Structure of $^{13}_{\Lambda}C$ Hypernucleus Studied by the $(K^-,\pi^-\gamma)$ Reaction

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- Brief Introduction to E929 Experiment
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- Discussion on Λ-N spin-orbit interactions
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Brief Introduction to E929 Experiment

We measured

$^{13}C(K^-,\pi^-)^{13}{}_{\Lambda}C^*$ reaction followed by γ-decay

$^{13}{}_{\Lambda}C$ level structure precisely

We wish to investigate

Λ-nucleus spin-orbit interaction from spin-orbit doublet

other spin-dependent interactions from other states

Old experiments (CERN, BNL, emulsion) tell

$\Delta E_{LS}(\Lambda)$ is 0.5 MeV level or smaller

- at least 1 order of magnitude smaller than $\Delta E_{LS}(N)$

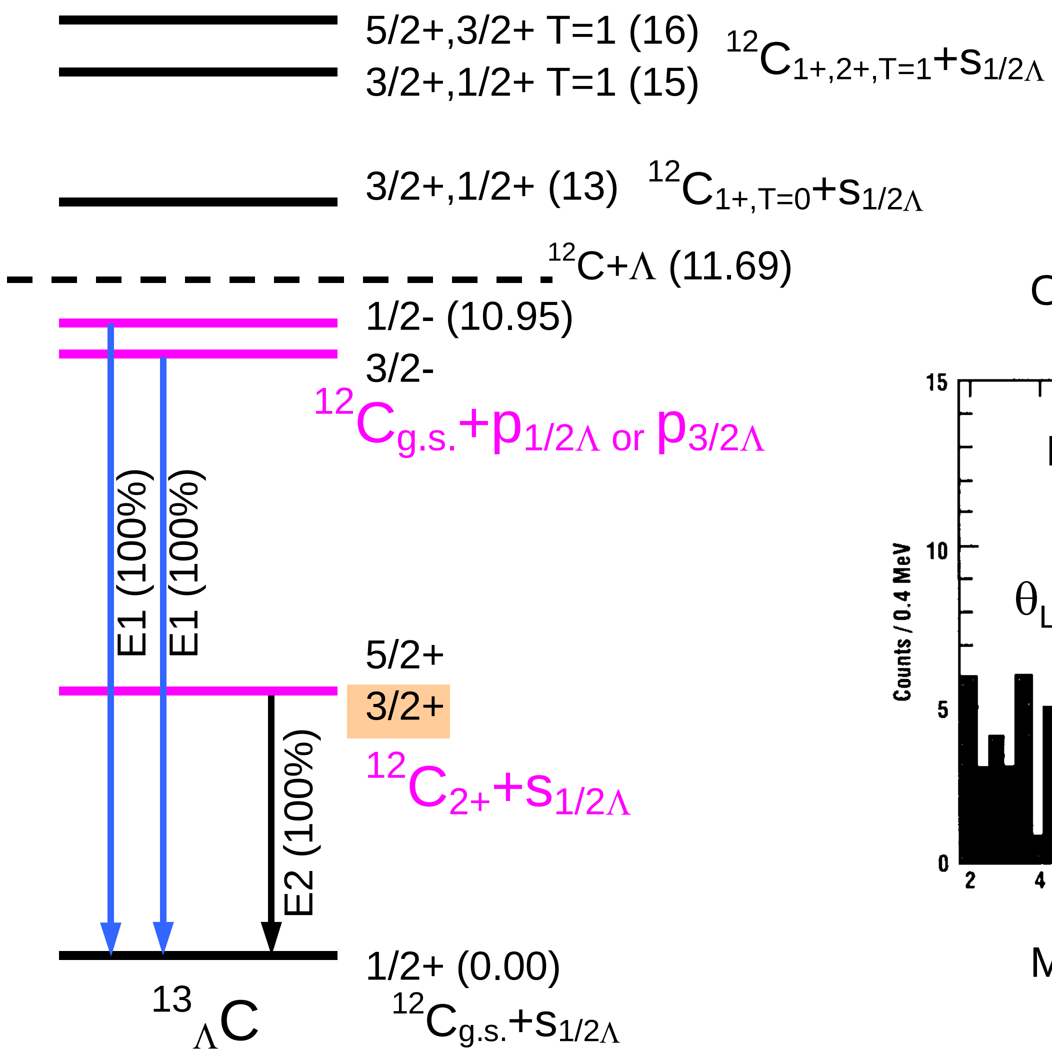
value of $\Delta E_{LS}(\Lambda)$ is still uncertain due to experimental resolution

