Recent data from E929 experiment at BNL
--- Λ Spin-Orbit Splitting in $^{13}{}_{\Lambda}C$ ---

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- Brief Introduction to E929 Experiment
- Experimental Setup
- Overview of Analysis Results
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Brief Introduction to E929 Experiment

Goal of the Experiment

"Estimate Λ spin-orbit interaction with the world best accuracy."

Brief history

- CERN experiment on $^{16}{}_{\Lambda}O$ in 1978 (Heidelberg-Saclay-Strasbourg)
  ΔE_{LS} < 0.3 MeV (energy difference only)
  $\Rightarrow$ ΔE_{LS} = 0.7±0.7 MeV (energy difference and yield ratio)
- BNL experiment on $^{12}{}_{\Lambda}C$ in 1979
  $\Delta E_{0+ - 2+}$ (~ ΔE_{LS}) < 0.42 MeV (0.82 MeV)
- BNL experiment on $^{13}{}_{\Lambda}C$ in 1981
  $\Delta E_{0°-15°}$ (~ ΔE_{LS}) = 0.36±0.30 MeV

  } difference of (K^-,π^-) angular distribution (ΔL=0 and 2)
- Emulsion reanalysis on $^{12}{}_{\Lambda}C$ and $^{16}{}_{\Lambda}O$ in 1986 (Dalitz-Davis-Tovee)
  $\Delta E_{0+ - 2+}$ (~ ΔE_{LS}) ~ 0.8 MeV ($^{12}{}_{\Lambda}C$)
- $\Delta E_{LS}(\Lambda)$: 1 order of magnitude smaller than $\Delta E_{LS}(N)$
- But, Λ spin-orbit splitting determined only with 0.5 ~ 1 MeV accuracy.

How precisely ?

- 30 keV in statistical error
  Magnetic spectrometer (3 MeV) $\Rightarrow$ γ-ray detector (0.3 MeV)
- Need to reduce systematic error

Ideas of the Experiment

Spin-orbit doublets in $^{13}_{\Lambda}C$

- 1/2-: $^{12}C_{g.s.(0+)} + p_{1/2\Lambda}$, 3/2-: $^{12}C_{g.s.(0+)} + p_{3/2\Lambda}$
- populated at the same time
  - difficult to see as separated peaks in excitation energy
- need to populate separately

Measure $^{13}C(K^-,\pi^-)^{13}_{\Lambda}C$ reaction both at small and large angles

- recoil-less nature of (K^-,π^-) reaction
  - momentum transfer $\Delta Q \sim p_\pi \theta_\pi$
- angular momentum transfer $\Delta L \sim R\Delta Q$
  - 0 ~ 9 degrees: 1/2- ~ 80% ($\Delta L=0$)
  - 9 ~ 16 degrees: 3/2- ~ 80% ($\Delta L=2$)

☞ $^{13}C_{g.s.}$(1/2-)

These ideas are same as old BNL experiment.

What's new ?

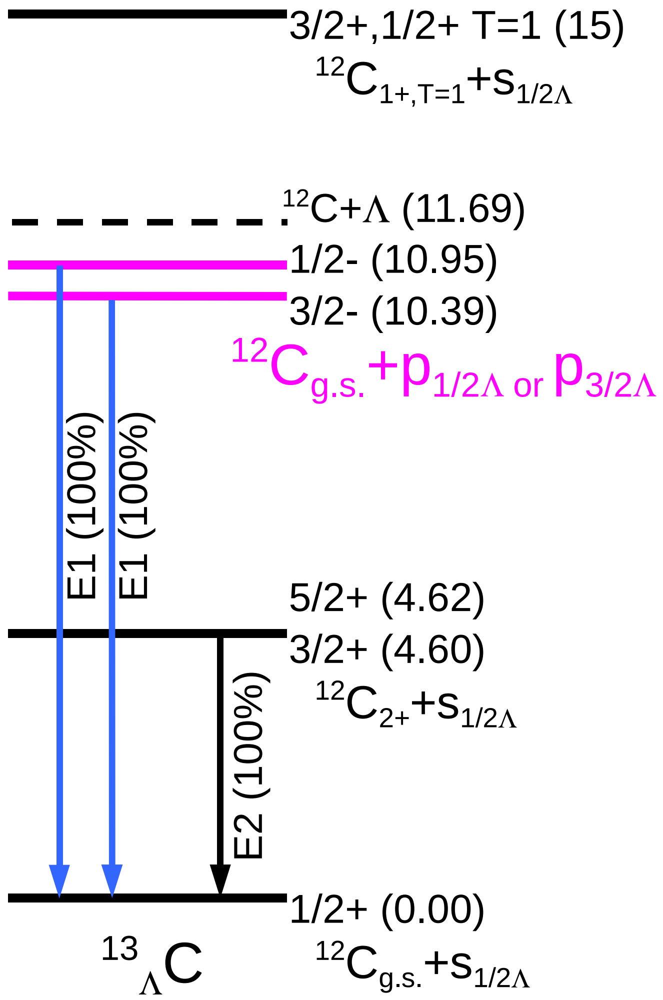
- use γ-ray detector ⇒ better energy resolution
- large acceptance spectrometer and γ-ray detector

