

*Search for  
Alpha Cluster Condensed State in  $^{16}\text{O}$   
via  $^{16}\text{O}(\alpha, \alpha')$  Scattering  
- New state as a candidate of ACC -*

**Tomotsugu WAKASA**  
for the RCNP-E189 collaboration  
*Department of Physics, Kyushu University*

# Contents



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  - Chain state (*Asymmetric*) and  **$\alpha$  cluster condensed state (*Symmetric*)**

- *Experiment*

- Advantage of  $(\alpha, \alpha')$  scattering
- Use of ice target as a pure  $^{16}\text{O}$  target

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  - New  $0^+$  state at 13.6 MeV and  $\Gamma=0.6$  MeV

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  - New state is consistent with prediction for ACC

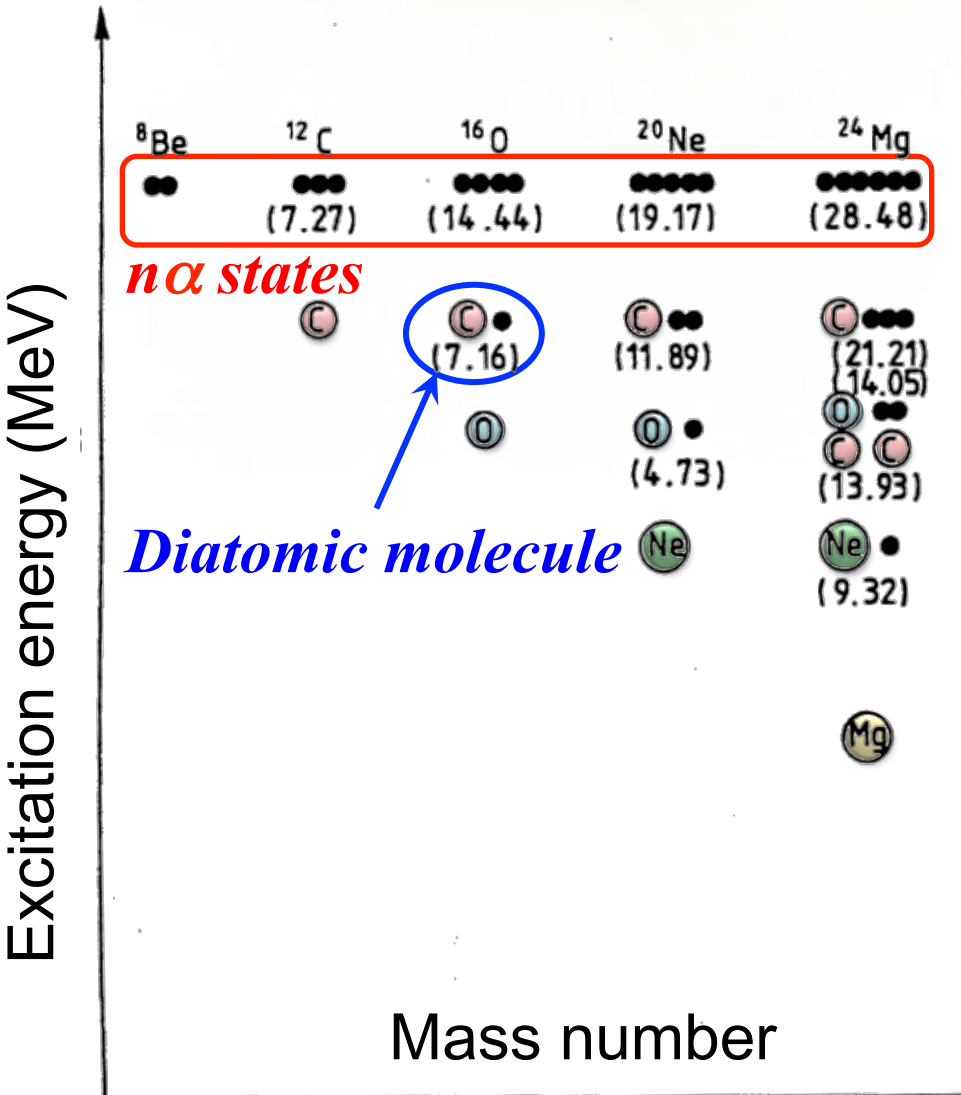
- *Summary*

# Ikeda Diagram

*K.Ikeda, N.Takigawa, and H.Horiuchi  
Suppl. Prog. Phys. Jpn. (1969) 464.*

- **Threshold rule**
  - Several cluster types will appear around the **threshold energy of breakup into constituent clusters (threshold rule)**
  - **Example**
    - $3\alpha$  at 7.3 MeV in  $^{12}\text{C}$
    - $\text{C}+\alpha$  at 7.2 MeV in  $^{16}\text{O}$
    - $4\alpha$  at 14.4 MeV in  $^{16}\text{O}$

- **Cluster Physics**
  - Diatomic Molecules ( $^{16}\text{O}=\text{C}+\alpha$ ) exist ?
  - Structure of  $n\alpha$  states of  $4n$ -particle nuclei



# $N\alpha$ Cluster States in $4N$ Nuclei

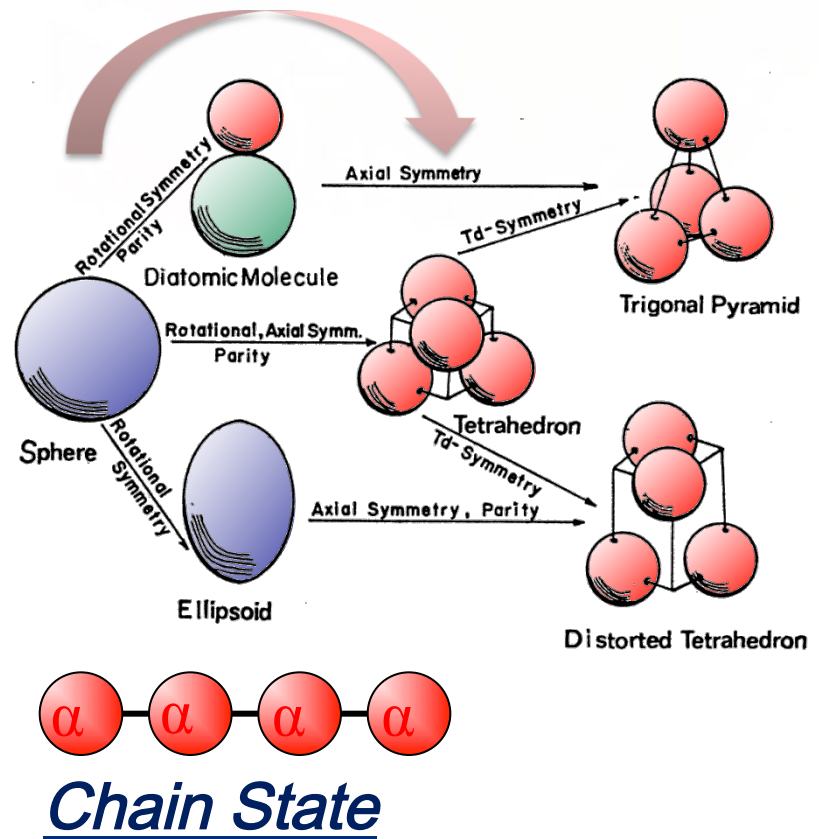
*N.Onishi and R.K.Sheline, NPA165 (1971) 180*