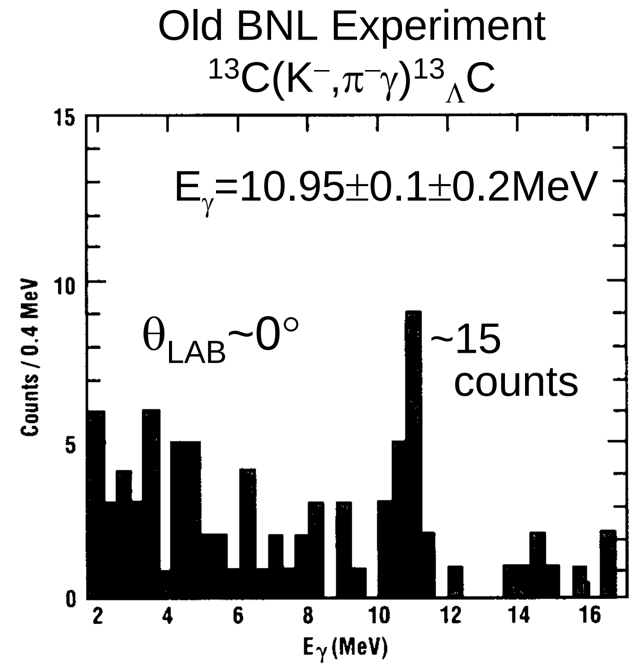
- especially for magnetic spectrometer experiments

E929 can improve accuracy down to 50 keV level by γ-ray spectroscopy

Level scheme and γ decay

$^{13}C(K^-,\pi^-)^{13}{}_{\Lambda}C$ reaction $\Rightarrow$ neutron-hole $\otimes$ $s_{1/2\Lambda}$, p_{Λ}

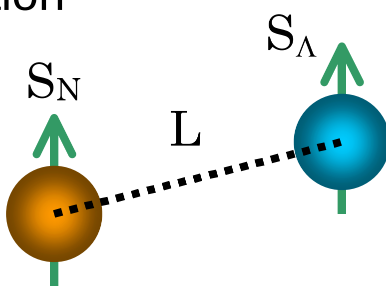




M.May et al., PRL78 (1997) 4343

New feature in Λ-nucleus spin-orbit interaction

symmetric (V_{LS}) and anti-symmetric (V_{ALS}) spin-orbit interaction



$$V_{LS} = v_{LS}\,(\vec{S}_N + \vec{S}_\Lambda)\cdot\vec{L}, \quad V_{ALS} = v_{ALS}\,(\vec{S}_N - \vec{S}_\Lambda)\cdot\vec{L}$$

Λ spin-orbit ($U_{LS}(\Lambda)$) and N spin-orbit ($U_{LS}(N)$) interactions

$$U_{LS}(\Lambda) = u_{LS}(\Lambda)\,\vec{S}_\Lambda\cdot\vec{L} = \frac{V_{LS} - V_{ALS}}{2}, \quad U_{LS}(N) = u_{LS}(N)\,\vec{S}_N\cdot\vec{L} = \frac{V_{LS} + V_{ALS}}{2}$$

${}^{13}_{\Lambda}C$ structure and V_{LS} / V_{ALS}

- $p_{3/2-\Lambda}$ - $p_{1/2-\Lambda}$ splitting
  essentially sensitive to $U_{LS}(\Lambda)$
- level energy of 3/2+ (${}^{12}C_{2+}$+$s_{1/2\Lambda}$) state
  sensitive to $U_{LS}(N)$

$$Ex\left(3/2+;{}^{13}_{\Lambda}C\right) - Ex\left(2+;{}^{12}C\right) = \underset{\Delta}{-23} + \underset{S_\Lambda}{58} + \underset{S_N}{427} - \underset{T}{46}\ keV$$

