Lambda Spin-Orbit Splitting in $^{13}{}_{\Lambda}C$

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- Short History and Ideas of E929 Experiment
- Experimental Setup
- Results: $3/2^{-}$-$1/2^{-}$ splitting in $^{13}{}_{\Lambda}C$
- Summary

AGS/E929 Collaboration

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Short History and Ideas of E929 Experiment

History of Study on Lambda Spin-Orbit Force

Long history

- Longer than my research career !
- started with the spectrometer experiment

Why spin-orbit force ?

- importance of spin-orbit force in normal nuclei
- more details of the lambda-nucleus interaction
  spin dependent forces: spin-orbit, spin-spin, tensor ...
- new feature in lambda-nucleon spin-orbit interaction
  symmetric spin-orbit:
  $$V_{LS} = \vec{L}_{\Lambda N} \cdot \frac{\left(\vec{S}_\Lambda + \vec{S}_N\right)}{2} V_{LS}$$
  anti-symmetric spin-orbit:
  $$V_{ALS} = \vec{L}_{\Lambda N} \cdot \frac{(\vec{S}_\Lambda - \vec{S}_N)}{2} V_{ALS}$$

Experimental results

- spin-orbit splitting was mainly studied for lambda in p-shell
- splitting seems to be very small (< 0.5 MeV) $\Leftrightarrow$ nuclei: ΔE_{LS}~6MeV
- difficulties to determine absolute value of the splitting
  mainly due to the small splitting and limited energy resolution
  also problems in experimental methods in the past

Example of Experiments in the Past

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

Ideas of the experiment

- strong population of "substitutional" states at small angle due to small momentum transfer
- strong population of states with larger angular momentum transfer at larger angle

$$\left.\begin{array}{ll} ^{13}C_{g.s.}(1/2-) \Rightarrow \text{at small angle: } {}^{13}{}_\Lambda C^*(1/2-) & \Delta L=0 \\ \Rightarrow \text{at large angle: } {}^{13}{}_\Lambda C^*(3/2-) & \Delta L=2 \end{array}\right\} \text{Spin-Orbit Doublets}$$

- look at peak positions at 0 degree and 15 degrees

Result of the experiment

- no clear peak position shift was observed

$$\Delta E_{LS} = 0.35 \pm 0.3\,\mathrm{MeV}$$

- difficulties to get finite value of spin-orbit splitting

  due to limited momentum resolution of spectrometer ~ 2 MeV/c

  and limited statistics

  correlation between spectrometer angle and excitation energy calibration $\Rightarrow$ source of systematic error (No magnetic spectrometer perfectly understood !)

