

DREB 2012 (Pisa, Italy)  
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# **Study of $^{16}\text{C}$ by Neutron Knockout Reaction**

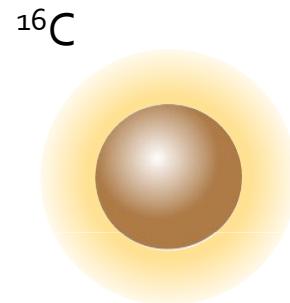
# Outline

- Motivation
- Known Information
- Experimental Method
- Experimental Setup
- Data Analysis
- Result
- Discussion

# Motivation

## Very Few Previous Experiments

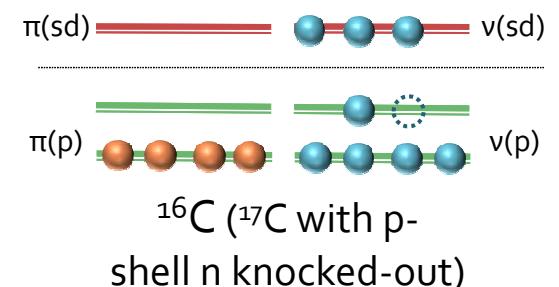
- Lack of information about high-lying states in  $^{16}\text{C}$
- Especially, for spectroscopic information
- No bound states in  $^{16}\text{B}$  : No  $\beta$ -decay Measurement



## Importance of Cross-Shell Interaction

- Cross-shell interaction is the essential part to explain the features of nuclei far from the stability, especially, neutron-rich ones.

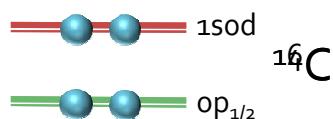
(K. Sieja, *et al.*, *Nucl. Phys. A* 857 (2011) 9–15 )



# Known Information

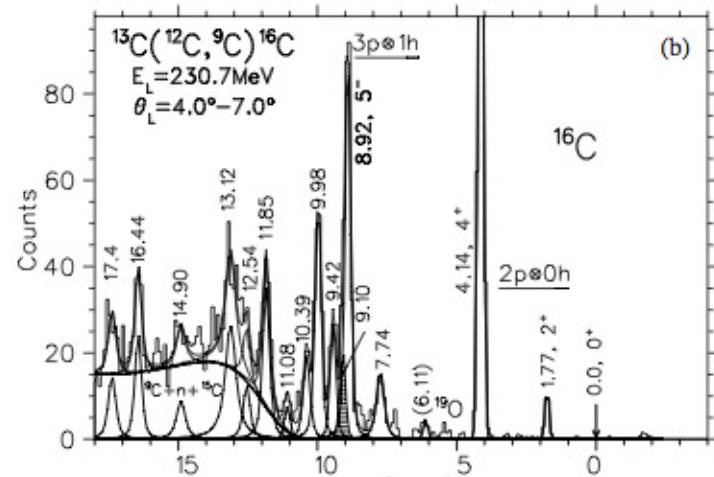
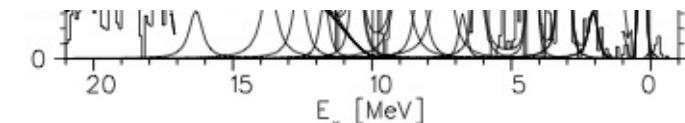
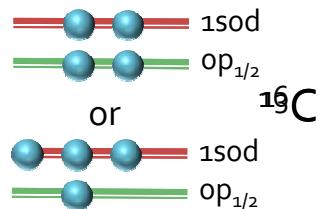
## $^{14}\text{C}(\text{t}, \text{p})^{16}\text{C}$

- 2n transfer reaction
- 6 bound states & 1 unbound state
- G.S. of  $^{14}\text{C}$ :  $\nu(\text{op})$  closure  
→  $\nu(1\text{sod})^2$  dominant



## $^{13}\text{C}(\text{t}, \text{p})^{16}\text{C}$

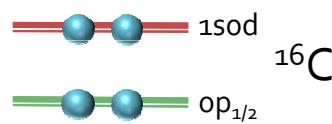
- 3n transfer reaction
- 14 states ( $7.74 \sim 17.4$  MeV)
- $\nu(\text{sd})^2$  &  $\nu(\text{sd})^3(\text{p})^{-1}$  dominant
- states with large 'J' were favorably excited



# Known Information

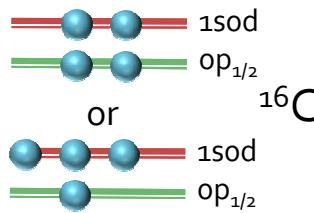
## $^{14}\text{C}(\text{t},\text{p})^{16}\text{C}$

- $2n$  transfer reaction
- 6 bound states & 1 unbound state
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→  $\nu(1s\text{od})^2$  dominant



## $^{13}\text{C}(\text{^{12}C},\text{^{9}C})^{16}\text{C}$

- $3n$  transfer reaction
- 14 states ( $7.74 \sim 17.4$  MeV)
- $\nu(\text{sd})^2$  &  $\nu(\text{sd})^3(\text{p})^{-1}$  dominant
- states with large ' $J'$  were favorably excited



$E_x$ (MeV)	$J^\pi$	
	$^{14}\text{C}(\text{t},\text{p})^{16}\text{C}$	$^{13}\text{C}(\text{^{12}C},\text{^{9}C})^{16}\text{C}$
0.00	$0^+$	
1.77	$2^+$	$2^+$
3.03	$0^+$	
3.98	$2^-$	
4.09	$3^+$	
4.14	$4^+$	$4^+$
6.11	$(2^+, 3^-, 4^+)$	$S_n = 4.25$
7.74(2)		$(1^- \sim 4^-)$
8.92(2)		$5^-$
9.10(3)		
9.42(2)		
9.98(2)		

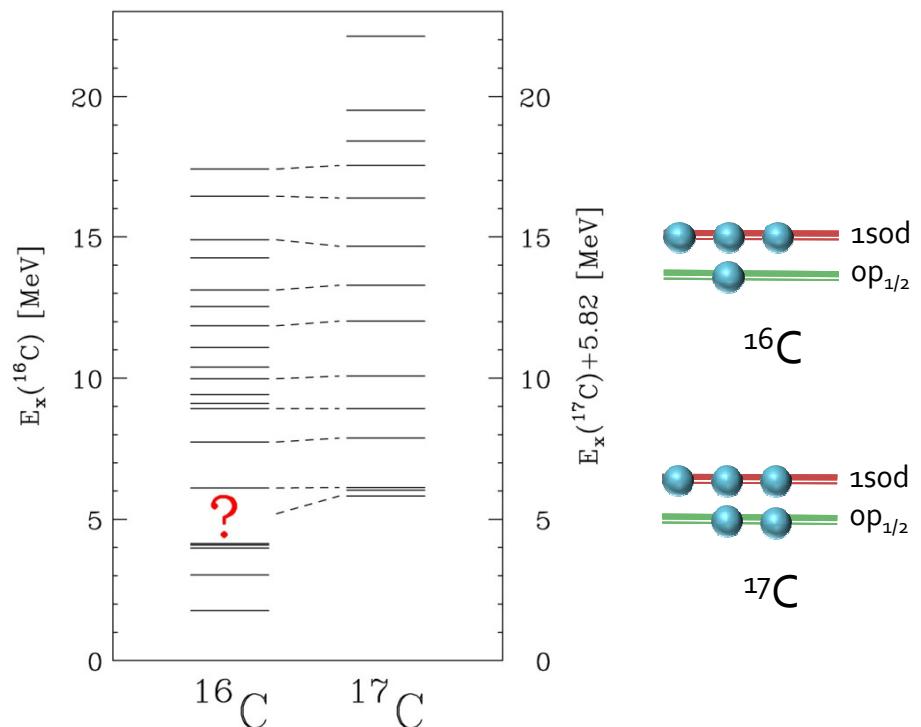
H.T. Fortune, *Phys. Lett. B* **70**, 408–410 (1977).  
H.G. Bohlen, et al. *Nucl. Phys. A* **734**, 345–348 (2004)