- *Configurations of  $4\alpha$  cluster states in  $^{16}\text{O}$*

- Symmetric state
  - Tetrahedron
  - Cluster Condensed State
- Asymmetric state
  - Trigonal Pyramid
  - Distorted Tetrahedron (Diamond)
  - Chain state

In this talk:  
Focus on  $4\alpha$  state in  $^{16}\text{O}$   
and symmetric (ACC) state

## Tetrahedron or Condensed State





A.Tohsaki, H.Horiuchi et al.  
 Phys. Rev. Lett. 87 (2001)192501

# New $\alpha$ Cluster Wave Function

## - $\alpha$ Cluster Condensed Type -

- *New  $\alpha$ -cluster w.f. describing  $\alpha$ -particle Bose condensation*

$$|\Phi_{n\alpha}\rangle = (C_{\alpha}^{+})^n |VAC\rangle$$

$$C_{\alpha}^{+} = \int dR e^{-R^2/R_0^2} \int dr_1 \cdots dr_4$$

$$\times \varphi_{0s}(r_1 - R) a_{\sigma_1 \tau_1}^{+}(r_1) \cdots \varphi_{0s}(r_4 - R) a_{\sigma_4 \tau_4}^{+}(r_4)$$

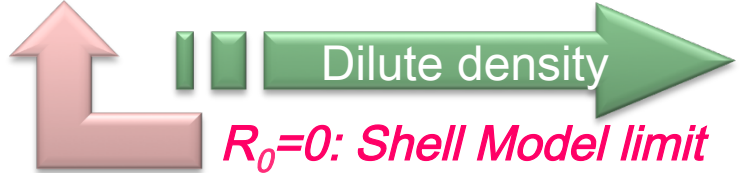
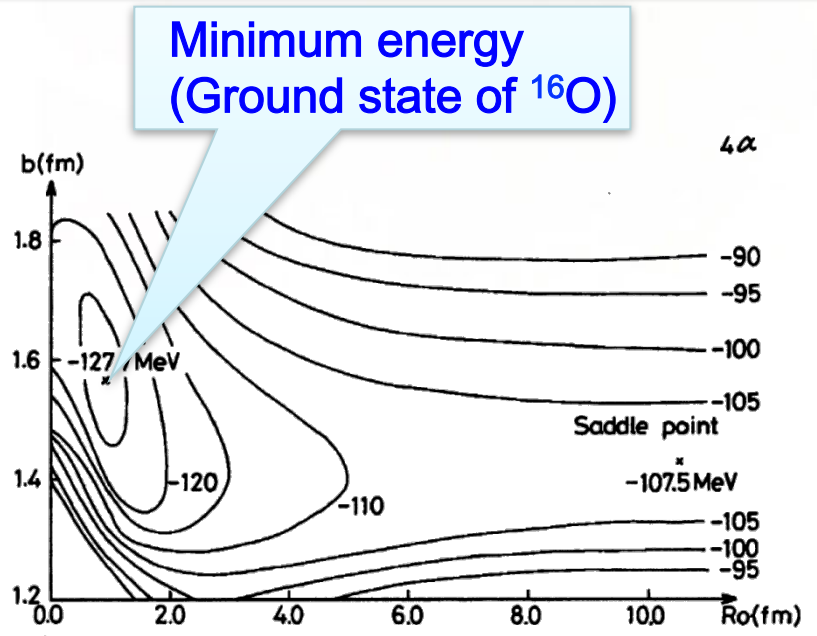
- $\Phi_{0s}$ : Wave function for 0s state
- $R_0$ : Width (length) parameter for  $\alpha$  clusters in 4n nuclei

- *Total  $n\alpha$  wave function*

$$|\Phi_{n\alpha}\rangle \propto A \left\{ e^{-2/B^2(X_1^2 + \cdots + X_n^2)} \phi(\alpha_1) \cdots \phi(\alpha_n) \right\}$$

- $B = (b^2 + 2R_0^2)^{1/2}$
- $b$ : Width (length) parameter for nucleons in  $\alpha$  clusters
- $\phi(\alpha_i)$ : Internal wave function of i-th  $\alpha$  cluster

Two parameters:  
 ◆  $R_0$  : distance between  $\alpha$  clusters  
 ◆  $b$  : size of  $\alpha$  cluster



**Strong  $\alpha$ -particle correlations in g.s.**



# Prediction of $4\alpha$ Dilute State $^{16}\text{O}$

- Prediction of  $\alpha$ -particle condensed state -

		$E_{calc}$ (MeV)	$E_{exp}$ (MeV)	$\sqrt{\langle r^2 \rangle}_{calc}$ (fm)	$\sqrt{\langle r^2 \rangle}_{exp}$ (fm)	$R_0$ (fm)
$^{16}\text{O}$	$K=1$	-124.8	-127.62 (g.s.)	2.59	2.73	1.0
	$K=2$	-116.0	-116.36 (11.26 MeV)	3.16		2.5
	$K=3$	-110.7	-113.62 (14.0 MeV ?)	3.97		4.1
	$E_{3\alpha}$	-110.0	-113.18			

Alpha Cluster  
Condensation



Other  $0^+$  states in  $^{16}\text{O}$

- ◆  $0_2^+$  at 6.06 MeV :  $^{12}\text{C}(0^+) + \alpha$  in S state
- ◆  $0_4^+$  at 12.05 MeV :  $^{12}\text{C}(2^+) + \alpha$  in D state

Large  $R_0$  value

- Center of mass momenta  $P=0$   
(Condensed state)
- Dilute state  
(Consistent with nuclear matter)

# Levels in $^{16}\text{O}$

-  $0^+$  at 14.0 MeV is *NOT* commonly accepted-

- *Experimentally discovered levels*

- About 100 levels below 20 MeV
- Over 50 levels were identified in a single study of  $^{12}\text{C}+\alpha$