Ideas of the E929 Experiment

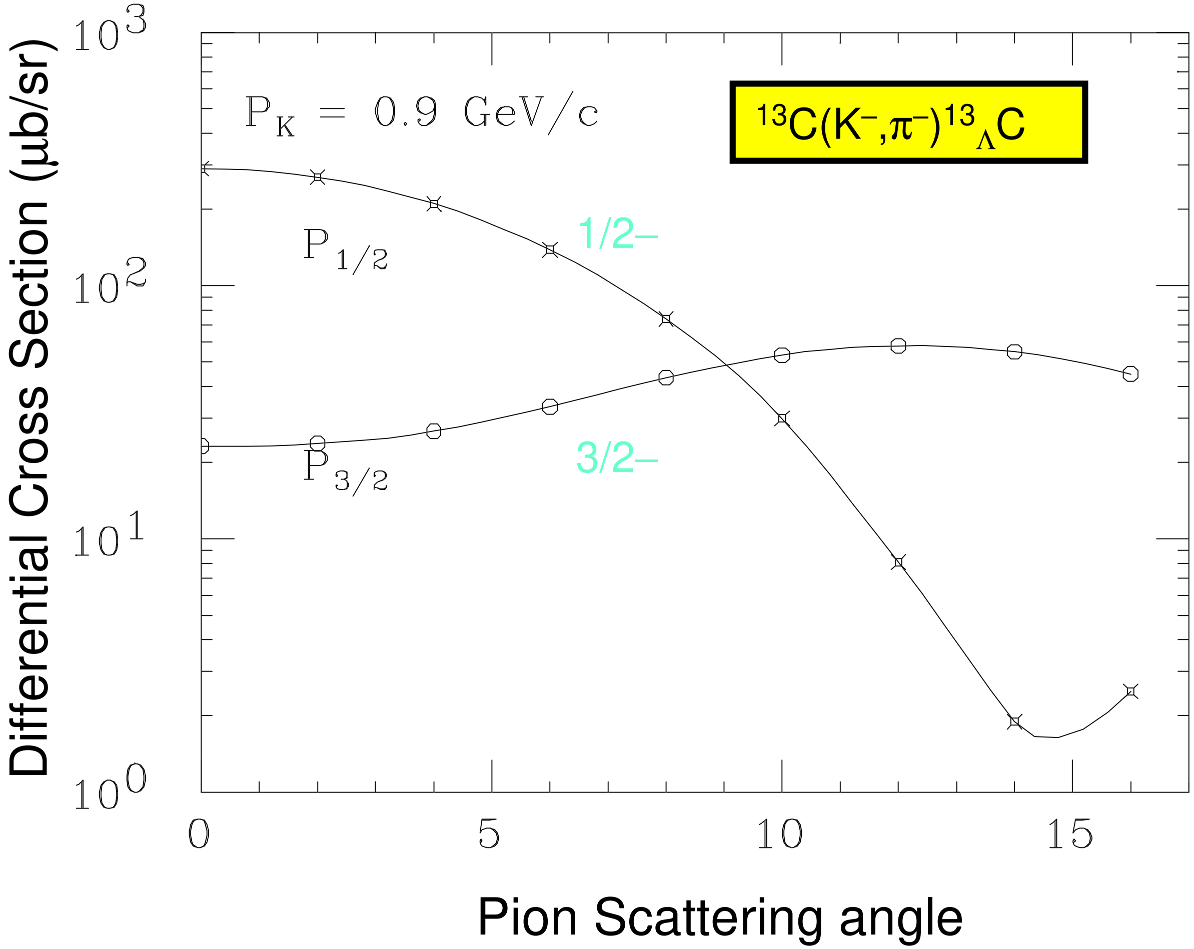
$^{13}C(K^-,\pi^-)^{13}{}_{\Lambda}C$ reaction both at small and large angles

- basic idea of selective population of hypernuclear states is OK
  theoretical calculation + spectrometer acceptance says
  - 0 ~ 9 degrees: N(1/2-) / (N(1/2-)+N(3/2-)) ~ 0.8
  - 9 ~ 16 degrees: N(3/2-) / (N(1/2-)+N(3/2-)) ~ 0.8

- spectrometer: covered wide angular range
  possible to measure both small and large angle data at the same time $\Rightarrow$ reduce systematic error

- ^{13}C target: $^{13}{}_{\Lambda}C$ has simple hypernuclear structure
  lambda in p-shell $\oplus$ $^{12}C_{g.s.}$ core $\Rightarrow$ 3/2- and 1/2- spin-orbit doublets

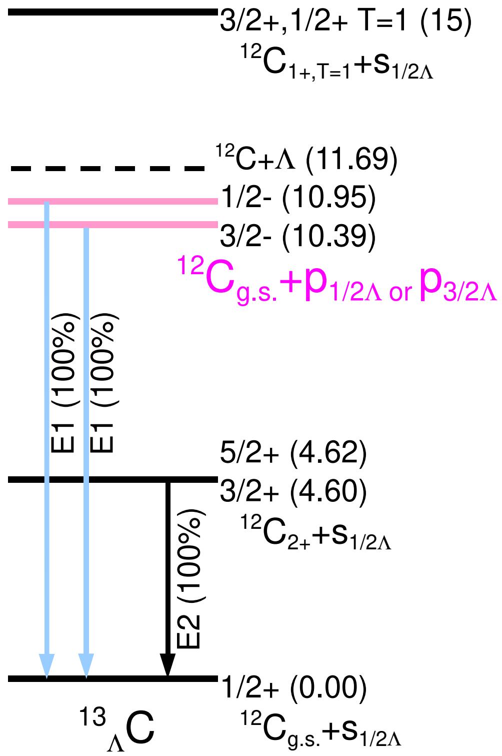
Theoretical cross section calculation by Motoba