by D.J.Millener

We can estimate the values of V_{LS} and V_{ALS}

Experimental Setup

General Setup

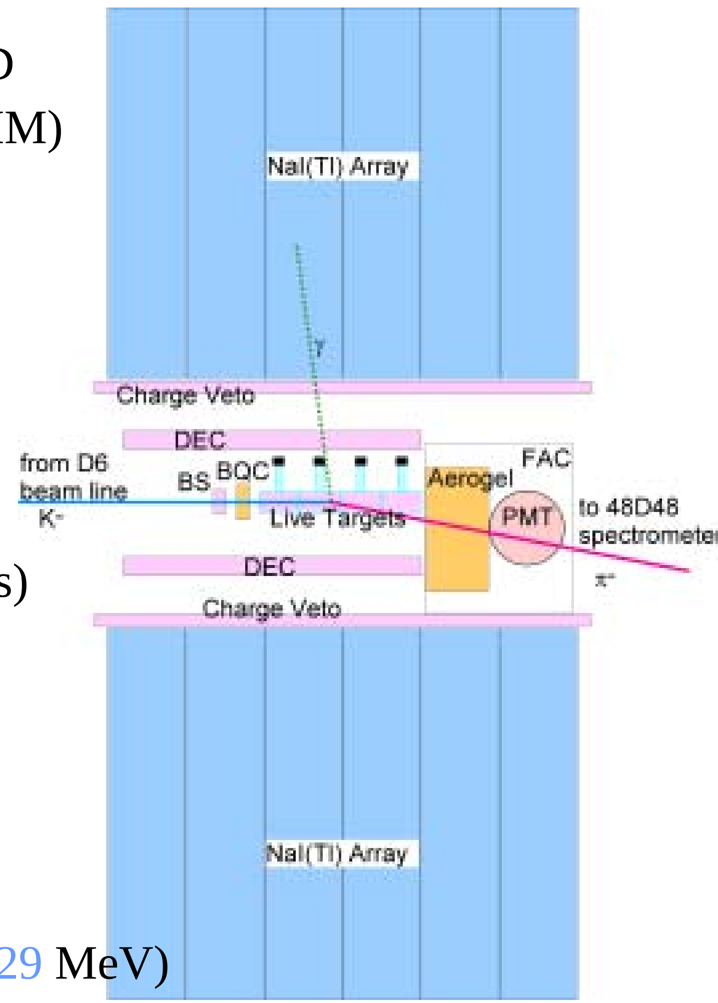
AGS D6 beam line

- ~ 10^5 K^-/burst, $K^-/\pi^- > 1$, p_K = 930 MeV/c, 21 G K^- on target

48D48 spectrometer

- large angular acceptance, clear particle ID
- momentum resolution ~ 15 MeV/c (FWHM)

^{13}C benzene target ~ 10 g/cm^2



γ-ray detector

NaI(Tl) detector

- 2 sets of 6×6 array of modules
- module size 2.5” ×2.5” ×12”

energy resolution

- central 2×2 array: 8% at 0.662 MeV(^{137}Cs)
  mainly used for this analysis
- other modules: ~13% at 0.662 MeV

