A01 公募研究
三原子のX線測定による三粒子と原子核間のポテンシャルの研究

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12 Sep 2013

観測と実験で解き明かす中性子星の核物質
公募研究交流会＠仙台

中性子星とストレンジネス

- ナイーブに考える → Fermi gas model（相互作用off）
  - 中性子物質のフェルミ運動量 $p_F \sim 330(\rho/\rho_0)^{1/3}$ MeV/c
  - フェルミエネルギー: $p_F^2/2m \sim 58\ (\rho/\rho_0)^{2/3}$ MeV
    → $\rho/\rho_0 \sim 5$くらいでハイペロン・中性子の質量差を超える

→（中心部では）ハイペロンが現れるのがむしろ自然

- 当然詳細は相互作用による
  → 領域Aの対象
  - S=−1（Λ、Σ）: 領域A02（田村、江角、岡田・・・）
  - S=−2（Ξ、ΛΛ、・・・）: 領域A01（高橋、家入、谷田・・・）

本研究では特にΞに注目

なぜΞ？

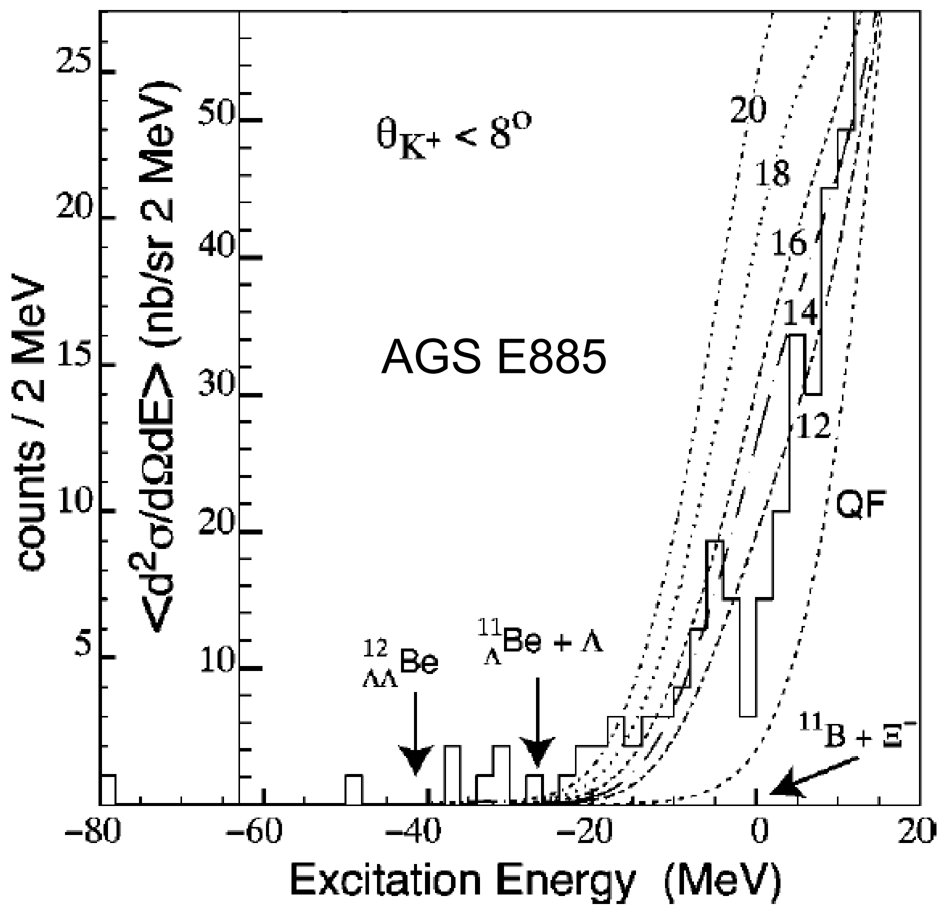
- 負電荷を持つ：電子（ミューオン）に置き換わる
- Λが存在する状況を考える。$\Lambda\Lambda \to \Xi^- p$は起こるか？
  - 質量は28 MeVほど損
  - フェルミエネルギーは得。例えば $\rho_\Lambda \sim \rho_0$、$\rho_\Xi = \rho_p \sim 0$とすると、40 MeVくらい得する。
  - クーロン力も（ちょっとだけ）お得。

  → 起こり得る（もちろん本当に起こるかは相互作用次第）
- 同様に負電荷を持つΣ^-と比べると、
  - ストレンジネスあたりの励起エネルギーは小さい。$\Sigma^-\Lambda \to \Xi^- n$は質量的に（50 MeVほど）得。
  - $\Sigma^- n$相互作用はかなり強い斥力

  → Σ^-よりもΞ^-の方が重要

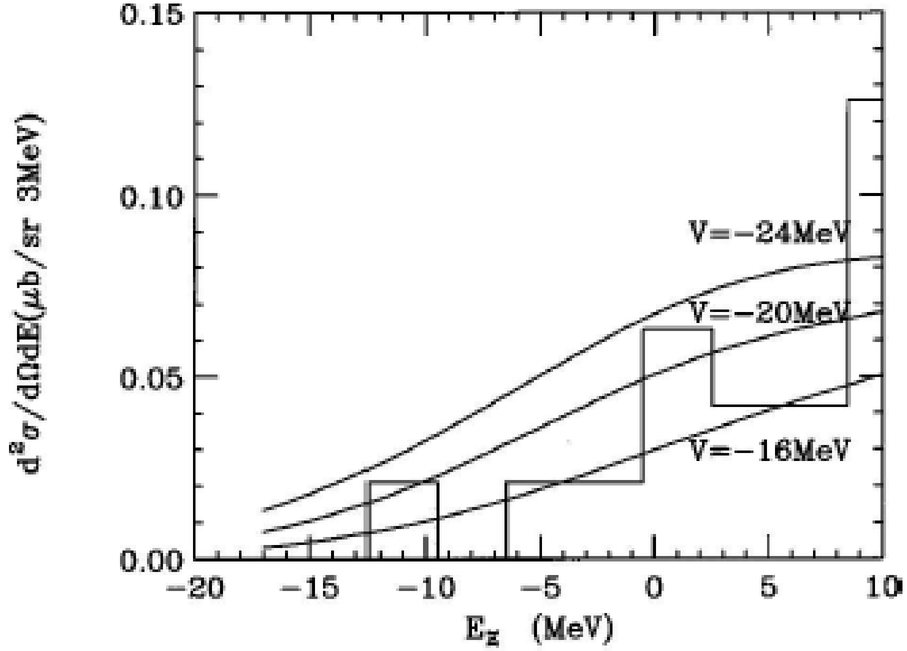
Experimental information

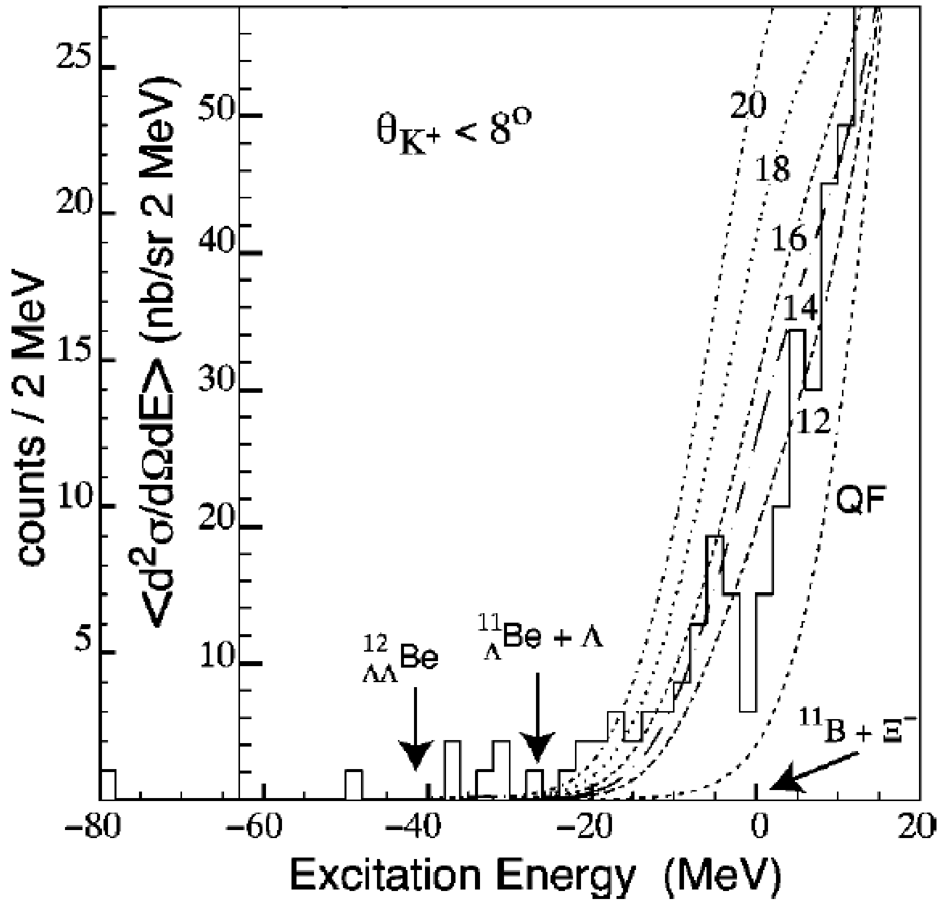
- Ξ nuclei in emulsion
  - V=24±4 MeV?? [C.B. Dover, A.Gal, Ann. Phys. 146 (1989) 309.]
  - Formation is not guaranteed experimentally, rather doubtful
- $^{12}C(K^-,K^+)$ reactions
  - Two experiments, KEK-PS E224 & BNL-AGS E885
  - Both shows significant events in the Ξ bound region, after considering the effect of poor experimental resolution



Naïve Interpretation

- Simple model
  - Rigid ^{11}B core + Ξ^- ← core excitation is ignored
  - Woods-Saxon potential with negligible width