# Known Information

Pairs	$E_x(^{17}\text{C})$	$E_x(^{16}\text{C})$	$\Delta E_x$
0	0.00 (3/2 <sup>+</sup> )	?	?
1	0.31 (5/2 <sup>+</sup> )	6.11 (3 <sup>-</sup> )	5.80
2	2.06 (7/2 <sup>+</sup> )	7.74 (4 <sup>-</sup> )	5.68
3	3.10 (9/2 <sup>+</sup> )	8.92 (5 <sup>-</sup> )	5.82
4	4.25	9.98	5.73
5	6.20	11.85	5.65
6	7.47	13.12	5.65
7	8.85	14.90	6.05
8	10.56	16.44	5.88
9	11.71	17.4	5.69



One-to-one correspondence in  $E_x$   
between  $^{17}\text{C}$  and  $^{16}\text{C}$  ascribed to  
 $v(\text{sd})^3$  in  $^{17}\text{C}$  &  $v(\text{sd})^3(1\text{p})^{-1}$  in  $^{16}\text{C}$

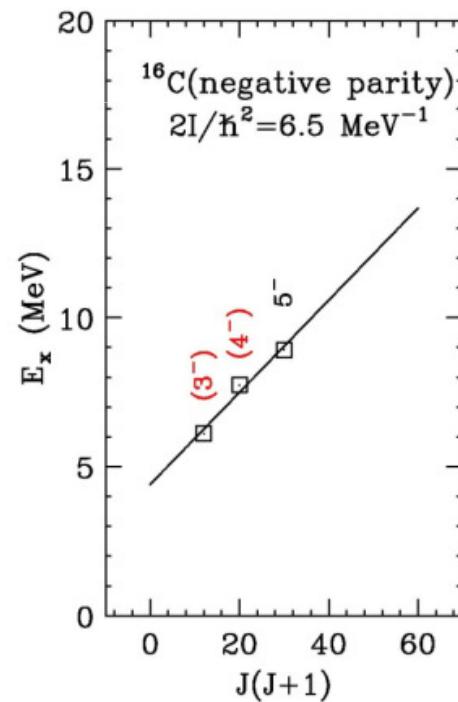


# Known Information

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$J^\pi$  of  $^{17}\text{C}$   
state

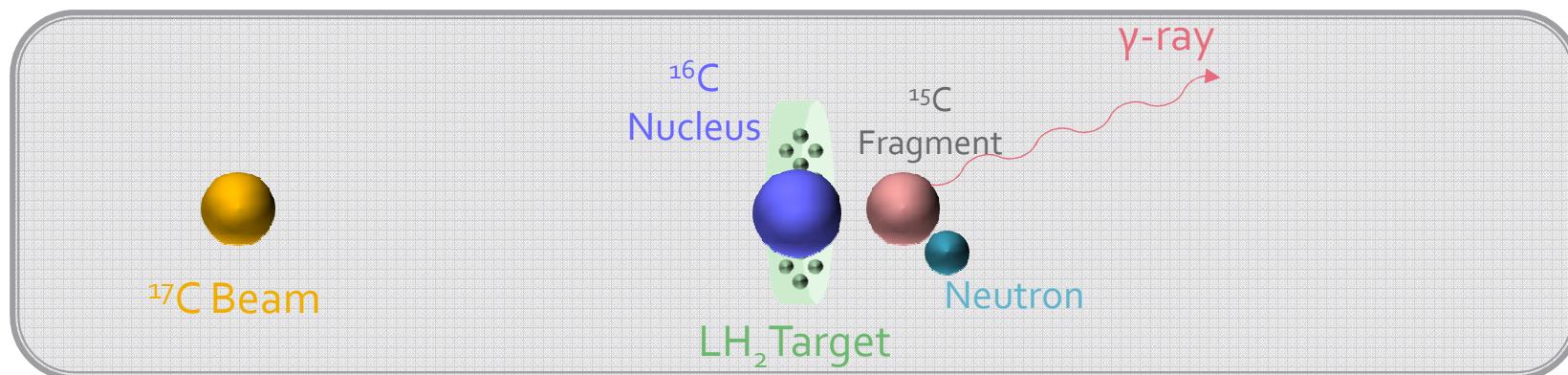
$J^\pi$  of  $^{16}\text{C}$   
state



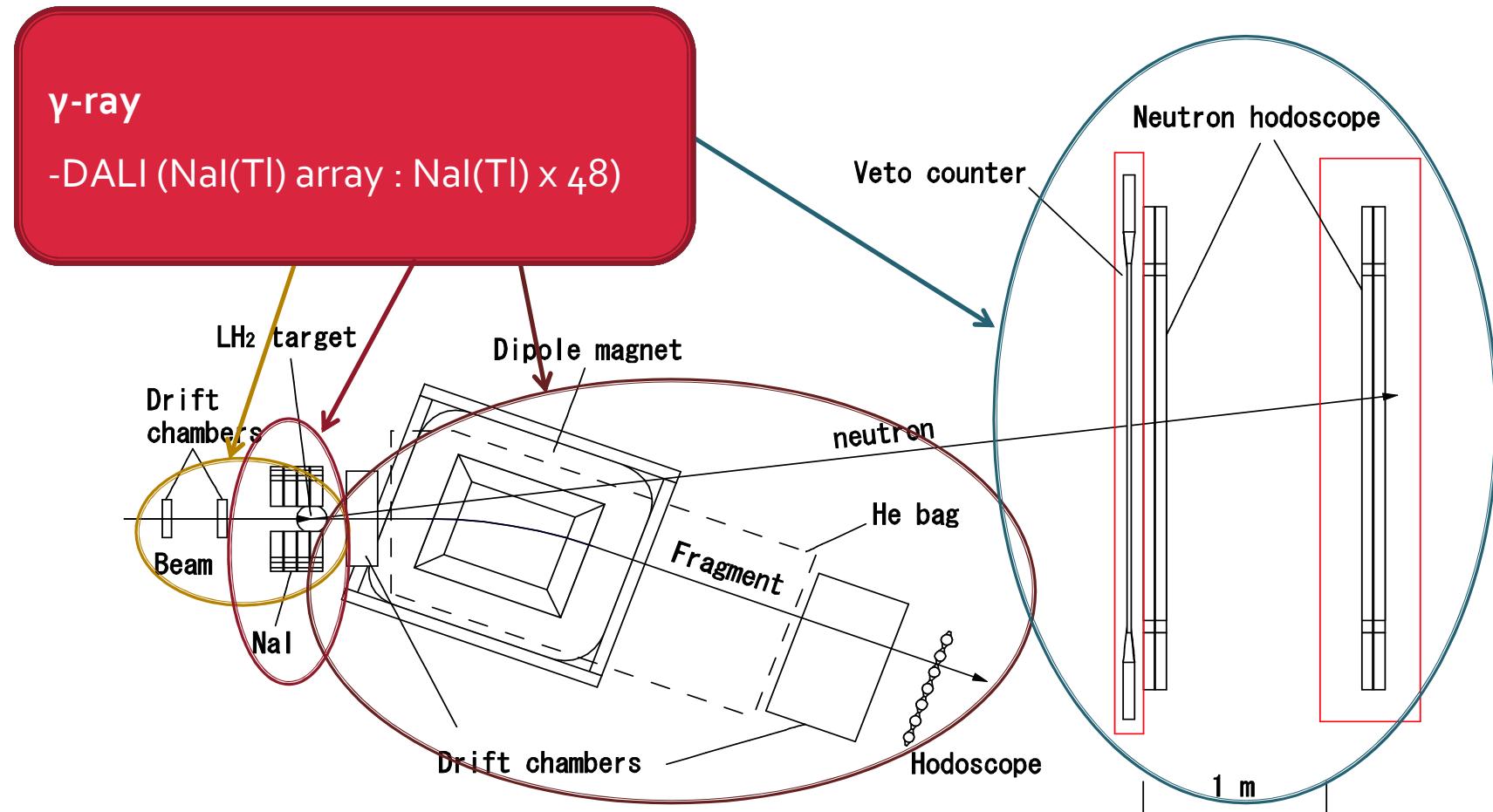
Rotational-band-like structure (Missing partner)

