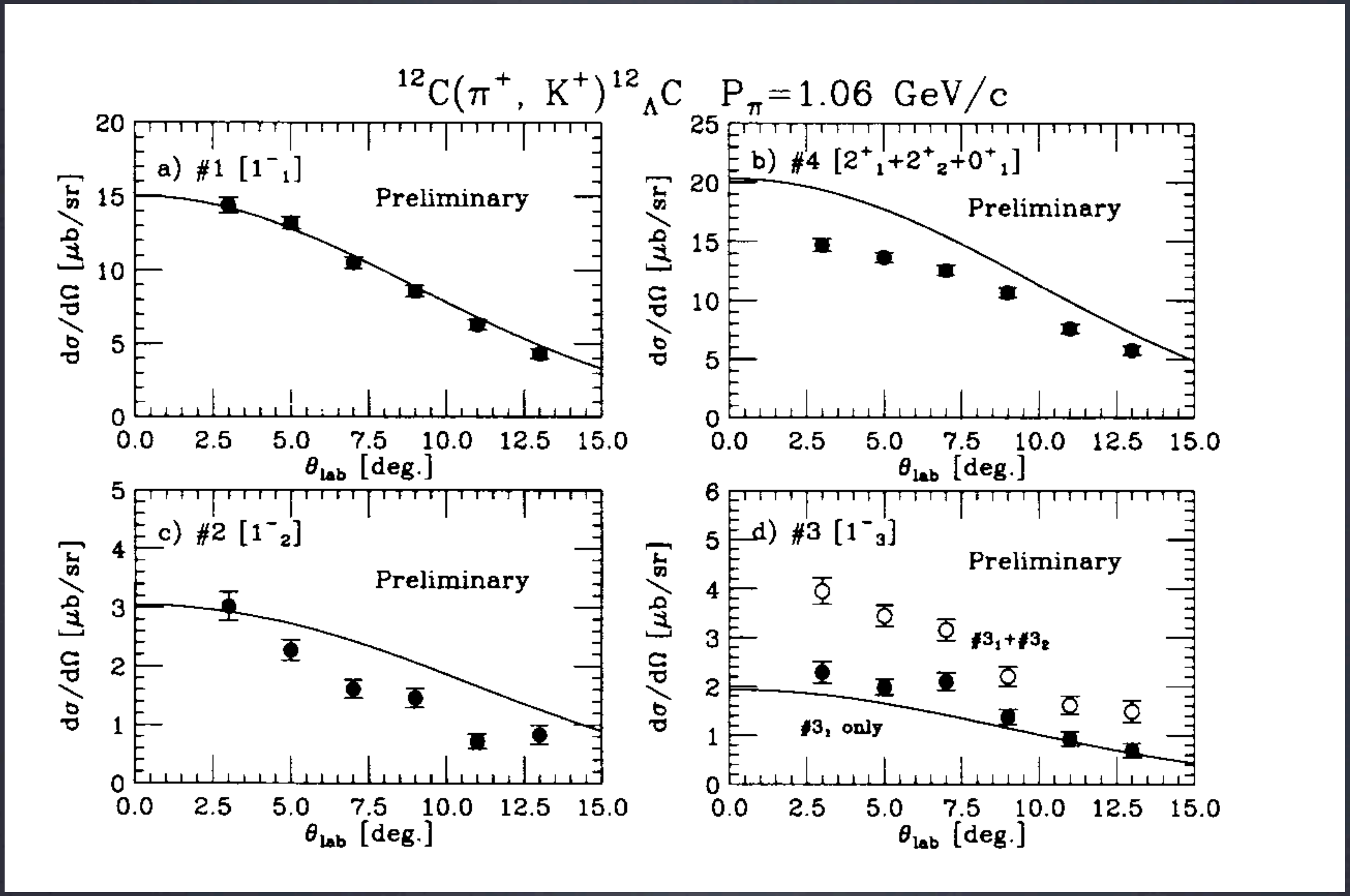
- Targets: ^{10}B, ^{12}C, ^{28}Si, ^{89}Y, ^{139}La, ^{208}Pb
  - $^{12}{}_{\Lambda}C$: First observation of core-excited states
  - Confirmed Λ Shell Structures up to $^{208}{}_{\Lambda}Pb$





T.Hasegawa et al., Phys. Rev. C53 (1996) 1210

E336 : $^{12}{}_{\Lambda}C$：角度分布

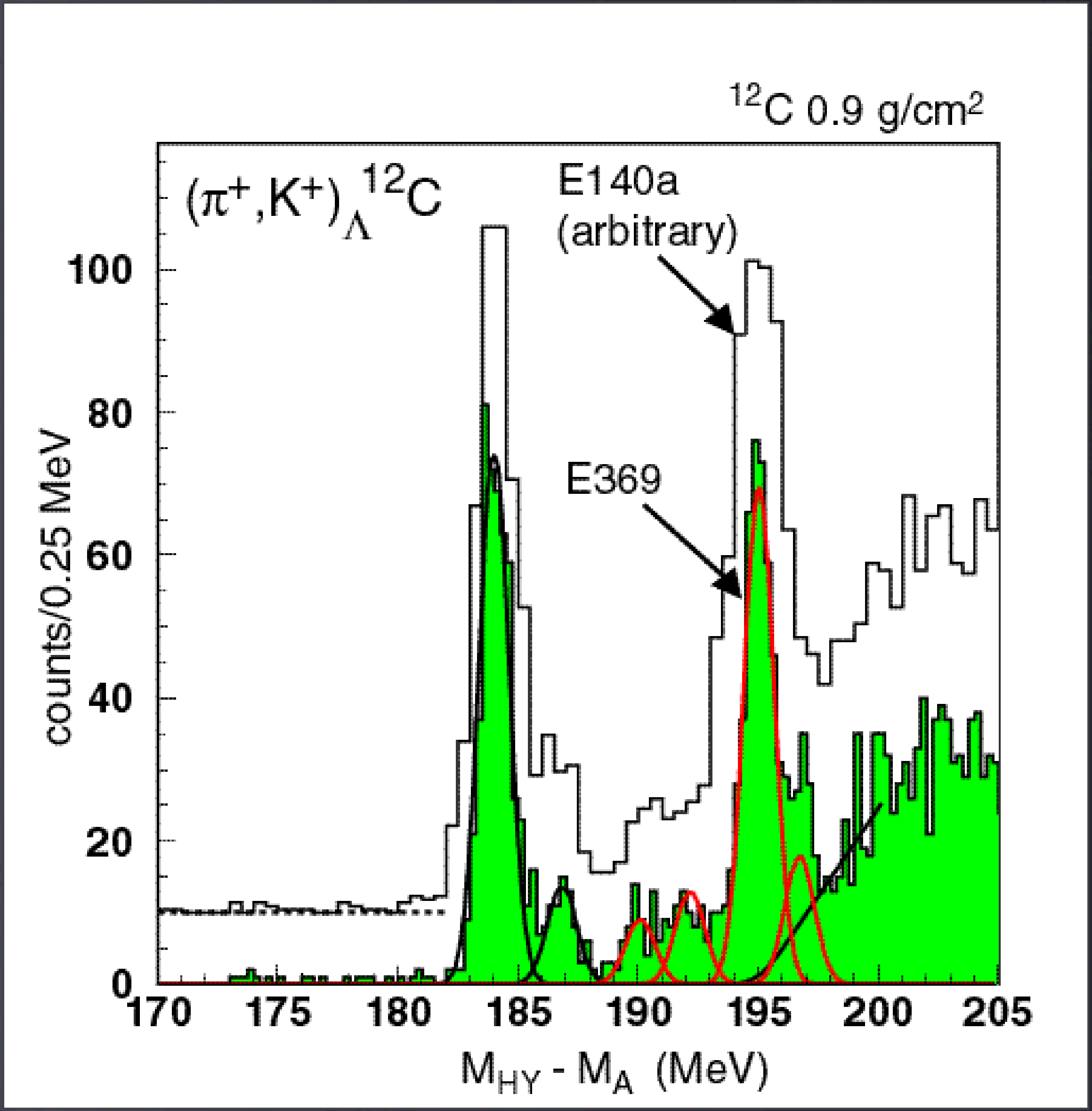


T.Takahashi et al., Nucl. Phys. A670 (2000) 265c.
Cal. by K.Itonaga et al., Phys. Rev. C49 (1994) 1045.

E369: $_{\Lambda}^{12}C$

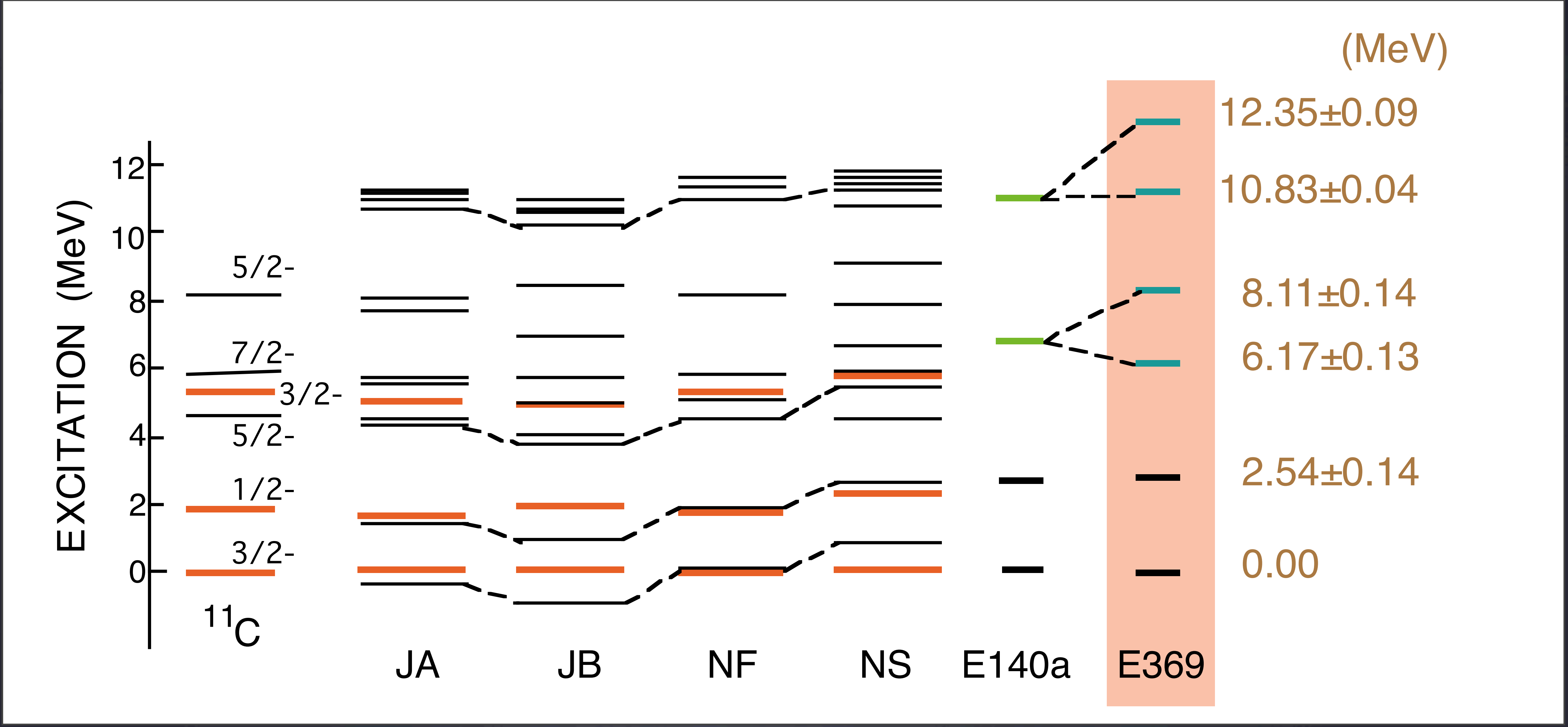
- Best energy resolution
- ΔE(FWHM) = 1.45 MeV

2.0 MeV



Core-excited states of $^{12}_{\Lambda}C$

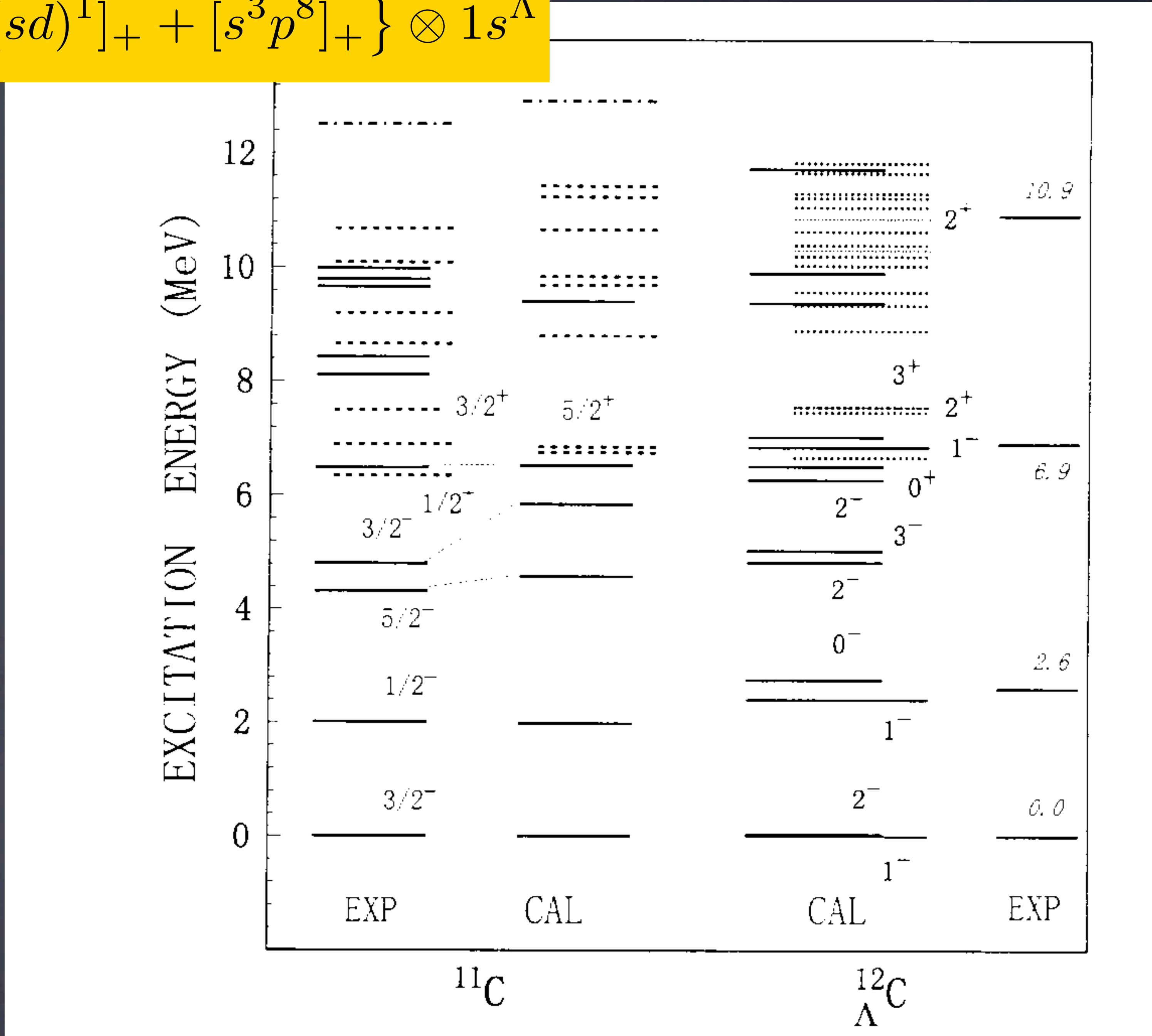
New states are resolved.
Effects of ΛN spin-dependent forces