Reduction of systematic errors is necessary

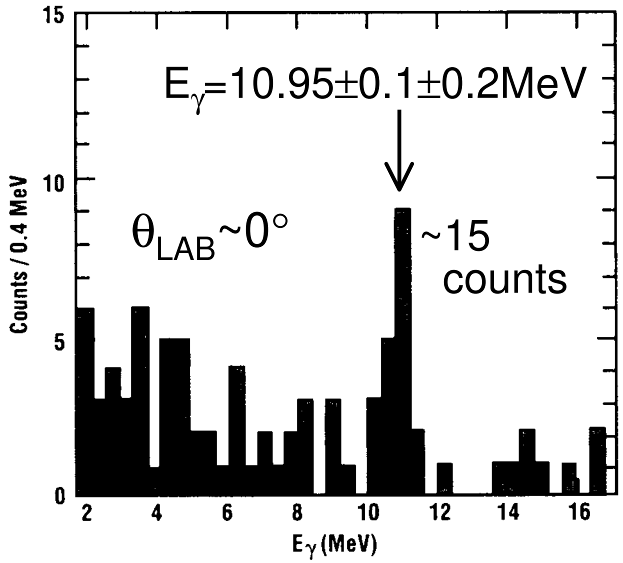
- used spectrometer just to select pion scattering angle
  for selective population of either of 3/2- or 1/2- state only

- used gamma-ray detector to measure excitation energy
  spectrometer and gamma-ray detector are independent
  almost free from systematic error !
  measured gamma-rays around 11 MeV
  effect of Doppler shift exist, but it's small
    - 100 keV in the extreme case
    - much smaller and correctable



11 MeV gamma-ray from ${}^{13}_{\Lambda}C$ hypernucleus

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



Better energy resolution and statistics are essential

- used NaI(Tl) gamma-ray detector
  ~ 0.3 MeV (FWHM) at 11 MeV
  not Ge detector due to detection efficiency

- precision of peak energy ~ 30 keV (r.m.s.), if $N\gamma$ ~ 100

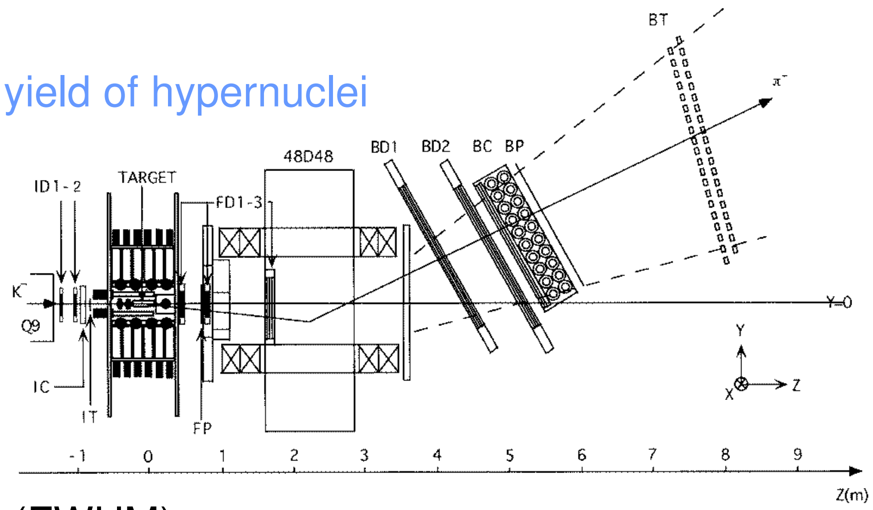
- used 2 sets of 6×6 array of NaI(Tl) modules
  has large volume for better detection efficiency
  segmented for stability under high counting rate
  has mirror symmetry (reduce Doppler shift effect)

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, $K^-/\pi^- > 1$
- 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
  strong background
  used to discriminate K^- decay in-flight events ($K^- \to \mu^- \nu$ or $K^- \to \pi^- \pi^0$)
  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 gamma-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 gamma-ray detector