# Experimental Method

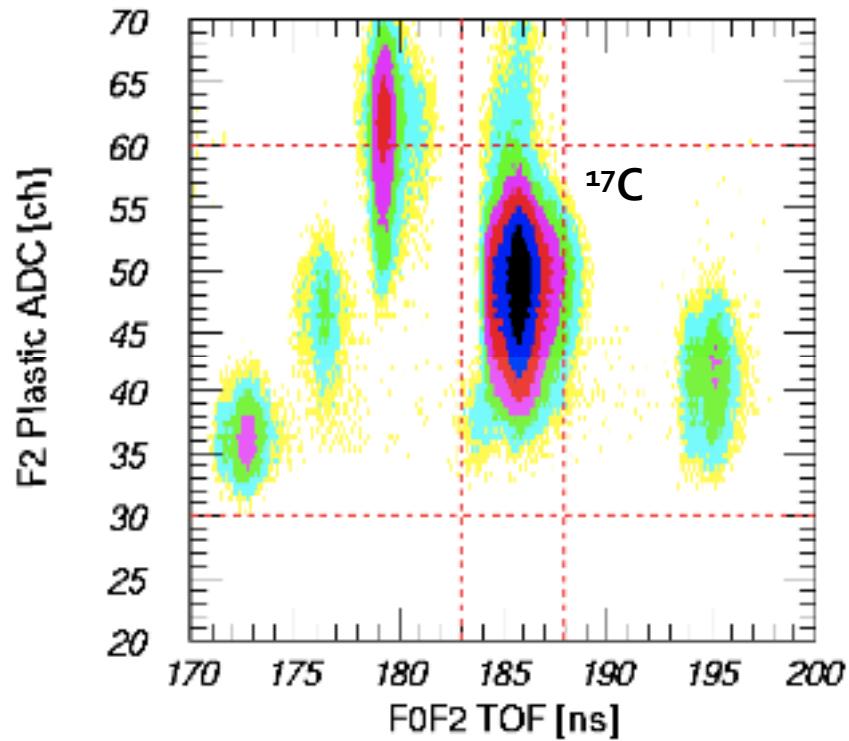
1. **Reaction :** Secondary Beam ( $^{17}\text{C}$ , 70 MeV/u) + Secondary Target ( $\text{LH}_2$ , 119 mg/cm<sup>2</sup>)  
→ Target nuclei in the excited state ( $^{16}\text{C}^*$ )
  - One Neutron Knockout :  $^{17}\text{C}(\text{p},\text{pn})^{16}\text{C}^*$
2. **Fragments :** Detect all of them
  - Charged particle (nucleus) : Dipole + Hodoscope
  - Neutron : Neutron detector
  - $\gamma$ -ray : NaI(Tl) array
3. **Reconstruction**
  - Invariant mass :  $E_{inv} = \sqrt{(E_n + E_f)^2 - |\mathbf{p}_n + \mathbf{p}_f|^2}$
  - Relative energy :  $E_{rel} = E_{inv} - (M_n + M_f)$
  - Excitation energy :  $E_x = E_{rel} + S_n + E_\gamma$



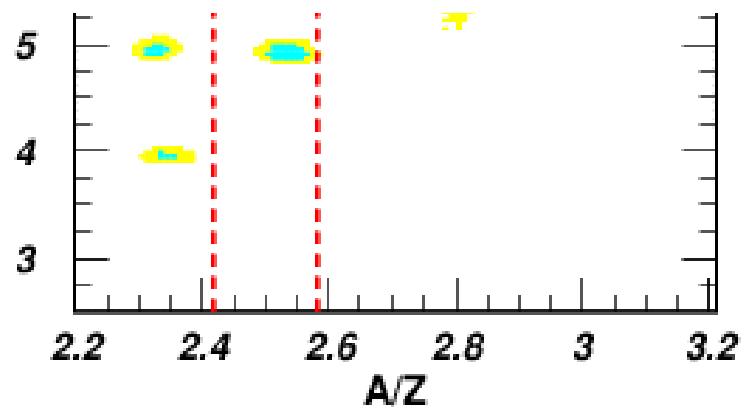
# Experimental Setup



# Data Analysis : PID

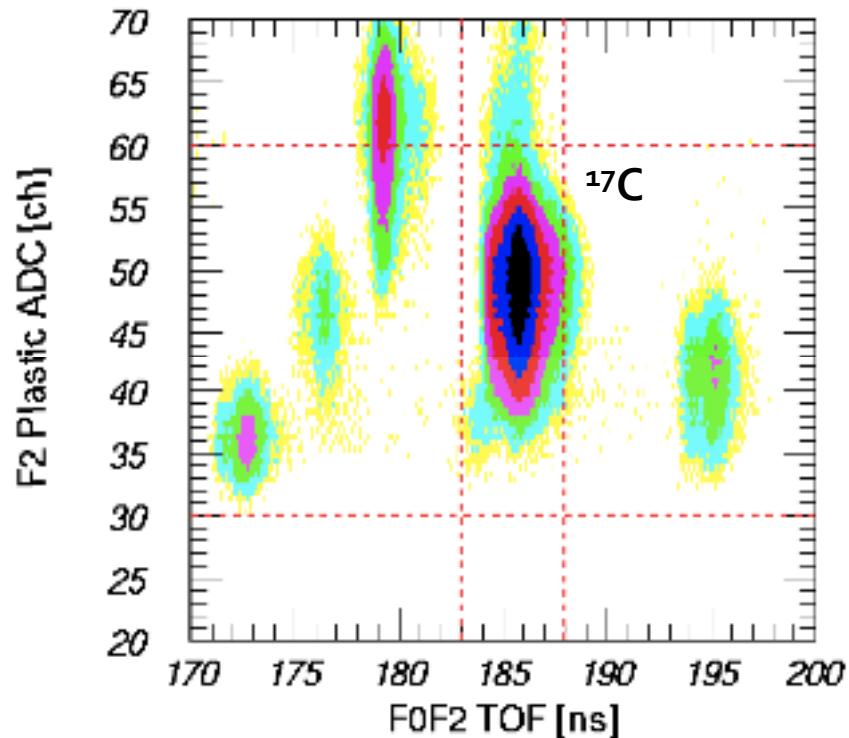


Beam PID  
( $^{17}\text{C}$  selected)