Parity-mixing intershell coupling

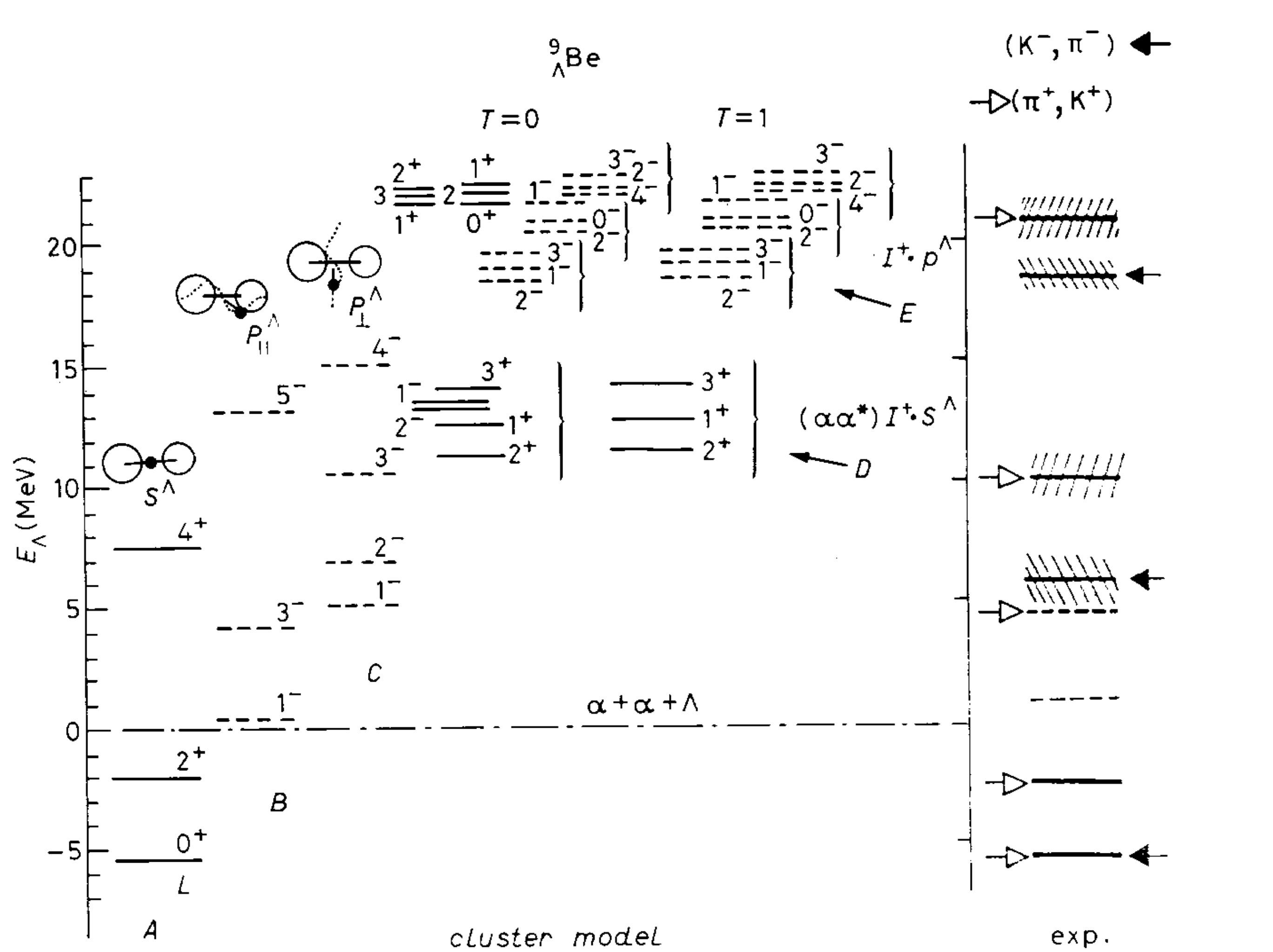
- T. Motoba, in HYP97(Nucl. Phys. A 639 (1998) 135c.)

$$|^{12}_{\Lambda}\mathrm{C}; J^{+}\rangle = [s^4p^7]_- \otimes 1p^{\Lambda} + \{[s^4p^6(sd)^1]_+ + [s^3p^8]_+\} \otimes 1s^{\Lambda}$$

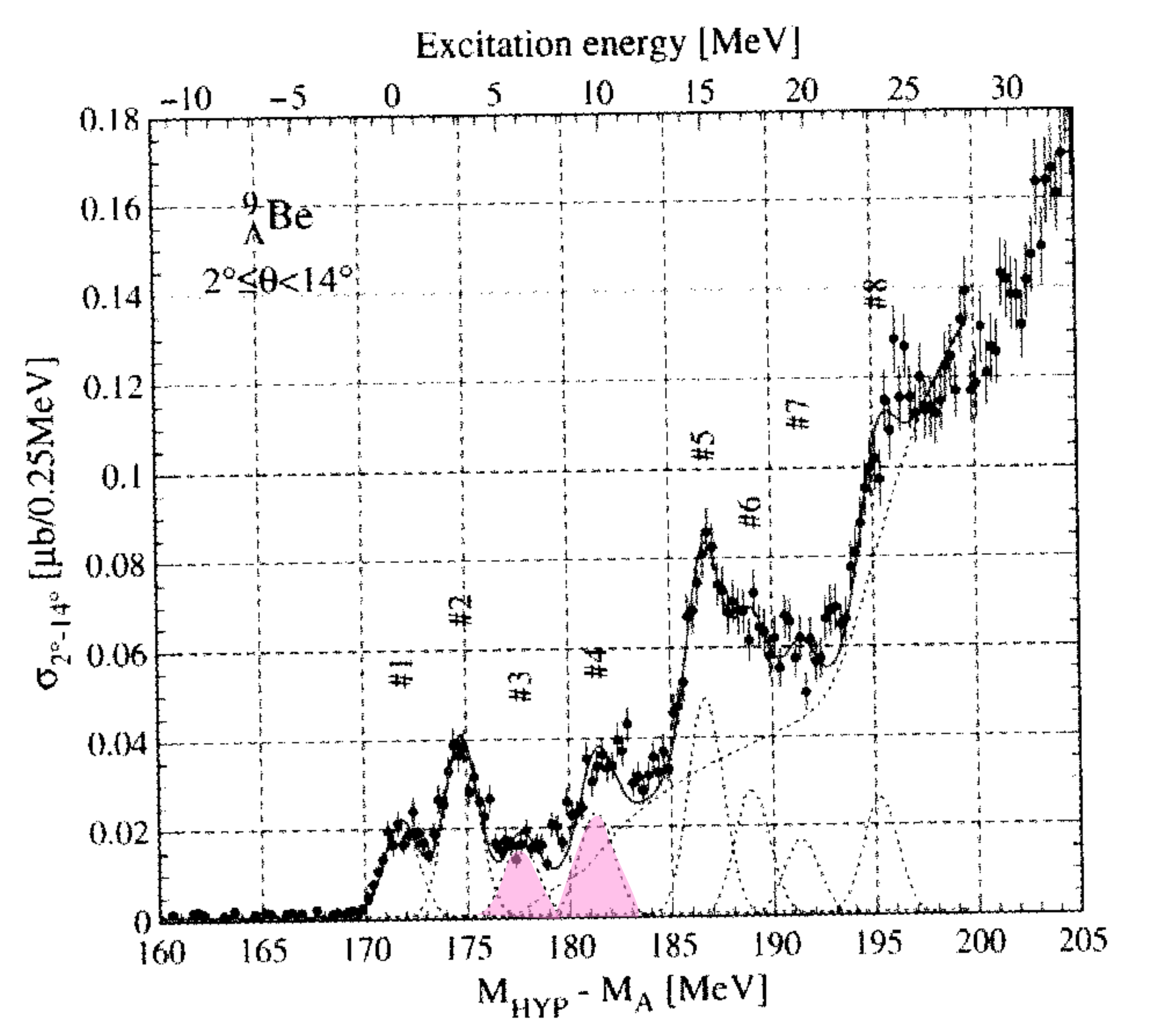


E336: $^{9}_{\Lambda}Be$

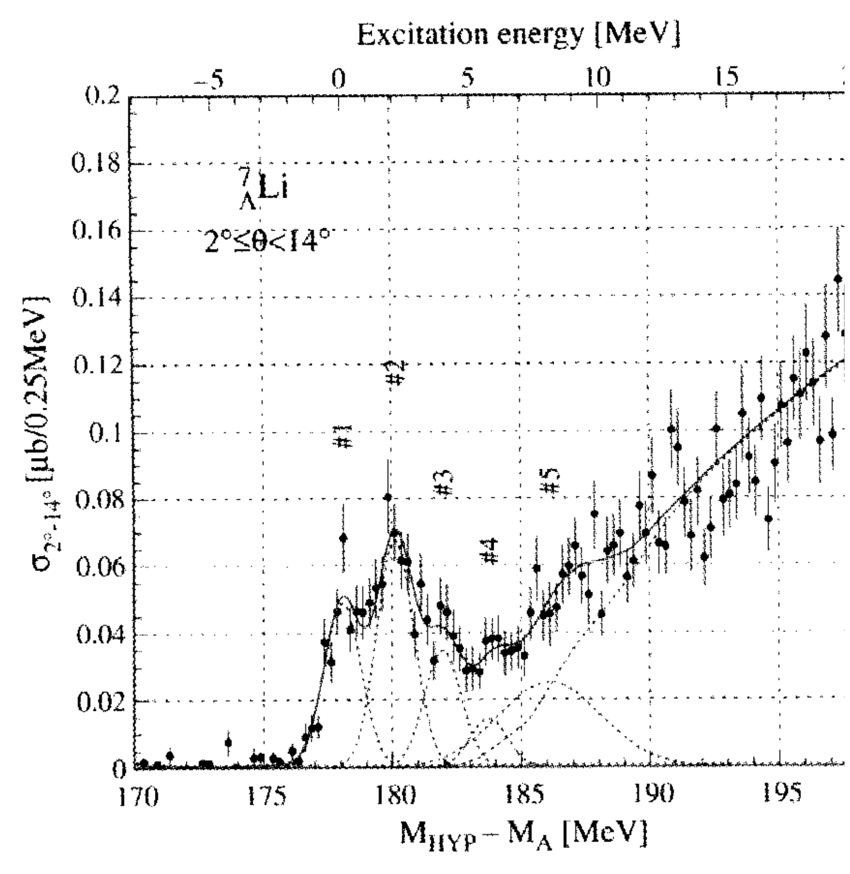
- Observation of "genuine" hypernuclear states or "Supersymmetric" states

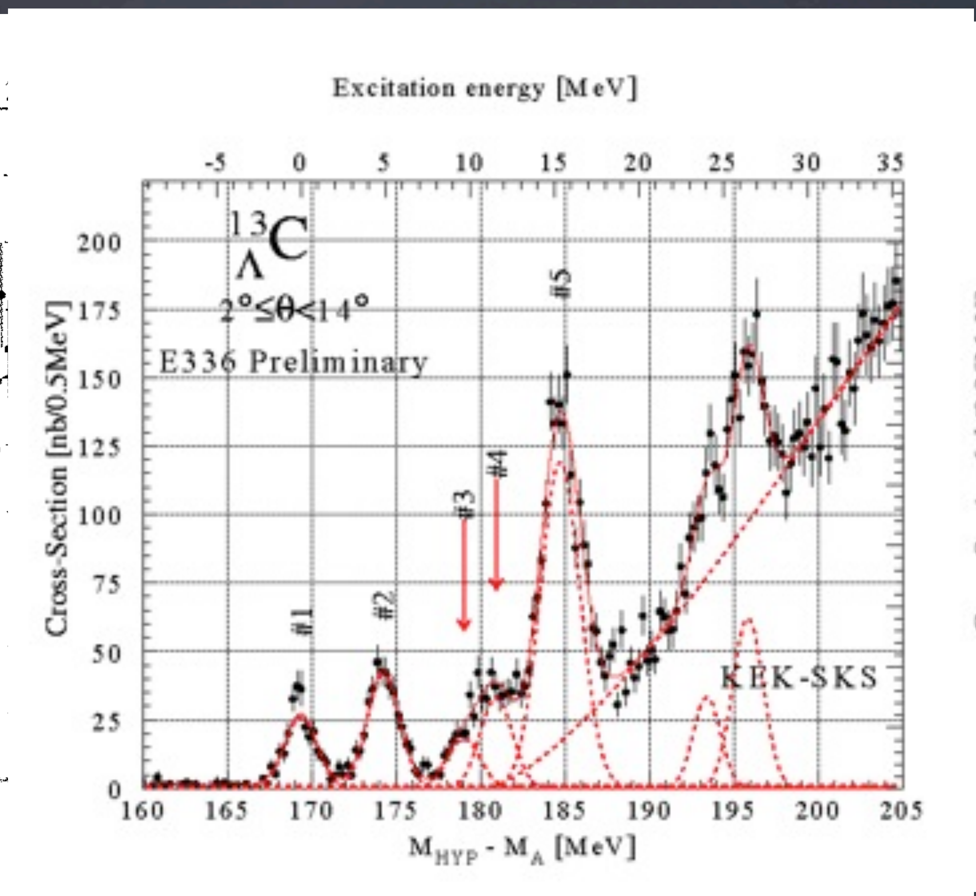


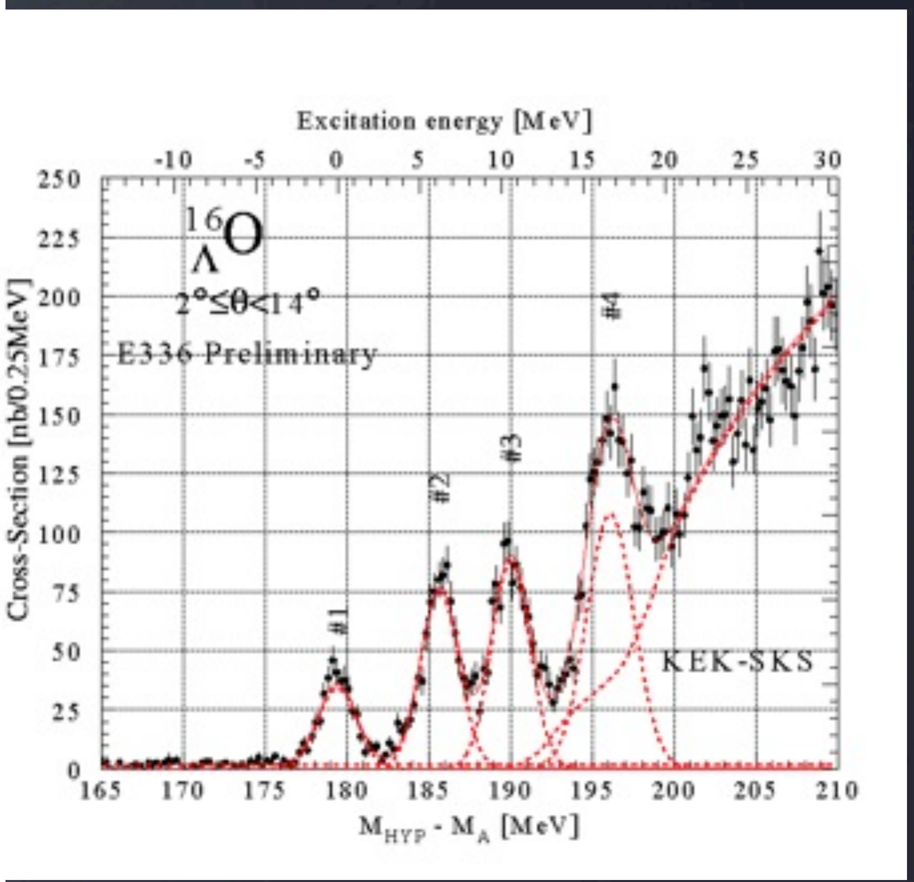
T.Motoba, Il Nuovo Cim. 102A (1989) 345.