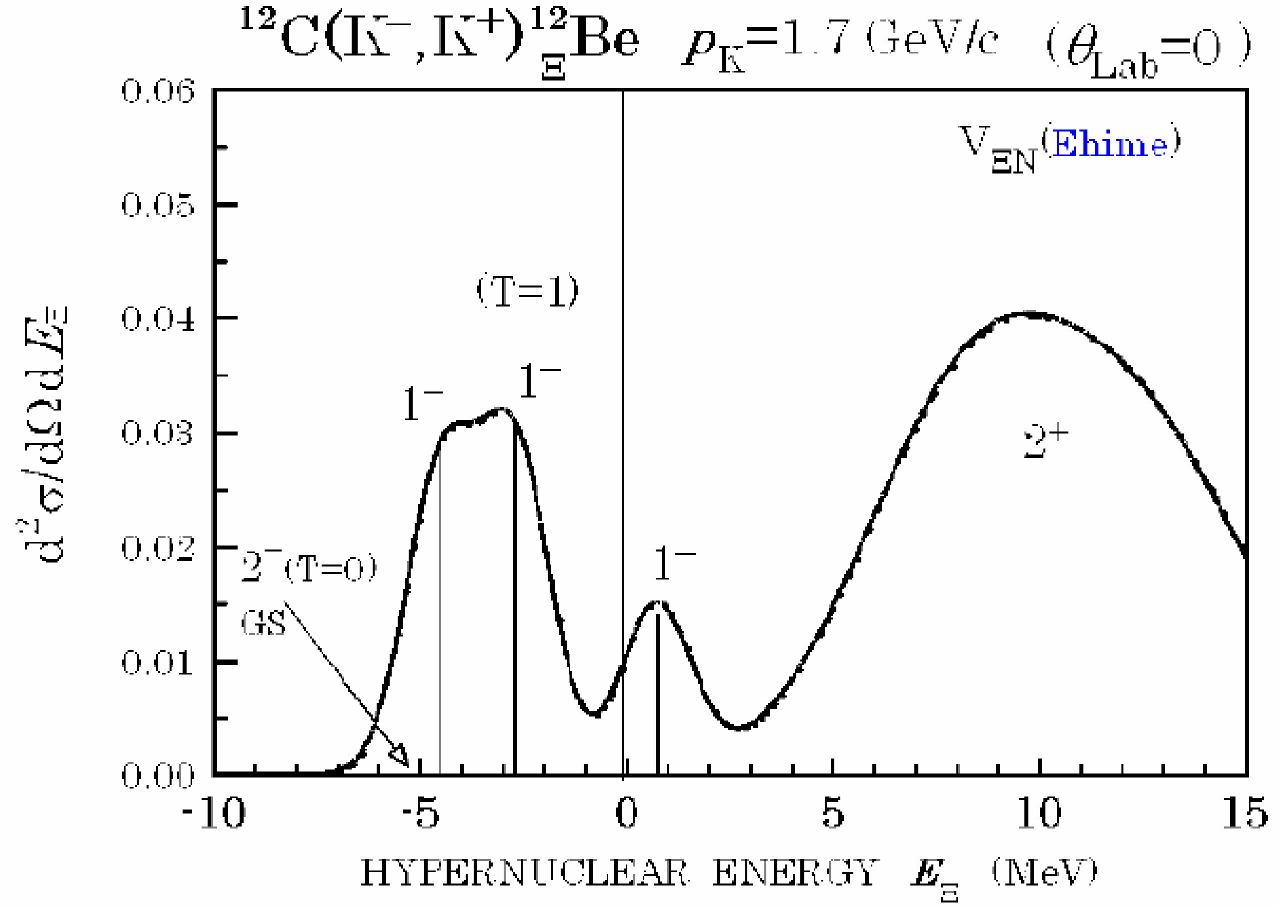


V=-14~-16 MeV??

Problems (1)

- Core excitation
  - Cross-sections of ground/excited states depend strongly on ΞN interaction detail

    → If excited states dominate, **underestimation** results.



Sugimoto & Motoba

Ehime potential (weak)

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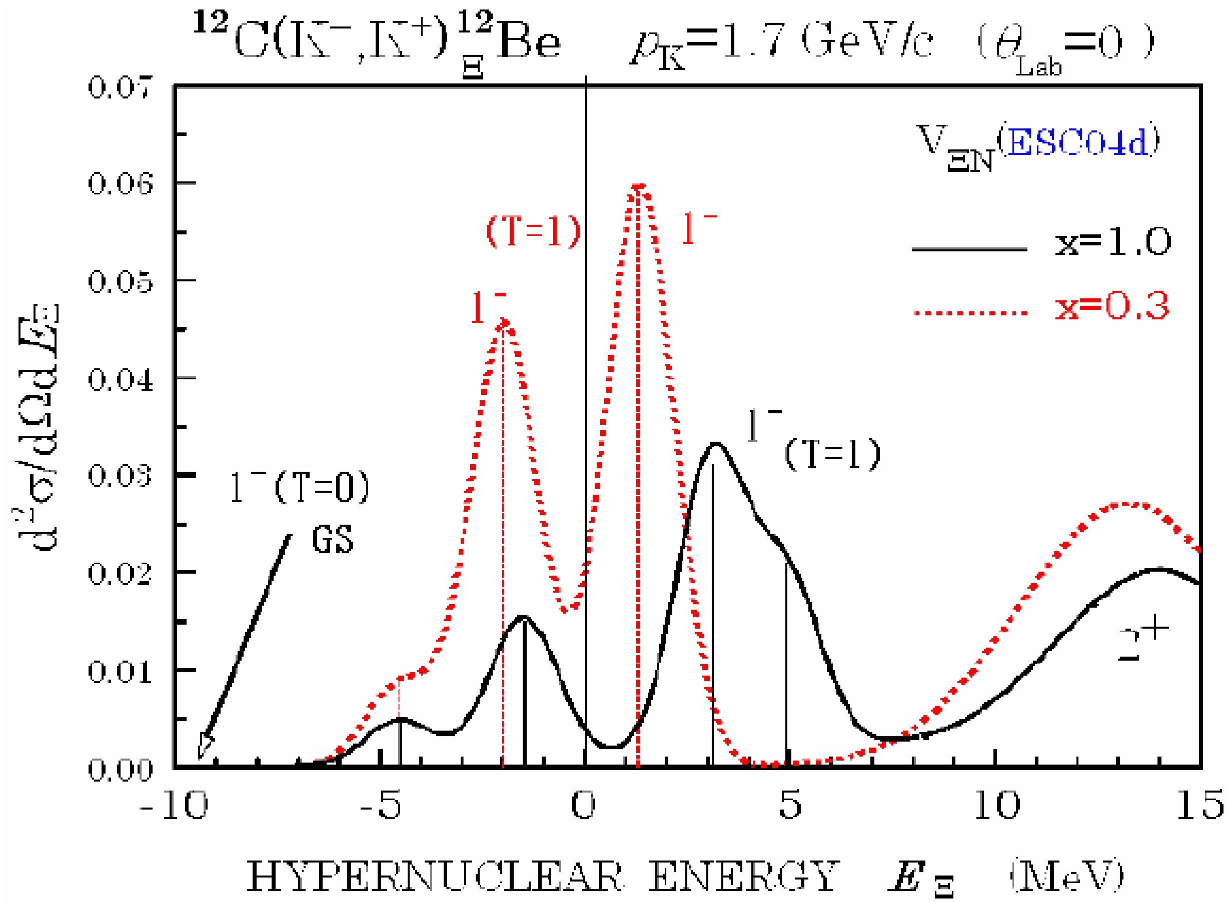
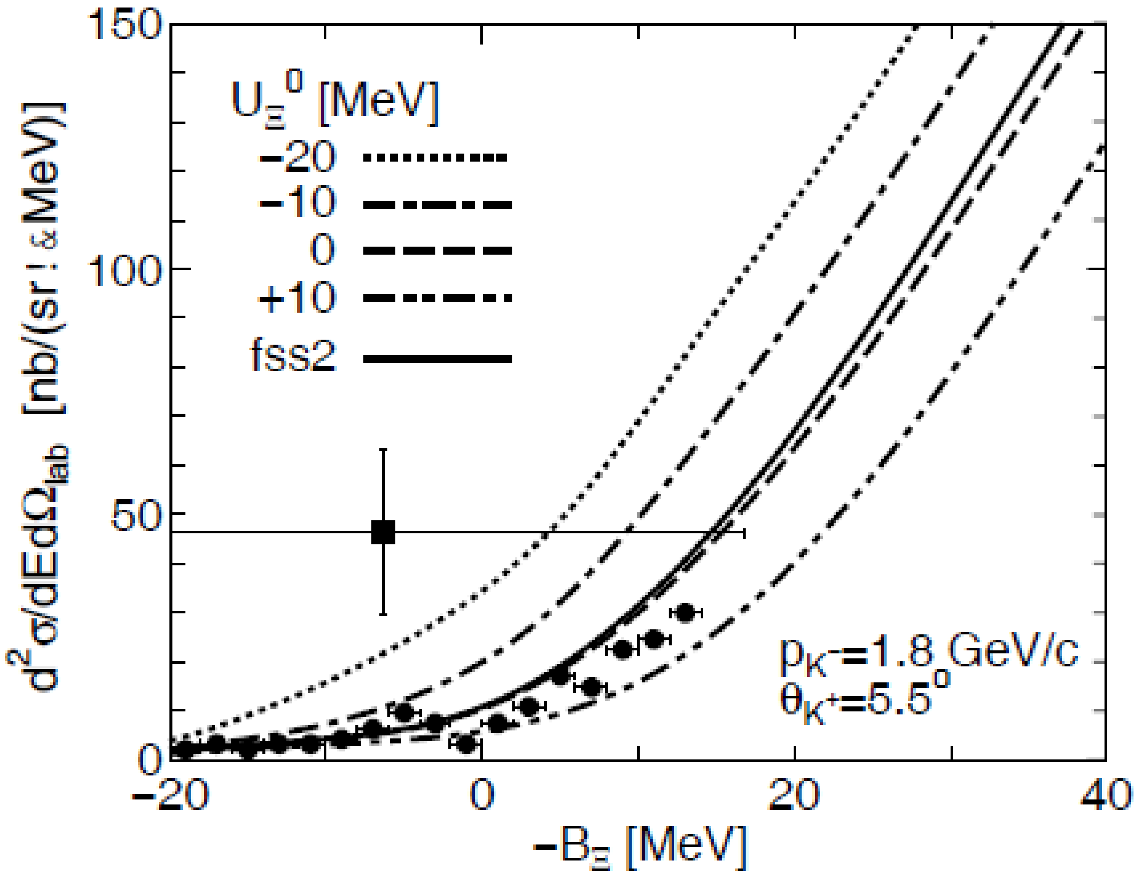


Sugimoto & Motoba

ESC04d potential (strong spin-spin force)

Problems (2)

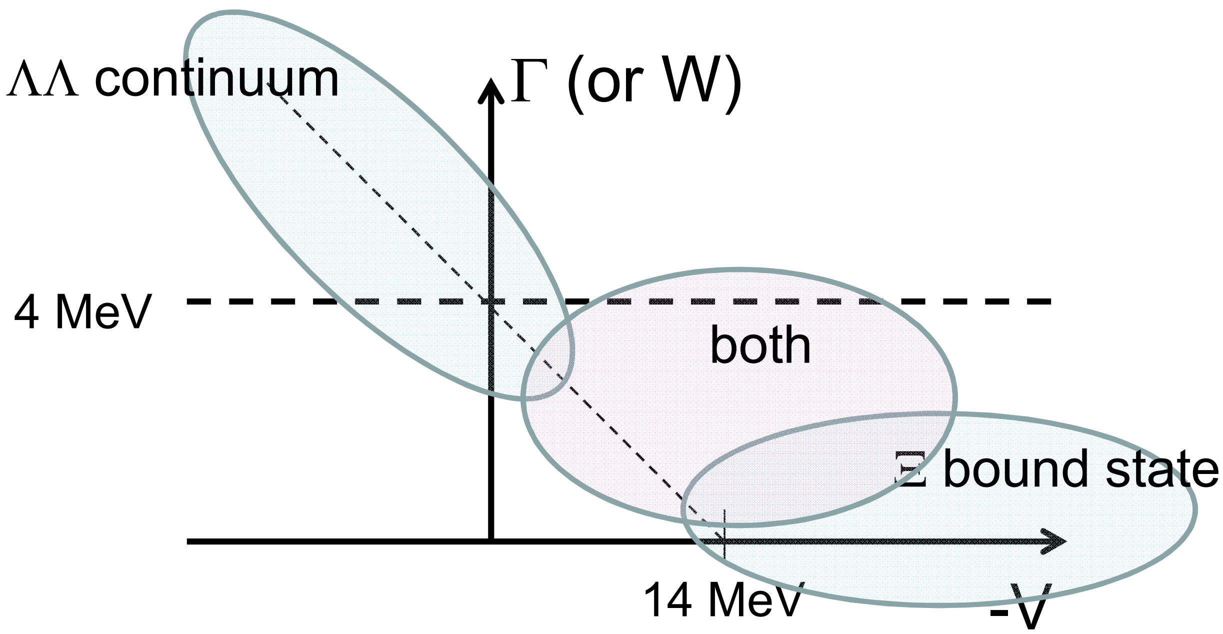
- ΞN→ΛΛ conversion
  - ΛΛ continuum can appear at the same energy as Ξ states
  - Calculation by Kohno and Hashimoto
    → E885 spectrum can be explained with V = 0 MeV
    (Γ = 4 MeV)



V~-14 MeV is an **overestimation**

So, what can we say?