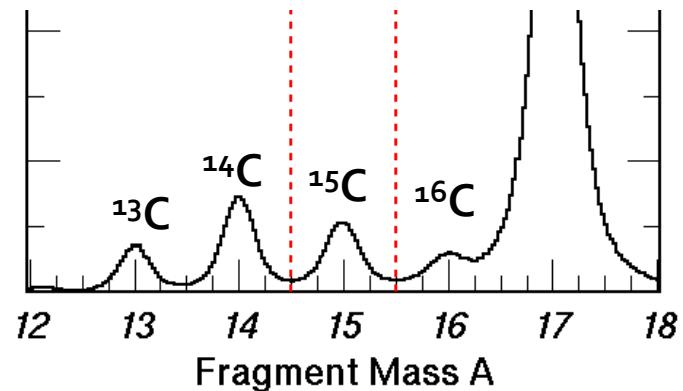


Fragment PID  
( $^{15}\text{C}$  selected)

# Data Analysis : PID



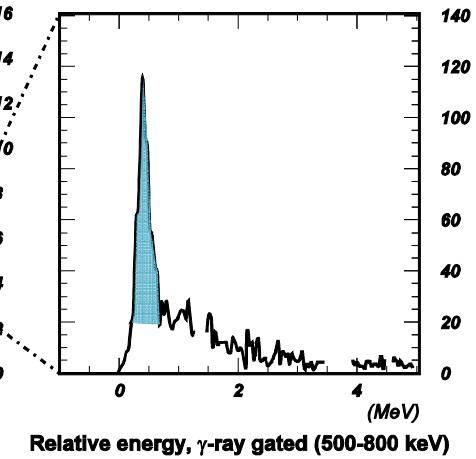
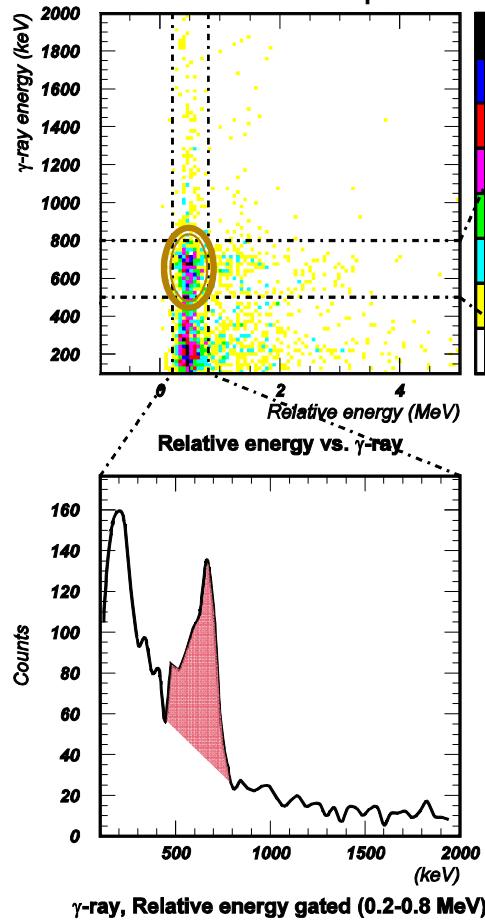
Beam PID  
( $^{17}\text{C}$  selected)



Fragment Mass  
( $^{15}\text{C}$  selected)

# Data Analysis : Preliminary Result

Without acceptance correction



Relative Energy Spectrum  
0.46 MeV

$\gamma$ -ray Energy Spectrum  
0.74 MeV  
(excited state of  $^{15}\text{C}$ )

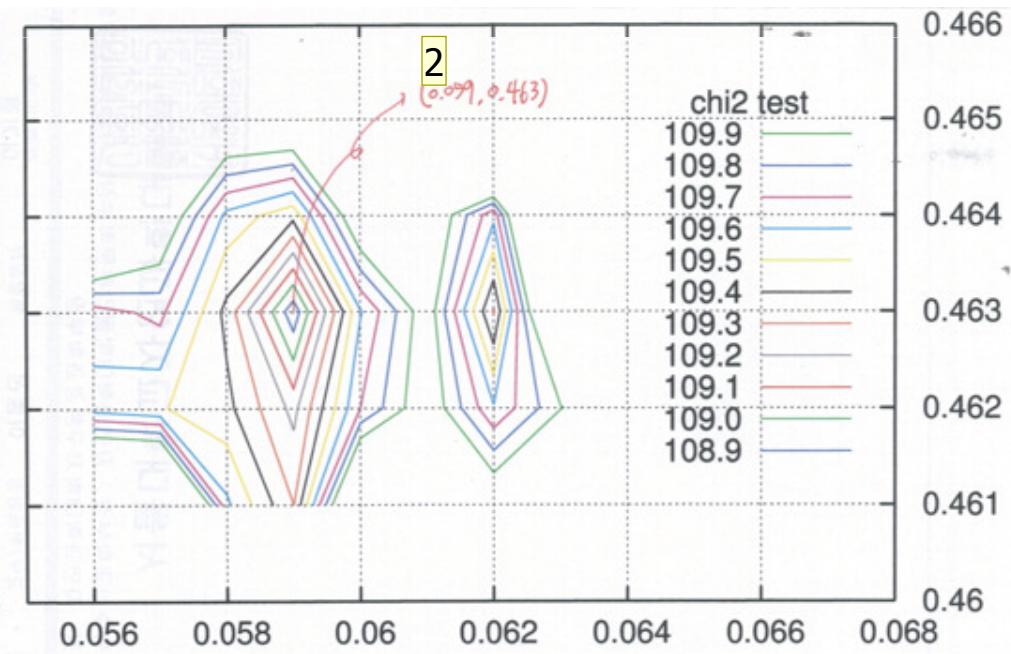
$$\text{Invariant Mass} : E_{inv} = \sqrt{(E_n + E_f)^2 - |P_n + P_f|^2}$$
$$\text{Excitation Energy} : E_x = E_{inv} - M_n - M_f + S_n + E^*$$

(n : neutron, f : fragment)

Two peaks in Coincidence  
(New State in  $^{16}\text{C}$ )

# Data Analysis : Fitting Method

- Fitting Method
  - Breit-Wigner function ( $I$ -dependent)  
(Lane and Thomas, *Rev. Mod. Phys.* 30 (1958), 257)
  - $\chi^2$ -fitting method
    - Trial fit with many response functions with different  $E$  and  $\Gamma$  : finding  $\chi^2_{\min}$
    - Fitting error range :  
$$\chi^2 \leq \chi^2_{\min} + 1$$