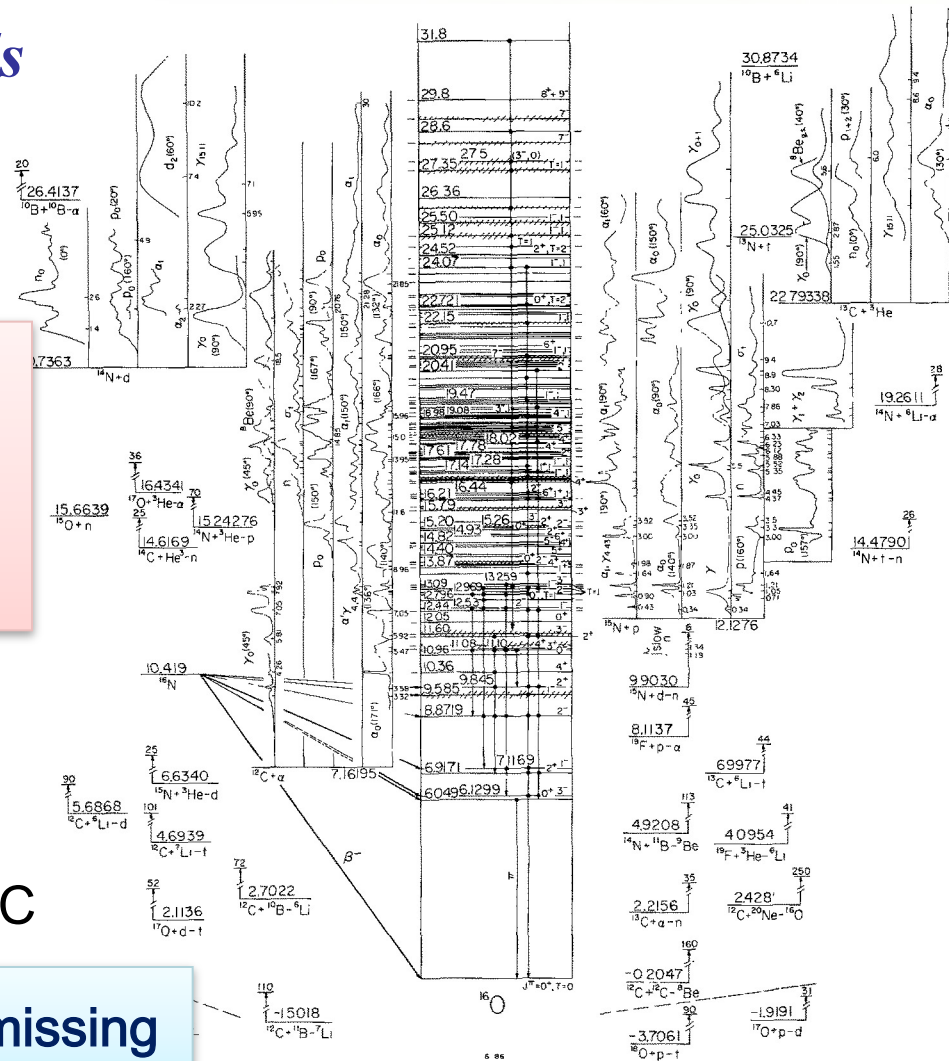
Over 50 levels were identified in a single study of resonances in  $^{12}\text{C}+\alpha$

⇒ Some states should be confirmed by other experimental studies

- *There are several levels which were NOT listed in TOI/NNDC*

- 87 levels below 20 MeV in NNDC

$0^+$  at 14.0 MeV and  $\Gamma=4.8$  MeV is missing



# Level Diagram of $^{16}\text{O}$ in NNDC

- Same as Table of Isotopes -

Nucleus	$E_{\text{level}}(\text{keV})$	$J^{\pi}$	$T_{1/2}$
$^{16}\text{O}$	0.0	$0^+$	STABLE
$^{16}\text{O}$	6049.4 10	$0^+$	67 ps 5
$^{16}\text{O}$	11260	$(0^+)$	2500 keV
$^{16}\text{O}$	11520 4	$2^+$	71 keV 3
$^{16}\text{O}$	11600 20	$3^-$	800 keV 100
$^{16}\text{O}$	12049 2	$0^+$	1.5 keV 5
$^{16}\text{O}$	12440 2	$1^-$	91 keV 6
$^{16}\text{O}$	12530 1	$2^-$	0.111 keV 10
$^{16}\text{O}$	12796 4	$0^-$	40 keV 4
$^{16}\text{O}$	12968.6 4	$2^-$	1.34 keV 4
$^{16}\text{O}$	13020 10	$2^+$	150 keV 10
$^{16}\text{O}$	13090 8	$1^-$	130 keV 5
$^{16}\text{O}$	13129 10	$3^-$	110 keV 30
$^{16}\text{O}$	13259 2	$3^-$	21 keV 1
$^{16}\text{O}$	13664 3	$1^+$	64 keV 3
$^{16}\text{O}$	13869 2	$4^+$	89 keV 2
$^{16}\text{O}$	13980 2	$2^-$	20 keV 2
$^{16}\text{O}$	14032 15	$0^+$	185 keV 35

ground state

$^{12}\text{C}(0^+)+\alpha$  in S

$4\alpha$  cluster state

$^{12}\text{C}(2^+)+\alpha$  in D

$0^+$  at 14.0 MeV and  $\Gamma=4.8$  MeV is missing

NOT ACC since  $\Gamma=185$  keV (TOO narrow)

# Theoretical Prediction for ACC in $^{16}\text{O}$

## - ACC near $4\alpha$ threshold of 14 MeV-

A. Tohsaki, H. Horiuchi et al.  
 Phys. Rev. Lett. 87 (2001) 192501

- Theoretical Prediction with ACC w.f.**

- g.s. :  $\alpha$ -cluster correlation
- Around 10 MeV :  $4\alpha$  cluster state
  - $0^+$  at 11.26 MeV?
- Around 14 MeV :  $4\alpha$  ACC
  - Should be searched for