energy calibration

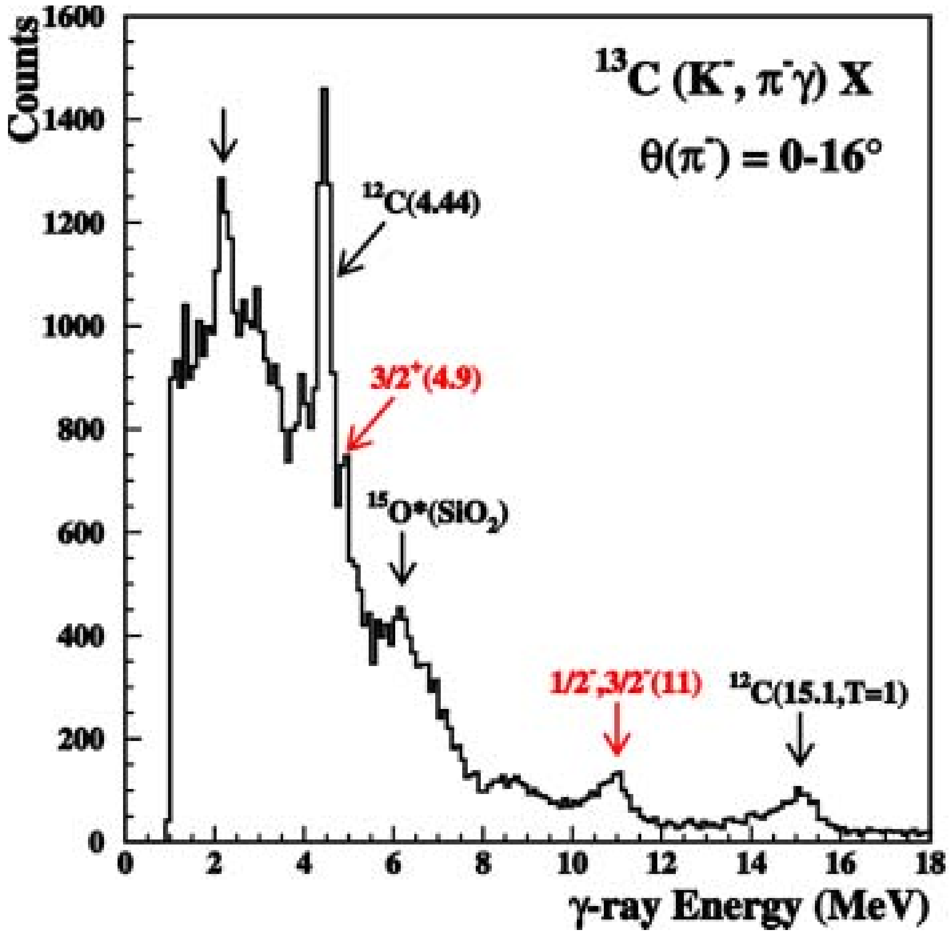
- LED pulsing
- ^{22}Na γ-ray (0.511, 1.275 MeV)
- ^{58}Ni(n,γ) (8.999 MeV), ^{13}C(α,nγ)^{16}O (6.129 MeV)

Overview of Analysis Results

γ-ray spectrum

several discrete peaks

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



Selection of hypernuclear γ-ray is possible to select spectrometer information

known nuclear γ-rays can be used for off-line energy calibration

3/2+ $\rightarrow$ g.s. transition was observed

spin-orbit doublet were very close with each other

Separation of γ-ray transitions

necessary to separate $p_{3/2-}$→g.s. and $p_{1/2-}$→g.s. transitions

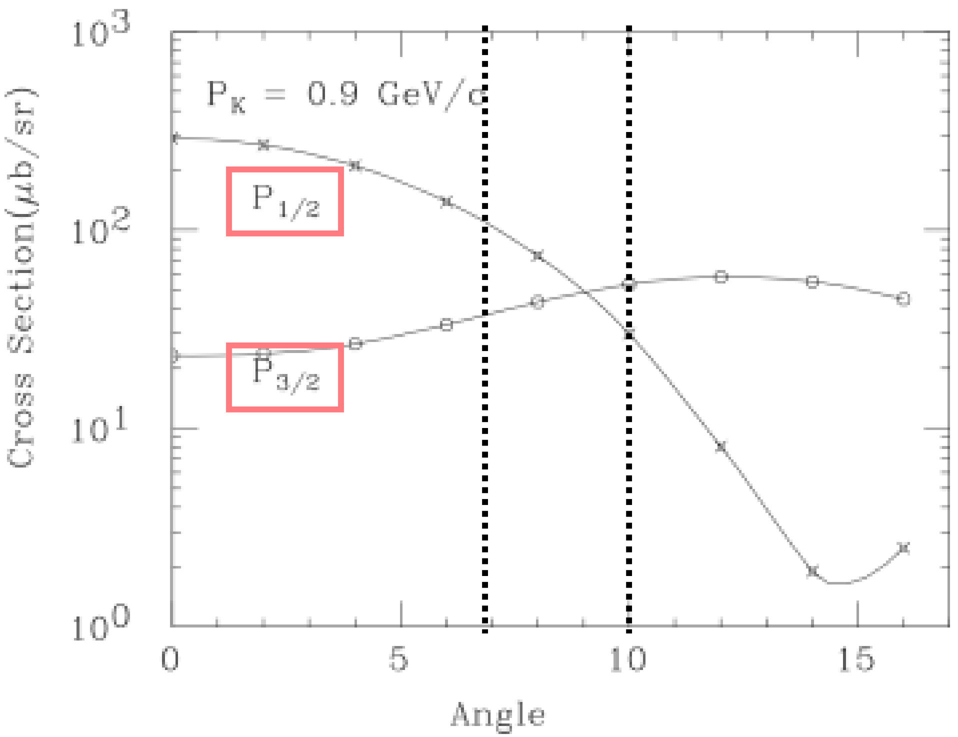
- difference of angular dependences of differential cross section