} reduce statistical error

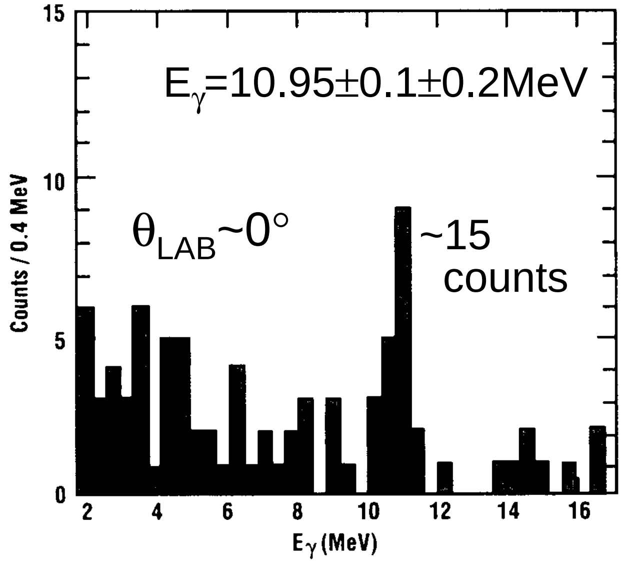
- measure $^{13}C(K^-,\pi^-\gamma)^{13}_{\Lambda}C$ reaction
  - free from strong θ-Ex correlation
- small and large angle data at the same time

} reduce systematic error

Level Scheme and γ Decay



Old BNL Experiment
$^{13}C(K^-,\pi^-\gamma)^{13}{}_{\Lambda}C$



M.May et al., PRL78 (1997) 4343

Experimental Setup

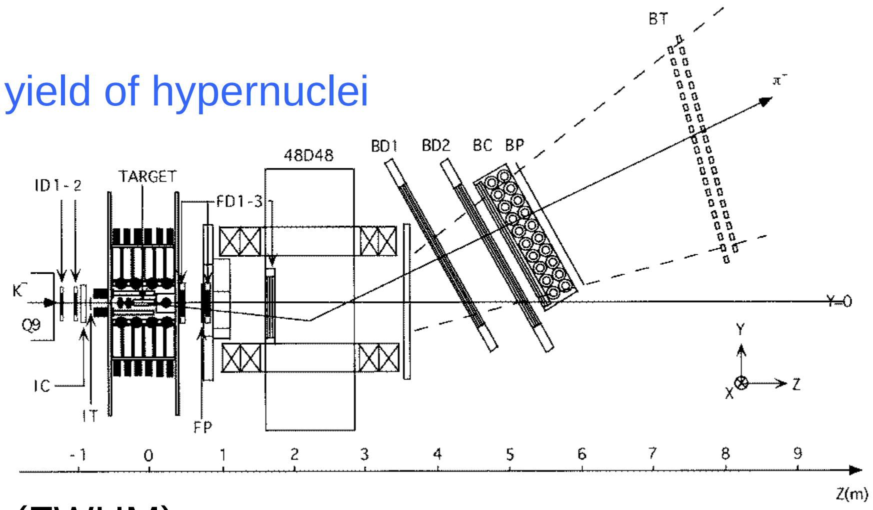
General Setup

AGS D6 beam line

- intense and clean kaon beam
- p_K = 930 MeV/c ⇐ optimized for yield of hypernuclei
- ~ 10^5 K^-/burst, K^-/π^- > 1
- 21G K^- on target