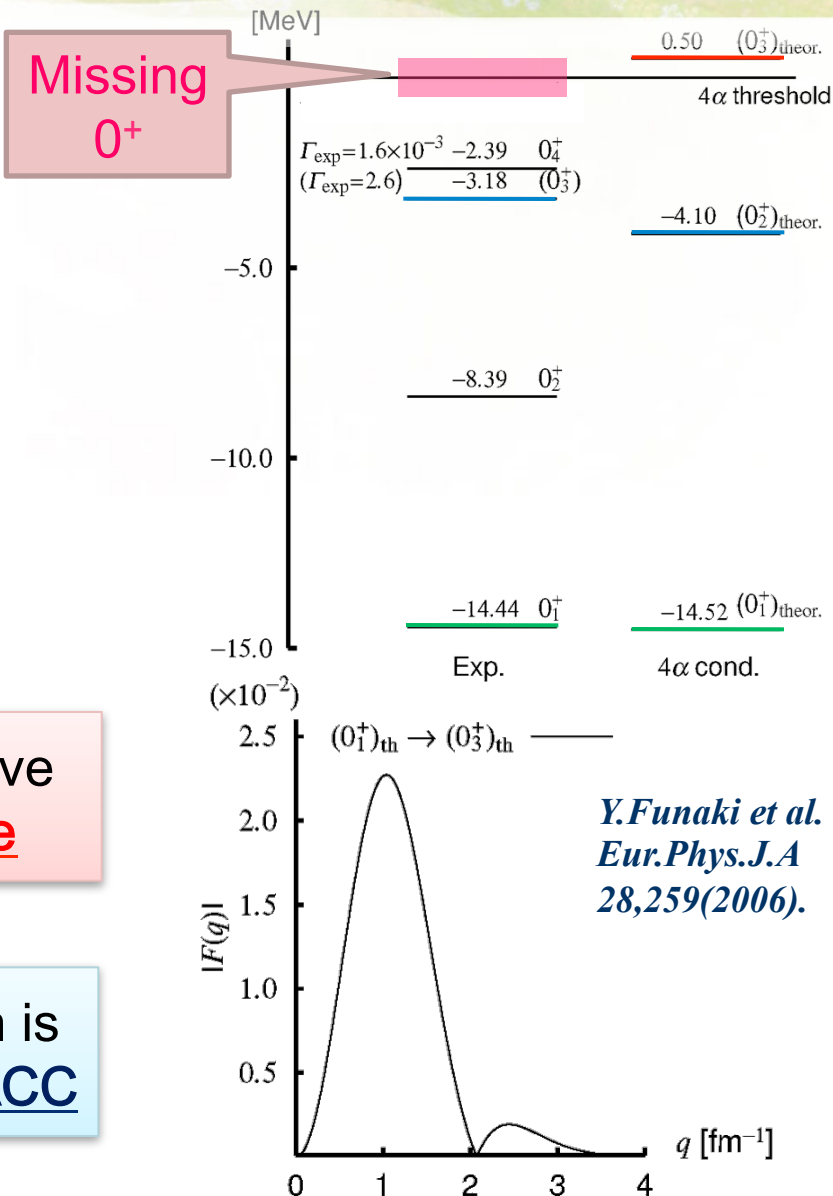
- Signature of ACC (diluteness)**

- Prediction of form factor for ACC

Absolute value of form factor is sensitive to diluteness(r.m.s.) of  $\alpha$  cluster state



Precise measurement of cross section is essential to confirm  $\alpha$  cluster state as ACC



# RCNP-E189 Experiment



- *Search for ACC state in  $^{16}\text{O}$* 
  - Investigation of 14.0 MeV  $0^+$  state in  $^{16}\text{O}$ 
    - Observed only in  $^{12}\text{C}+\alpha$
    - Not yet confirmed
    - Not yet listed in Table of Isotopes / NNDC
  - Search for new  $\alpha$ -cluster  $0^+$  state as ACC around  $4\alpha$  threshold
    - Search for  $0^+$  around 14 MeV
    - Width should be significantly large compared with  $\Gamma=185$  keV of  $0^+$  at 14.0 MeV
      - Large  $\Gamma$  is a signature of ACC

13090 8,  $1^-$ ,  $\Gamma=130.5$  keV, [FGHMPQX],  $\Gamma_\gamma=34.5$  eV, %IT=0.0264, %p=71, % $\alpha$ =29, T=1  $\gamma_{7117}$  59728 ( $\dagger_\gamma$  3.18)  $\gamma_{6048}$  70398 ( $\dagger_\gamma$  0.5812)  $\gamma_0$  130848 ( $\dagger_\gamma$  100)

13129 10,  $3^-$ ,  $\Gamma=110.30$  keV, [EFGHM], %IT=?, %p=1, % $\alpha$ =99, T=0

13259 2,  $3^-$ ,  $\Gamma=21.1$  keV, [FGHMOPQRWXY], %IT=?, %p=?, % $\alpha$ =?, T=0

13664 3,  $1^+$ ,  $\Gamma=64.3$  keV, [MNO], %IT<0.0015, %p=14, % $\alpha$ =86, T=0

13869 2,  $4^+$ ,  $\Gamma=89.2$  keV, [EHMOQRSTUW], %IT=?, %p=0.6, % $\alpha$ =99.4, T=0

13980 2,  $2^-$ ,  $\Gamma=20.2$  keV, [EMO], %p=?, % $\alpha$ =?

14032 15,  $0^+$ ,  $\Gamma=185.35$  keV, [HQ], %IT=?, % $\alpha$ =100

14100 100,  $3^-$ ,  $\Gamma=750.200$  keV, [H], % $\alpha$ =100

14302 3,  $4^-$ ,  $\Gamma=34.12$  keV, [KM]

4 $\alpha$  cluster  
Condensed State ?

# Experimental Procedure



- $0^+$  ACC has spin-scalar isoscalar nature

- Spin-scalar and isoscalar probe is best
  - C.f. (p,p') excites both scalar and vector

- ◆ High level density around 14 MeV
- ◆ Expected large  $\Gamma$  of ACC



Selective  
Excitation of ACC

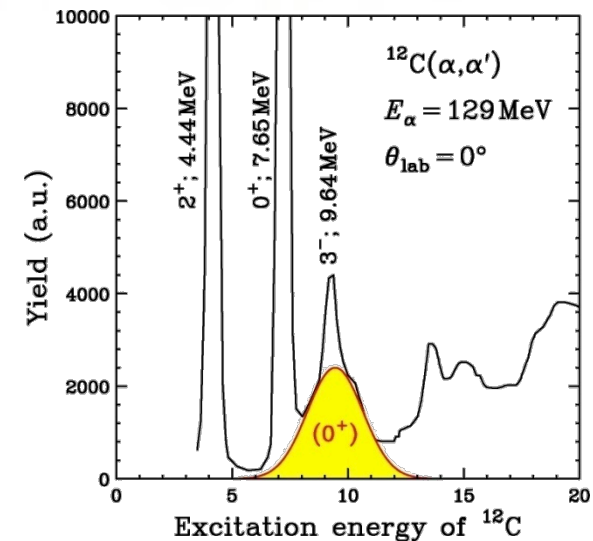
- ( $\alpha, \alpha'$ ) scattering
  - Spin-scalar only
  - Isoscalar only
- ( $\alpha, \alpha'$ ) excites  $0^+$  at 10 MeV in  $^{12}\text{C}$  clearly
  - Experimentally, observation of this state is relatively difficult in (p,p')
  - Excite ACC state effectively