$^{13}C_{g.s.}(1/2-)$ → $^{13}{}_{\Lambda}C^*(1/2-)$ $\Delta L=0$

$^{13}C_{g.s.}(1/2-)$ → $^{13}{}_{\Lambda}C^*(3/2-)$ $\Delta L=2$

$^{13}C(K^-,\pi^-)^{13}{}_{\Lambda}C^*$

- theoretical estimation (by T.Motoba)



Estimation of the 3/2⁻-1/2⁻ energy splitting

$0° < \theta_\pi < 7°$

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

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

$7° < \theta_\pi < 10°$

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

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

$10° < \theta_\pi < 16°$

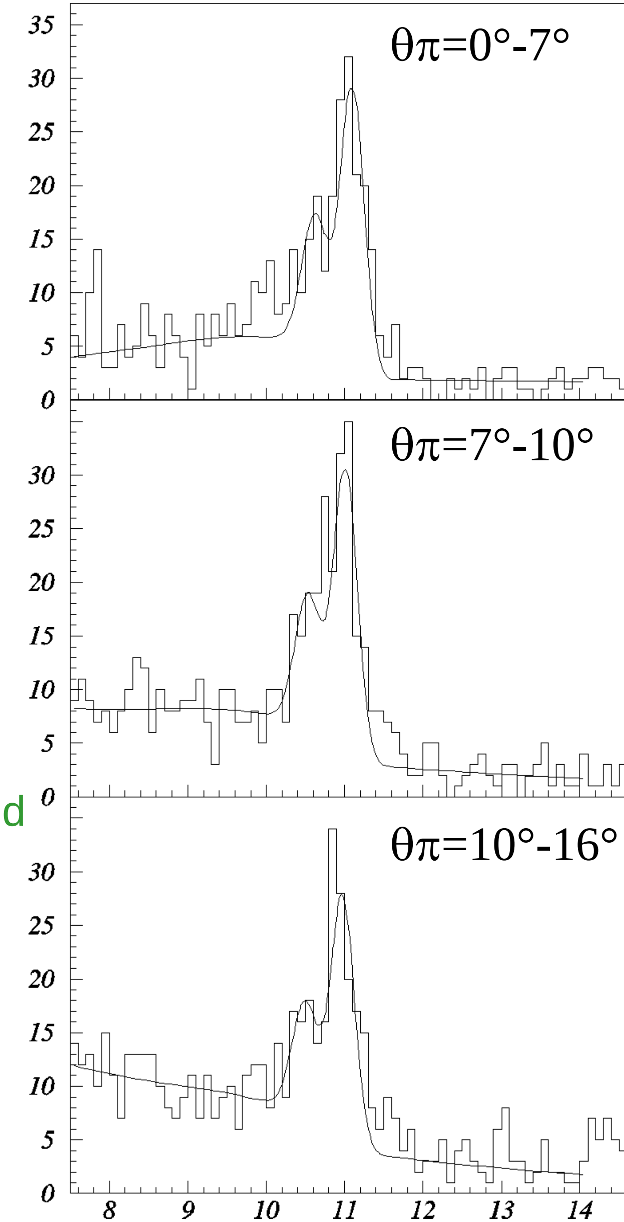
$E_\gamma = 10.980 \pm 0.032\,\mathrm{MeV}$