E336: $_{\Lambda}^{7}$Li , $_{\Lambda}^{13}$C, $_{\Lambda}^{16}$O



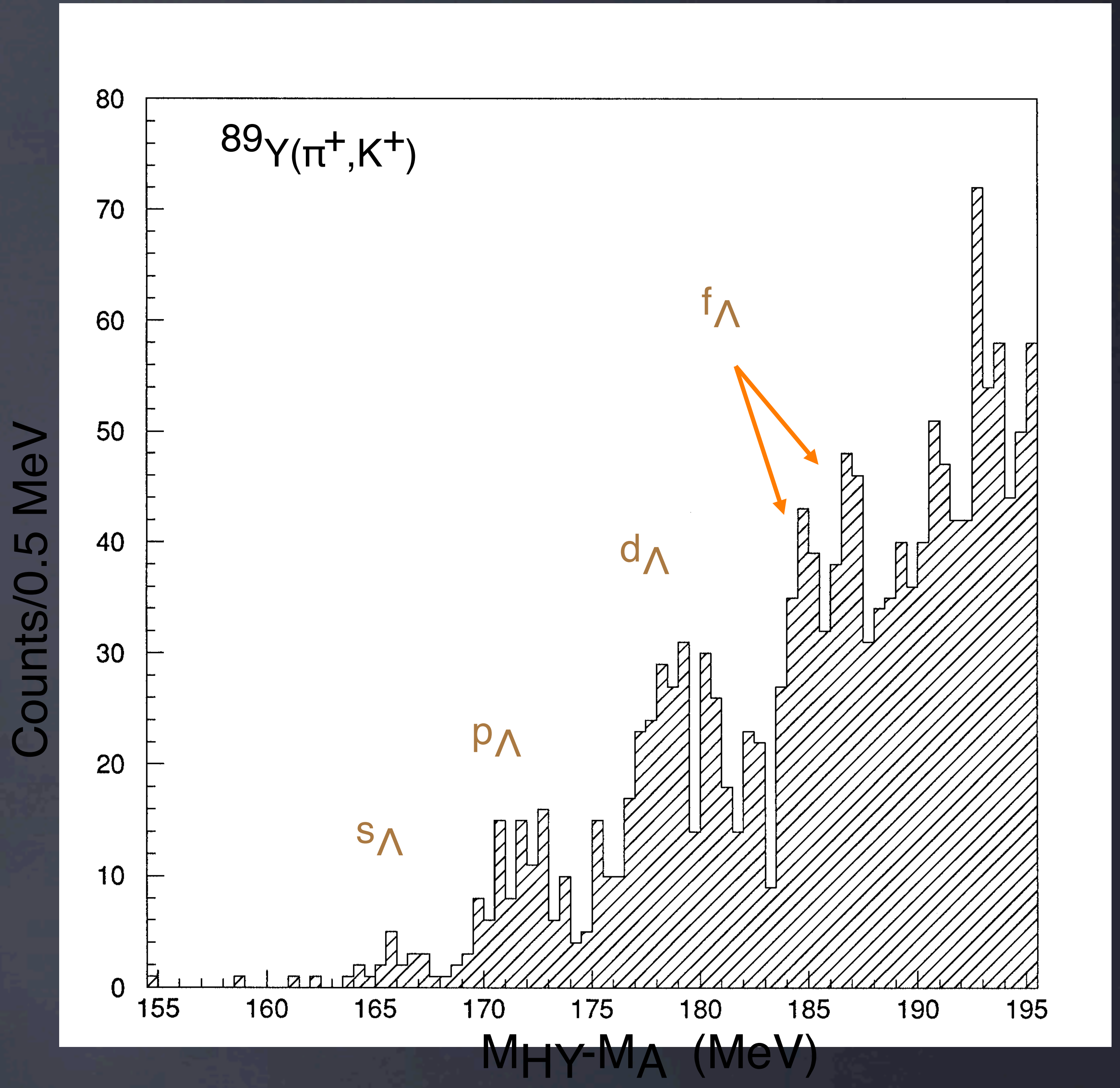




$\Delta E(2^+ - 0^+) = 0.04 \pm 0.32$ MeV

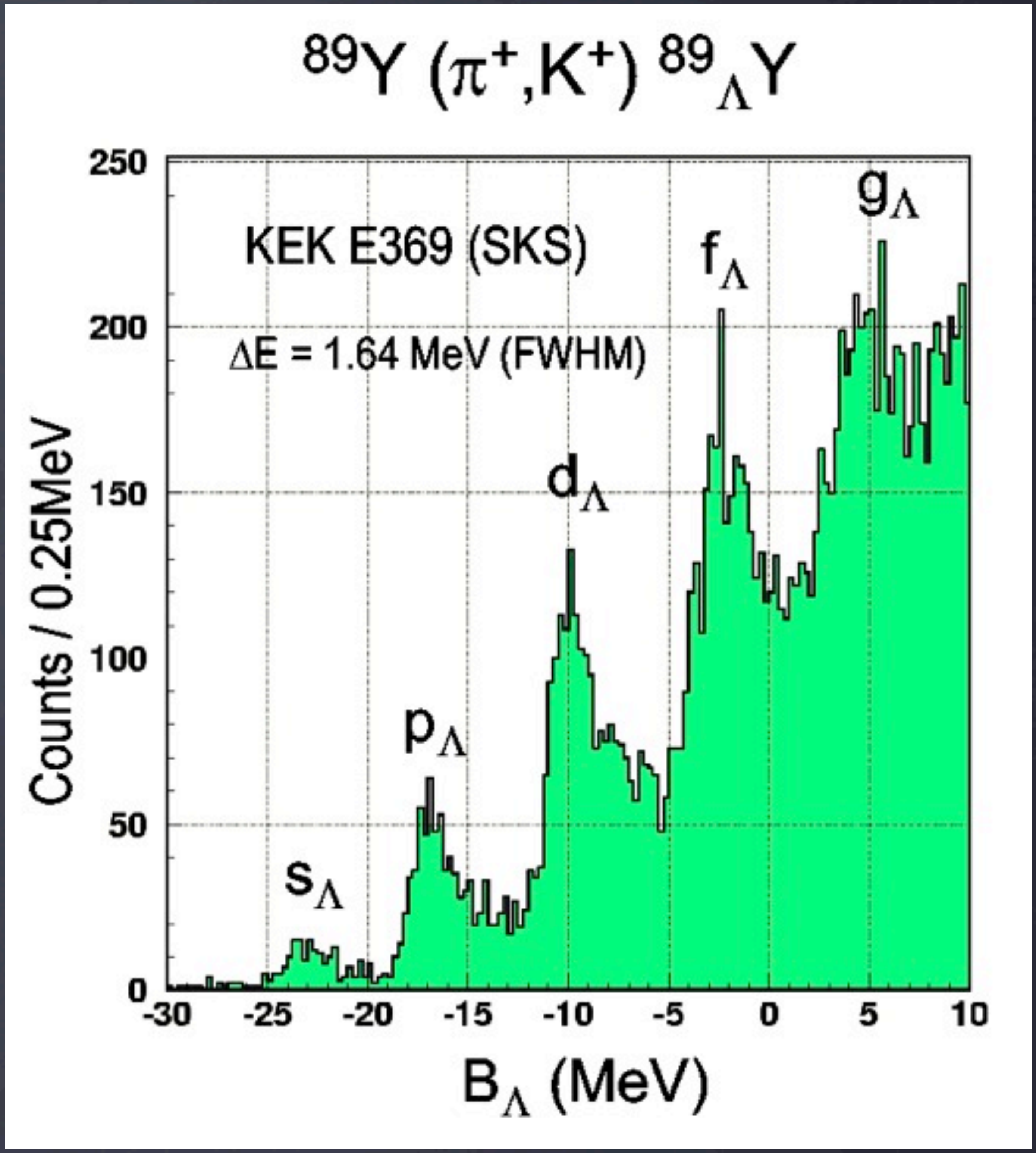
$^{89}{}_{\Lambda}Y$: in E140a

- KEK-PS E140a
ΔE=2.2 MeV



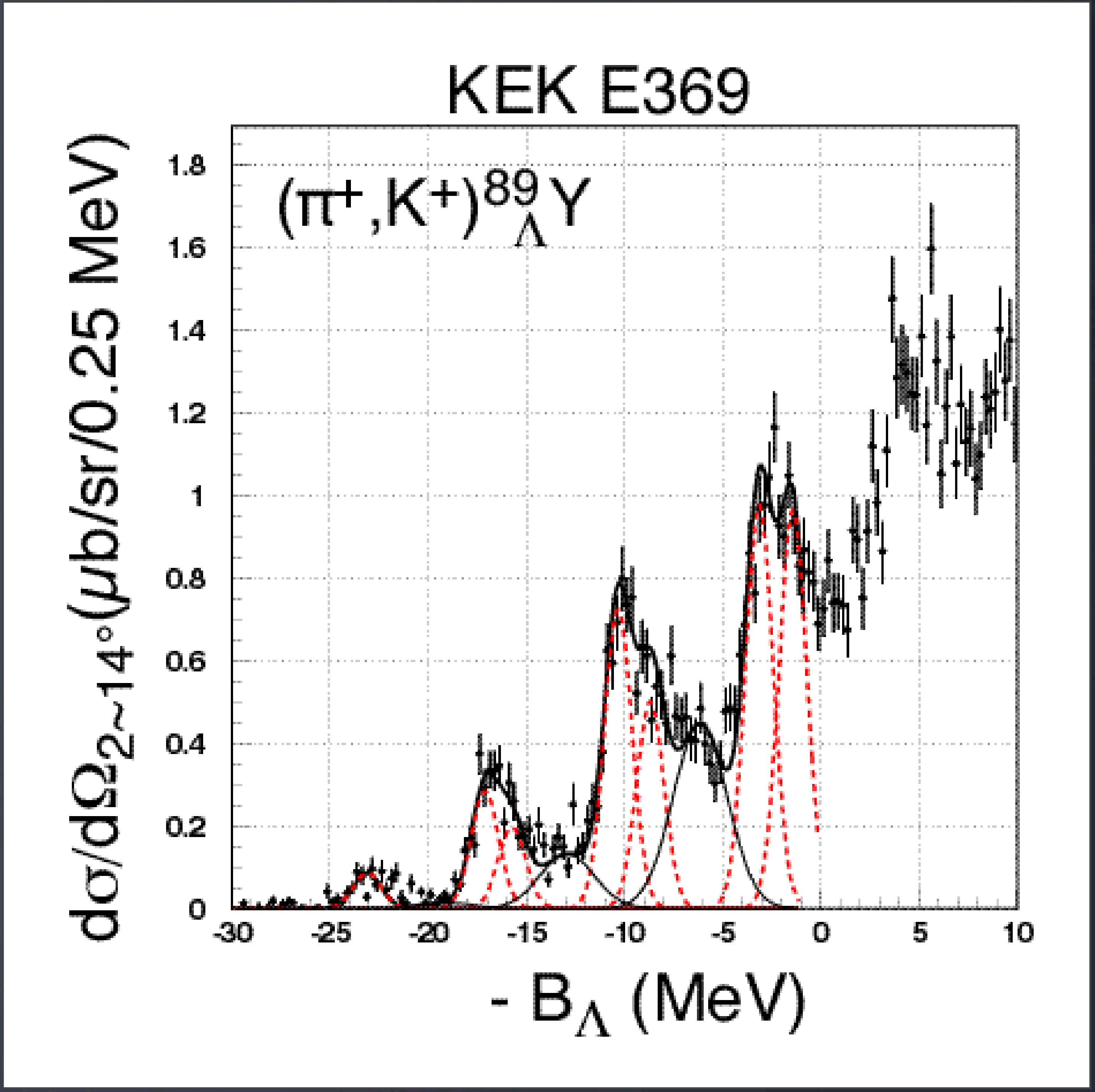
$^{89}{}_{\Lambda}Y$: in E369

- Single Gaussian(σ)
- p: 2.4±0.2 MeV
- d: 3.0±0.2 MeV
- f: 4.6±0.5 MeV



E369: $_{\Lambda}^{89}Y$

- $B_{\Lambda s}$=23.1±0.1 MeV
- Energy Splitting
  - ΔE_f=1.70±0.10 MeV
  - ΔE_d=1.63±0.14 MeV
  - ΔE_p=1.37±0.20 MeV
- Peak Ratio
  - R/L_f=0.99±0.07
  - R/L_d=0.69±0.06
- Extra n-hole at +4.1±0.1 MeV, width=3.2±0.2 MeV

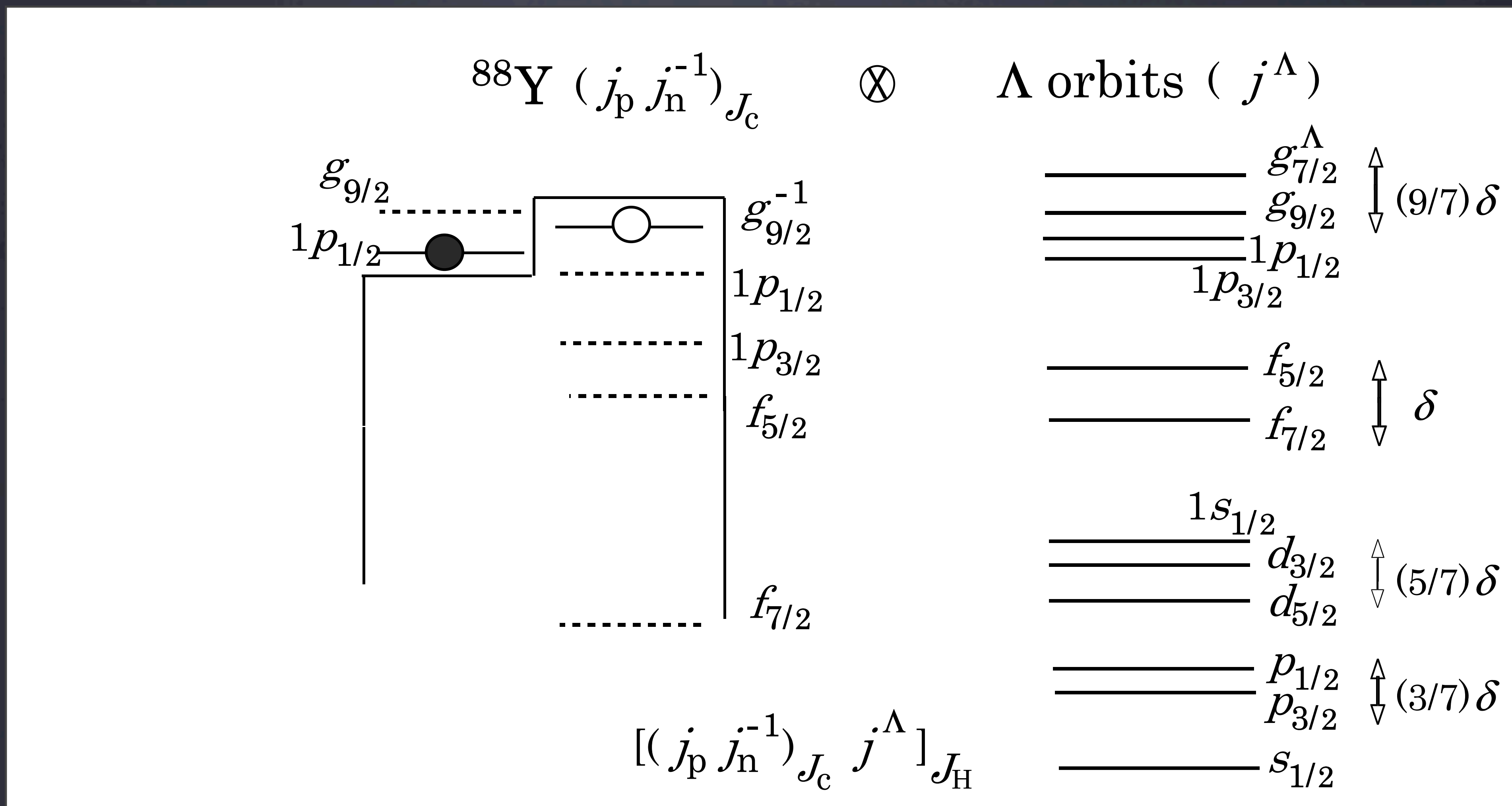


- SplittingがLSによるものとすると、大きすぎる。
- Splittingは(2ℓ+1)に比例するべきだが、これと異なる。
- L/Rのピーク比が、Kinematical Factorからずれている。

Table 1

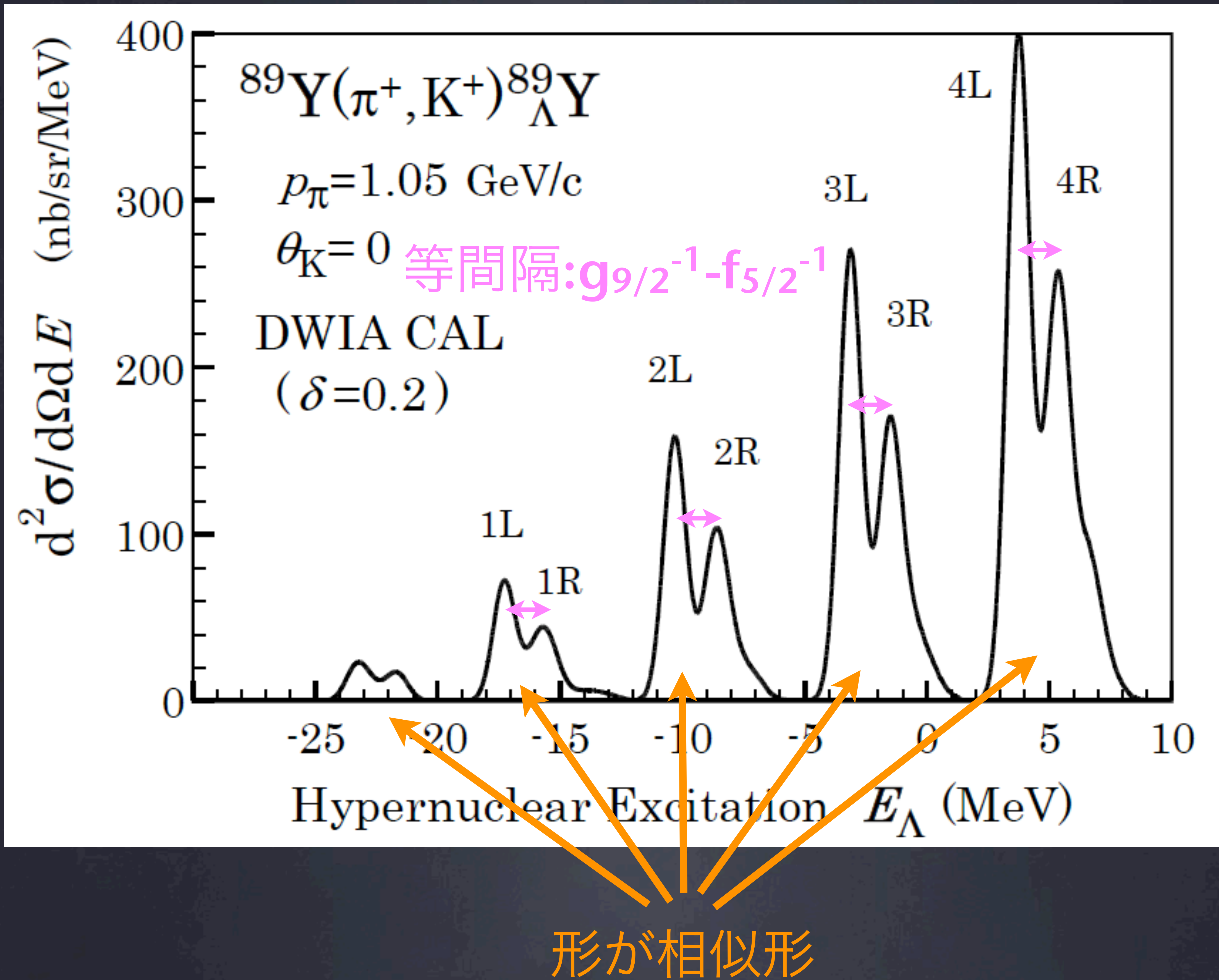
Experimental energy spacings (ΔE_i) and cross sections ($\bar{\sigma}$, averaged over $\theta_K^{\mathrm{Lab}} = 2^\circ - 14^\circ$) for a series of major peaks (Left and Right subpeaks) in the $^{89}\mathrm{Y}(\pi^+, K^+)^{89}_{\Lambda}\mathrm{Y}$ reaction [11]. The cross sections and their ratios are compared with theoretical predictions using the DWIA [4]. See the text for NSC97f.