- need relative and absolute energy calibrations

Short term relative calibration

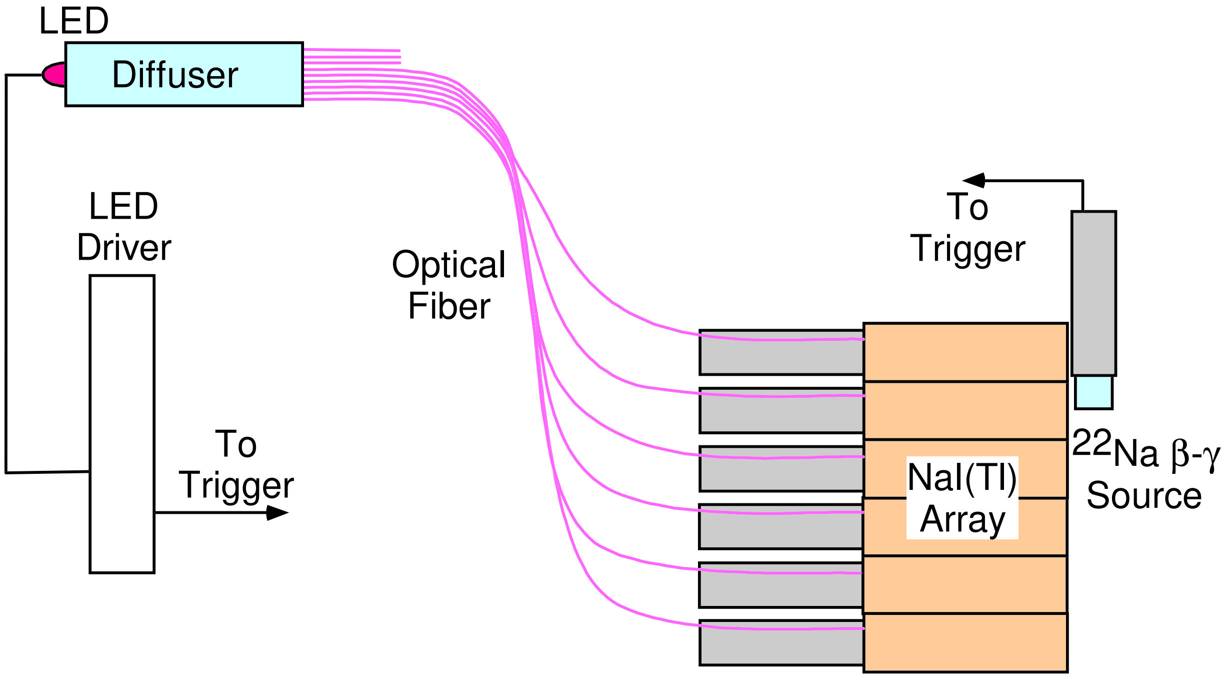
- LED pulsing on all modules

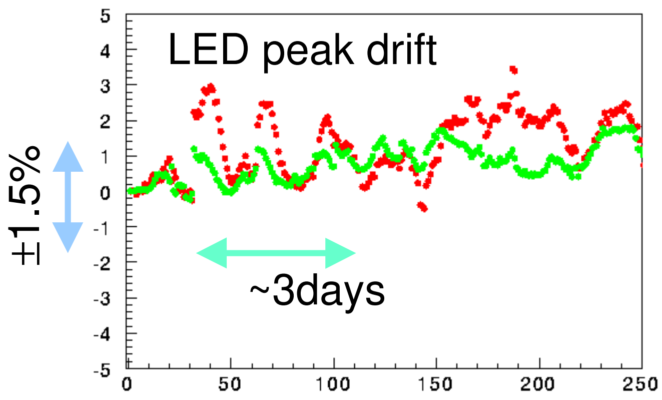
Long term relative calibration

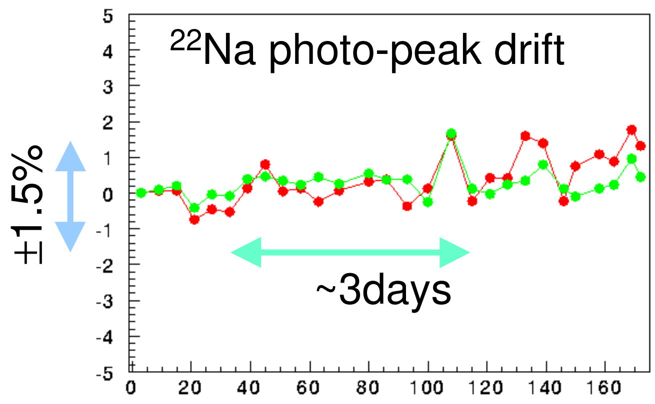
- ^{22}Na gamma-ray on several modules

Absolute energy calibration for all modules

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


LED
Diffuser
LED
Driver
To
Trigger
Optical
Fiber
To