- ΞA potential is still quite a lot uncertain
  - V~-14 MeV can be underestimate or overestimate
- Ξ bound state vs $\Lambda\Lambda$ continuum
  - Shallower real part ⇔ Larger imaginary part
    (actual balance is model dependent)

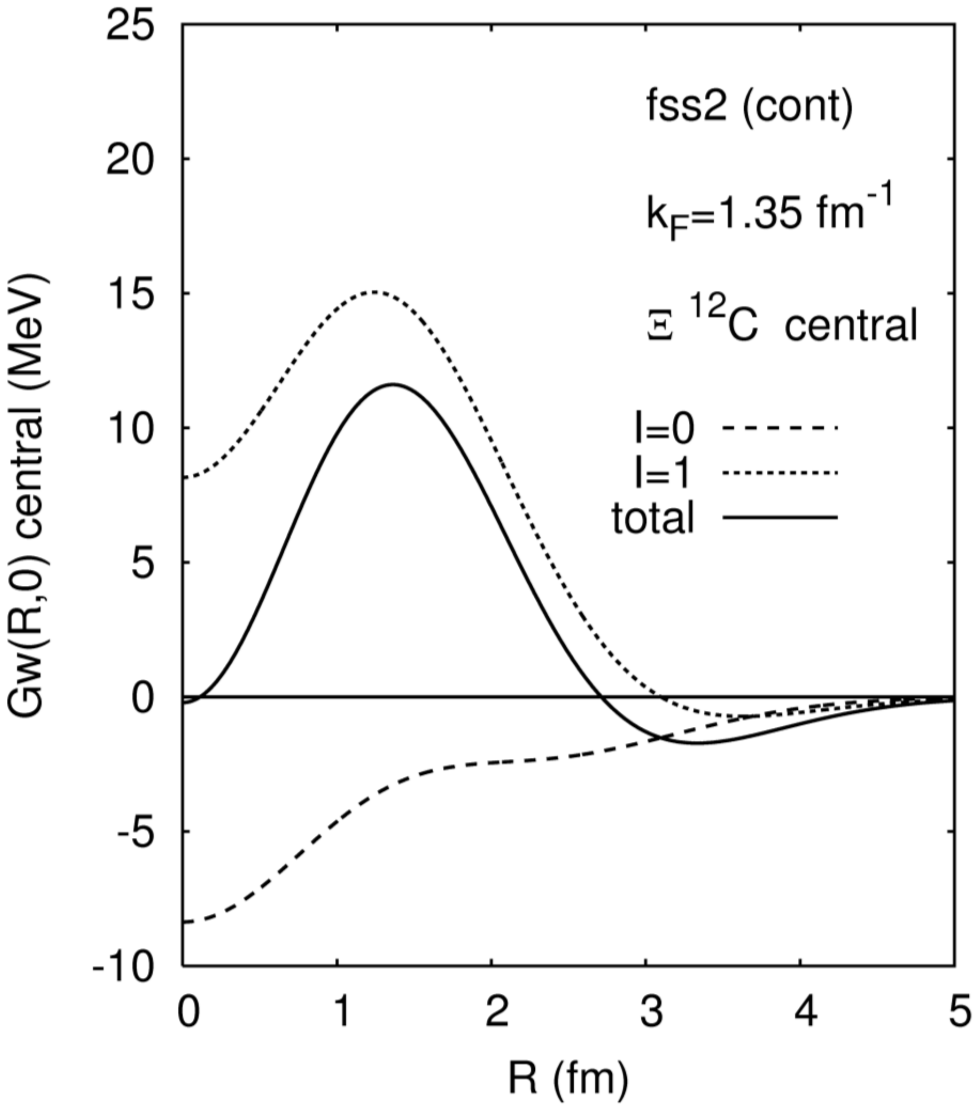


ΞN interaction model and ΞA optical potential (examples)

Model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ_Ξ
NHC-D	0	–2.6	0.1	–2.1	–0.2	–0.7	–1.9		
	1	–3.2	–2.3	–3.0	–0.0	–3.1	–6.3	–25.2	0.9
Ehime	0	–0.9	–0.5	–1.0	0.3	–2.4	–0.7		
	1	–1.3	–8.6	–0.8	–0.4	–1.7	–4.2	–22.3	0.5
ESC04d*	0	6.3	–18.4	1.2	1.5	–1.3	–1.9		
	1	7.2	–1.7	–0.8	–0.5	–1.2	–2.8	–12.1	12.7

- One boson exchange (NHC-D, Ehime)
  - strong attraction in odd states → strong A dependence
- ESC04d*
  - strong attraction in $^3S_1$ (T=0)

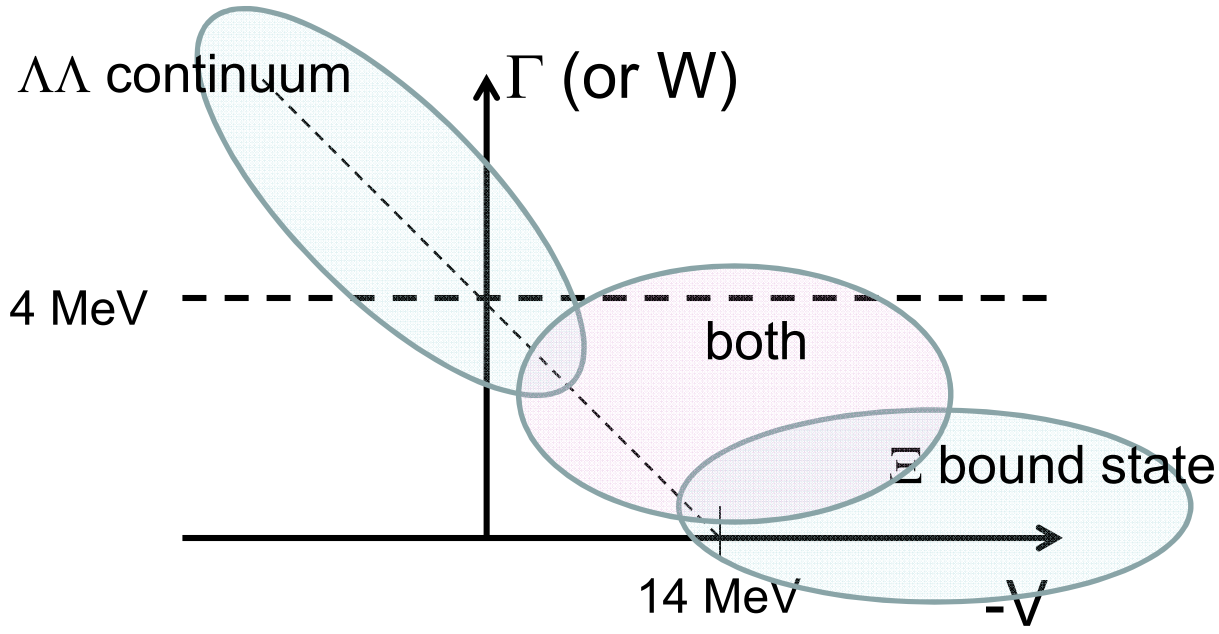
Quark cluster model potential



- Example: Kyoto-Niigata/fss2 + G-matrix
- Potential shape is non-trivial, but overall rather weak.
- Integral is almost 0