48D48 spectrometer

- large angular acceptance
  $0° < \theta\pi < 16°$
- clear particle identification
- momentum resolution ~ 10 MeV/c (FWHM)
  enough to select hypernuclear events



Target

- ^{13}C benzene target ~ 10 g/cm^2
- worked as liquid scintillation detector
  used to discriminate K^- decay in-flight events ($K^-\to\mu^-\nu$ or $K^-\to\pi^-\pi^0$) ← strong background
  segmented into 4 cells

Detectors around target

- for beam defining and background reduction

Gamma-ray Detector

NaI(Tl) detector

- 2 sets (top and bottom) of 6×6 array of modules
  - used 4×4 array for γ-ray detection
  - surrounding 1 layer to collect energy leak from 4×4 array
- module size 2.5”×2.5” ×12”

Energy resolution

- central 2×2 array: 8% (FWHM) at 0.662MeV (^{137}Cs) ⇐ current analysis
- other modules: ~13% (FWHM) at 0.662MeV

Gamma-ray Energy Calibration

Segmented γ-ray detector

- need relative and absolute energy calibrations

Short term relative calibration

- LED pulsing on all modules

Long term relative calibration

- ^{22}Na γ-ray on several modules

Absolute energy calibration for all modules

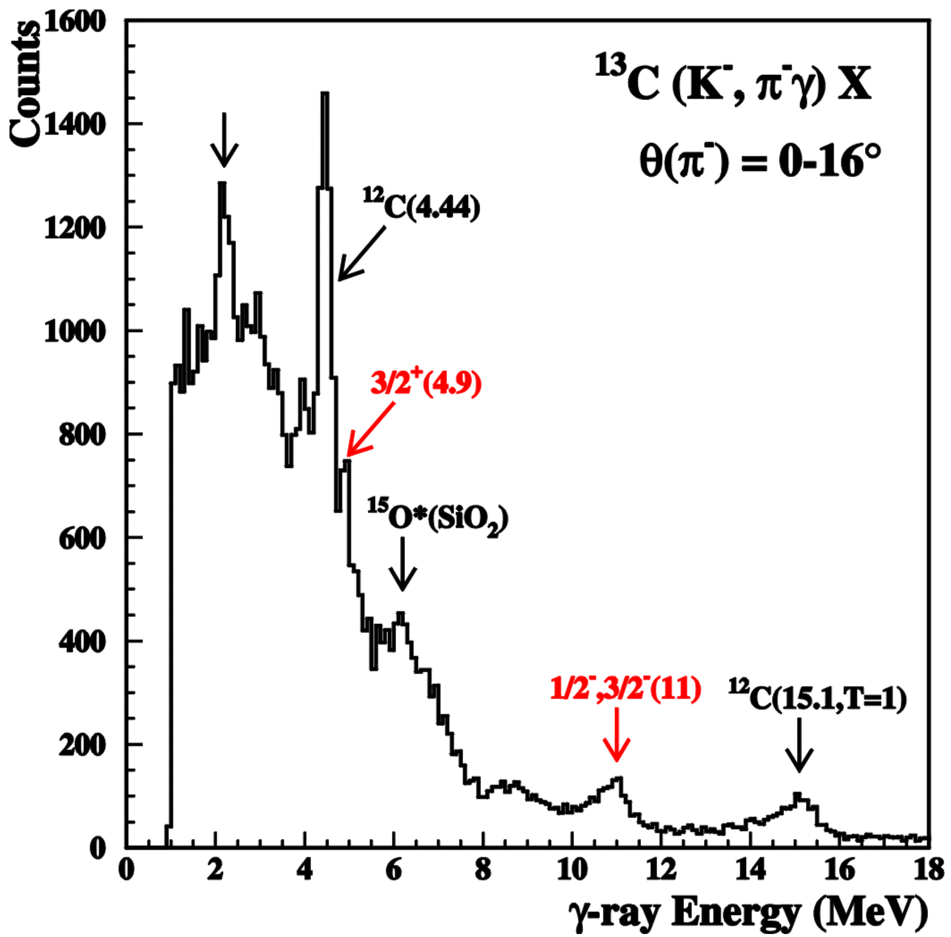
- ^{22}Na γ-rays: 0.511 MeV, 1.275 MeV
- high-energy γ-rays: 8.999 MeV (^{58}Ni(n,γ)), 6.129 MeV (^{13}C(α,nγ)^{16}O)