## Diapositiva 13

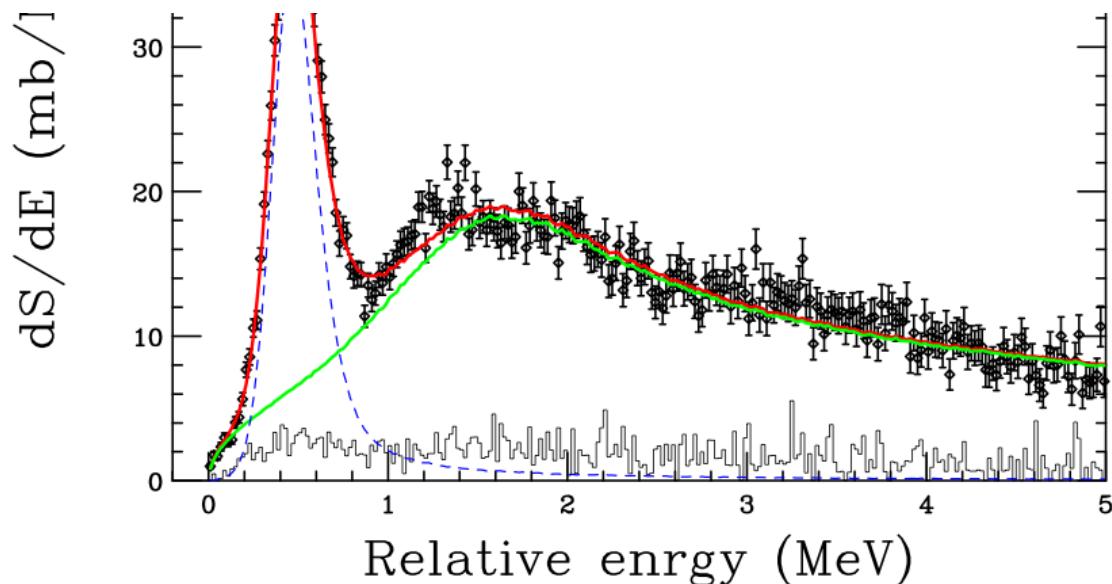
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- 2 Fit again to get more clear contour plot.

종원 황; 23/03/2012

# Result : Invariant Mass Spectrum

Acceptance corrected



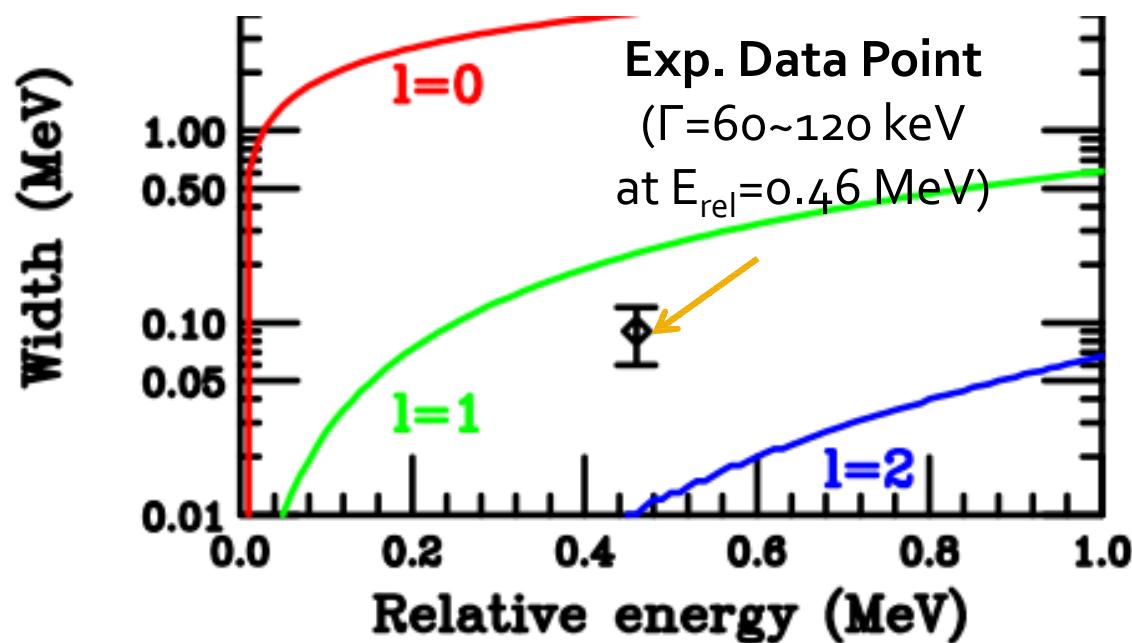
$$E_{rel} = E_{inv} - (M_{^{15}C} + M_n)$$

## The Peak

- $E_{rel} = 463 \pm 3$  keV
- $\Gamma = 60 \sim 120$  keV
- $\sigma = 13.92 \pm 0.13$  mb

# Discussion : Width (60~120 keV)

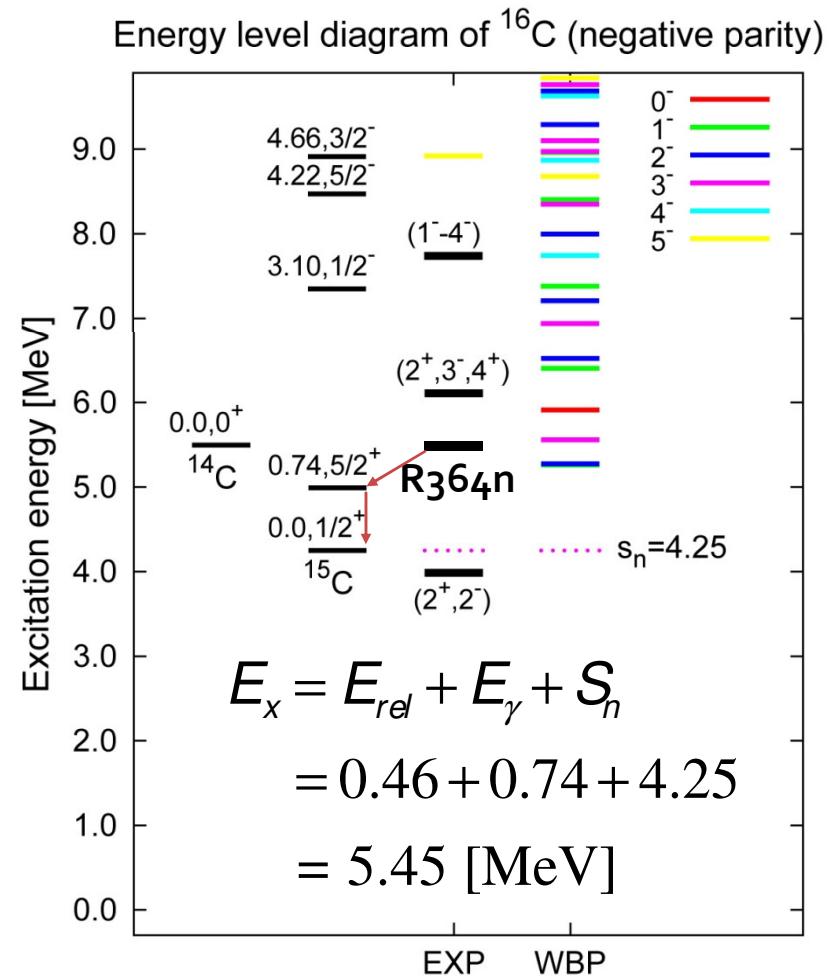
- Theoretical single-particle width ( $\Gamma_{sp}$ ) in decay of a neutron with  $l$



Calculated value means  
maximum.