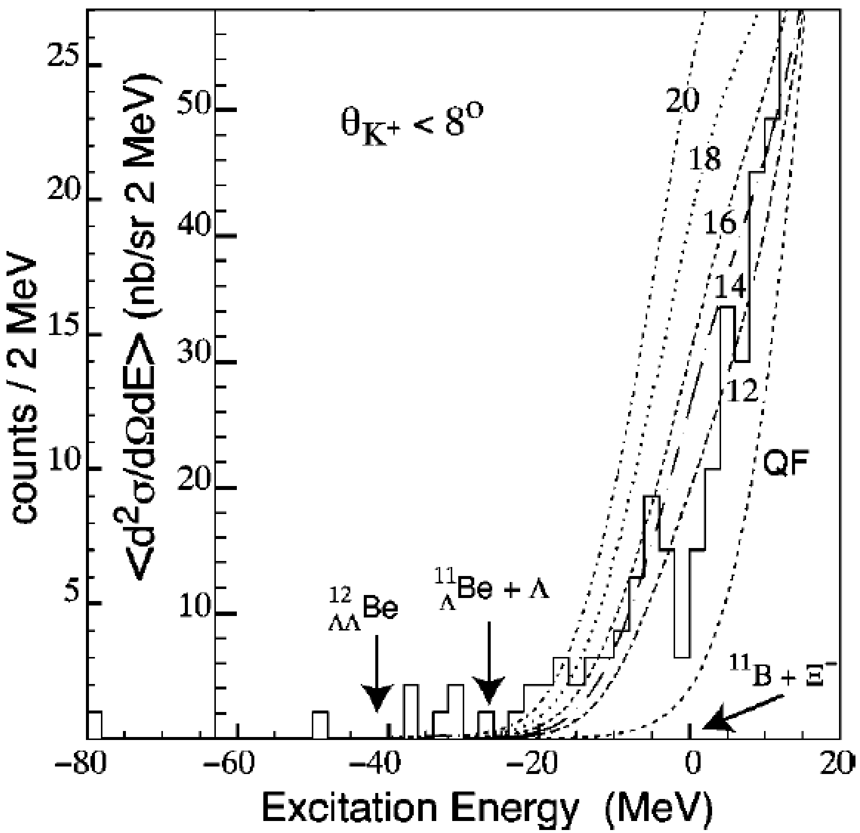
What we know

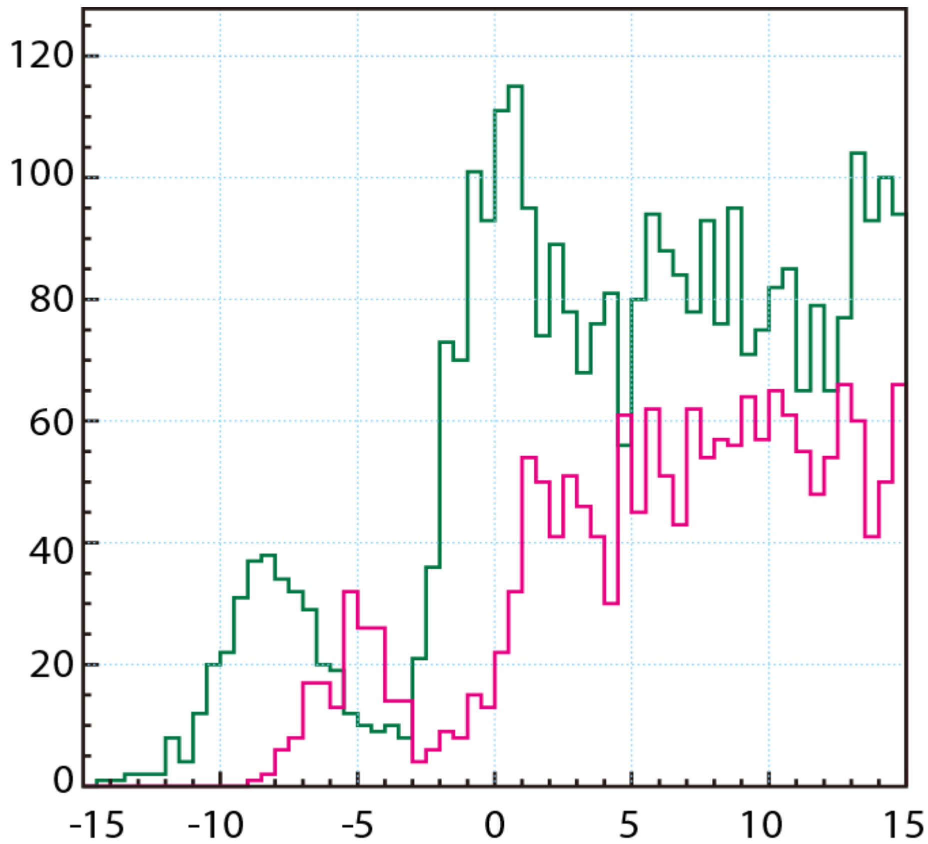
- ΞA potential is still quite a lot uncertain
  - Theory: no strong principle
  - Experiment: Naïve interpretation of E885 data (V~-14 MeV) can be underestimate or overestimate
- Ξ bound state vs ΛΛ continuum



Ξ nuclei spectroscopy

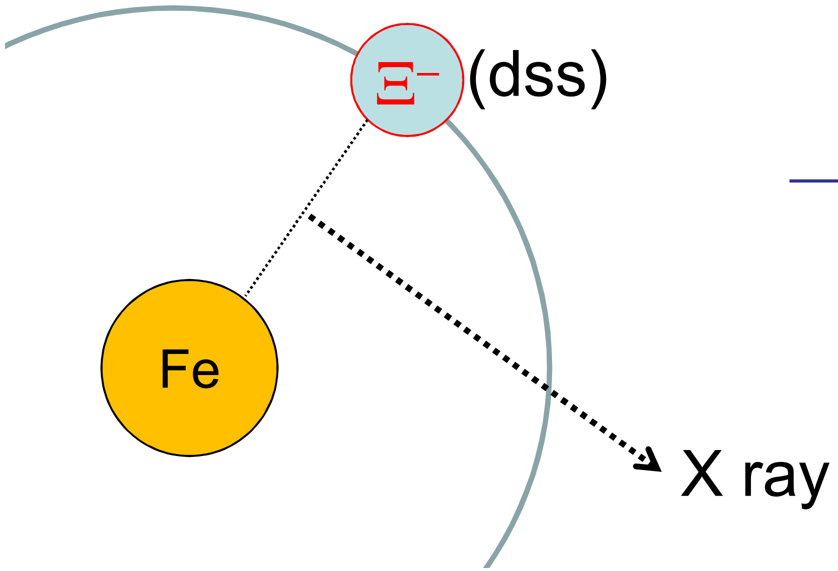
- Need distinct peaks to obtain definite information
  - Only applicable to attractive & narrow potential
  - What can we do if the potential is less attractive or absorptive?

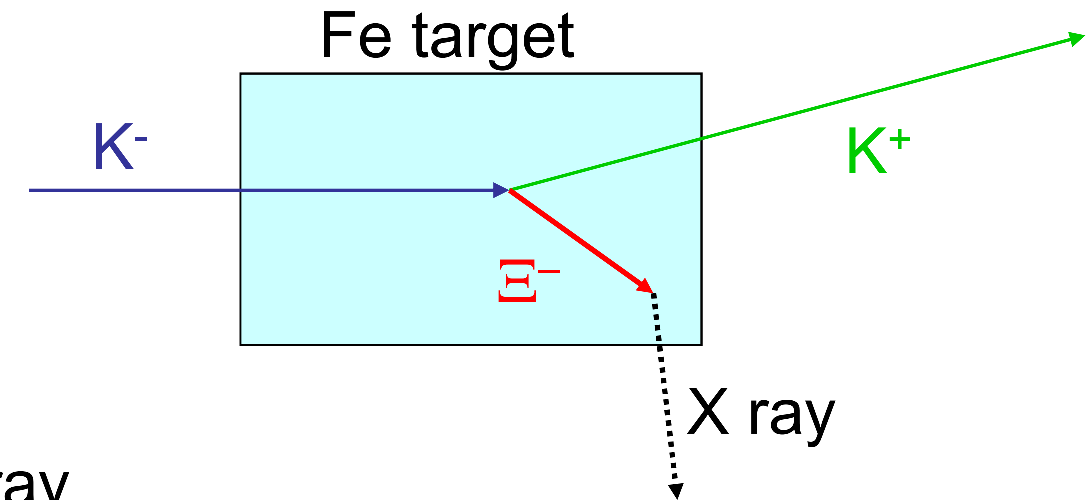




X-ray spectroscopy of Ξ atom

- World first measurement of X rays from Ξ-atom
  - Gives direct information on the ΞA optical potential
- Produce Ξ^- by the Fe(K^-,K^+) reaction, make it stop in the target, and measure X rays.
- Aiming at establishing the experimental method



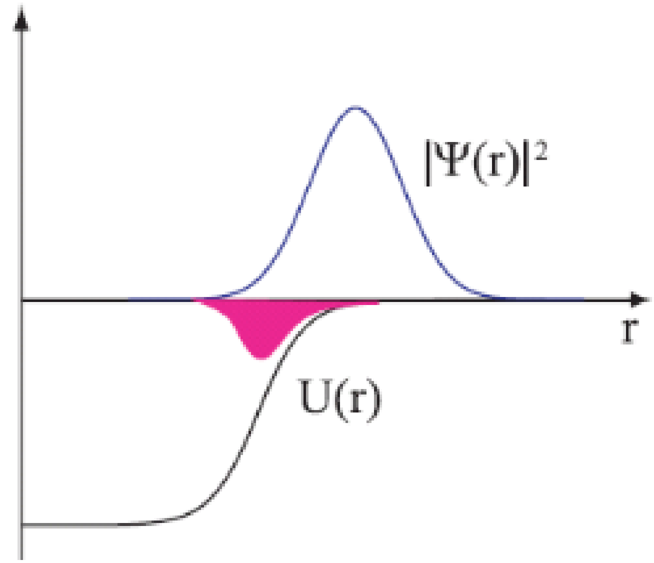


Principle of the experiment

- Atomic state – precisely calculable if there is no hadronic interaction
- 1st order perturbation

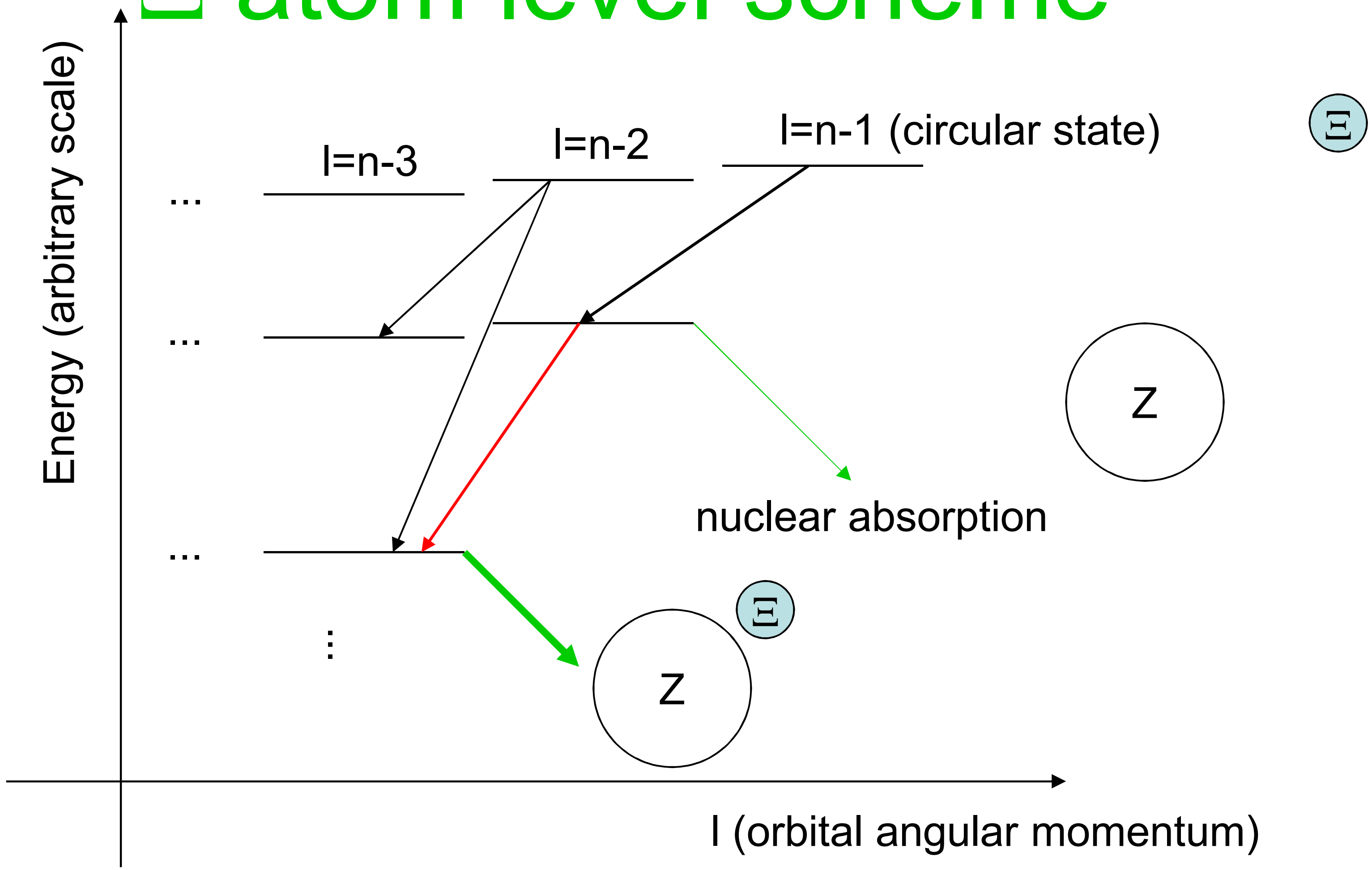
$$\Delta E = \int |\Psi_{\Xi}(r)|^2 U_{\Xi}(r) dr$$

  - If we assume potential shape, we can accurately determine its depth with only one data
  - Shape information can be obtained with many data
  - Even if 1st order perturbation is not good, this is still the same.



- Peripheral, but direct → complementary to Ξ nuclei
- Applicable regardless of potential type (repulsive, ...)