Overview of Analysis Results

γ-ray Spectrum

Several discrete peaks

- from normal nuclei (black arrows)
- from hypernuclei (red arrows, ${}^{13}_{\Lambda}C$)

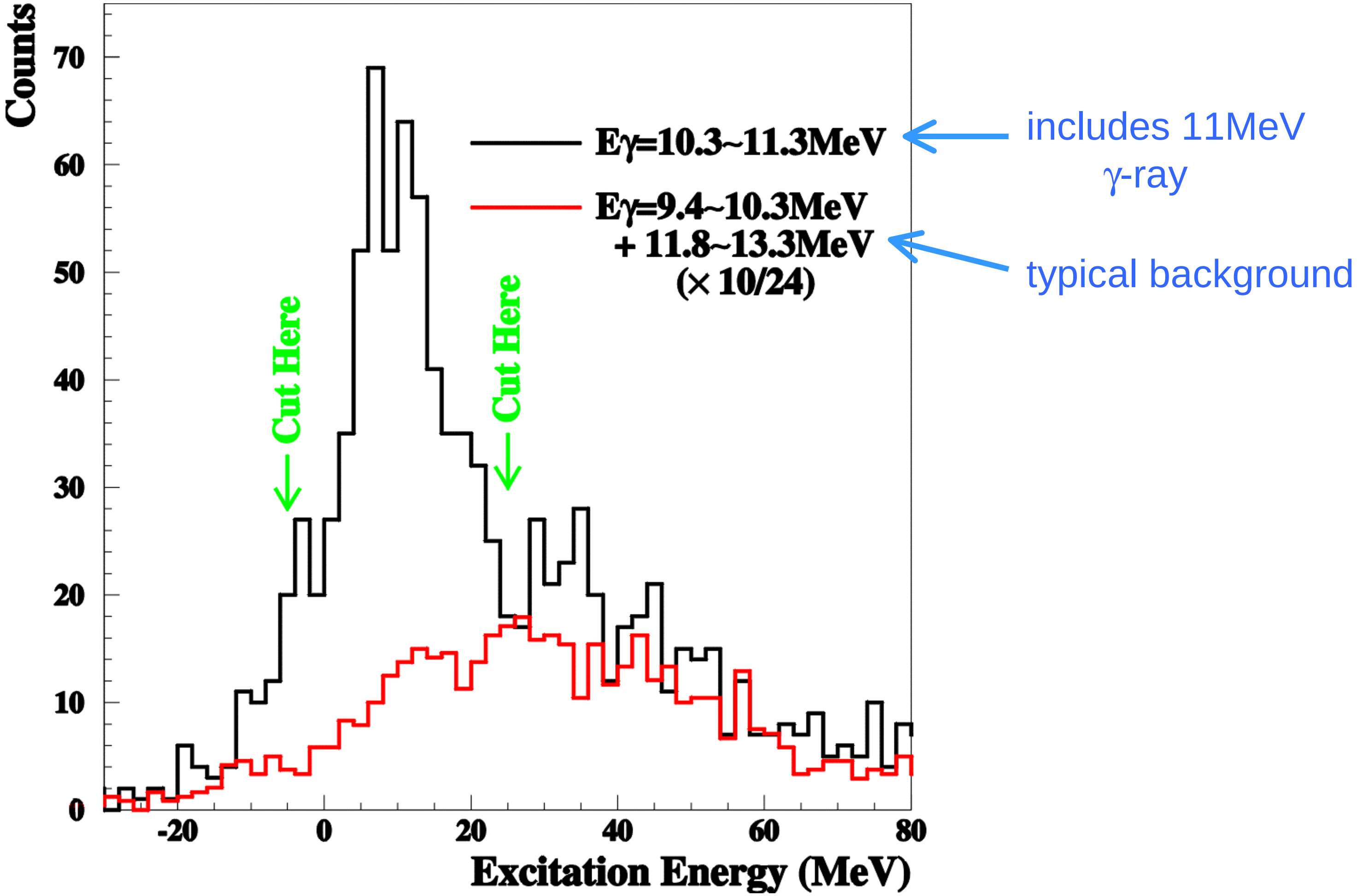


Excitation Energy Spectra

11 MeV γ-rays are coming from bound region