peak	E_Λ^{exp}	$\bar{\sigma}^{\mathrm{exp}}$	ΔE_i (MeV)		$\Delta E_i/\Delta E_1$ ratio			$\bar{\sigma}_L/\bar{\sigma}_R$	
	(MeV)	(μb/sr)	exp	NSC97f	exp	NSC97f	WS	exp	calc
s_Λ	−23.11	0.60							
p_Λ 1L	−17.10	2.00							
1R	−15.73	1.38	1.37	0.46	1.00	1.00	1.00	1.45	1.00
d_Λ 2L	−10.32	5.10							
2R	−8.69	3.52	1.63	0.72	1.19	1.57	2.16	1.45	0.55
f_Λ 3L	−3.13	6.87							
3R	−1.43	6.79	1.70	0.92	1.24	2.00	3.36	1.01	0.44



^{88}Y $(j_p\, j_n^{-1})_{J_c}$ ⊗ Λ orbits (j^{Λ})
$g_{9/2}$
$1p_{1/2}$
$g_{9/2}^{-1}$
$1p_{1/2}$
$1p_{3/2}$
$f_{5/2}$
$f_{7/2}$
$[(j_p\, j_n^{-1})_{J_c}\; j^{\Lambda}]_{J_H}$
$g_{7/2}^{\Lambda}$
$g_{9/2}$
$1p_{1/2}$
$1p_{3/2}$
$(9/7)\,\delta$
$f_{5/2}$
$f_{7/2}$
δ
$1s_{1/2}$
$d_{3/2}$
$d_{5/2}$
$(5/7)\,\delta$
$p_{1/2}$
$p_{3/2}$
$(3/7)\,\delta$
$s_{1/2}$

T. Motoba *et al.*, Nucl. Phys. A 804 (2008) 99-115.



E369: $_{\Lambda}^{51}V$

Splitting in d-(and p-) orbit(s)

$B_{\Lambda s}$=(20±0.13)+0.56 MeV

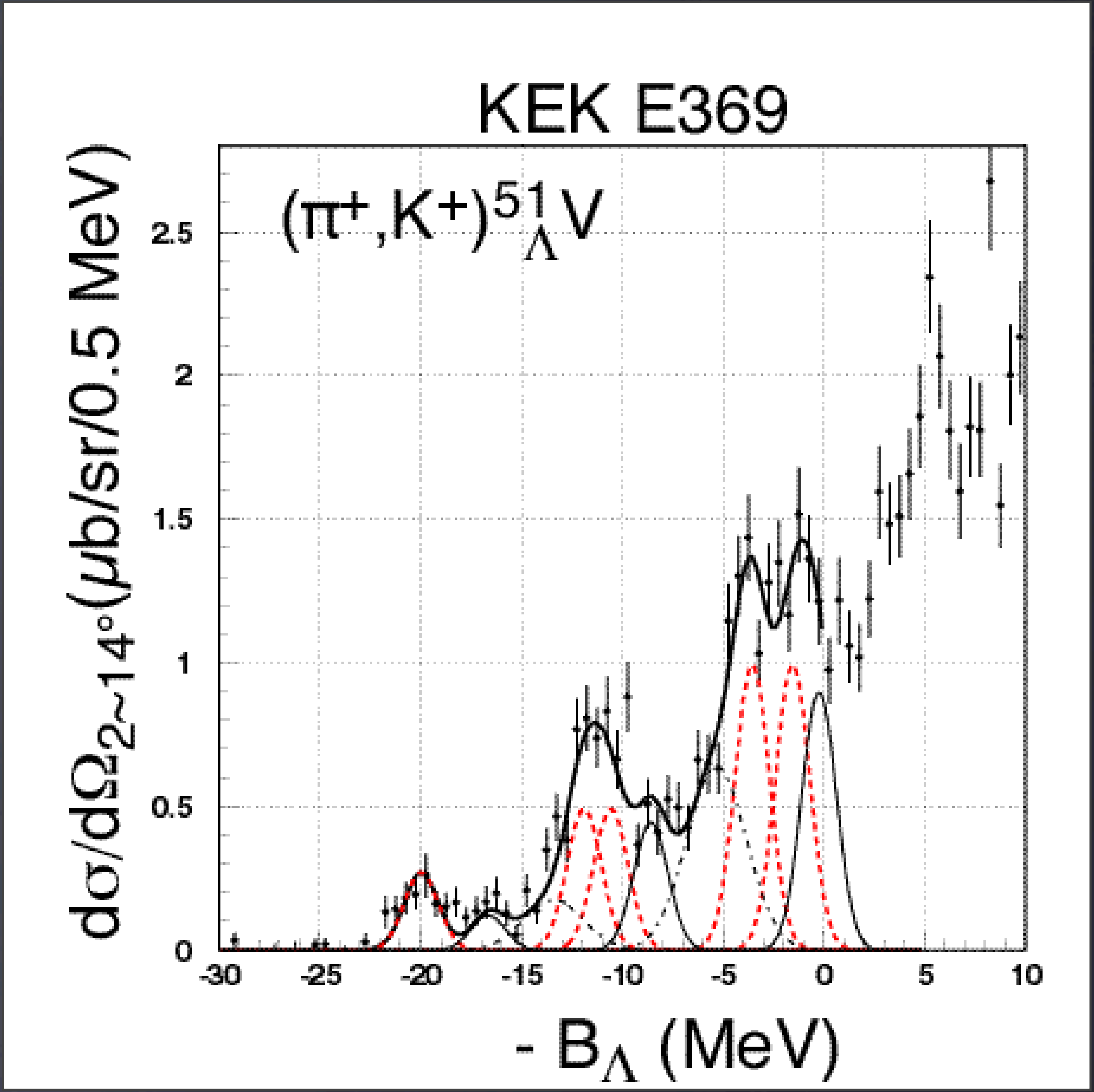
Width=1.95 MeV

Peak Ratio=1(fixed)

Extra n-holes

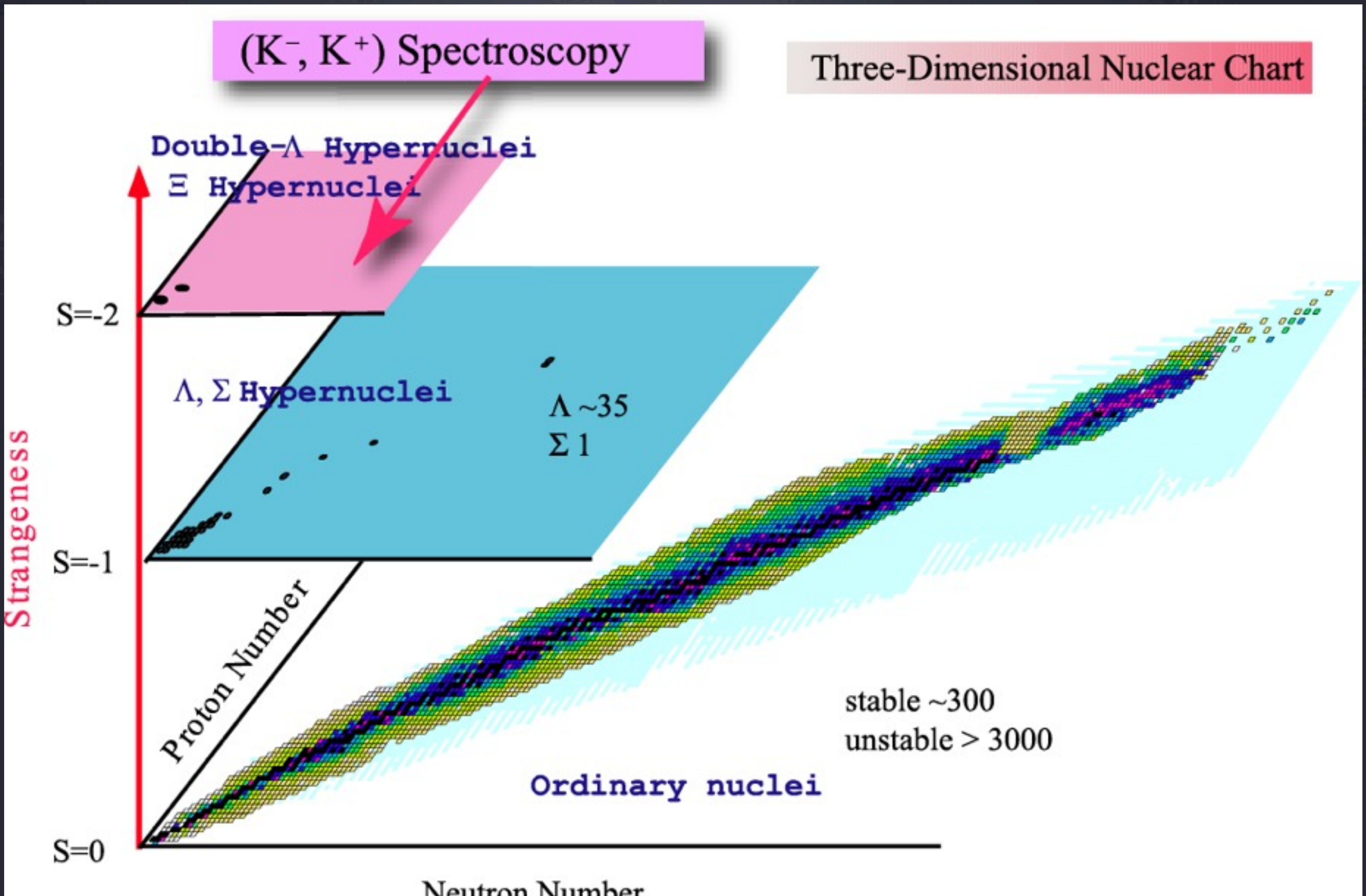
At +3.3±0.2 MeV, width=1.95 MeV

At +6.6±0.2 MeV, width=3.46 MeV



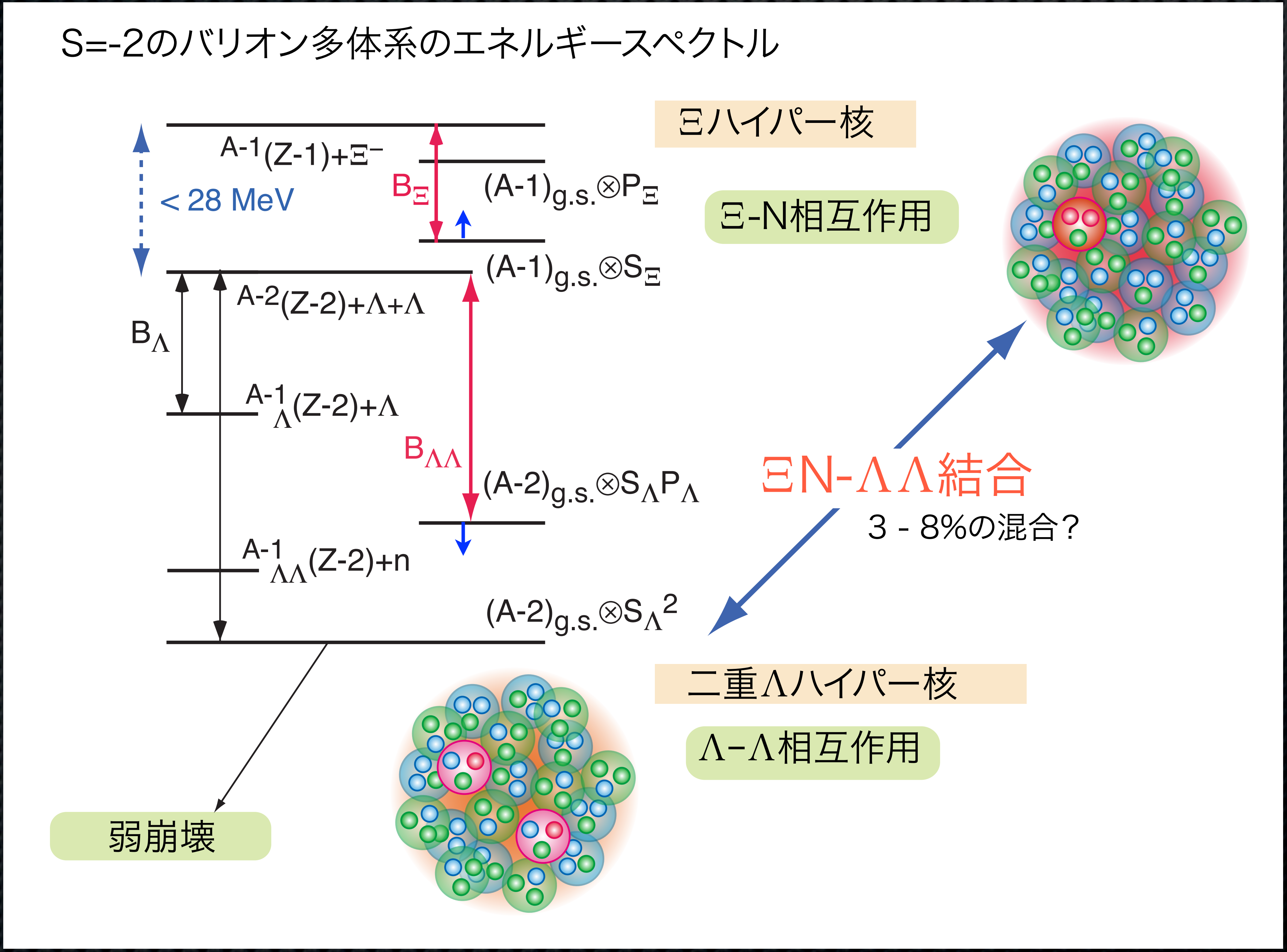
S=-2へ： (K^-,K^+)