Trigger
NaI(Tl)
Array
22Na β-γ
Source


LED peak drift
±1.5%
~3days


22Na photo-peak drift
±1.5%
~3days

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

Gamma-ray Energy Resolution

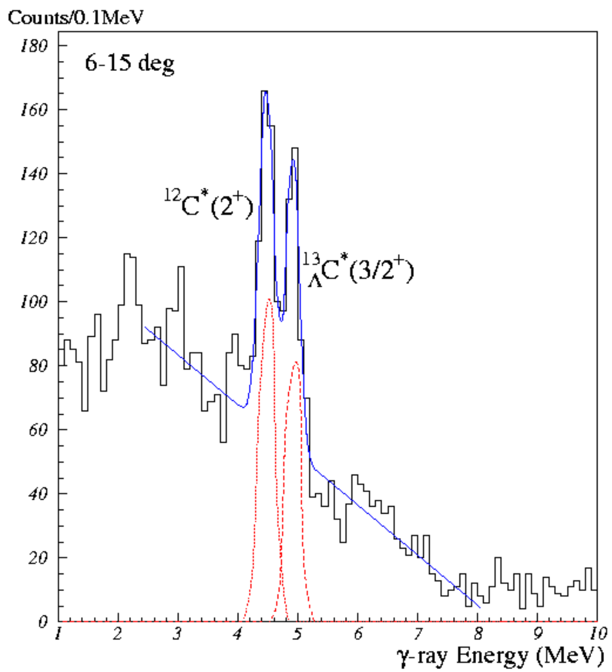
4.44 MeV gamma-ray from $^{12}C^*(2+)$

- $\Delta E\gamma$ ~ 220 keV (FWHM) at 4.44 MeV
- $\Delta E\gamma$ ~ 340 keV (FWHM) by $(E\gamma)^{1/2}$ extrapolation to 11 MeV
- systematic error of absolute energy ~ 30 keV ⇐ to be improved