Ξ atom level scheme

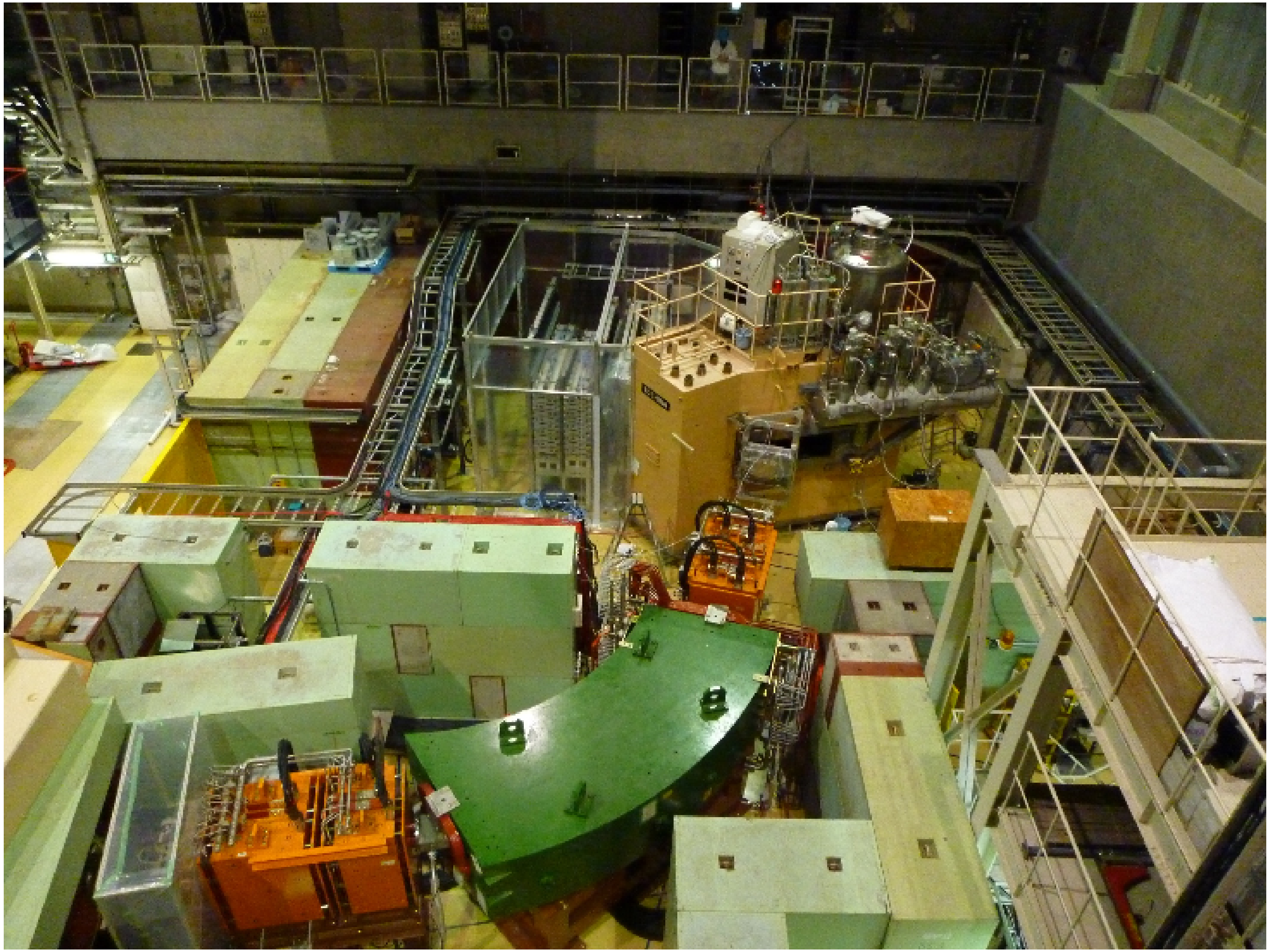


X ray energy shift – real part

Width, yield – imaginary part

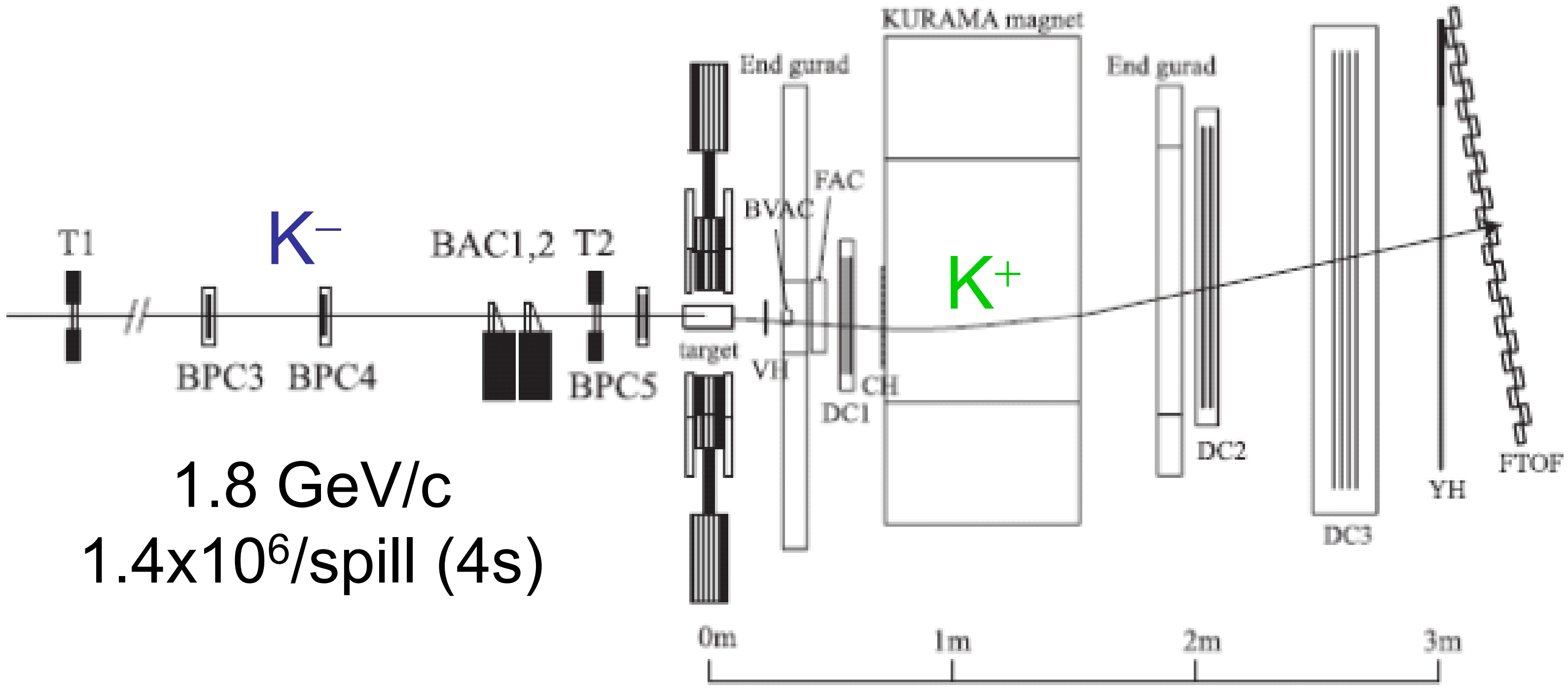
Successfully used for π^-, K^-, $\bar{p}$, and Σ^-

Experimental Setup



K1.8 beamline of J-PARC

(K^-,K^+) detection system

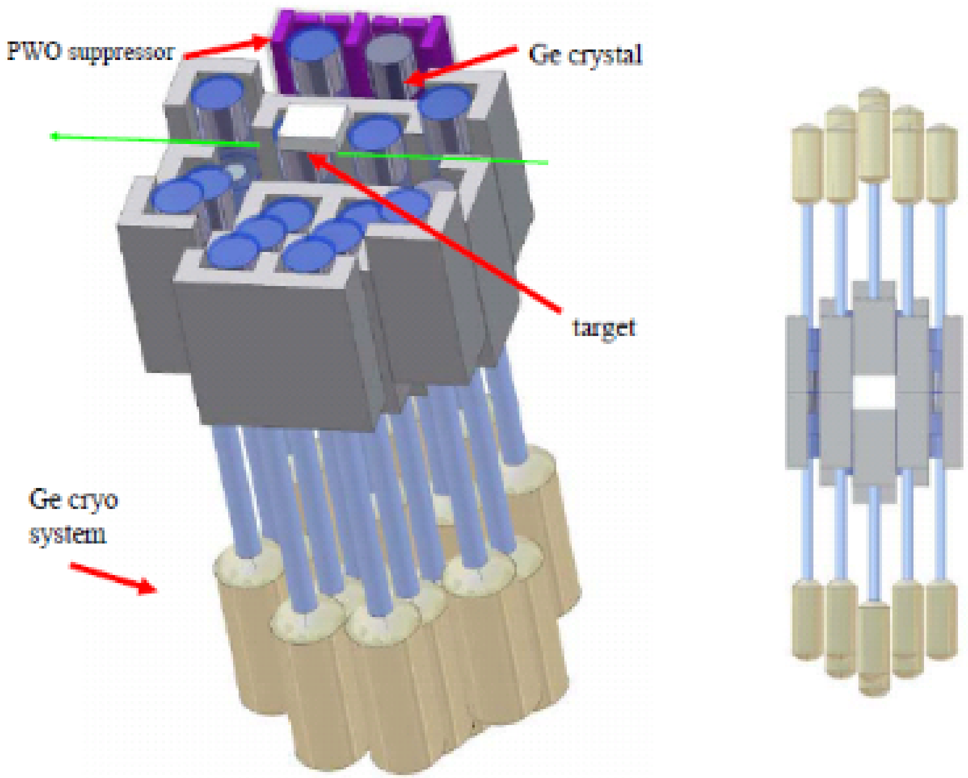


1.8 GeV/c
1.4×10^6/spill (4s)

- Long used at KEK-PS K2 beamline (E373, E522, ...)
  - Minor modification is necessary to accommodate high rate.
- Large acceptance (~0.2 sr)

X-ray detection

- Hyperball-J
  - 32 Ge detectors
  - PWO anti-Compton
- Detection efficiency
  - 16% at 286 keV
- High-rate capability
  - < 50% deadtime
- Calibration
  - In-beam, frequent
  - Accuracy ~ 0.05 keV
- Resolution
  - ~2 keV (FWHM)



Run Plan

- Expected beam time: 2015?? (hopefully)
  - Unfortunately, J-PARC is under shutdown due to radiation accident. Operation might resume by the end of 2014.
  - Beam intensity: ~ 30 kW (~10%)
- Making larger detectors to compensate low intensity
  - KURAMA gap: 50 cm → 80 cm, x1.5 larger acceptance
- Two step strategy
  - In the first beam time, only ~10% of statistics may be obtained.