- High resolution measurement

- Clearly resolve ACC from neighboring states

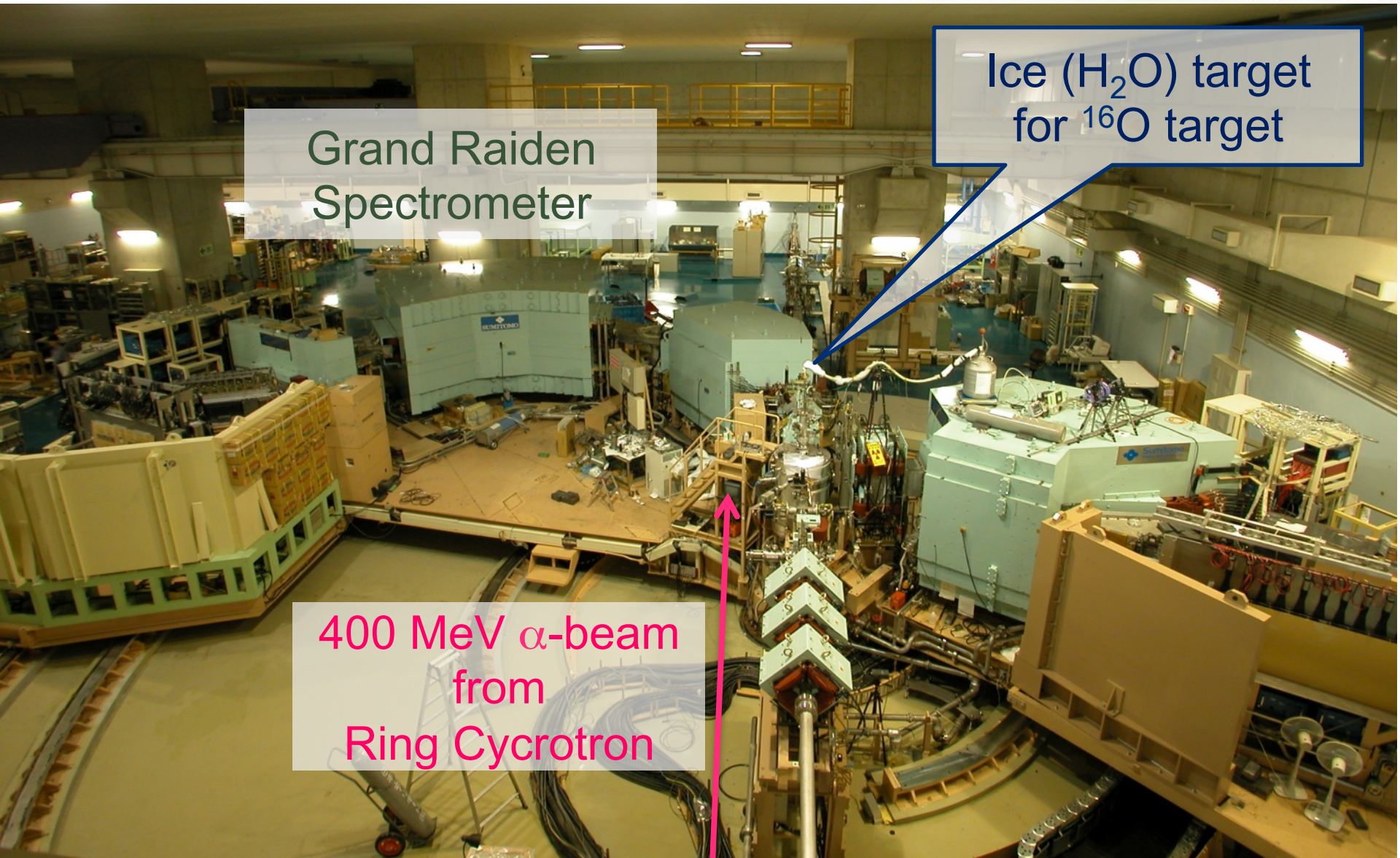
- Measure angular distribution

- Distinctive assignment of L



# Experimental Setup

## *Grand Raiden and WS Beam Line*



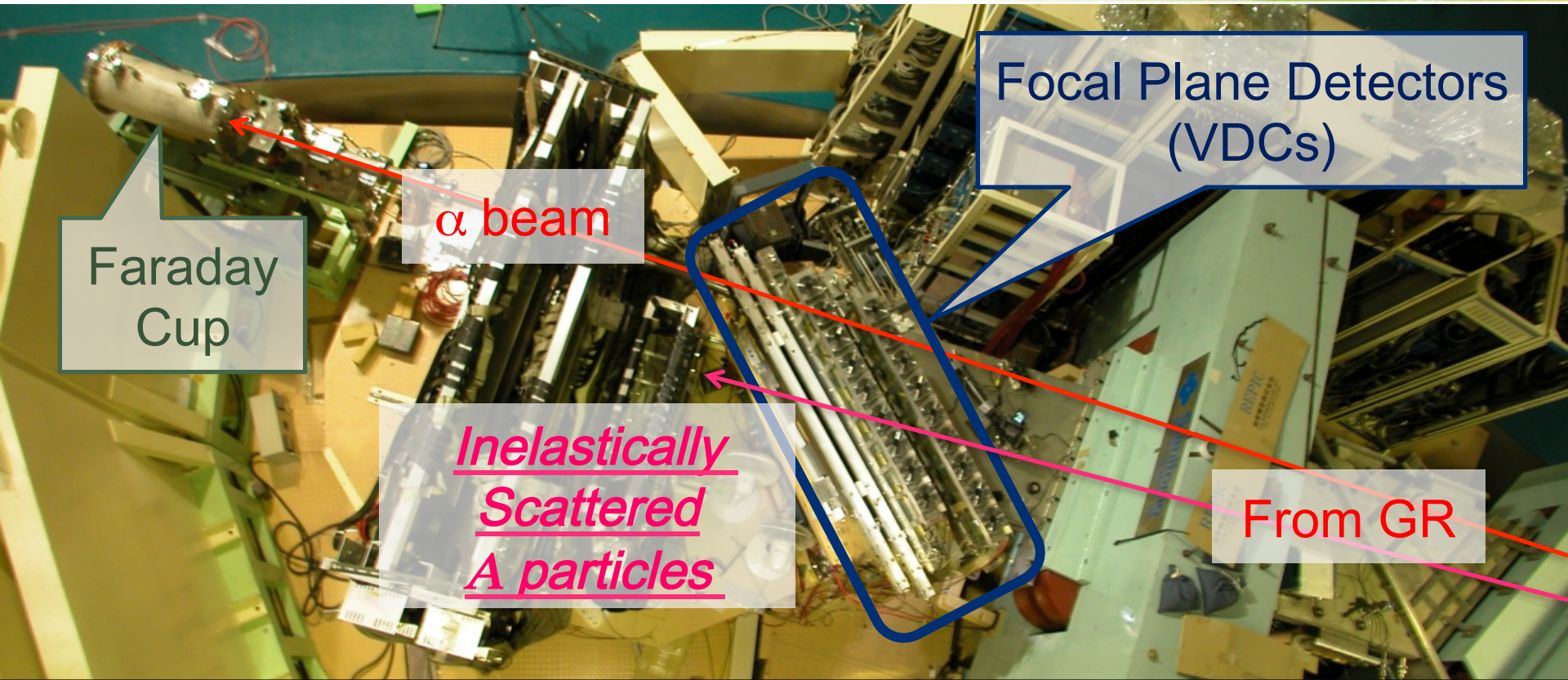
Grand Raiden  
Spectrometer

Ice ( $\text{H}_2\text{O}$ ) target  
for  $^{16}\text{O}$  target

400 MeV  $\alpha$ -beam  
from  
Ring Cycrotron

# Experimental Setup

- *0 degree measurement* -



ACC state with  $L=0$  is most strongly excited at 0 degrees ( $q=0$ )  
 $\rightarrow$  0 degree measurement is essential to identify ACC