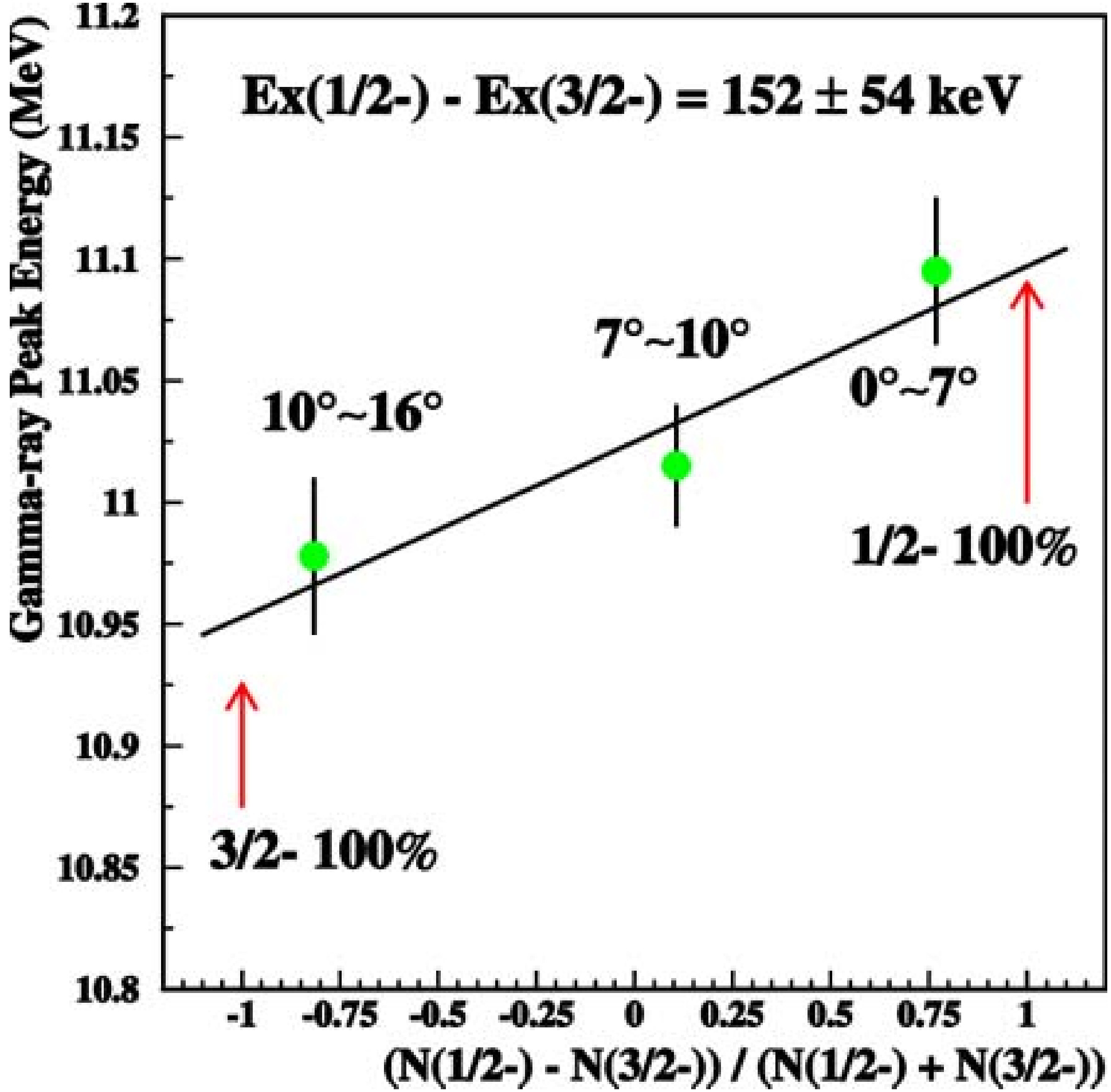
$$\frac{N(1/2^-) - N(3/2^-)}{N(1/2^-) + N(3/2^-)} = -0.816$$

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-))