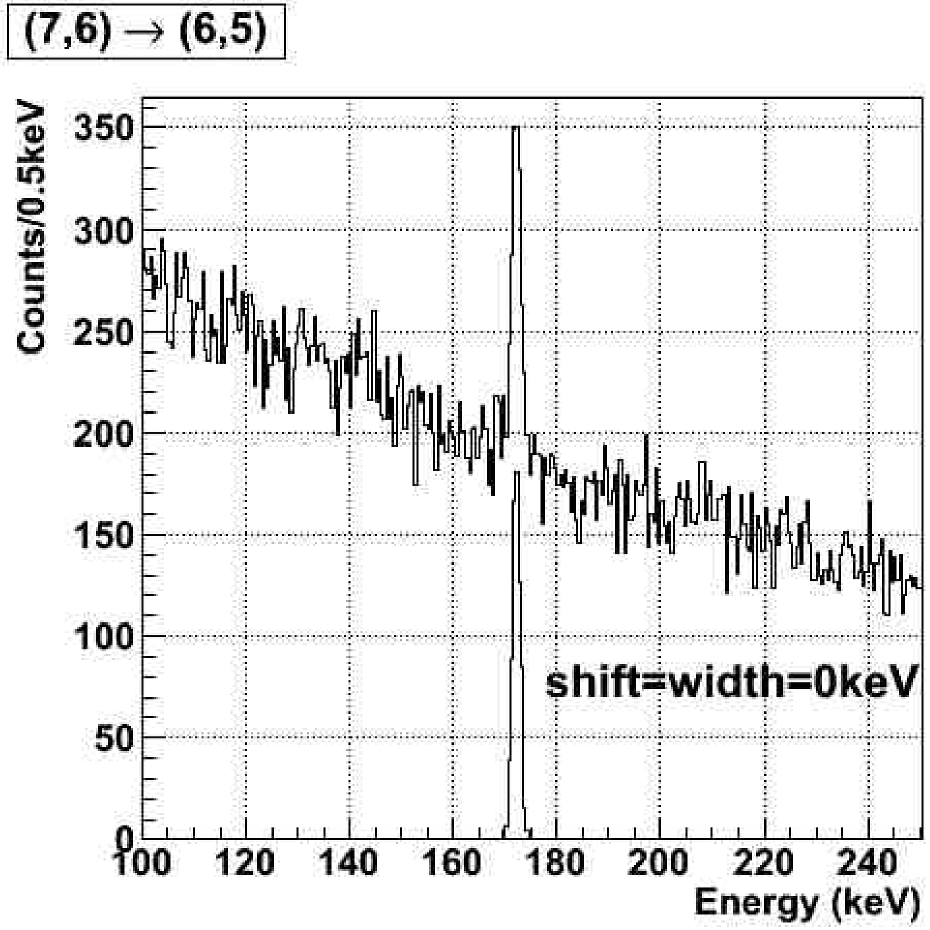
    → What can we do with that statistics?

⇩

We can take rather good data

Expectation with ~10% stat. (1)

- Observation of X rays is certainly possible
  - 7 → 6 transition: 720 counts with 410 counts/keV BG

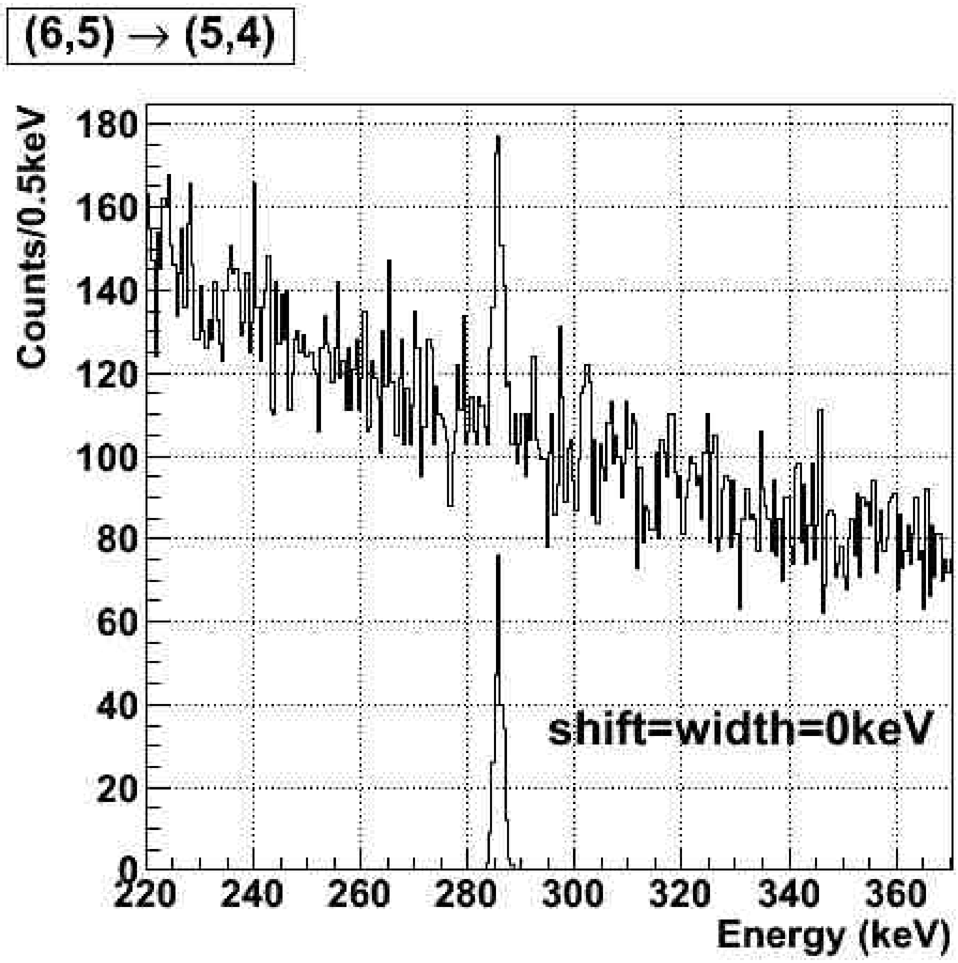


n≧6では強い相互作用の影響はほとんど見えない

Rather easy
(but no physics information)

Expectation with ~10% stat. (2)

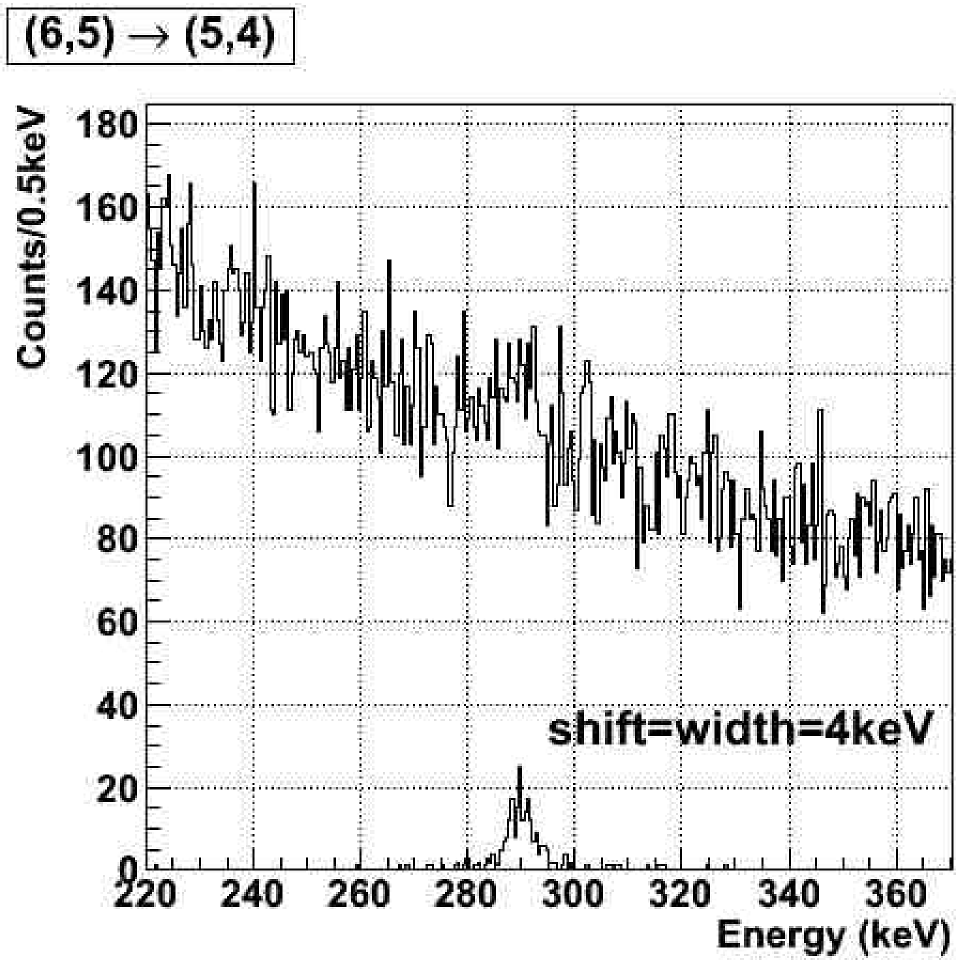
- Can we see the 6→5 transition we are interested in?
  - Depends on absorption (width & yield)



If the width is 0, it's certainly possible

Expectation with ~10% stat. (3)

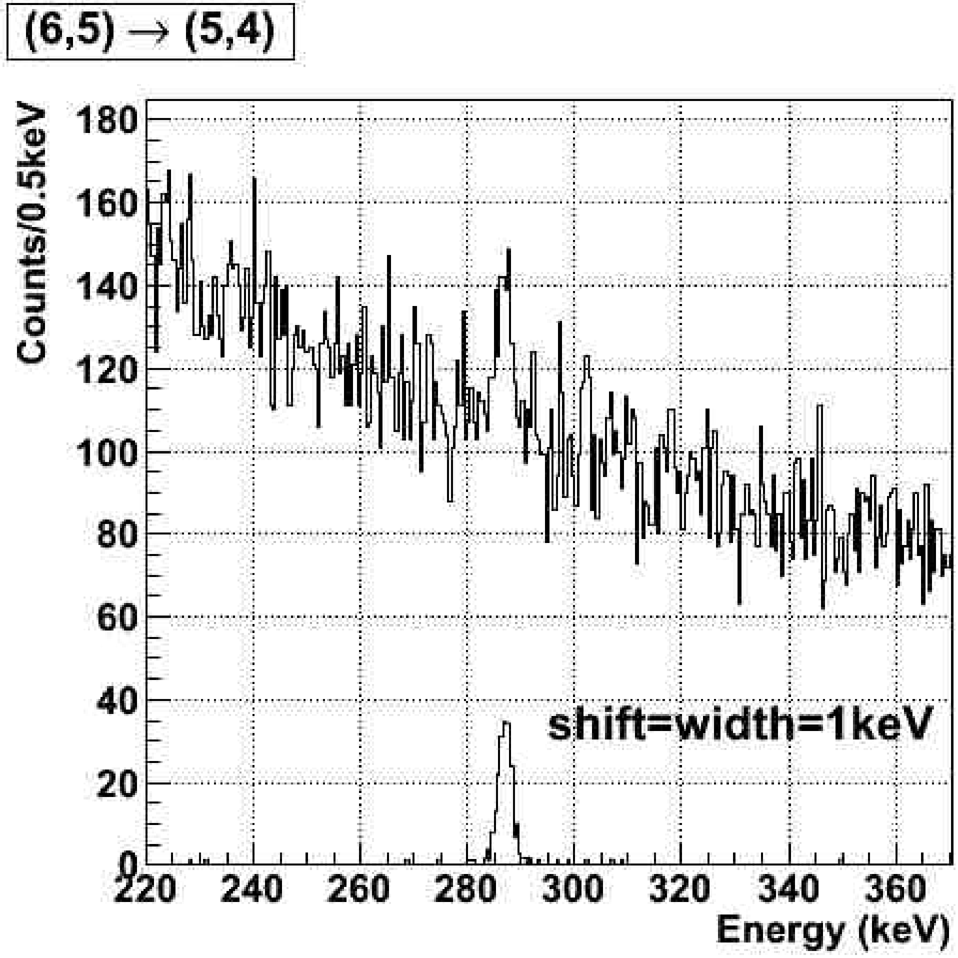
- Can we see the 6→5 transition we are interested in?
  - Depends on absorption (width & yield)