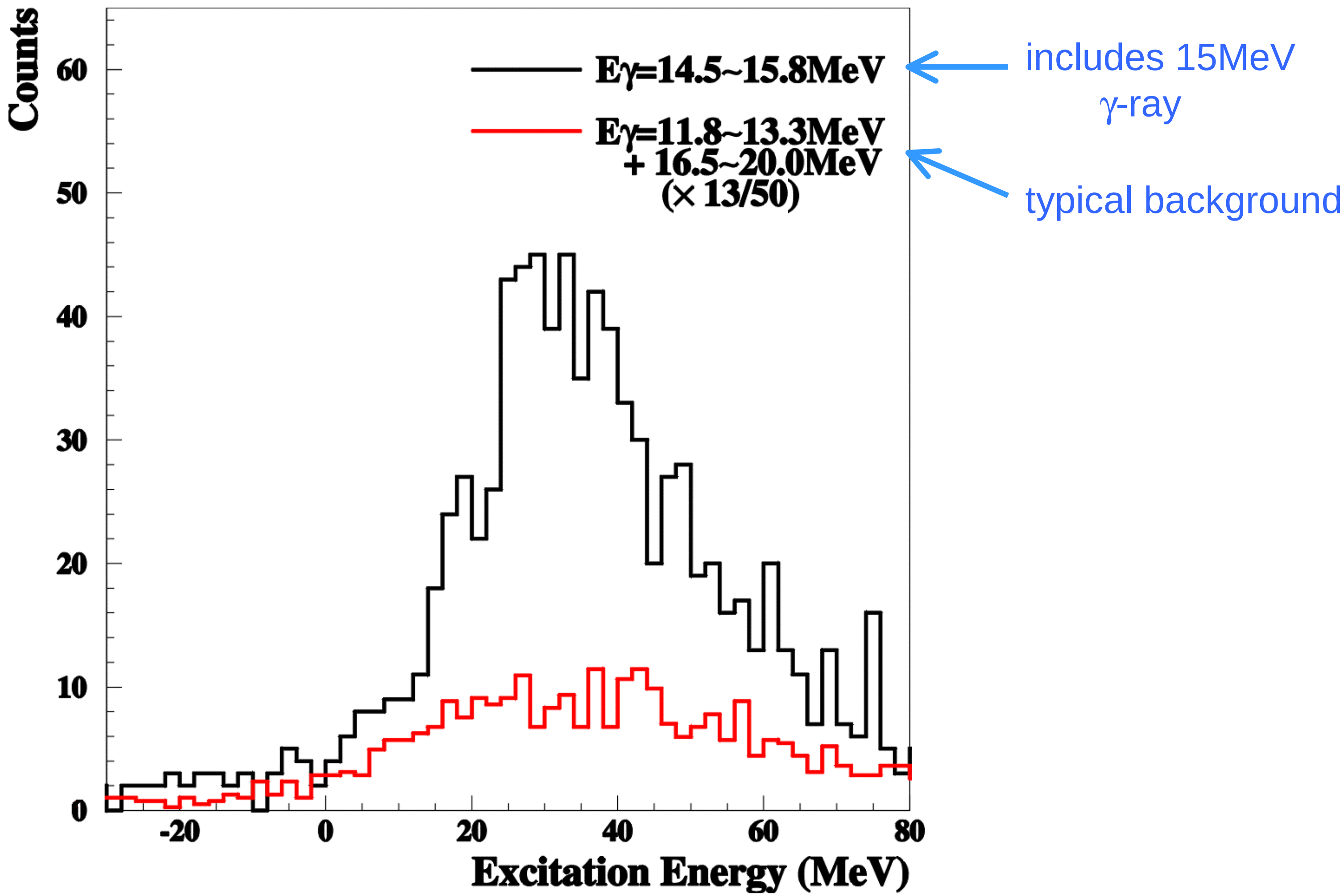
Consistent with 10 MeV/c (FWHM) momentum resolution

Apply excitation energy cut, Ex = -5 ~ 25 MeV



Excitation energy spectrum for 15.11 MeV γ-ray

- mainly coming from Ex ~ 30 MeV
- presumably coming from $^{13}C(K^{-},\pi^{-}\Lambda)^{12}C^{*}$(15.1,T=1) reaction