The peak  
is likely through p-wave  
neutron emission.  
(negative parity)

# Discussion : Energy (0.46 MeV)



New State at 5.45 MeV in  $^{16}\text{C}$  (R<sub>364</sub>n)

n

$5/2^+_1$  state at 0.74 MeV in  $^{15}\text{C}$

$\gamma$

Ground state in  $^{15}\text{C}$

Triple Coincidence  
n- $\gamma$ - $^{15}\text{C}$

# Discussion : Cross Section (13.92 mb)

- One-neutron Knock-out Cross Section
  - $^{17}\text{C} \rightarrow ^{16}\text{C}^* + \text{n}$
- Calculation of Theoretical Cross Section
  - Formalism : Glauber model
    - Based on eikonal approximation
    - $\sigma_{knockout} = \sigma_{stripping} + \sigma_{diffractive} + \sigma_{Coulomb}$
    - P. G. Hansen & J. A. Tostevin, Direct Reactions with Exotic Nuclei. *Annu. Rev. Nucl. Part. Sci.* **53**, 219–261 (2003).
  - MOMDIS (C.A. Bertulani et al., *Com. Phys. Comm.* **175** (2006) 372)
    - Based on Glauber model
    - Parameters for the calculation
      - Wood-Saxon pot. for a single particle w.f. of a knocked-out neutron in  $^{17}\text{C}$
      - Nucleon density distribution of  $^{17}\text{C}$

# Discussion : Cross Section (13.92 mb)

Shell model calculation for spectroscopic factor (WBP int.) :  $\langle ^{17}\text{C}|^{16}\text{C} \rangle$

State	$E_x$ (MeV)	$C^2S$	State	$E_x$ (MeV)	$C^2S$
$0^+_1$	0.0	0.034979	$1^-_1$	5.26	0.033679
$2^+_1$	2.39	1.606712	$2^-_1$	<u>5.27</u>	<u>0.80104</u>
$0^+_2$	3.58	0.000020	$3^-_1$	5.56	0.026169
$2^+_2$	4.81	0.319859	$0^-_1$	5.91	0.047583
$4^+_1$	4.92	0.381353	$1^-_2$	6.40	0.418044
$3^+_1$	5.86	0.285278	$2^-_2$	6.51	0.129464

Theoretical cross section calculation  
(by MOMDIS)

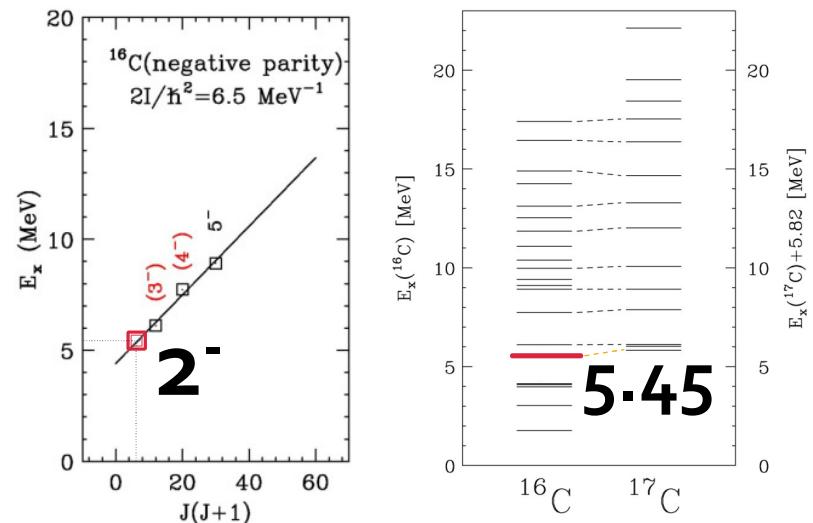
For  $2^-_1$  state,

$$\sigma_{sp} = 39.39 \text{ [mb]}$$

$$\sigma_{th} = \sigma_{sp} \times C^2 S = 15.53 \text{ [mb]}$$

$$\sigma_{exp} = 13.92 \pm 0.13 \text{ [mb]}$$

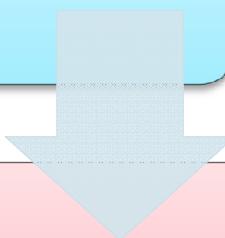
The state at 5.45 MeV is consistent with  $2^-_1$  state.



# Summary

## Investigation of $^{16}\text{C}$ unbound states

- $^{17}\text{C}$  beam at 70 MeV/u, LH<sub>2</sub> target
- One neutron knockout :  $^{17}\text{C} \rightarrow ^{16}\text{C}^* + \text{n}$
- Triple coincidence : neutron –  $\gamma$ -ray –  $^{15}\text{C}$



## Discovery of the new state

- Peak :  $E_{\text{rel}}=0.46$  MeV,  $\Gamma=60\sim120$  keV,  $\sigma=13.92$  mb
- **2<sup>-</sup> state at 5.45 MeV** ( $\sigma_{\text{exp}}$  is consistent with  $\sigma_{\text{theory}}$ )
- Evidence for existence of rotational band-like structure

We found a new state at 5.45 MeV in  $^{16}\text{C}$  ( $J^\pi = 2_-^+$ ). Usefulness of the fragment-n- $\gamma$  coincidence measurement (based on the invariant method) for nuclear spectroscopy was demonstrated.