# Ice Target for Pure $^{16}\text{O}$ Target



- *Ice ( $\text{H}_2\text{O}$ ) target*

- Pure  $^{16}\text{O}$  target

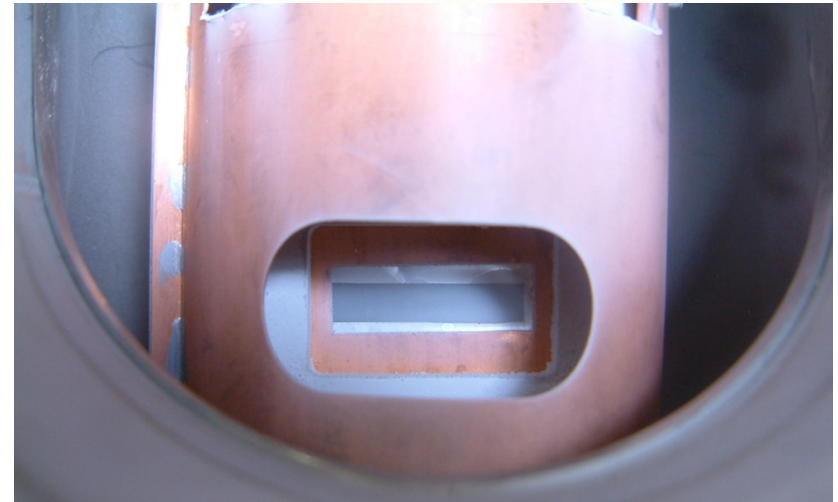
- $p+\alpha$  events can be clearly separated kinematically

- $\text{H}_2\text{O}$  is cooled down to 77 K (Liquid  $\text{N}_2$ )

- Thickness: 9 mg/cm<sup>2</sup>

- Area: 30 mm × 6mm (Very large)

- For Background-free spectra

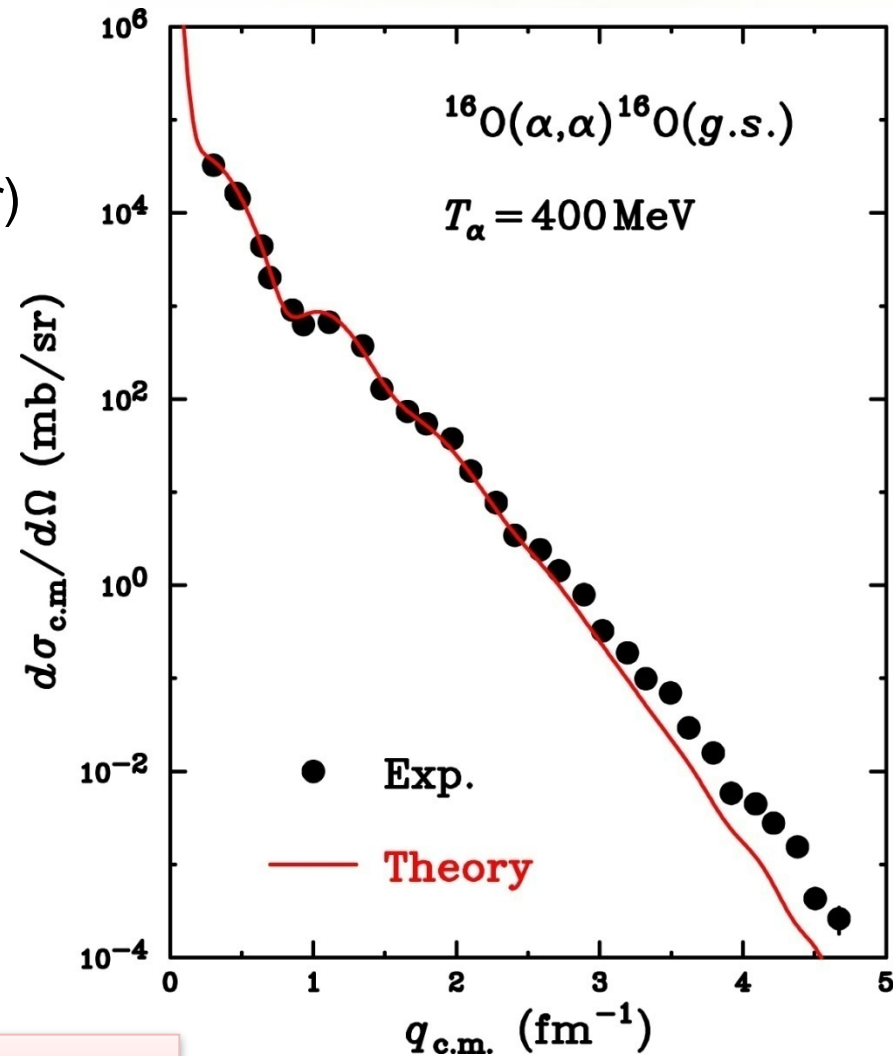


*T. Kawabata et al.  
Nucl. Instrum, Methods  
Phys. Res. A 459, 171 (2001)*

# Elastic Scattering Cross Section



- *Wide  $q$  and  $\sigma_{c.m.}$  region*
  - From 0 to 5  $\text{fm}^{-1}$
  - From  $10^5$  to  $10^{-4}$   $\text{mb/sr}$  (=0.1  $\text{nb/sr}$ )
- *High sensitivity (good  $S/N$ )*
  - Sensitive to ACC state
    - Broad resonance state
    - **Small  $\sigma$  in  $\text{mb/sr/MeV}$**
- *Optical model analysis*
  - Single folding model with N- $\alpha$  int.
  - **Well reproduction up to 3  $\text{fm}^{-1}$**
  - Underestimation beyond 3  $\text{fm}^{-1}$ 
    - N-a determined at low energy
    - **$q < 2.3 \text{ fm}^{-1}$  for inelastic data**