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

- Ex(3/2+) = 4.915±0.013(sta.)±0.03(sys.) MeV

  ⇔ Ex(3/2+) = 4.89±0.07 MeV KEK/E336 Collab., HYP97
- improved from KEK/E336

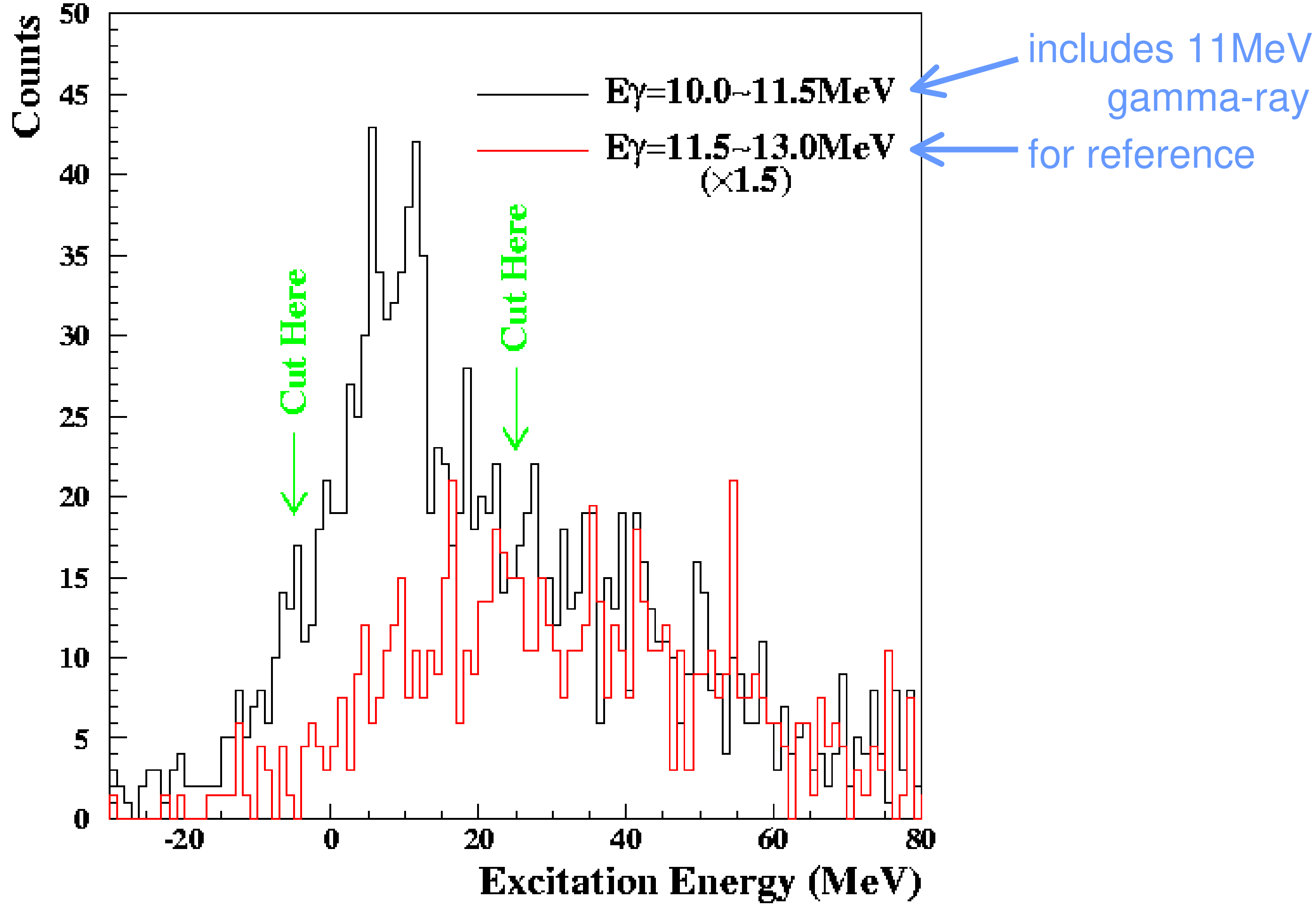


Excitation Energy Spectra

11 MeV gamma-rays are coming from bound region

Consistent with 10 MeV/c (FWHM) momentum resolution

Excitation energy cut, Ex = -5 ~ 25 MeV, is OK



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

$0° < \theta\pi < 7°$

$$E_\gamma = 11.04 \pm 0.023\,\mathrm{MeV}$$

$$\frac{N\left(1/2^-\right) - N\left(3/2^-\right)}{N\left(1/2^-\right) + N\left(3/2^-\right)} \approx 0.68$$

$7° < \theta\pi < 10°$

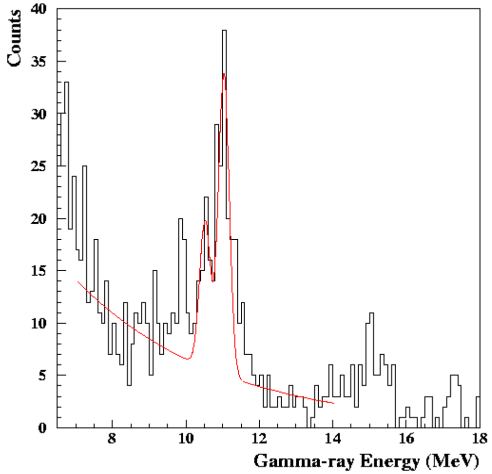
$$E_\gamma = 11.01 \pm 0.027\,\mathrm{MeV}$$

$$\frac{N\left(1/2^-\right) - N\left(3/2^-\right)}{N\left(1/2^-\right) + N\left(3/2^-\right)} \approx 0.10$$