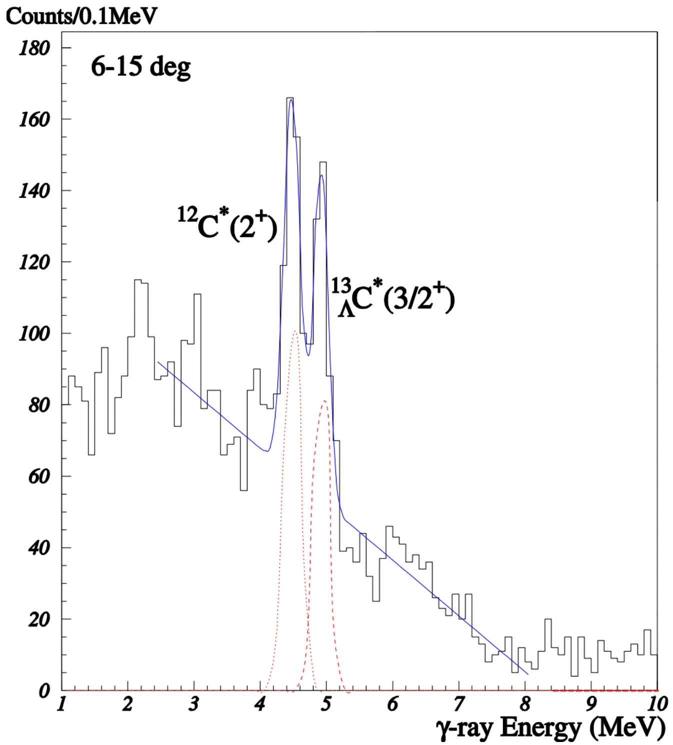
Energy Resolution of γ-ray Detector

4.44 MeV γ-ray from $^{12}C^*(2+)$

- $\Delta E\gamma$ ~ 220 keV (FWHM) at 4.44 MeV
- $\Delta E\gamma$ ~ 350 keV (FWHM) at 11 MeV by $(E\gamma)^{1/2}$ extrapolation

4.9 MeV γ-ray from $^{13}{}_{\Lambda}C^*(3/2+)$

- Ex(3/2+) = 4.915±0.013 MeV
  - ⇔ Ex(3/2+) = 4.89±0.07 MeV KEK/E336 Collaboration (HYP97)
- much improved from KEK/E336