# Collaborators

J. Hwang, Y. Satou. (Seoul National University, Korea)

T. Nakamura, N. Matsui, Y. Hashimoto, T. Nakabayashi, T. Okamura,

M. Shinohara (Tokyo Institute of Technology, Japan)

N. Fukuda, T. Sugimoto, Y. Kondo, T. Motobayashi, Y. Yanagisawa,

N. Aoi, S. Takeuchi, T. Gomi, H. Sakurai, H. Otsu, M. Ishihara (RIKEN, Japan)

Y. Togano, S. Kawai (Rikkyo University, Japan)

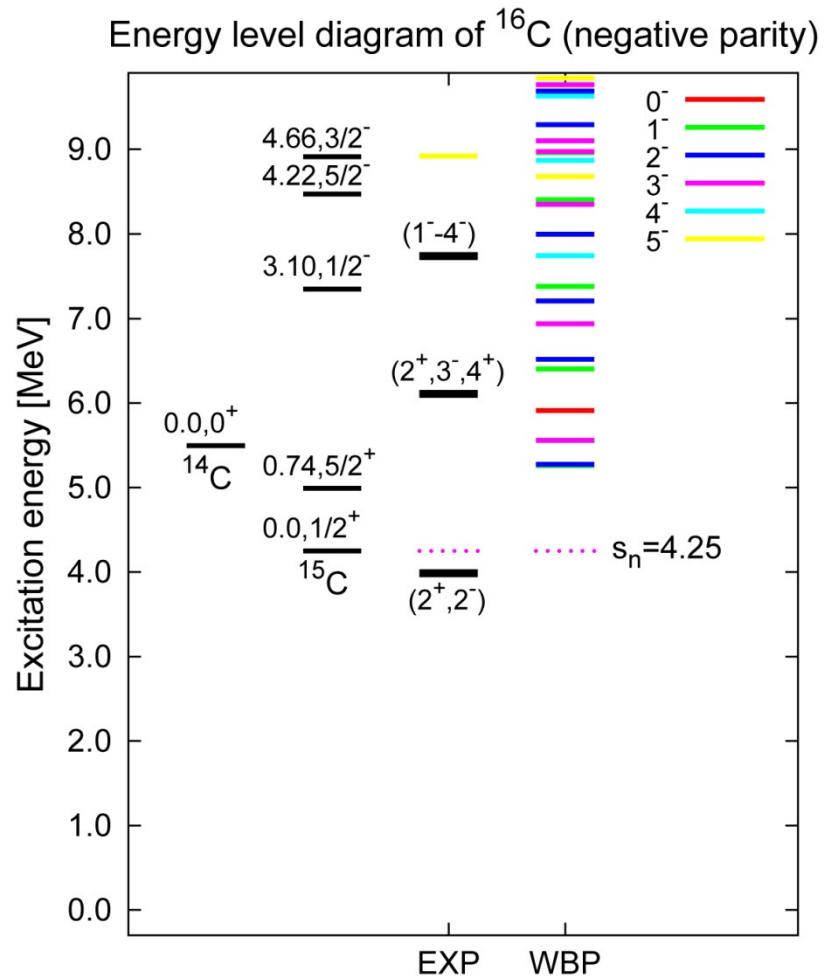
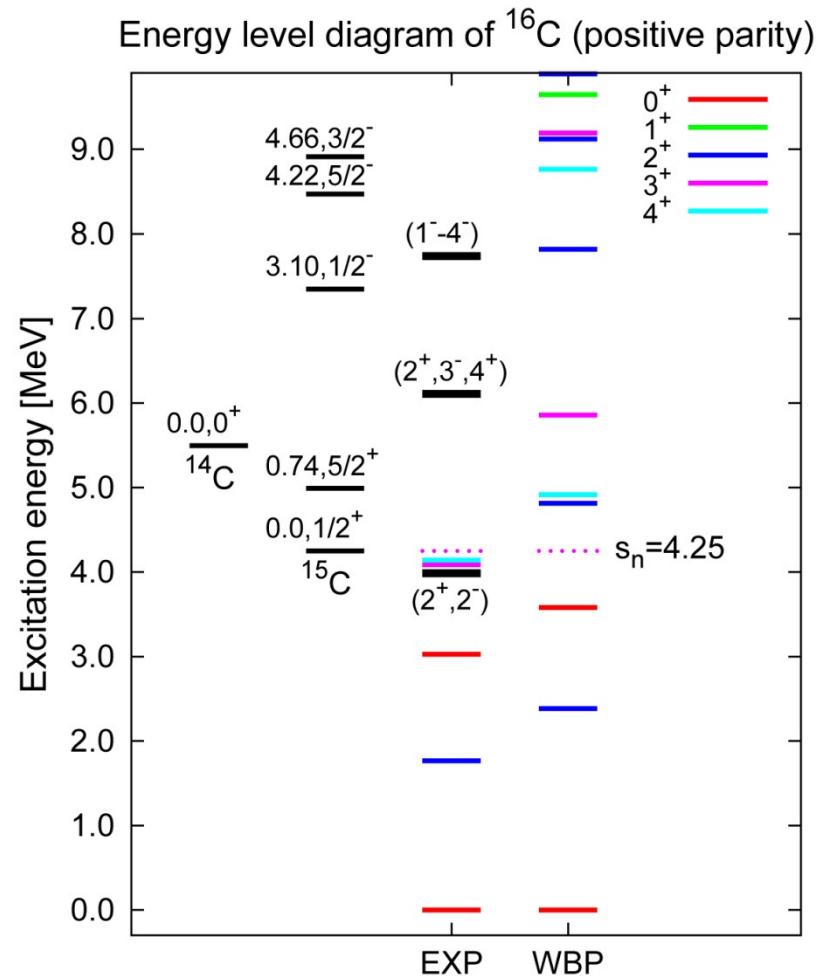
H.J. Ong, T.K. Onishi (University of Tokyo, Japan)

S. Shimoura, N. Tamaki (CNS, University of Tokyo, Japan)

T. Kobayashi, Y. Matsuda, N. Endo, M. Kitayama (Tohoku University, Japan)

**Thank you for your attention.**

# Known Information



# Motivation

- Importance of Cross-shell Interaction
  - K. Sieja, et al., Nucl. Phys. A 857 (2011) 9–15
    - Core polarization effect on  $p\text{-}sd$  &  $sd\text{-}pf$  shell nucleus
    - $p\text{-}sd$  shell example :  $^{16}\text{C}$  and  $^{18}\text{O}$ 
      1. USD : overestimation
      2. Core int. : better estimation with  $^{10}\text{He}$  core for  $^{16}\text{C}$  /  $^{16}\text{O}$  core for  $^{18}\text{O}$
    - Core polarization contributions from  $p_{1/2}$  protons scattered to higher shells for  $^{18}\text{O}$  case
    - “*The influence of the core polarization on the pairing and quadrupole multipoles studied here in the  $p\text{-}sd$  and  $sd\text{-}pf$  model spaces is a general mechanism and should be valid in any model space consisting of  $N-(N+1)$  H.O. shells.*”

Table 4

Excited levels (in MeV) in  $^{16}\text{C}$  and  $^{18}\text{O}$  obtained with  $p\text{-}sd$  interactions with various neutron–neutron parts, compared to experimental data.

Nucleus	$J^\pi$	EXP	USD	$^{16}\text{O}$ core	$^{10}\text{He}$ core
$^{16}\text{C}$	$2^+$	1.76	2.24	2.15	1.87
	$4^+$	4.14	4.68	4.55	3.88
$^{18}\text{O}$	$2^+$	1.98	2.21	1.84	1.46
	$4^+$	3.55	3.78	3.39	2.63