Strangeness Nuclear Physics



S=-2多体系

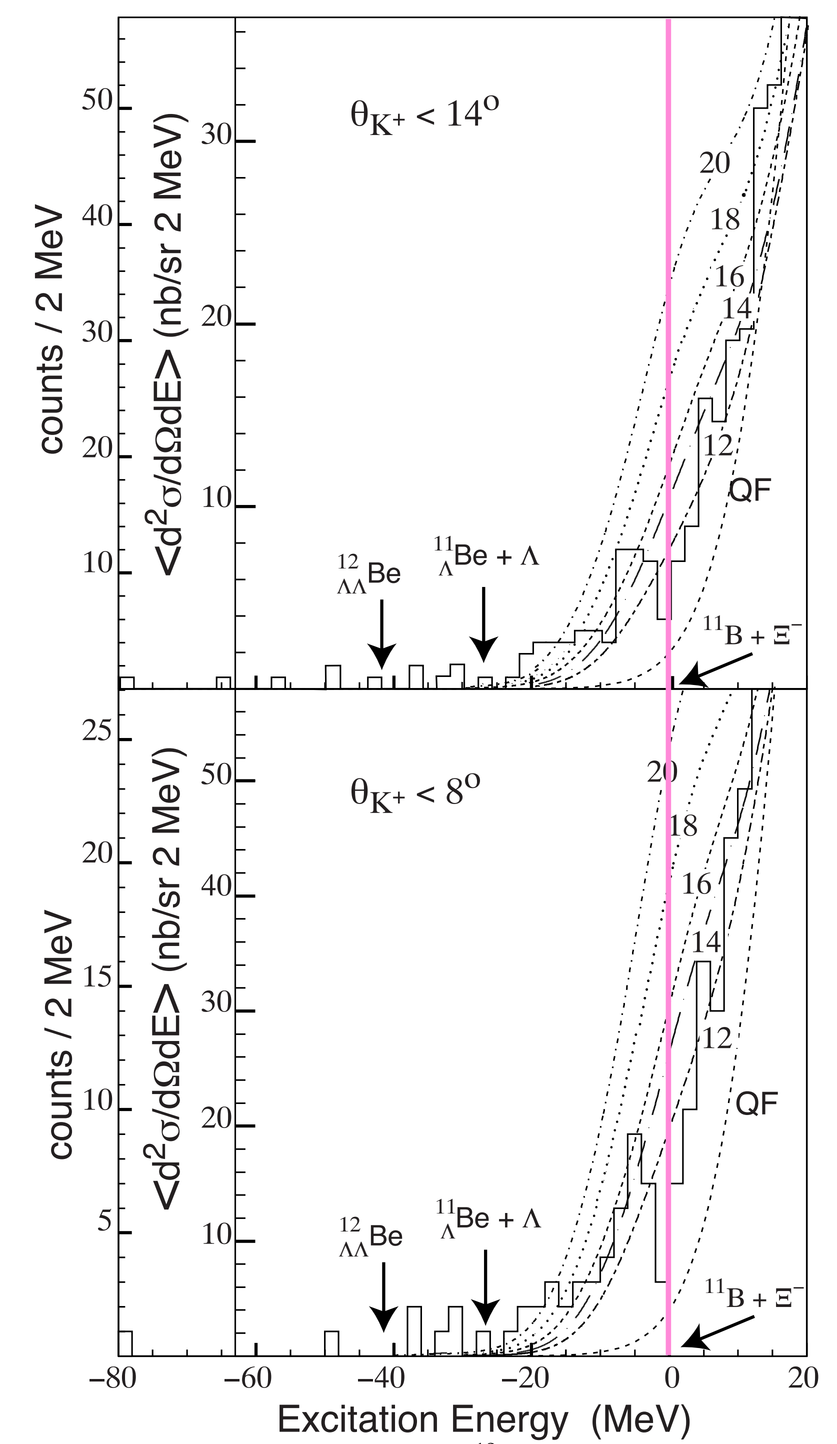
- バリオン混合の重要性



過去の実験データ

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

P. Khaustov et al., PRC61(2000) 054603.



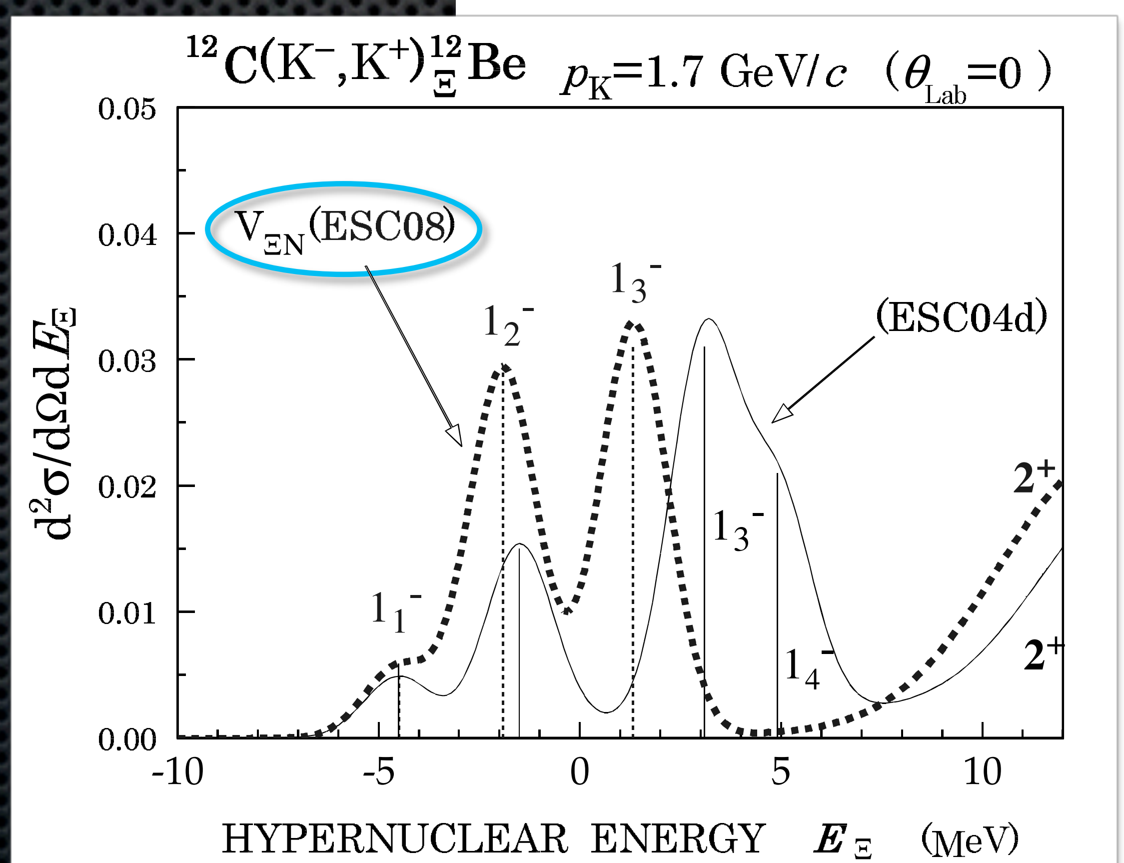
- BNL-E885
  - Evidence ?
  - U_Ξ=-14 MeV
  - 89±14 nb/sr
  - ΔE ~14 MeV(FWHM)
  - ΔΩ~19 msr

ΞN相互作用

- U_Ξ ~ -15 MeV

Table 3: $U_\Xi(\rho_0)$ and partial wave contributions.

model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ_Ξ
ESC08a	0	6.0	−1.0	−0.3	−2.6	1.3	−0.9		
	1	8.5	−28.0	0.6	0.4	−3.7	−0.6	−20.2	5.8
ESC08a’	0	5.6	−1.1	−0.3	−2.6	1.3	−0.9		
	1	8.4	−21.5	0.6	0.4	−3.7	−0.6	−14.5	7.0
ESC08b	0	2.4	1.9	−0.6	−1.2	−0.1	−0.7		
	1	9.1	−37.8	0.6	−0.5	−3.6	−1.3	−31.8	0.9
ESC04d	0	6.4	−19.6	1.1	1.2	−1.3	−2.0		
	1	6.4	−5.0	−1.0	−0.6	−1.4	−2.8	−18.7	11.3

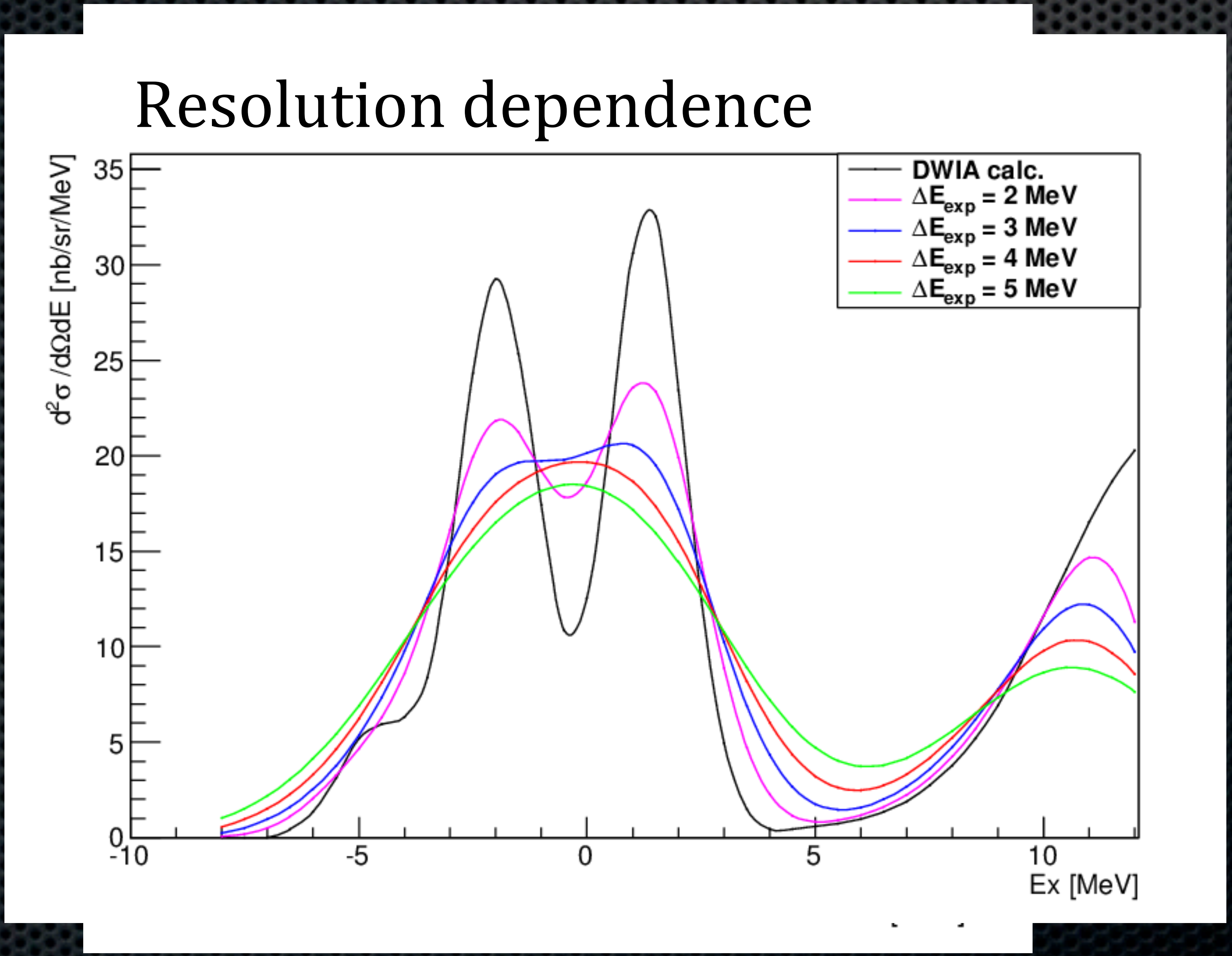


T = 1

DWIA spectrum from
T. Motoba and S. Sugimoto, NP A 835 (2010) 223.

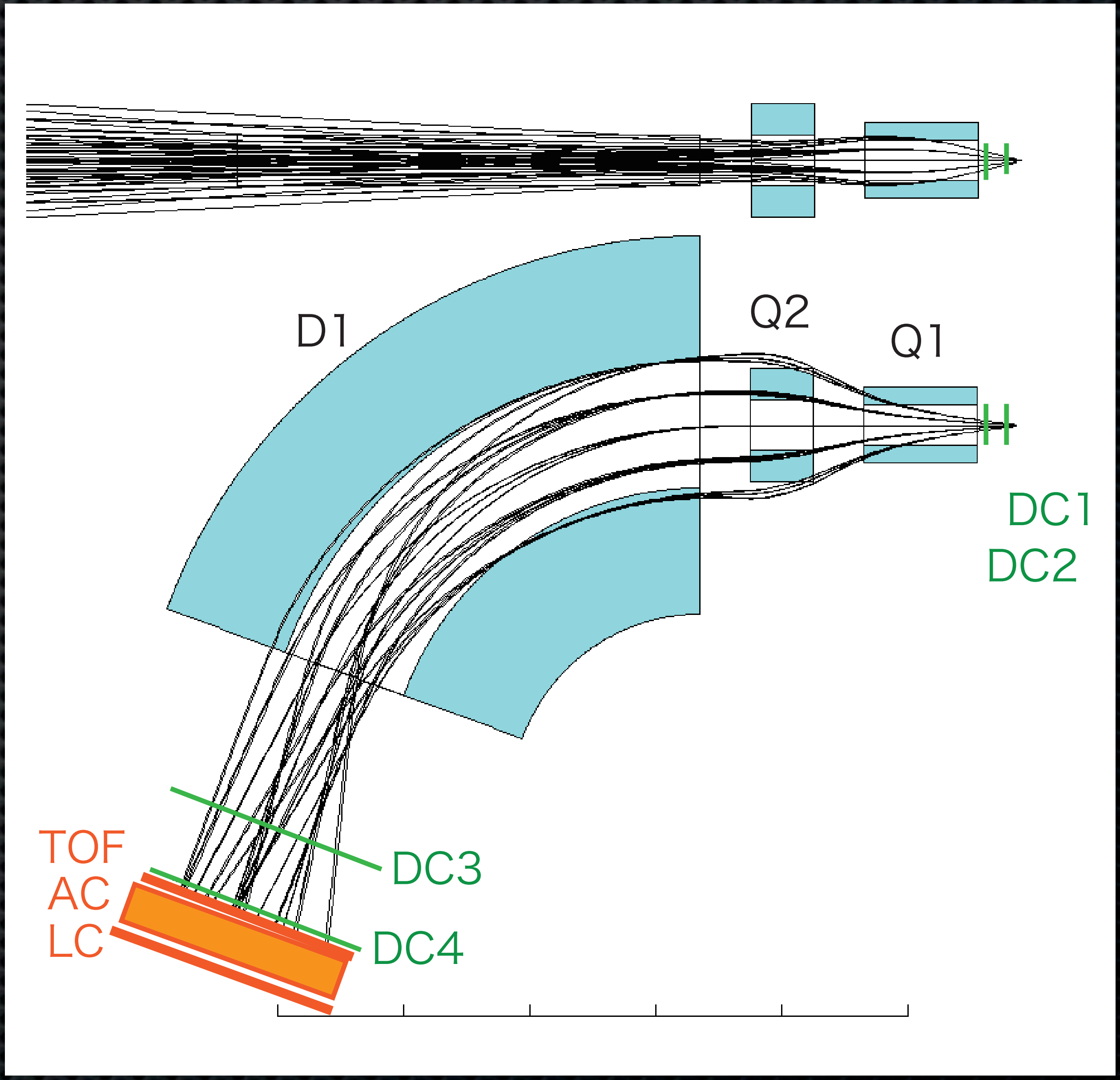
必要な分解能

- 2 MeV(FWHM)が必要



新しいスペクトロメーター

- S-2Sの建設(H23-H26): 特別推進
  - QQD構成
  - 立体角~60 msr
  - 運動量領域：±10%
  - $\Delta p/p<5\times10^{-4}$(FWHM)
  - ΔE=1.2 MeV



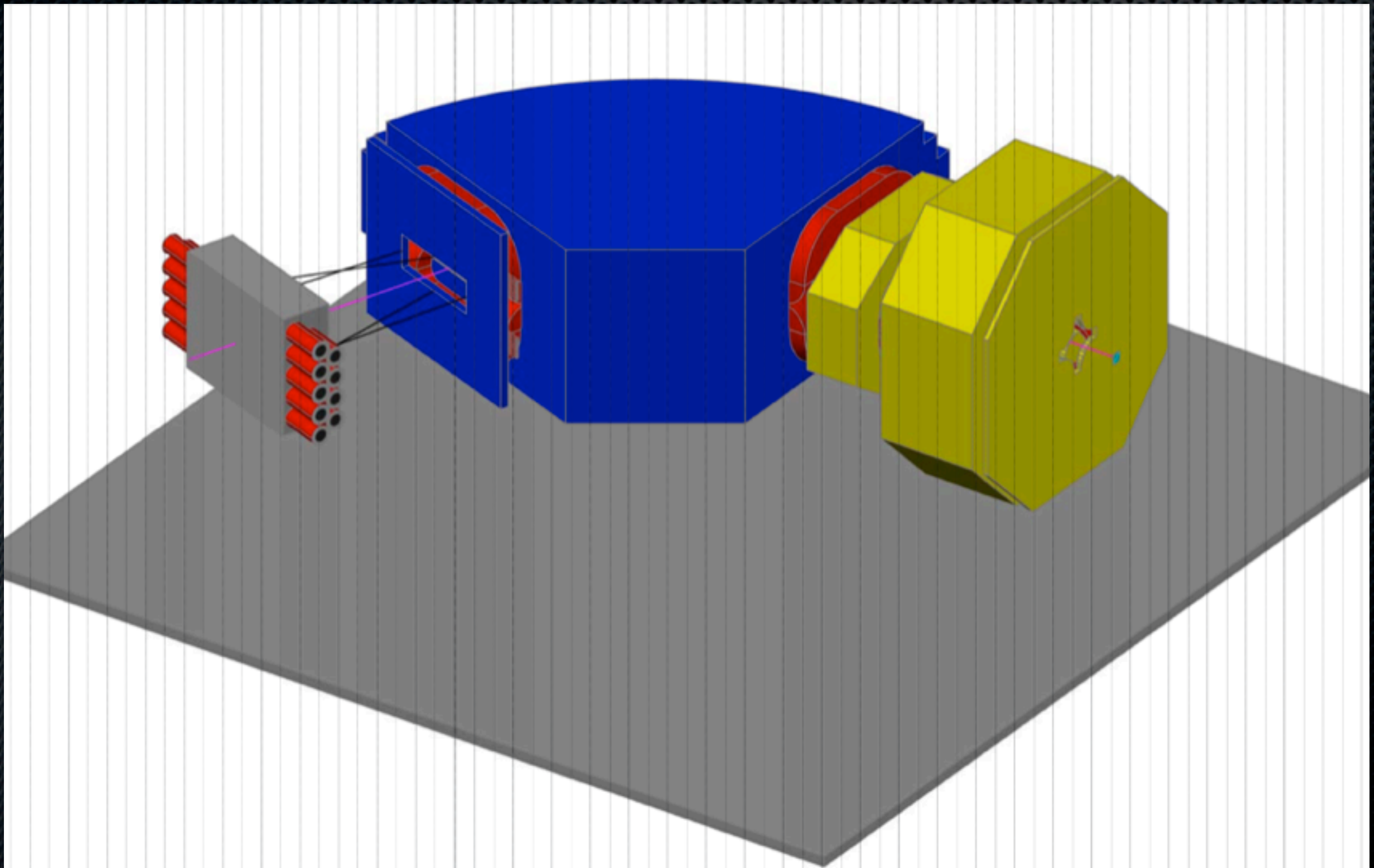
	立体角 ΔΩ (msr)	エネルギー分解能 ΔE (MeV)
BNL	19	14
SKS+	25	3
S-2S	60	1.2