1/2⁻-3/2⁻ splitting in $^{13}_{\Lambda}C$

Estimation of the 3/2⁻-1/2⁻ Energy Splitting

0° < θπ < 7°

$$E_{\gamma} = 11.103 \pm 0.029\ \mathrm{MeV}$$

$$\frac{N(1/2^-) - N(3/2^-)}{N(1/2^-) + N(3/2^-)} = 0.769$$

7° < θπ < 10°

$$E_{\gamma} = 11.016 \pm 0.024\ \mathrm{MeV}$$

$$\frac{N(1/2^-) - N(3/2^-)}{N(1/2^-) + N(3/2^-)} = 0.107$$

10° < θπ < 16°

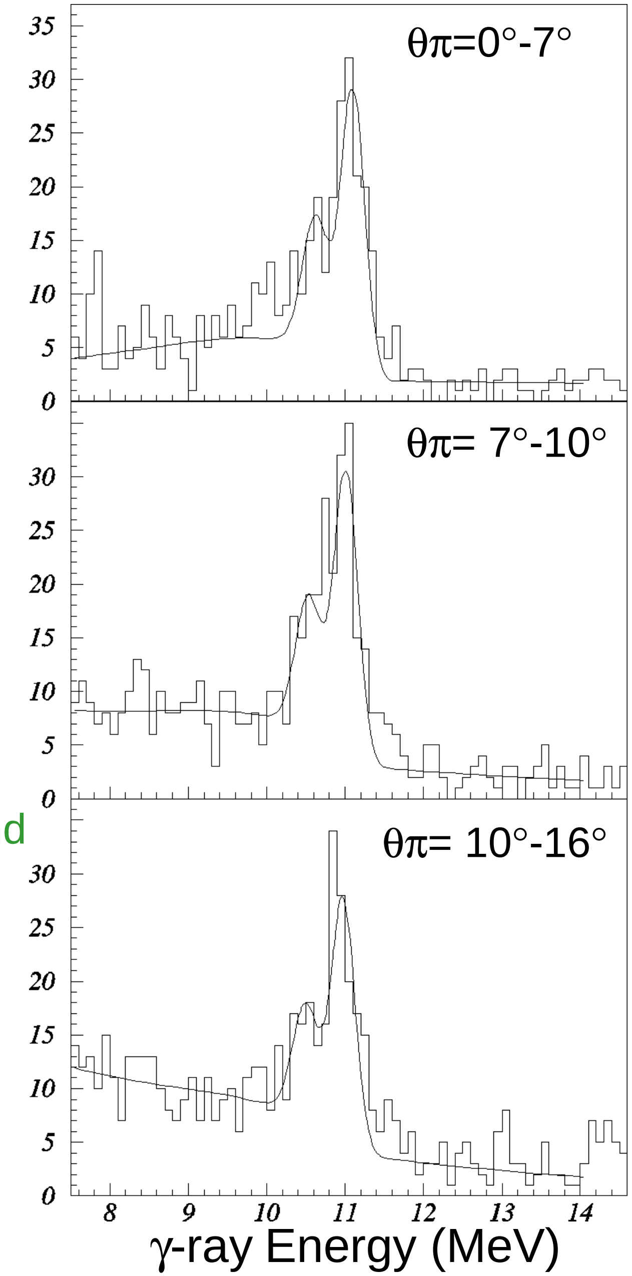
$$E_{\gamma} = 10.980 \pm 0.032\ \mathrm{MeV}$$

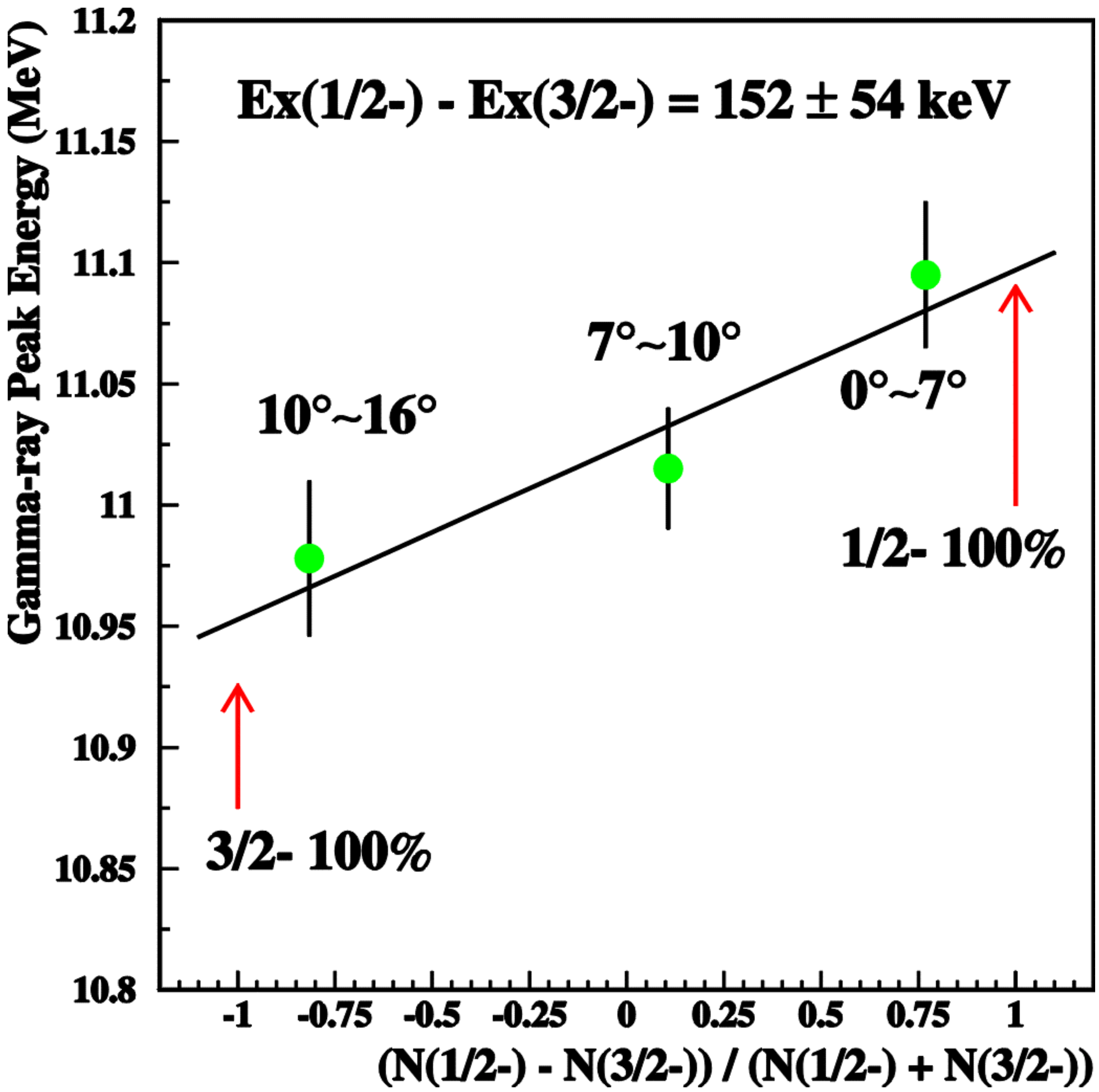
$$\frac{N(1/2^-) - N(3/2^-)}{N(1/2^-) + N(3/2^-)} = -0.816$$