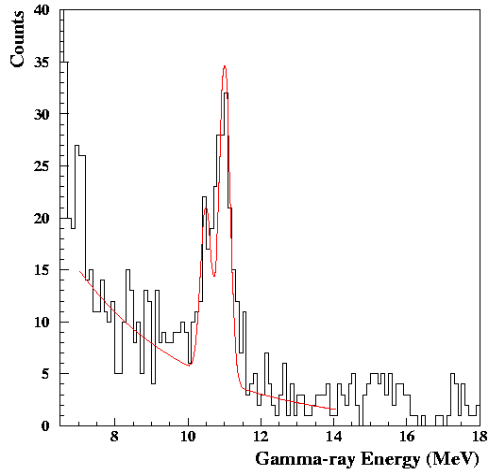
$10° < \theta\pi < 16°$

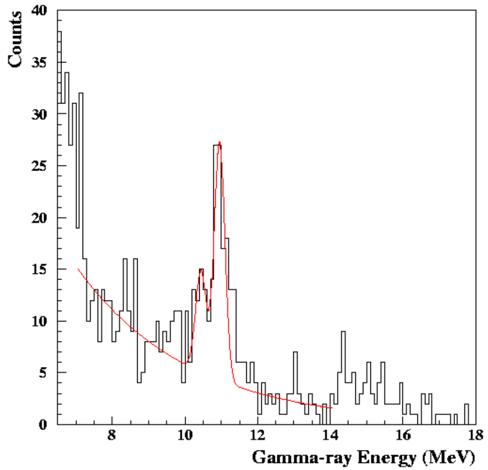
$$E_\gamma = 10.96 \pm 0.028\,\mathrm{MeV}$$

$$\frac{N\left(1/2^-\right) - N\left(3/2^-\right)}{N\left(1/2^-\right) + N\left(3/2^-\right)} \approx -0.71$$



fitting with
- photo peak
- single escape peak
- background





Known Sources of Systematic Errors

Still in progress !

Seems to be minor contribution to the overall error

Source of systematic error	Item	$0° < \theta_\pi < 9°$	$9° < \theta_\pi < 16°$	Difference
Energy resolution assumed	300 keV	-3 keV	-11 keV	+8 keV
	400 keV	+6 keV	+15 keV	-9 keV
Shape of background	pol. 1	-3 keV	± 0 keV	-3 keV
	pol. 2	-1 keV	+3 keV	-4 keV
Shape of single escape peak	450 keV	-9 keV	-8 keV	-1 keV
Fitting bin size	× 0.5	?	?	?
NaI(Tl) hit depth		?	?	?

Summary

- $^{13}C(K^-,\pi^-\gamma)^{13}{}_{\Lambda}C$ reaction was measured at AGS D6 beam line. Kaon momentum was P_K=930MeV.
- About 250 gamma-rays from $p \rightarrow s_{1/2}$ transitions of $^{13}{}_{\Lambda}C$ were observed by NaI(Tl) detector.
    - About 15 times larger statistics than former experiment.
- We got 220 keV (FWHM) energy resolution for 4.44 MeV gamma-ray, and extrapolated energy resolution at 11 MeV was 340 keV (FWHM).
    - About 6 times better energy resolution than spectrometer experiments.
- By changing window of the pion scattering angle, we estimated the energy splitting between the 1/2- and 3/2- states. We obtained the results:

$$Ex\left(1/2^-\right) - Ex\left(3/2^-\right) = 114 \pm 52\,\mathrm{keV}$$ (statistical only) Preliminary

    - still need study on systematic errors
    - need evaluation on the theoretical cross sections and spectrometer acceptance
- The $1/2^-$-$3/2^-$ energy splitting seems to be small, and explanation of the splitting needs also spin-dependent forces other than the spin-orbit force.
    - We cast the result to theorists !