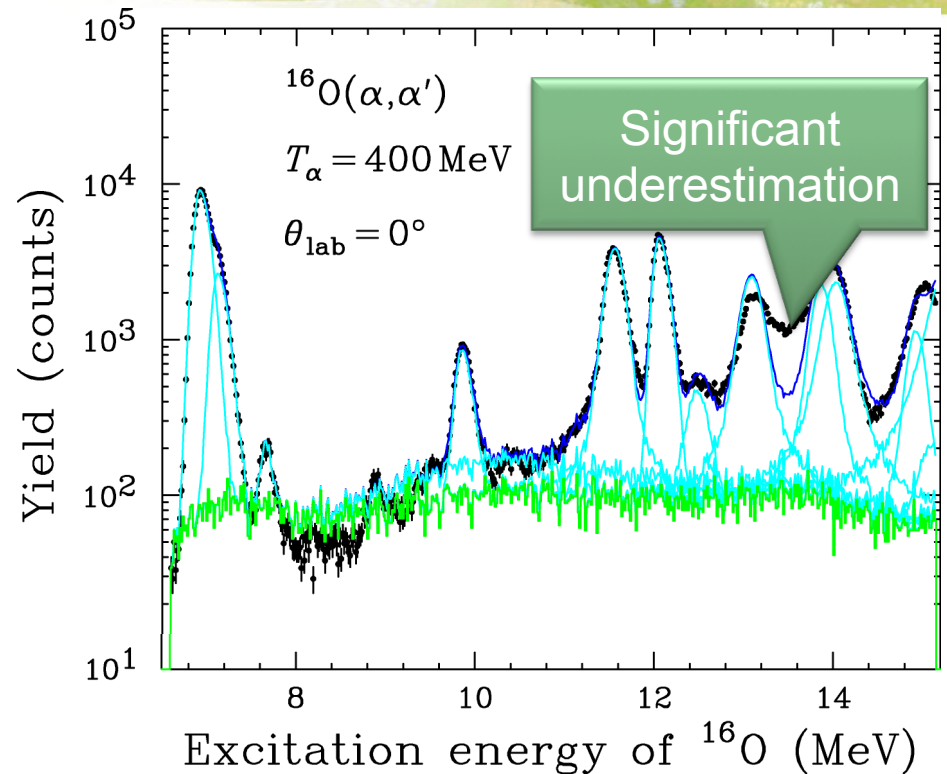


OMP's are reliable for analysis of inelastic data

# Result of Peak Fitting

## - Signature of new ACC state -

- *Hyper-Gaussian peak fitting was performed*
  - With known states only
    - w/o ACC state
  - With experimental B.G. (Green curve)
- *Significant underestimation around 13.6 MeV*
  - Not at 14.0 MeV
  - **Signature of new state**



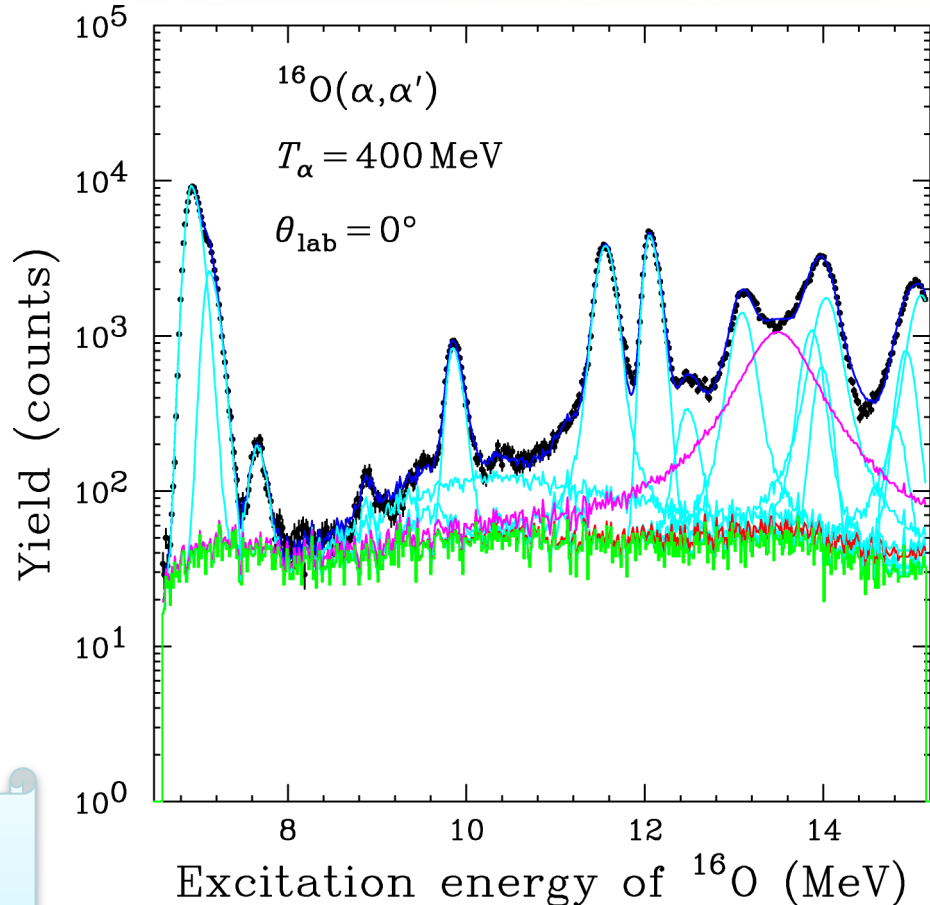
Underestimation at 13.6 MeV is independent of  $q$  (common for all data)  
 **$\Rightarrow$  Strong indication for new state**



# Comment on $0^+$ State at 14.0 MeV

- *Hyper-Gaussian peak fitting was performed*
  - With a new state (Magenta)
    - $E_x = 13.6$  MeV
    - $\Gamma \sim 600$  keV
  - With 14.0 MeV  $0^+$  state (Red)
    - Observed only in  $^{12}\text{C} + \alpha$
    - Candidate for  $\alpha$ -cluster condensed  $0^+$  state
  - With experimental B.G. (Green)
- *Exp. data could be reproduced fairly well w/o  $0^+$  at 14.0 MeV*