Fitting with

photo peak
+ single escape peak
+ Compton
(generated by MC)
+ background

resolution = 350 keV
exponential background




Ex(1/2-) - Ex(3/2-) = 152 ± 54 keV
Gamma-ray Peak Energy (MeV)
11.2
11.15
11.1
11.05
11
10.95
10.9
10.85
10.8
10°~16°
7°~10°
0°~7°
1/2- 100%
3/2- 100%
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
(N(1/2-) - N(3/2-)) / (N(1/2-) + N(3/2-))

Sources of Systematic Error

Error in γ-ray energy determination

Sources of error	Item	θ_π=0°-7°	θ_π=7°-10°	θ_π=10°-16°	Splitting
Fitting bin size	× 0.5	-7 keV	-11 keV	-13 keV	+19 keV
Energy resolution	300 keV	-16 keV	-2 keV	-19 keV	+2 keV
	400 keV	+7 keV	+2 keV	+19 keV	-9 keV
Background shape	linear	-8 keV	-1 keV	-2 keV	-10 keV
Peak fitting function	2 Gauss	-42 keV	-25 keV	-30 keV	-17 keV

Original parameters: energy resolution = 350 keV, bin size = 100 keV,
background shape: exponential,
fitting peak shape: MC result

Error in $1/2^-$ - $3/2^-$ yield ratio estimation

- $(N_{1/2-}-N_{3/2-})/(N_{1/2-}+N_{3/2-})$ needs theoretical input
- assumed factor 2 ambiguity in theoretical cross section
- ambiguity of energy splitting ~ 30 keV

Overall systematic error ~ 36 keV

Summary

- The $^{13}C(K^-,\pi^-\gamma)^{13}{}_{\Lambda}C$ reaction was measured at P_K=930MeV/c.
- About 250 γ-rays from p $\rightarrow$ $s_{1/2}$ transitions of $^{13}{}_{\Lambda}C$ were observed.
  - About 15 times larger statistics than old BNL experiment.
- We got 220 keV (FWHM) energy resolution at 4.44 MeV, and extrapolated energy resolution was 350 keV (FWHM) at 11 MeV .
  - About 6 times better energy resolution than spectrometer experiments.
- We estimated the 1/2- to 3/2- splitting.

$$Ex(1/2^-) - Ex(3/2^-) = 152 \pm 54(stat.) \pm 36(sys.)\,\mathrm{keV}$$

  - The $1/2^-$-$3/2^-$ energy splitting seems to be very small.
  - It's indicating smallness of Λ spin-orbit interaction and possible contribution of other spin-dependent forces.
- Excitation energies of several states of $^{13}{}_{\Lambda}C$ hypernucleus were estimated.

$$Ex(3/2^+) = 4.915 \pm 0.013\,\mathrm{MeV}$$

$$Ex(3/2^-) = 10.83 \pm 0.03\,\mathrm{MeV}$$ *Preliminary*

$$Ex(1/2^-) = 10.98 \pm 0.03\,\mathrm{MeV}$$ *Preliminary*