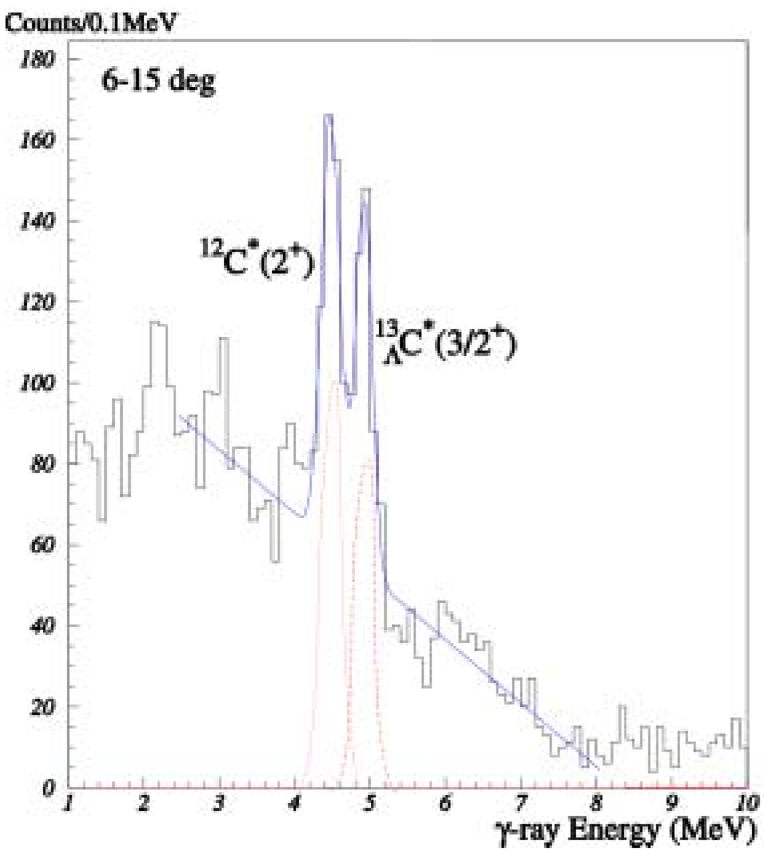
Level energy of 3/2+ state

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

- Ex(3/2+) = 4.880 ± 0.010(stat) ± 0.017(syst) MeV

  ⇔ Ex(3/2+) = 4.89 ± 0.07 MeV KEK/E336 Collaboration

- much improved from KEK/E336



Discussion on Λ-N spin-orbit interactions

$U_{LS}(\Lambda)$ spin-orbit interaction

estimated from $p_{1/2-}$ - $p_{3/2-}$ splitting

$$Ex(1/2^-) - Ex(3/2^-) = 154 \pm 54 \pm 36\ keV$$

consistent with old BNL data

$$Ex(1/2^-) = 10.982\ MeV$$

$$Ex(3/2^-) = 10.830\ MeV$$

theoretical prediction

- shell-model calculation (by D.J.Millener)

$$Ex(1/2^-) - Ex(3/2^-) = \underset{\Delta}{42} + \underset{S_\Lambda}{280} - \underset{T}{215}\ keV$$

consistent with ${}^{9}_{\Lambda}$Be data from BNL/E930

$$U_{LS}(\Lambda) \approx 40\ keV$$

- level compression due to threshold effect (by C.M.Keil et al.)

  $p_{1/2-}$ state is pushed down to avoid level crossing

  Ex(1/2-) and Ex(3/2-) difference get smaller

$U_{LS}(N)$ spin-orbit interaction

considerably large energy shift from Ex($^{12}C_{2+}$)

$$Ex(3/2^+; {}^{13}_{\Lambda}C) - Ex(2^+; {}^{12}C) = 441 \pm 10 \pm 17\ keV$$

combined with theoretical calculation

$$U_{LS}(N) \approx 500\ keV$$

$V_{LS} \sim V_{ALS}$

relatively natural in quark-based model

Summary

The $^{13}C(K^-,\pi^-\gamma)^{13}{}_{\Lambda}C$ reaction was successfully measured

- 11 MeV γ-rays from 1/2- and 3/2- states
- 4.9 MeV γ-rays from 3/2+ state

P-shell spin-orbit splitting in $^{13}{}_{\Lambda}C$ was estimated

$$Ex(1/2^-) - Ex(3/2^-) = 154 \pm 54 \pm 36\ keV$$

$$Ex(1/2^-) = 10.982 \pm 0.031(stat) \pm 0.056(syst)\ MeV$$

$$Ex(3/2^-) = 10.830 \pm 0.031(stat) \pm 0.056(syst)\ MeV$$

Excitation energy of 3/2+ state was obtained

$$Ex(3/2^+) = 4.880 \pm 0.010(stat) \pm 0.017(syat)\ MeV$$

$$Ex(3/2^+;{}^{13}_{\Lambda}C) - Ex(2^+;{}^{12}C) = 441 \pm 10 \pm 17\ keV$$

These data tell $V_{LS} \sim V_{ALS}$