S-2S

加藤、高橋仁、高橋俊、藤岡、広瀬

$\Delta p/p = 5 \times 10^{-4}$

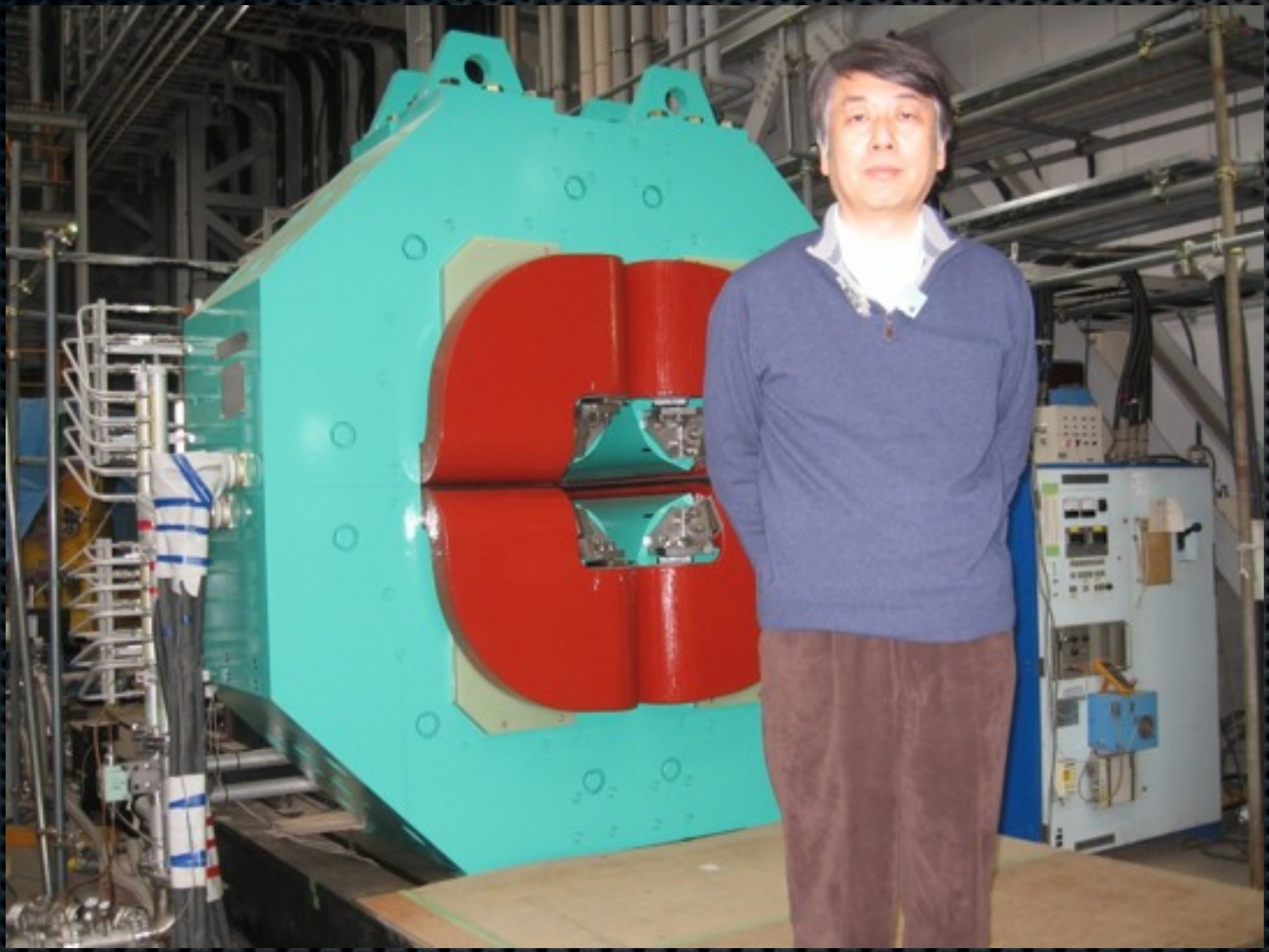
60msr



Q1 of S-2S

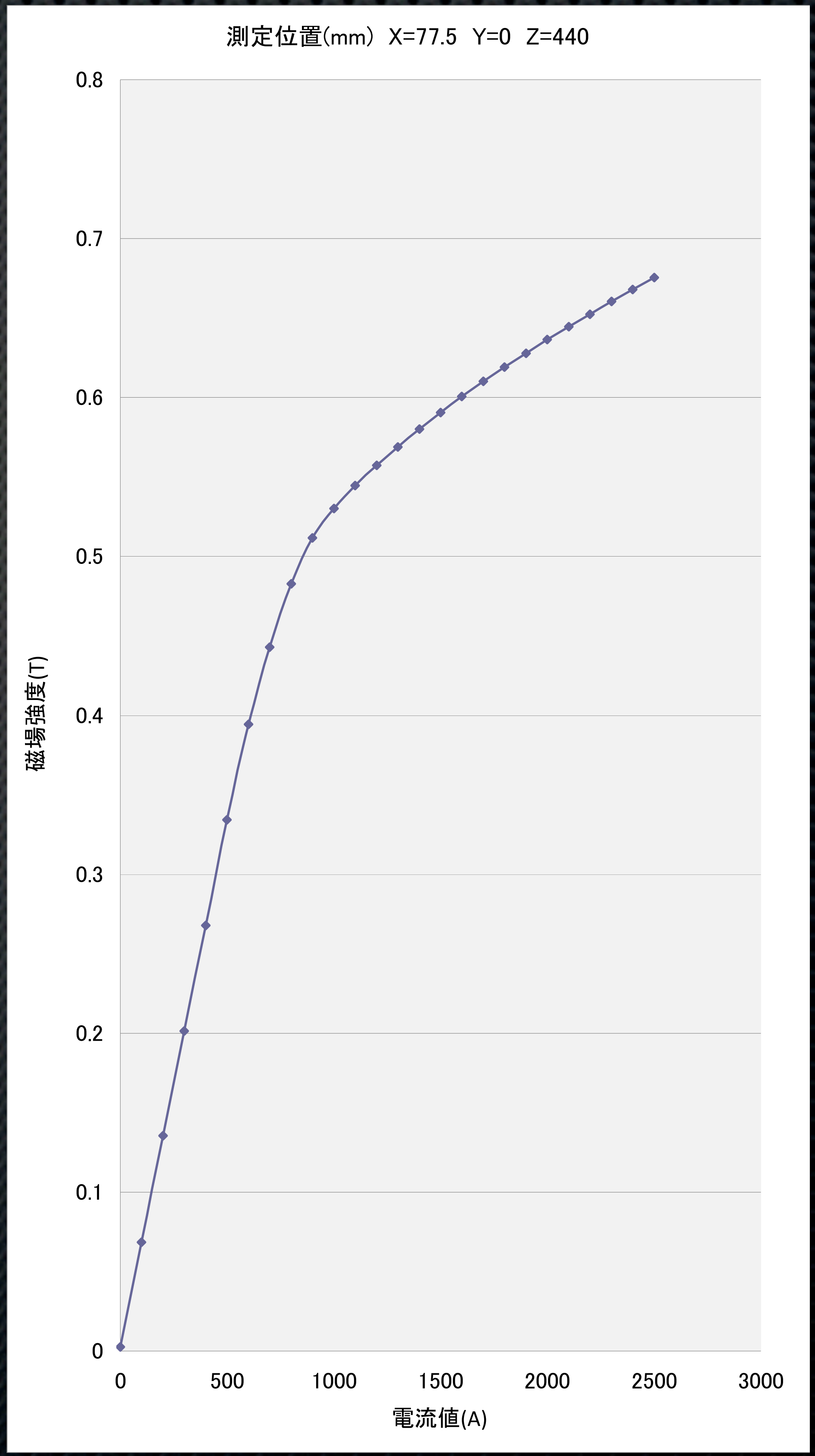
Feb. 15, 2013

Q1励磁テスト



KEK 北カウンターホール於

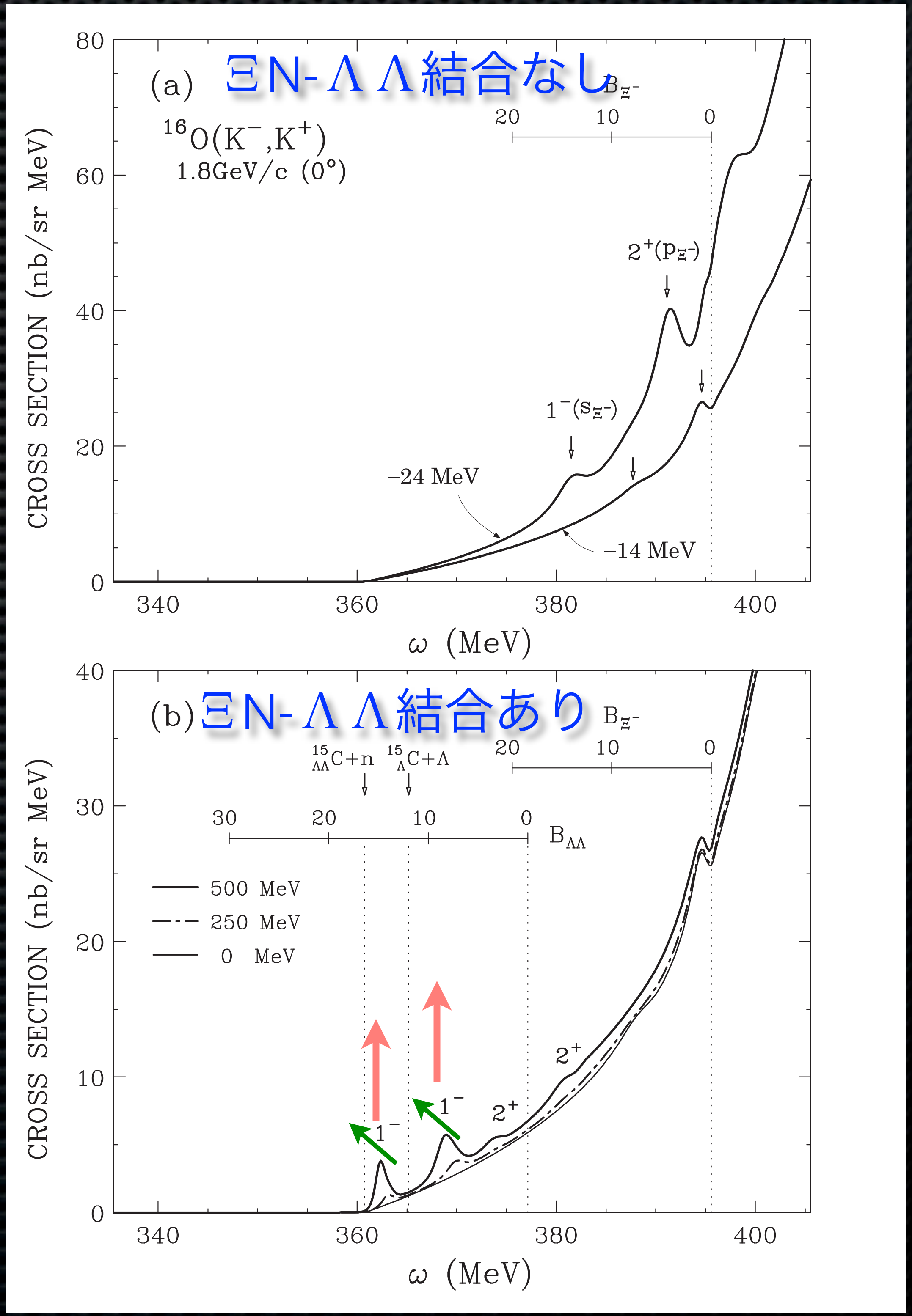
励磁特性



期待される成果 H26-H27

- 二重Λハイパー核とΞハイパー核の励起
  - ΞN-ΛΛ結合が重要な役割
    - 強く励起 ↑
    - 深く束縛 ↖
  - $[^{15}N(1/2^-,3/2^-)\otimes s_\Xi]_{1^-} \rightarrow [^{14}C(0^+,2^+)\otimes s_\Lambda\, p_\Lambda]_{1^-}$
    $[^{15}N(1/2^-,3/2^-)\otimes p_\Xi]_{2^+} \rightarrow [^{14}C(0^+,2^+)\otimes p_\Lambda{}^2]_{2^+}$
- ピークエネルギーの高精度測定(<100 keV)
  - ΞN-ΛΛ結合によるエネルギーのシフト ～1.17 MeV
- s_Λ - p_Λ間相互作用：→初めての測定

原田らの計算例 PLB690 (2010) 363. $^{16}O(K^-,K^+)$

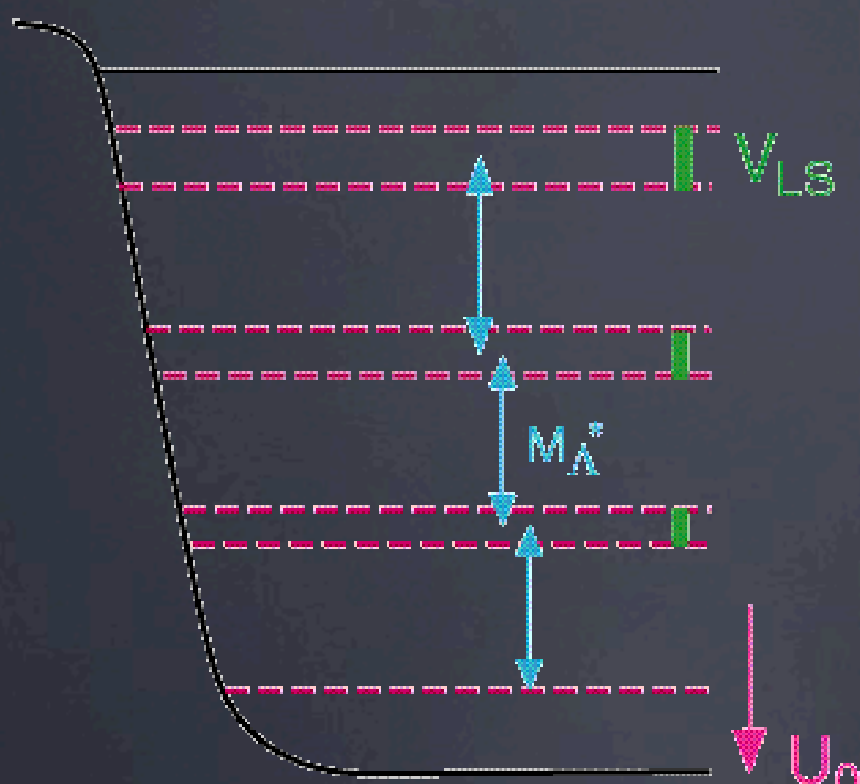


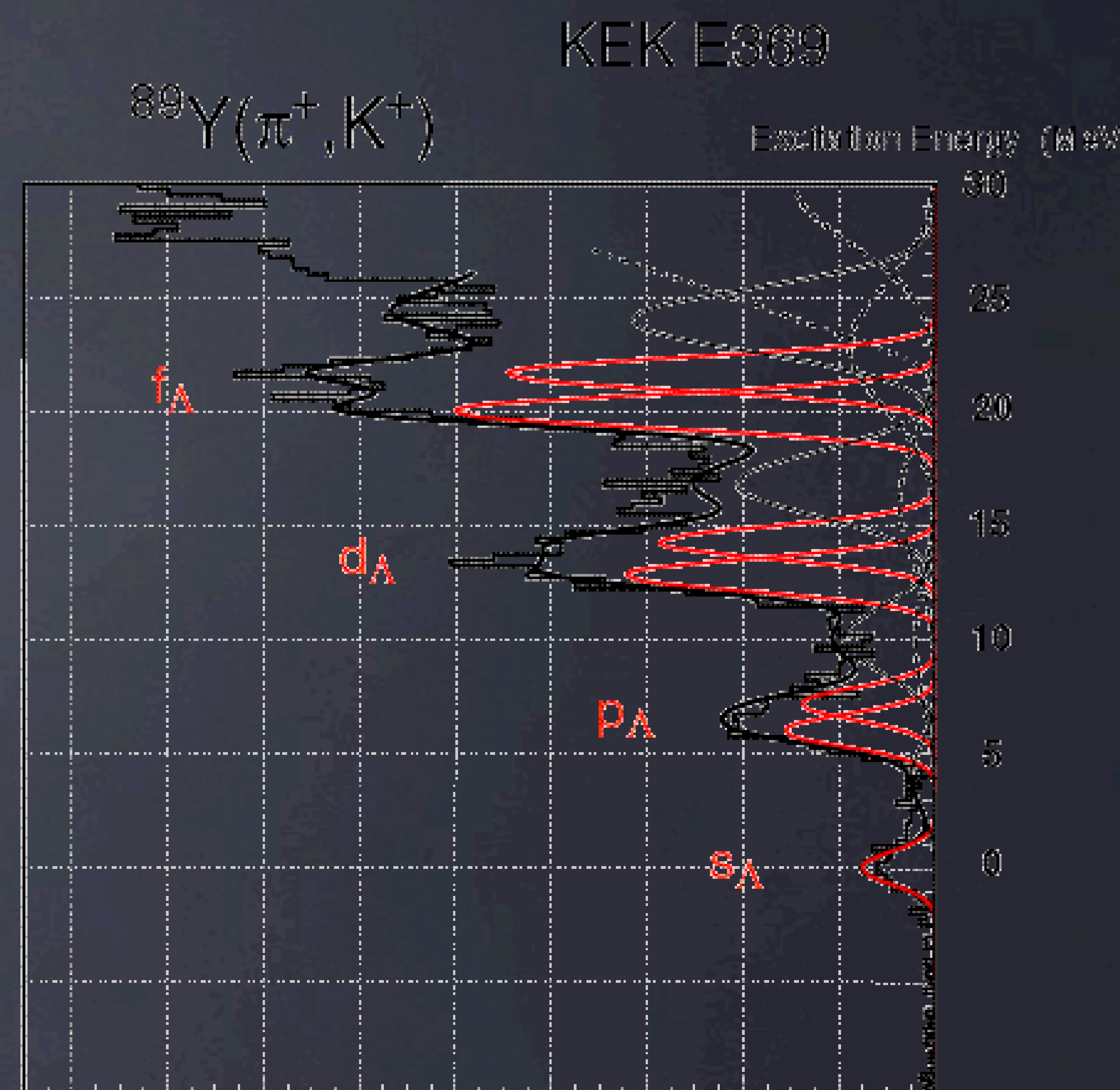
まとめ

- **SKS**スペクトロメーター
  - **15**年間にわたって世界をリード。多くの若手研究者を輩出。
- **(π,K)**スペクトロスコピー
  - 広い質量領域でのラムダー粒子軌道の観測
  - コア励起状態、**Genuine**ハイパー核状態等の観測
  - 元場さんを始めとする理論の助けのおかげ
- **S=-1**から**S=-2**へ
  - **(**K^-**,** K^+**)**スペクトロスコピーのための**S-2S**の建設
  - Ξハイパー核の探索。ΞN－ΛΛ結合。