If the width is 4 keV, (assumed in proposal) the peak is hardly seen

Expectation with ~10% stat. (4)

- Can we see the 6→5 transition we are interested in?
  - Depends on absorption (width & yield)



If the width is ~1 keV, peak can be seen

It may be more clearer because yield would be higher due to smaller absorption at the initial state

Shift accuracy: 0.1~0.2 keV
→ enough for 1 keV shift

Future Prospects（hope）

- First experiment
  - Determine actual yield & background
  - Establish experimental method
- Based on shift & width in iron,
  - If too small to be seen, use heavier target (Co, Ni)
  - If too large to be seen, use lighter target (Mn, Cr)
  - If we are lucky, take a few data points around, and then go to different mass region.
- Final goal: a few points for each n
  - ~10 data points in total
  - Potential shape, A dependence.
  - At full intensity, it will take a few weeks/target
- Gamma-ray spectroscopy of double Λ hypernuclei?

Summary

- ΞA potential is important for studies on neutron stars
- We will measure Ξ-atomic X rays
  - First of the series of experiments
  - For the first time in the world – aiming to establish the method
- Precision of X-ray energy ~ 0.05 keV
  - Good accuracy for expected energy shift (~1 keV)
  - Width: measurable down to ~ 1 keV, X-ray yield gives additional information on imaginary part.
- First beam in 2015 with smaller statistics
  - X ray itself can be observed with this statistics
- Ultimate goal: data over wide mass region

Backup slides

◆ Parameters in the cascade calculation of ^{56}Fe-Ξ^- atom

· Ξ^--nucleus strong interaction

Woods-saxon potential

$V_0 = -24$ MeV,　$W_0 = -3$ MeV,

$R_{real} = 1.1 \times A^{1/3}$ fm,　$R_{imag} = 1.1 \times A^{1/3}$ fm,

a = 0.65 fm

· Cascade parameters

1. Ξ^- initial distribution :

$P(l) \propto (2l + 1)\, e^{-al}$, a = -0.056 at $n_{start} = 50$

2. electron initial distribution:

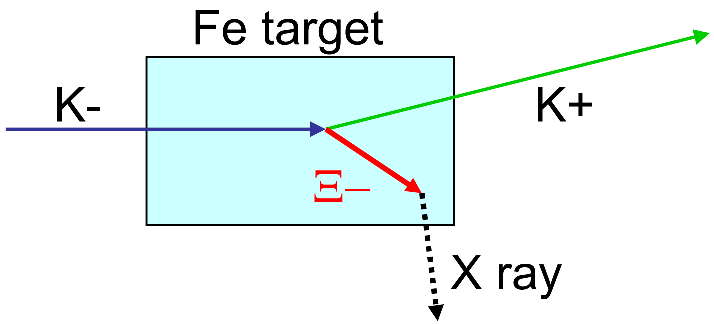
assuming completely filled.

K- /L-shell refilling processes are considered.

M- /N-shell are kept to be filled.

Summary of the experiment

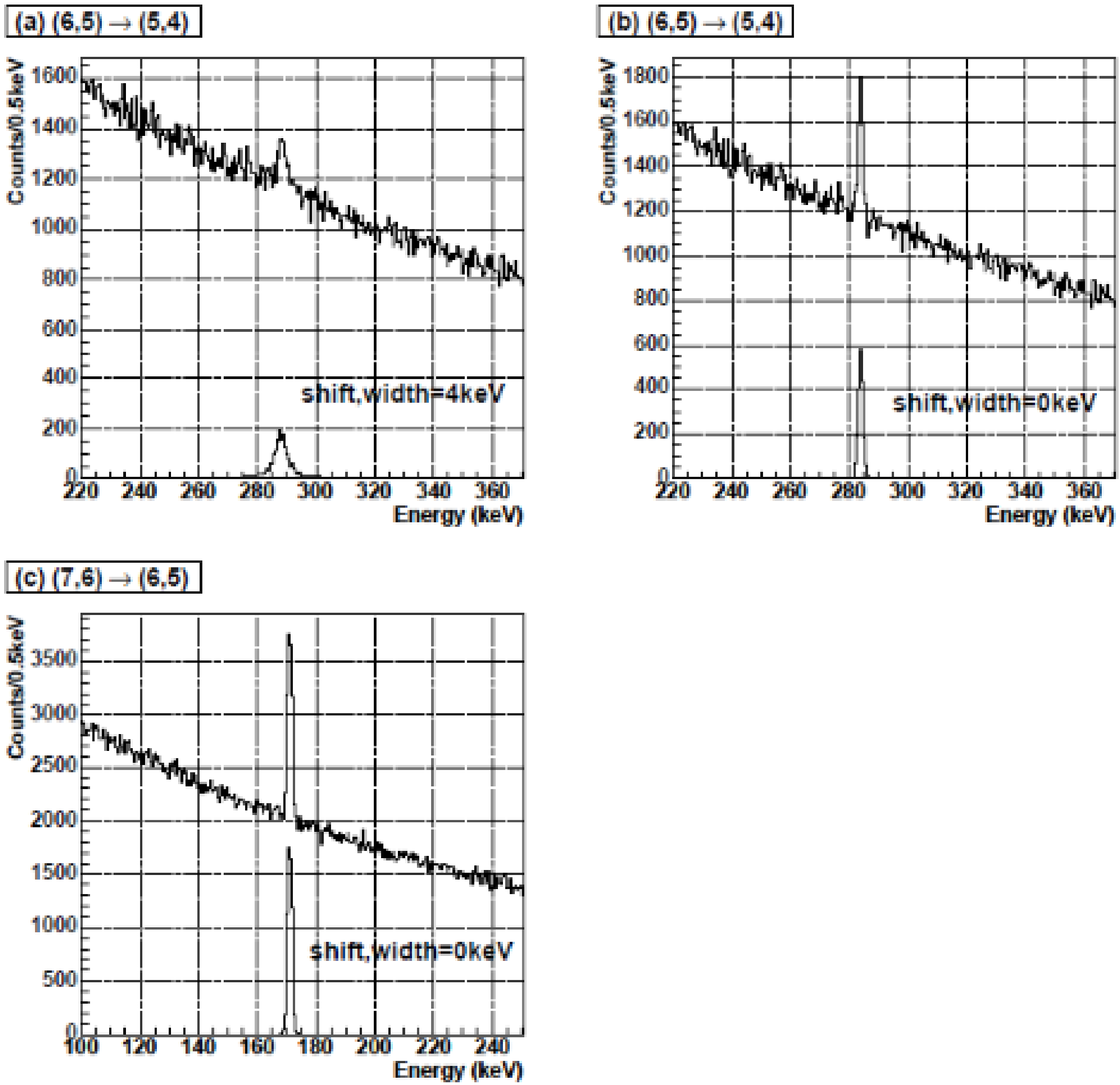
- Produce Ξ^- by the (K-,K+) reaction, make it stop in a Fe target, and measure X rays from Ξ^- atom.

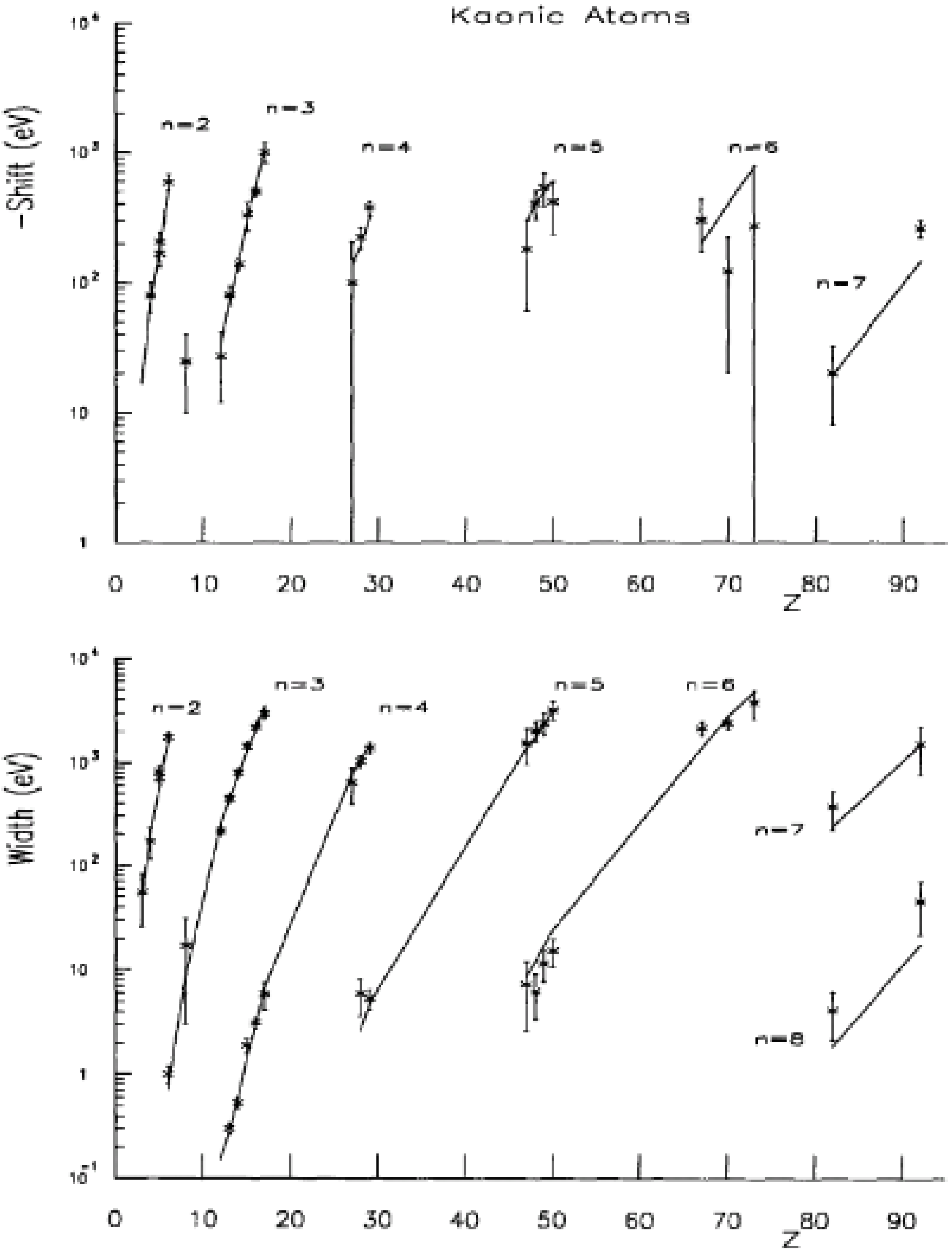


- Physics:
  - Ξ-nucleus interaction (optical potential)
  - Real part – shift of X-ray energy (up to ~10 keV)
    Imaginary part – width, yield
- Sensitivity
  - X-ray enerygy shift: ~0.05 keV