# Motivation

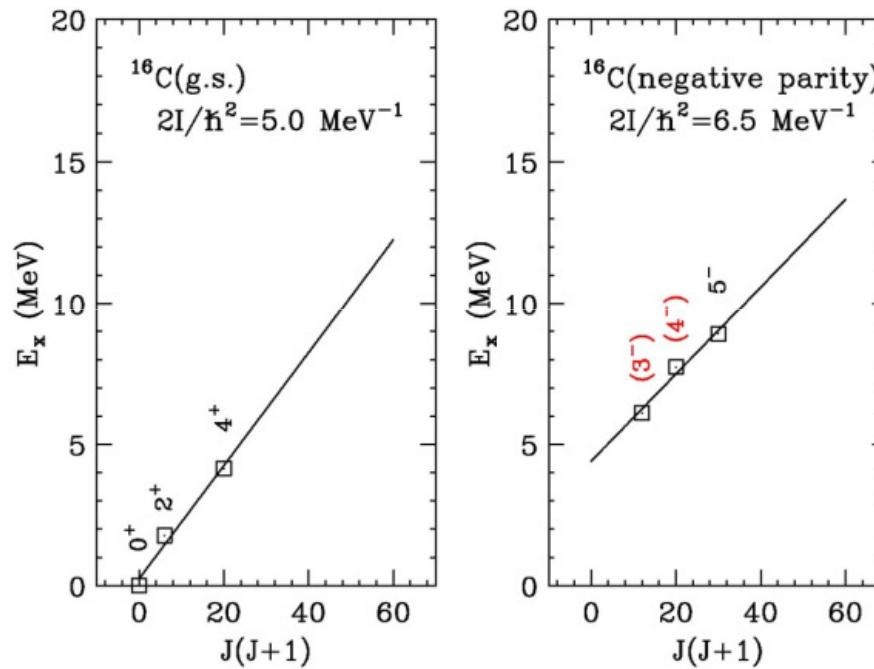
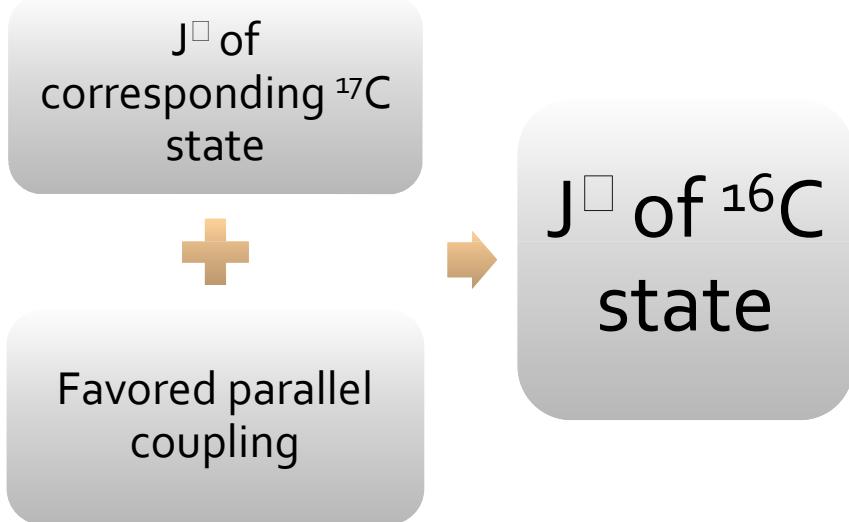
- Importance of Cross-shell Interaction
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    - "*The influence of the core polarization on the pairing and quadrupole multipoles studied here in the  $p\text{-}sd$  and  $sd\text{-}pf$  model spaces is a general mechanism and should be valid in any model space consisting of  $N-(N+1)$  H.O. shells.*"

Study of unbound excited states of  $^{16}\text{C}$

Several neutron p-hole states ( $\square(\text{sd})^3(\text{p})^{-1}$ )

More understanding on the **cross-shell** int.

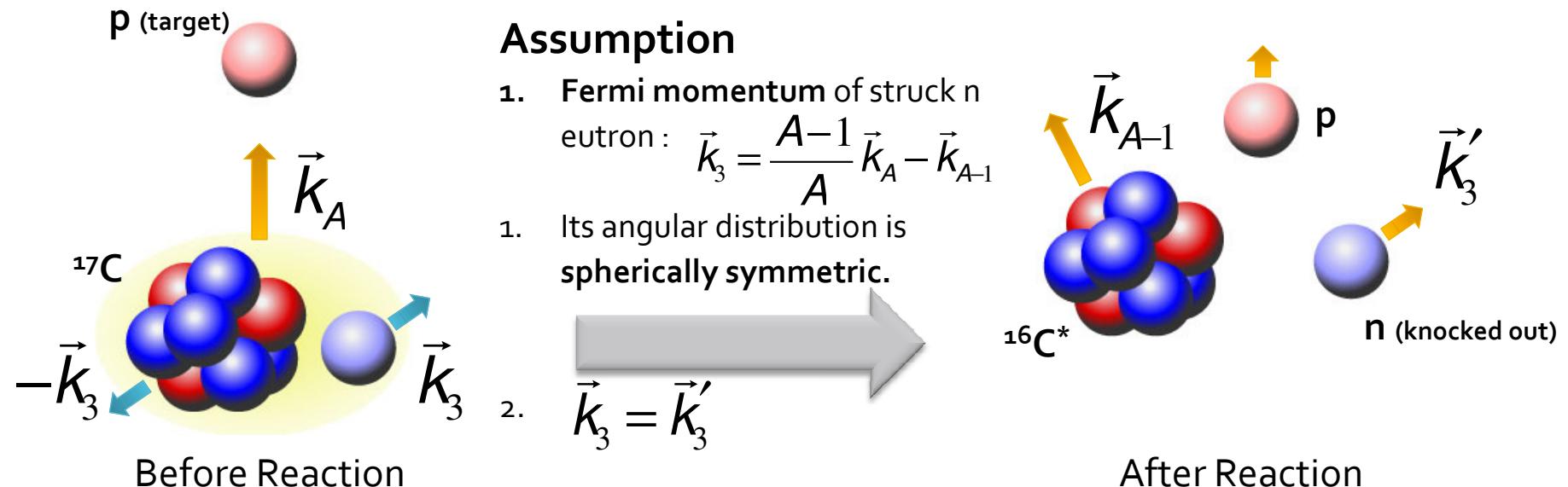
# Known Information



**Rotational-band-like structure  
(Missing partner)**

# Data Analysis

- Acceptance Correction
  - Knockout reaction : inclusive measurement  
→ No measurement for a knocked out neutron
  - Simple assumption is necessary.  
→ Sudden approximation



# Data Analysis

## ■ Fitting Result to Functions

- Response function : Breit-Wigner function
  - Lane and Thomas, Rev. Mod. Phys. 30 (1958), 257

$$\sigma_r(E) = A \frac{\Gamma_l(E)\Gamma_r}{\{E_r + \Delta E_l(E) - E\}^2 + \{\Gamma_l(E)/2\}^2}$$

- Shift function :  $\Delta E_l(E) = \Gamma_r \frac{S(E_r) - S(E)}{2P_l(E_r)}$
- Level width :  $\Gamma_l(E) = \Gamma_r \frac{P_l(E)}{P_l(E_r)}$
- $P_l$  : penetration factor,  $S_l$  : shift factor
- Channel radius :  $R = r_0(A_n^{1/3} + A_f^{1/3})$  with  $r_0 = 1.4$  [fm]

# Discussion : Energy (5.45 MeV)

Shell model calculation for spectroscopic factor (WBP int.)

State	$E_x$ (MeV)	$C^2S$	State	$E_x$ (MeV)	$C^2S$
$0^+_1$	0.0	0.034979	$1^-_1$	5.26	0.033679
$2^+_1$	2.36	0.319859	$2^-_1$	<u>5.27</u>	<u>0.80104</u> $1 A_n^{1/3}$
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Bound state

Correspondence in  $E_x$  between  $^{17}\text{C}$  and  $^{16}\text{C}$

Pairs	$E_x(^{17}\text{C})$	$E_x(^{16}\text{C})$	$\Delta E_x$
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3	3.10 (9/2 <sup>+</sup> )	8.92 (5 <sup>-</sup> )	5.82
...	...	...	...

5.45 MeV is reasonable value!