Single-particle motion of Λ in heavy hypernuclei

- **U_0=-30.5 MeV**
- **M_Λ^*=0.7~0.8xM_Λ**





Effective mass of Λ:

Y.Yamamoto

LDA treatment for Λ hypernuclei

$$
\begin{aligned}
\frac{M^*_\Lambda}{M_\Lambda} &= \left(\frac{\tilde{M}_\Lambda}{M_\Lambda}\right) \times \left(\frac{\bar{M}_\Lambda}{M_\Lambda}\right) \\
\frac{\tilde{M}_\Lambda}{M_\Lambda} &= \left[1 + 2M_\Lambda \frac{\partial U_\Lambda}{\partial p_\Lambda^2}\right]^{-1} \\
\frac{\bar{M}_\Lambda}{M_\Lambda} &= 1 - \frac{\partial U_\Lambda}{\partial \epsilon_\Lambda}
\end{aligned}
$$

$$
\begin{aligned}
\epsilon_\Lambda(\rho) &= \frac{p_\Lambda^2}{2M_\Lambda} + U_\Lambda(\rho, p_\Lambda, \epsilon_\Lambda) \approx \frac{p_\Lambda^2}{2M^*_\Lambda(\rho)} + U^0_\Lambda(\rho) \\
\epsilon^0_\Lambda(\rho) &= U^0_\Lambda(\rho) = U_\Lambda(\rho, p_\Lambda = 0, \epsilon^0_\Lambda)
\end{aligned}
$$

$$
\begin{aligned}
U_\Lambda(r) &= \alpha (t\sqrt{\pi})^{-3} \int d\mathbf{r}' U^0_\Lambda(\rho(r')) \exp(-|\mathbf{r} - \mathbf{r}'|^2/t^2) \rho(r') \\
M^*_\Lambda(r) &= \beta M^*_\Lambda(\rho(r)) + (1 - \beta) M_\Lambda
\end{aligned}
$$

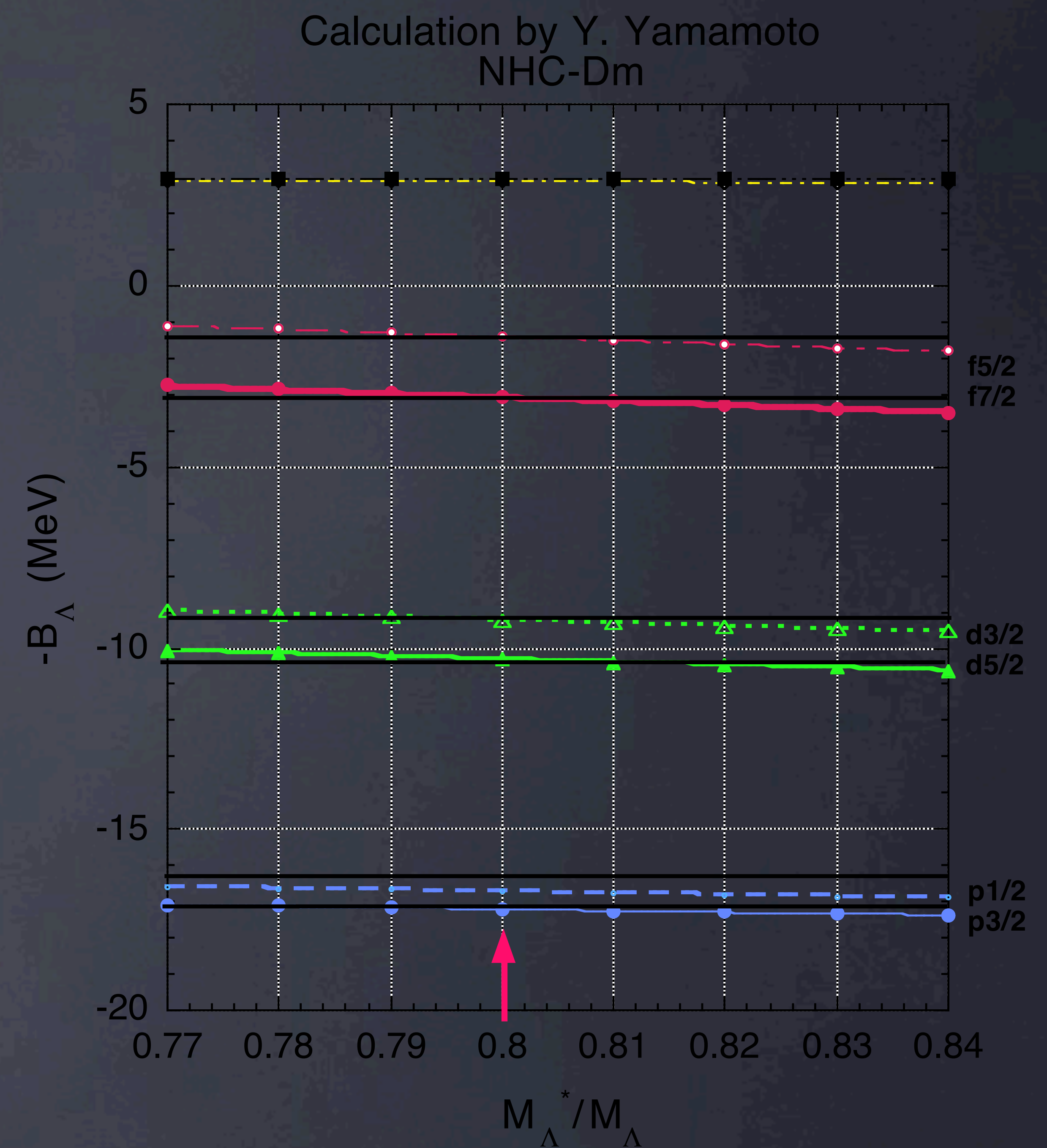
α and β are additional parameters for fitting)

$U^{ls}_B(r) = K_B \frac{1}{r} \frac{d\rho}{dr} \vec{l}\vec{\sigma}$ with $B = N, \Lambda$

where $K_N = -\frac{1}{2}\pi S_{LS}$ and $K_\Lambda = -\frac{1}{3}\pi(S_{LS} + S_{ALS})$

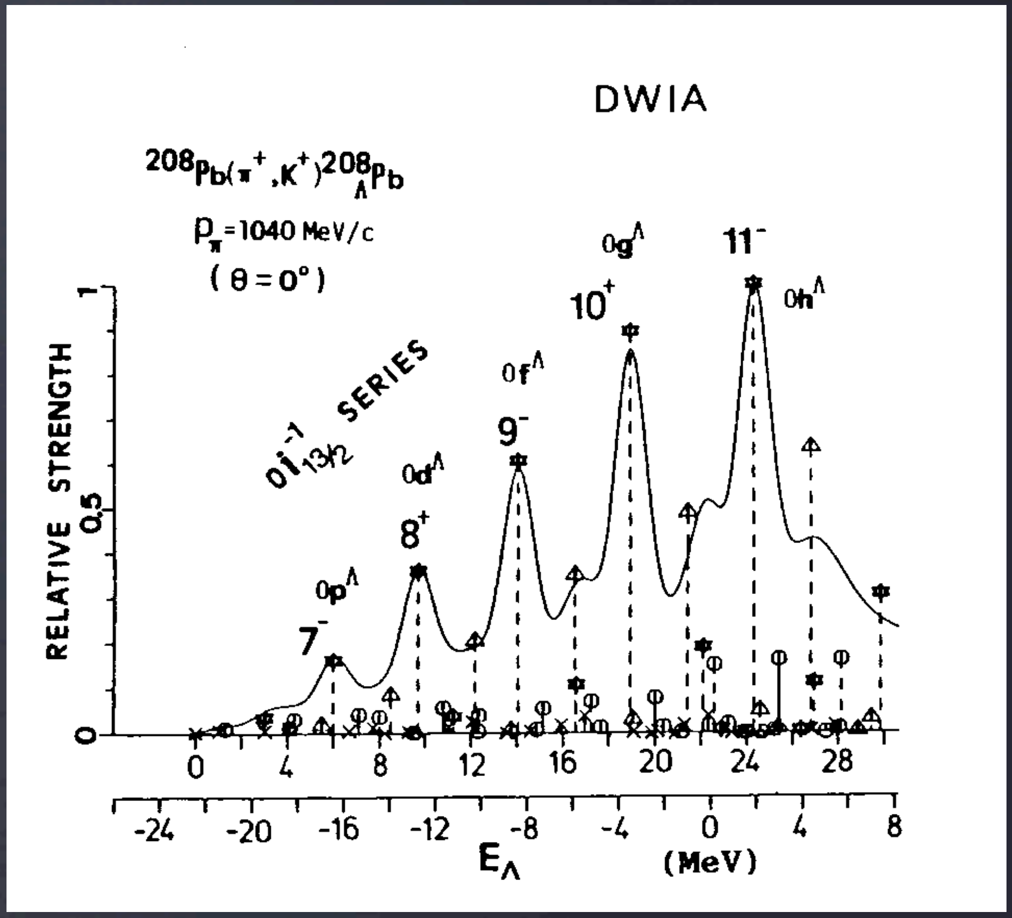
$S_{LS,ALS} = \frac{3}{\bar{q}} \int_0^\infty r^3 j_1(\bar{q}r)\, G^{3O}_{LS,ALS}(r)\, dr$

with $\bar{q} \sim 0.7\ \mathrm{fm}^{-1}$



Neutron-hole contributions

- Similar spectrum shape shifted by hole energy difference
- Strengths are roughly proportional to the spectroscopic factors
- Shape in each orbit should be the same



Spectroscopic Factors of ^{89}Y

- $1g_{9/2}^{-1}$: ~10
- $1f_{5/2}^{-1}$: ~3
  Ex=1.71 MeV
- **Others:**
  small/broad backgrounds

TABLE I. Spectroscopic factors obtained for $^{90}Zr(p,d)^{89}Zr$.

nlj	E_x (MeV)	C^2S	Simple shell model prediction	Average excitation energy E_j (MeV)
$1g_{9/2}$	0.	9.6		0.18
	2.75	0.29		
	9.03	0.11		
		10.00[a]	10	
$2p_{1/2}$	0.60	1.2		1.23
	8.10	0.11		
		1.31	2	
$2p_{3/2}$	1.09	2.1		1.95
	1.87	0.53		
	9.62	0.24		
		2.87	4	
$1f_{5/2}$	1.46	3.5[b]		3.27[c]
	2.10	0.66		
	3.0	0.46		
	3.4–7.0	1.7		
	9.86	0.64		
		6.96	6	
$1f_{7/2}$	4.1	0.82		10.3[c]
	5.2	0.35		
	7.0–11.6	2.8		
	11.6–16.0	2.1		
	16.0–21.0	0.43		
		6.50	8	
$1d_{3/2}$	16.0–21.0	1.2		

[a] $1g_{9/2}$ strength normalized to 10.0.
[b] Contains a small contribution (< 20%) from the 1.51 MeV ($\frac{9}{2}^+$) state.
[c] The spectroscopic strength was assumed always to be at the center of the broad regions.

Spectroscopic Factors of ^{51}V

- $1f_{7/2}^{-1}$: ~5
  <Ex>=0.56 MeV
- $2s_{1/2}^{-1}$: ~1.2
  Ex=~2.8 MeV
- $1d_{3/2}^{-1}$: ~0.9
  Ex=~3.2 MeV

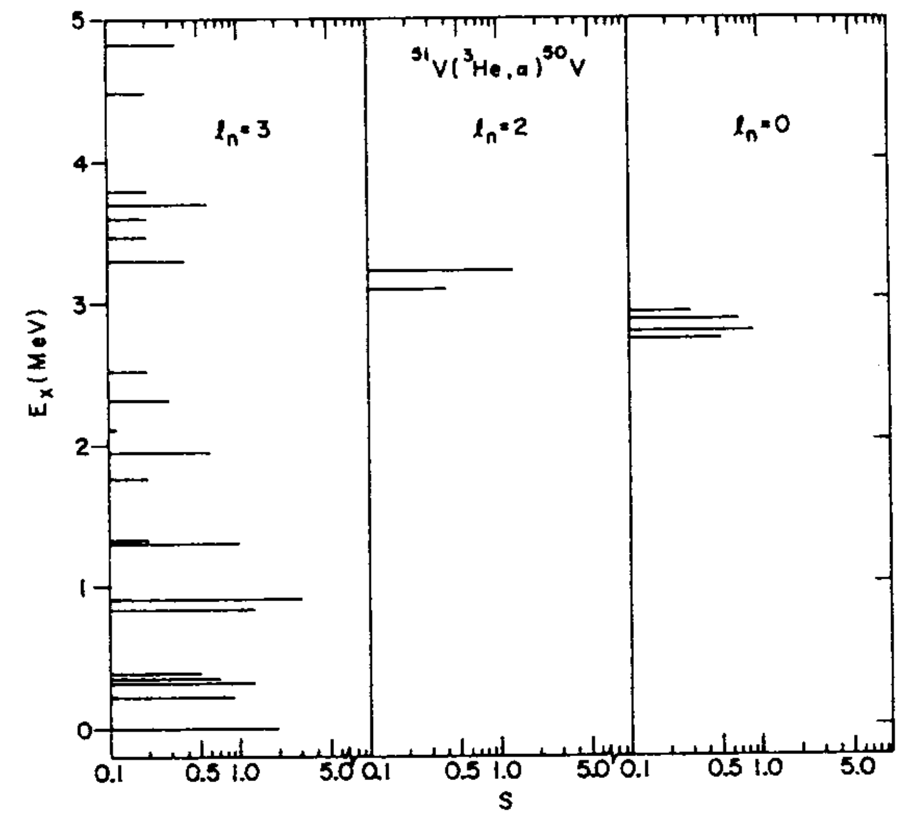
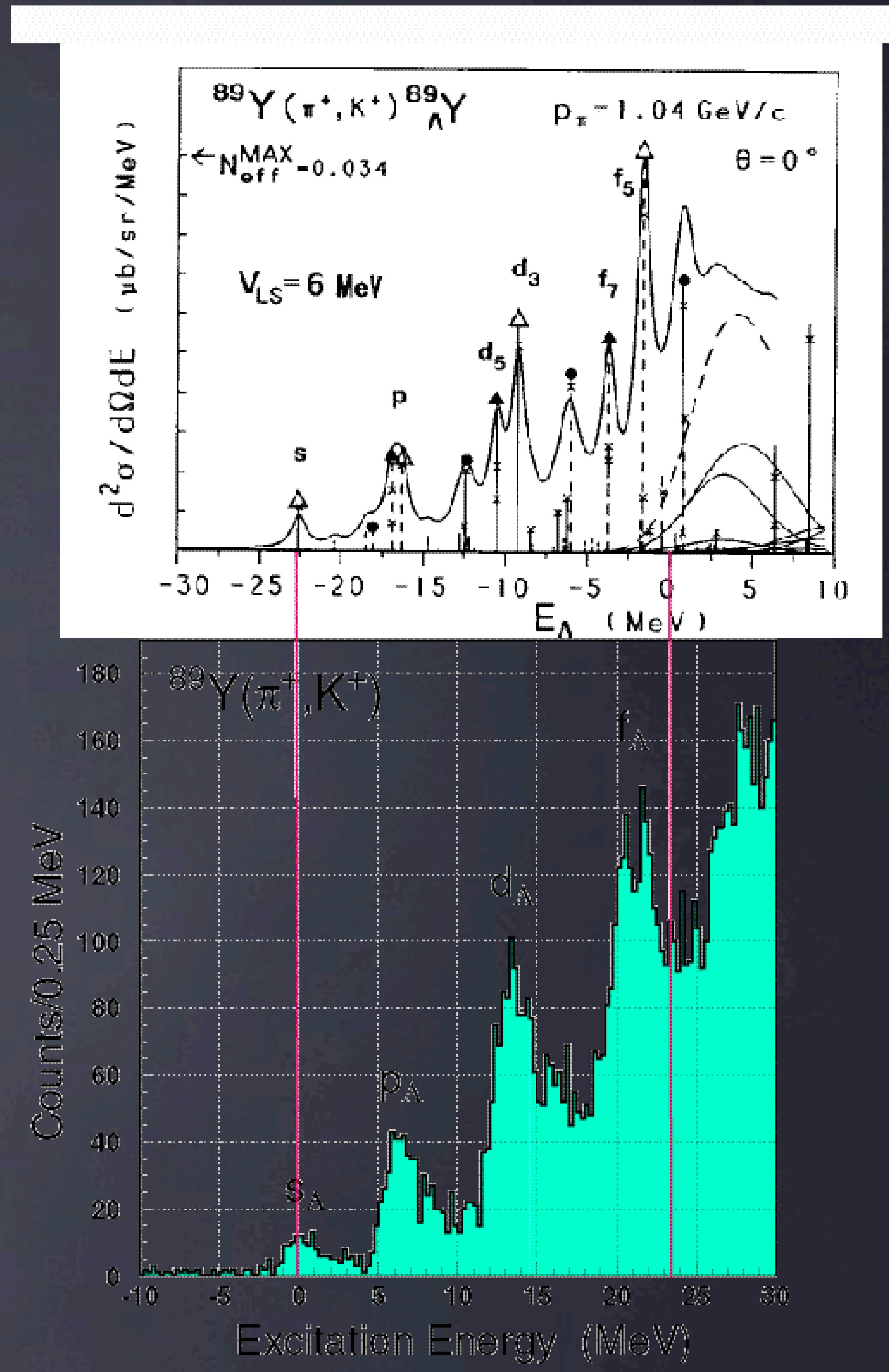


FIG. 13. The spectroscopic factors obtained from a DWBA analysis of the data on the ^{51}V(^{3}He,α)^{50}V reaction. Results for l_n = 3, 2, and 0 are indicated by the length of the bar at the appropriate excitation energy.