    → Good for expected shift of O(1keV)
  - Width: directly measurable down to ~ 1keV

Expected X-ray spectrum





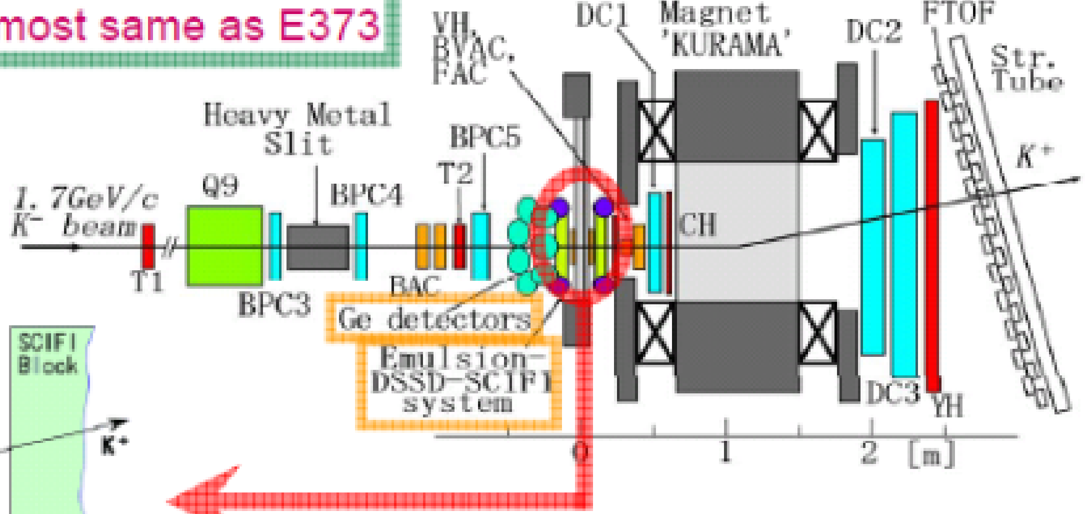
Kaonic Atoms
-Shift (eV)
n=2
n=3
n=4
n=5
n=6
n=7
Z
Width (eV)
n=8

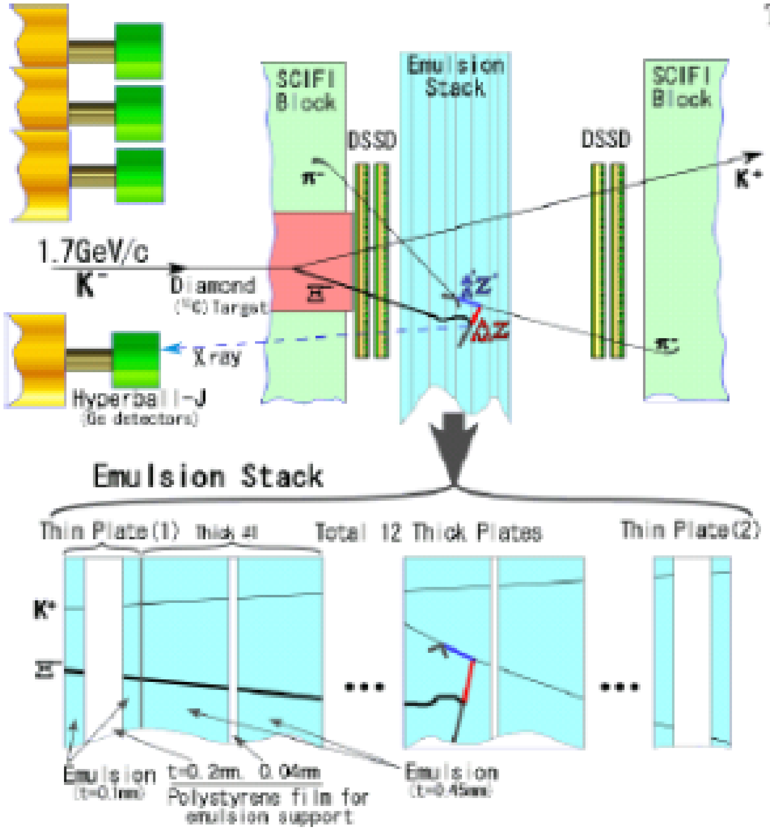
エマルジョン実験

Jun.30,2006
J-PARC.PAC

Setup of the proposed experiment

Almost same as E373





Beam : K⁻ (1.7GeV/c),

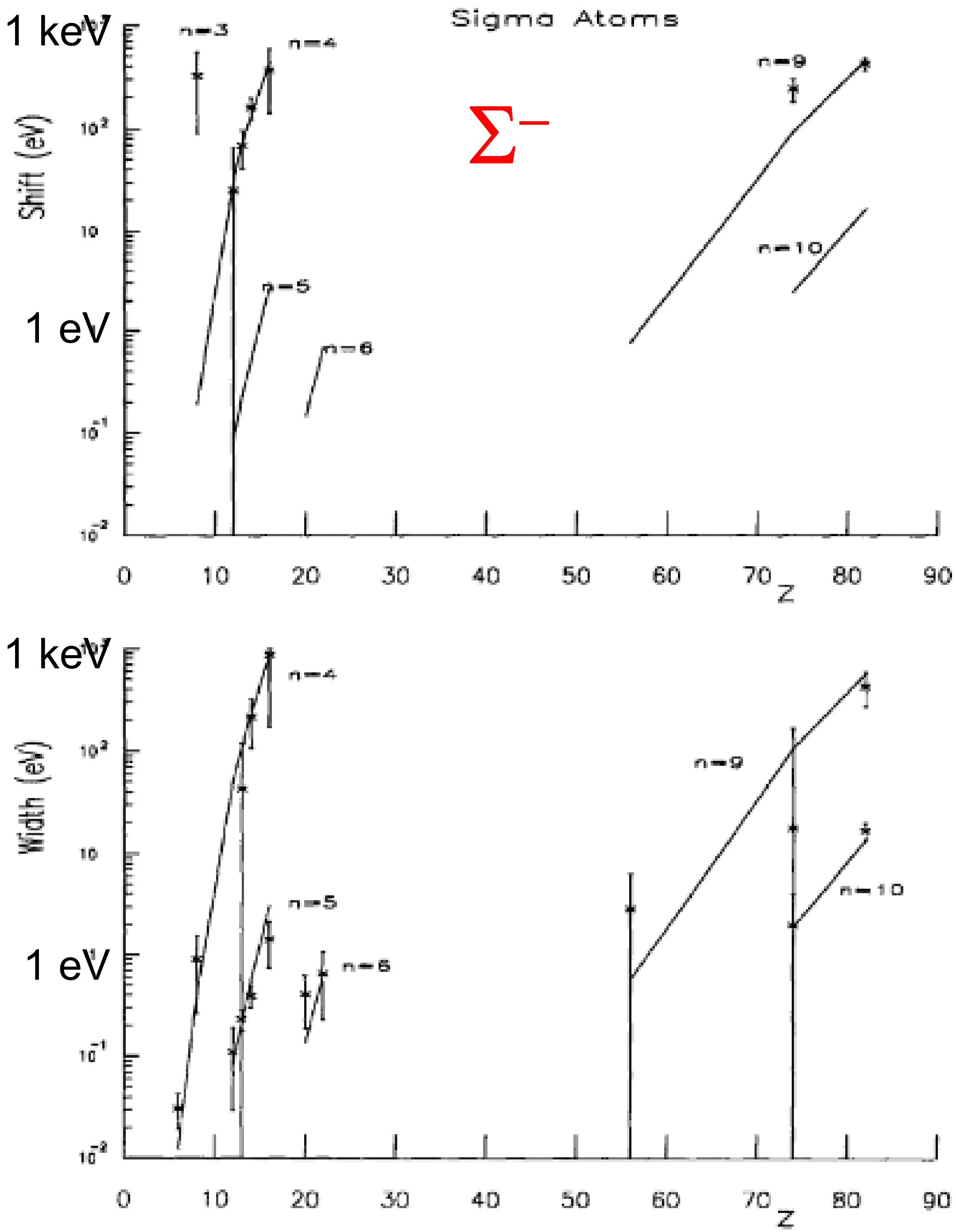
3×10^5 K⁻/spill with K⁻/π⁻ > 6

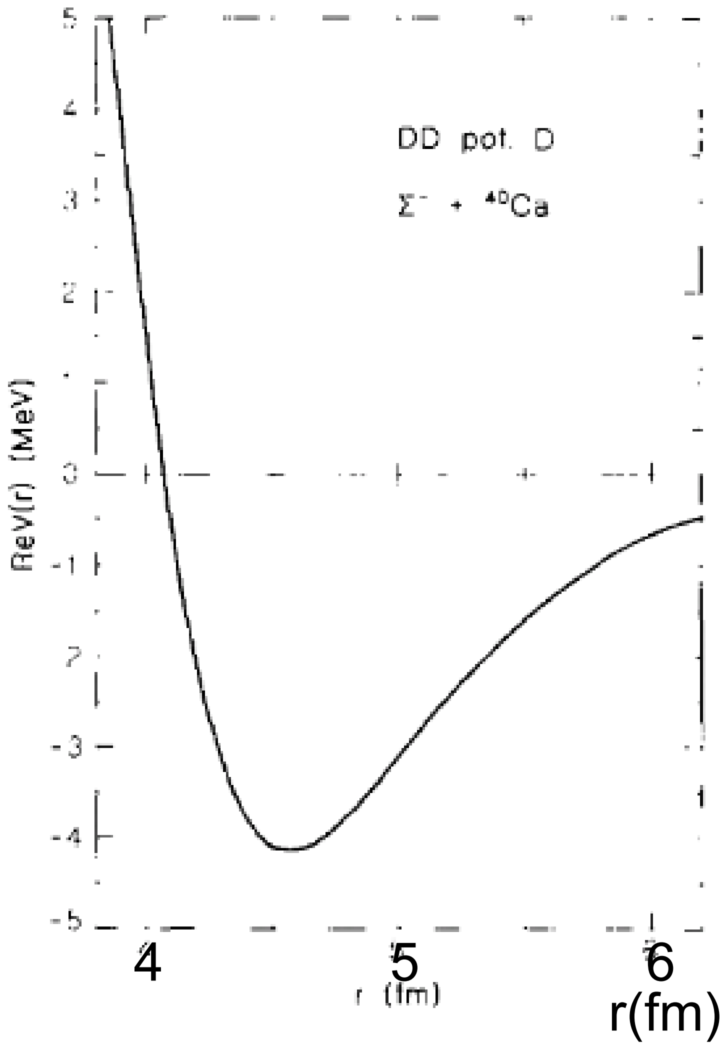
at K1.8 beam-line (~20% of 9μA)

Trigger : (K-, K+)

=> 10^4 Ξ⁻ stopping events

(more than 10 times higher stat. than E373)





(weakly) attractive at peripheral
(strongly) repulsive at center