Comparison with a calculation



- Overall peak structure: in good agreement, except peak intensity ratios.

Spin-Orbit Splitting in Nuclei

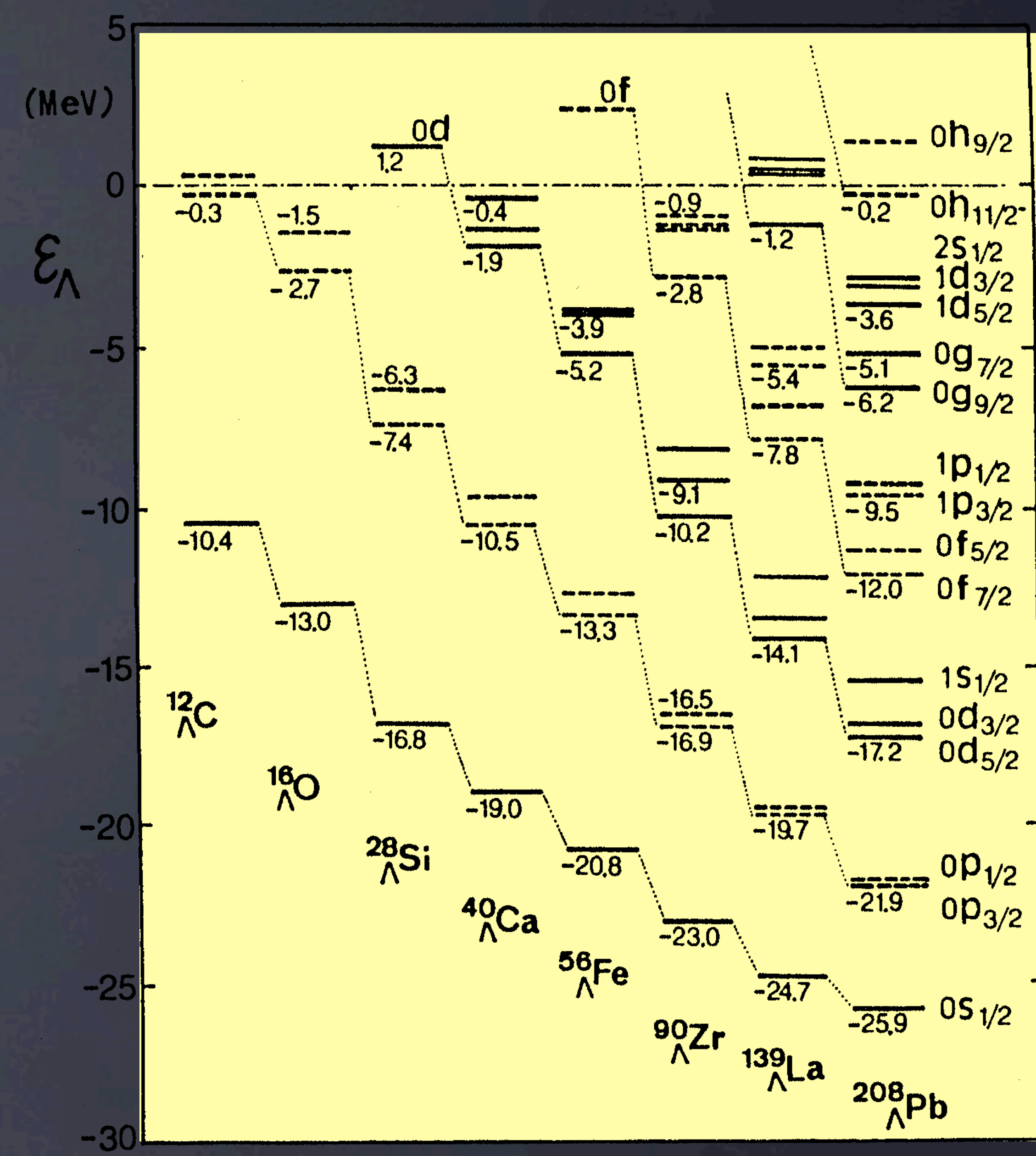
	Normal nuclei	Λ-hypernuclei
G-matrix **Bruckner S.O. splitting**	~40%	very small
Pauli rearrangement	**~15%**	**X**
Three-Body Force	**~20%**	**X(?)**
Other	**~25%**	

Y.Yamamoto

K.Anodo and H.Bando, PTP 66 (1981) 227.

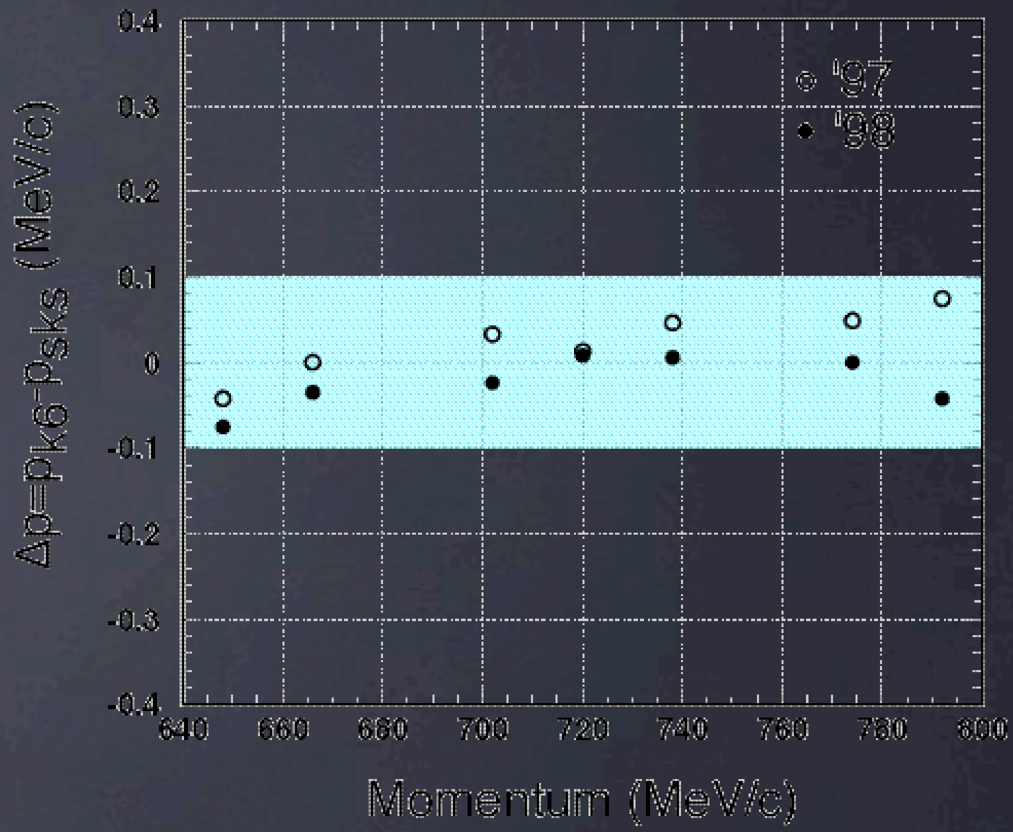
Advantage in heavy hypernuclei

- Λ-orbits with large angular momenta are bound.
  Large LS splittings
  $\Delta E \propto V_{LS}(l+1/2)A^{-2/3}$
- Two split peaks are comparably excited in the (π^+,K^+) reaction.



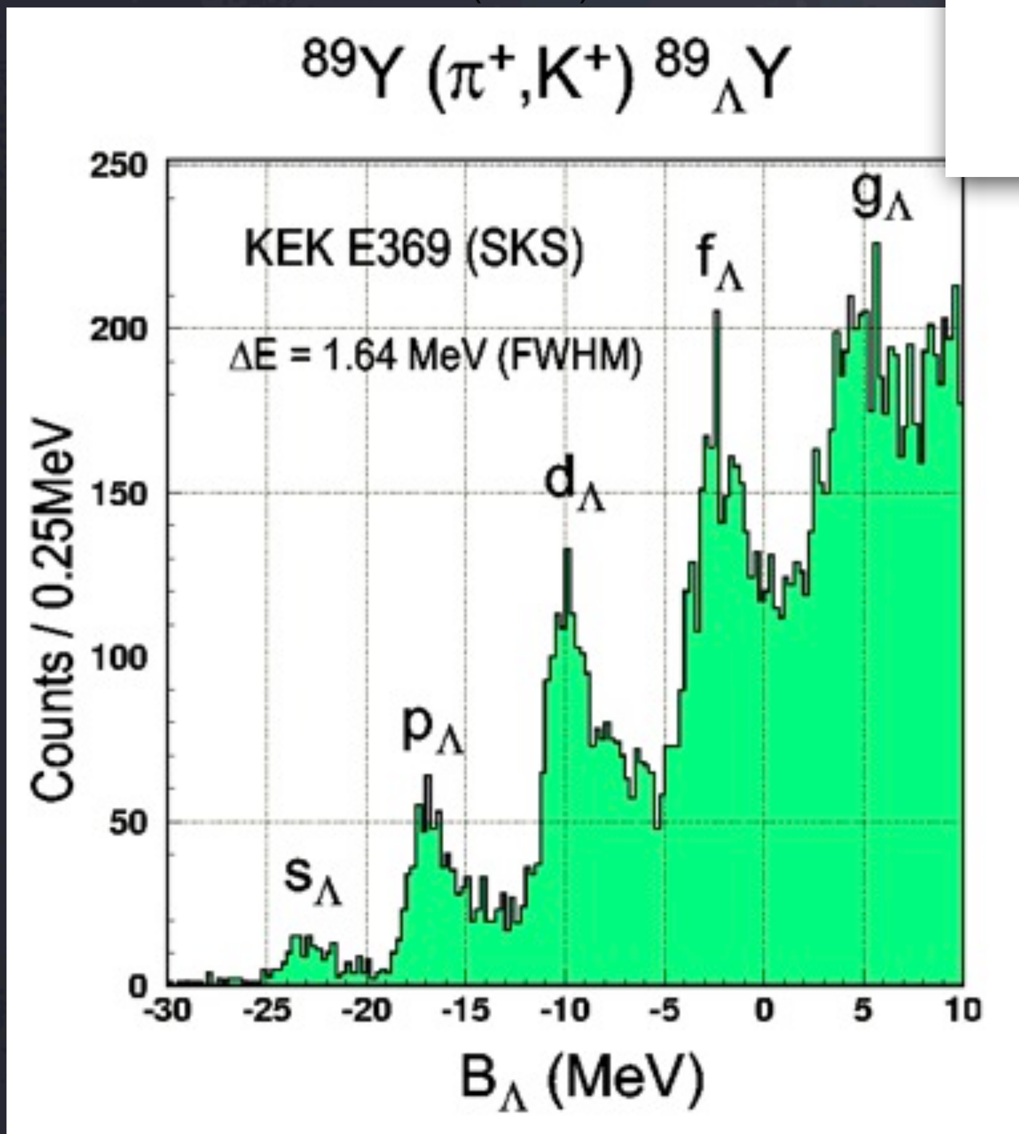
Energy Scale: linearity and offset

- **Beam-through Runs: 720 MeV/c±10%**
  - **No target, SKS at 2.2 T**
  - < ±0.1 MeV/c
- **Energy offset**
  - B($^{12}{}_{\Lambda}C_{g.s.}$)=10.75±0.19 MeV
    , in emulsion
  - **Long-term fluctuation**
    < 0.2 MeV
- **Total systematic error**
  < ~±0.2±0.19 MeV



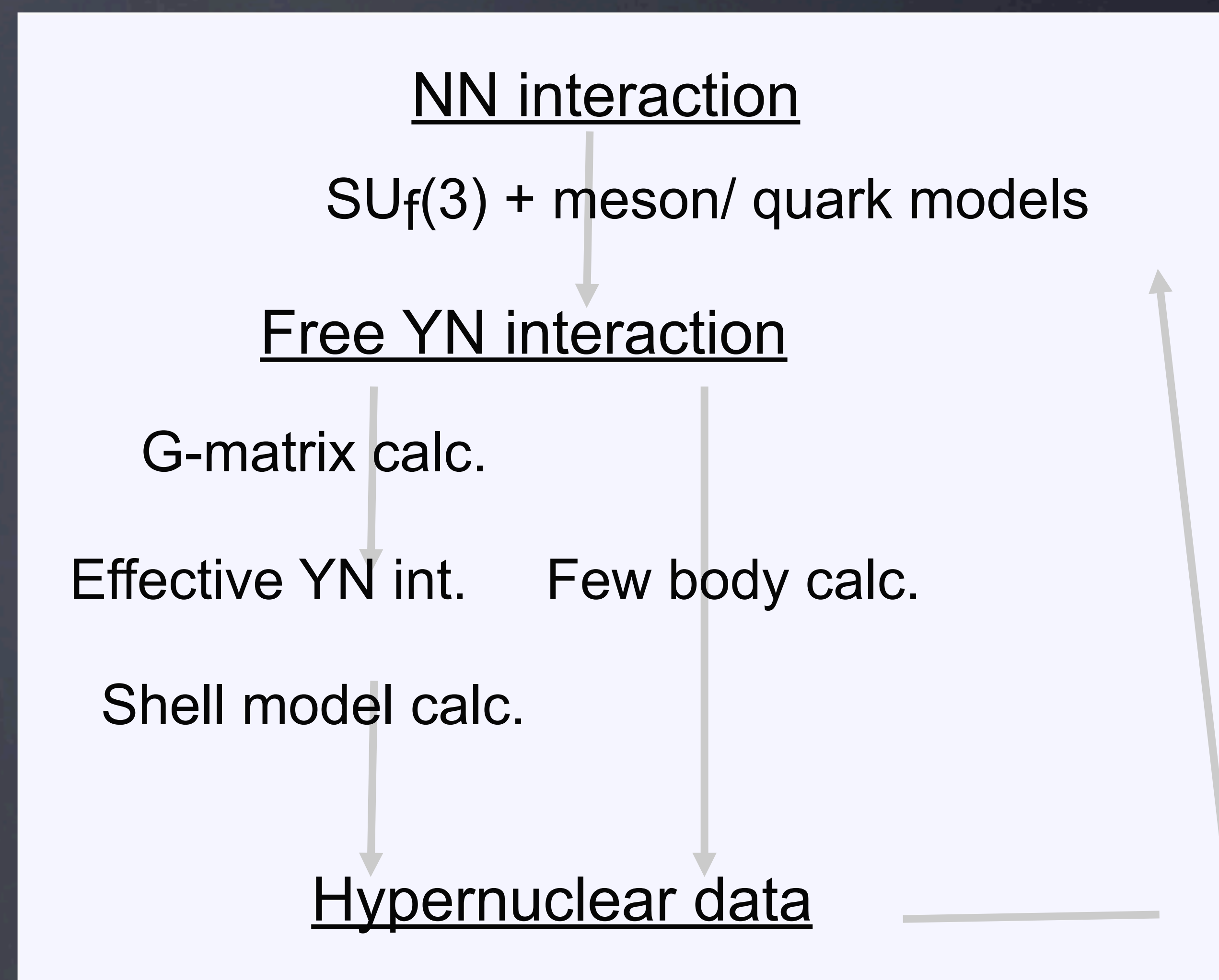
YN forces from hypernuclear structure

Hotchi et al., PRC 64 (2001) 044302



LN spin-spin, spin-orbit, tensor forces ?
LN <-> SN coupling force?

=> precise data necessary



L Single particle states

-> potential depth

U_L = -30 MeV

$V_{LN} < V_{NN}$

forbidden