14.0 MeV  $0^+$  state (red curve) is NOT clearly observed

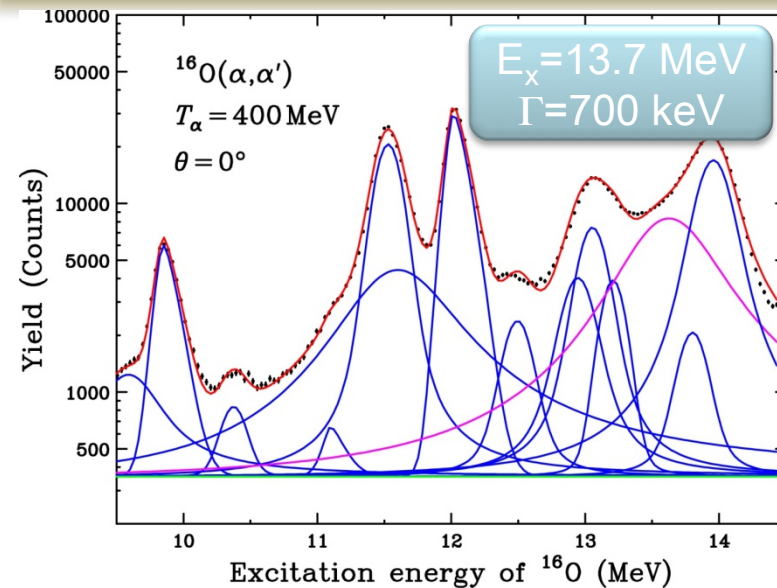
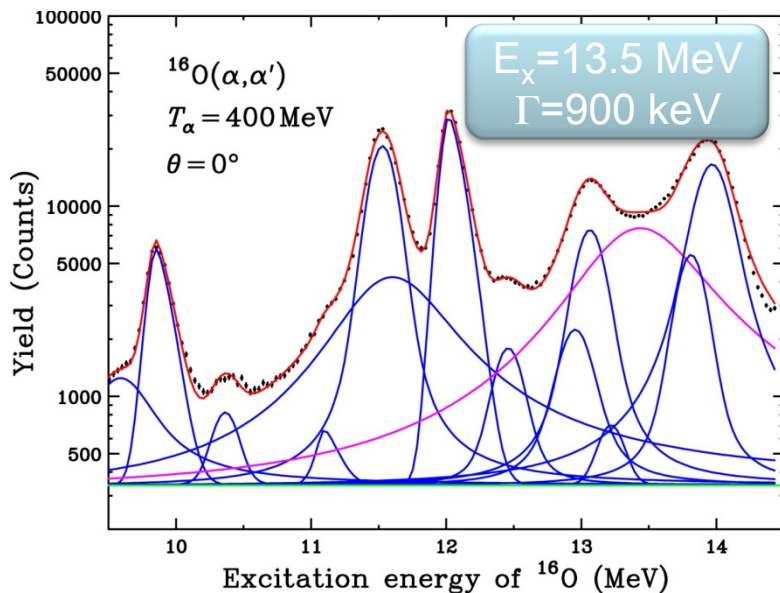
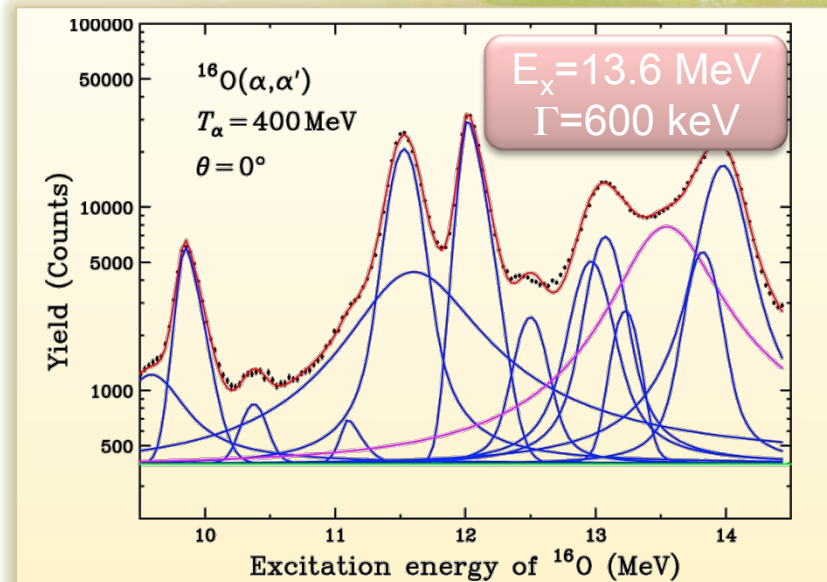


# Peak Fitting with New State

## - Correlation between $E_x$ and $\Gamma$ -

- *Reproduction with new state*
  - Best reproduction
    - $E_x=13.6\text{MeV}$ ,  $\Gamma=600\text{ keV}$
  - Strong correlation between  $E_x$  and  $\Gamma$

Difficult to deduce reliable (precise) values of  $E_x$  and  $\Gamma$  simultaneously



# Wavelet Analysis

Performed by Ihara-san

- *Wavelet analysis*

- Similar to Fourier transform
  - Keep information on time (=E<sub>x</sub>)
  - Information on frequency = ΔE

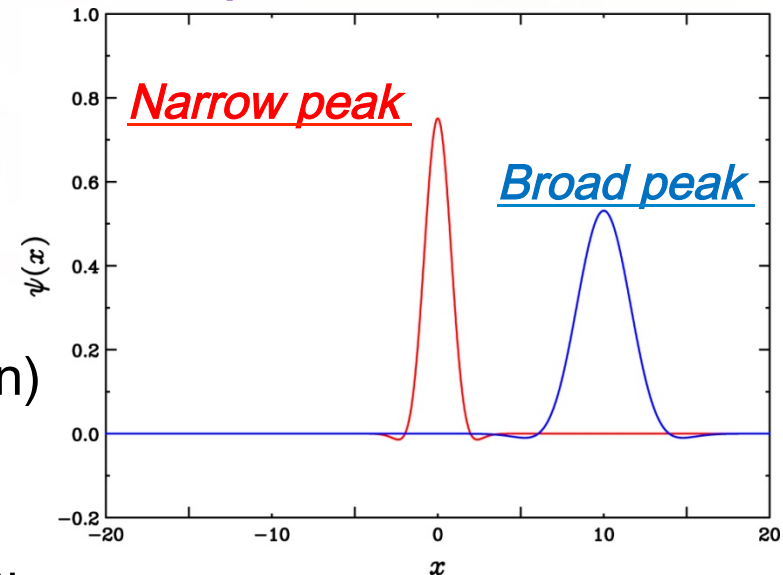
- *Wavelet function and coefficients*

- Used to reproduce exp. spectra
- Morlet type function (similar to Gaussian)

$$\psi(x) = \frac{1}{\sqrt[4]{\pi}} \cos\left(\frac{5}{2\pi} x\right) \exp\left(-\frac{x^2}{2}\right)$$

- Each peak is described by this function

## Example of wavelet function



Excitation energy of each state

$$C(E_x, \Delta E) = \frac{1}{\sqrt{\Delta E}} \int \sigma(E) \psi\left(\frac{E - E_x}{\Delta E}\right) dE$$

Width of each state



# Results of Wavelet Analysis

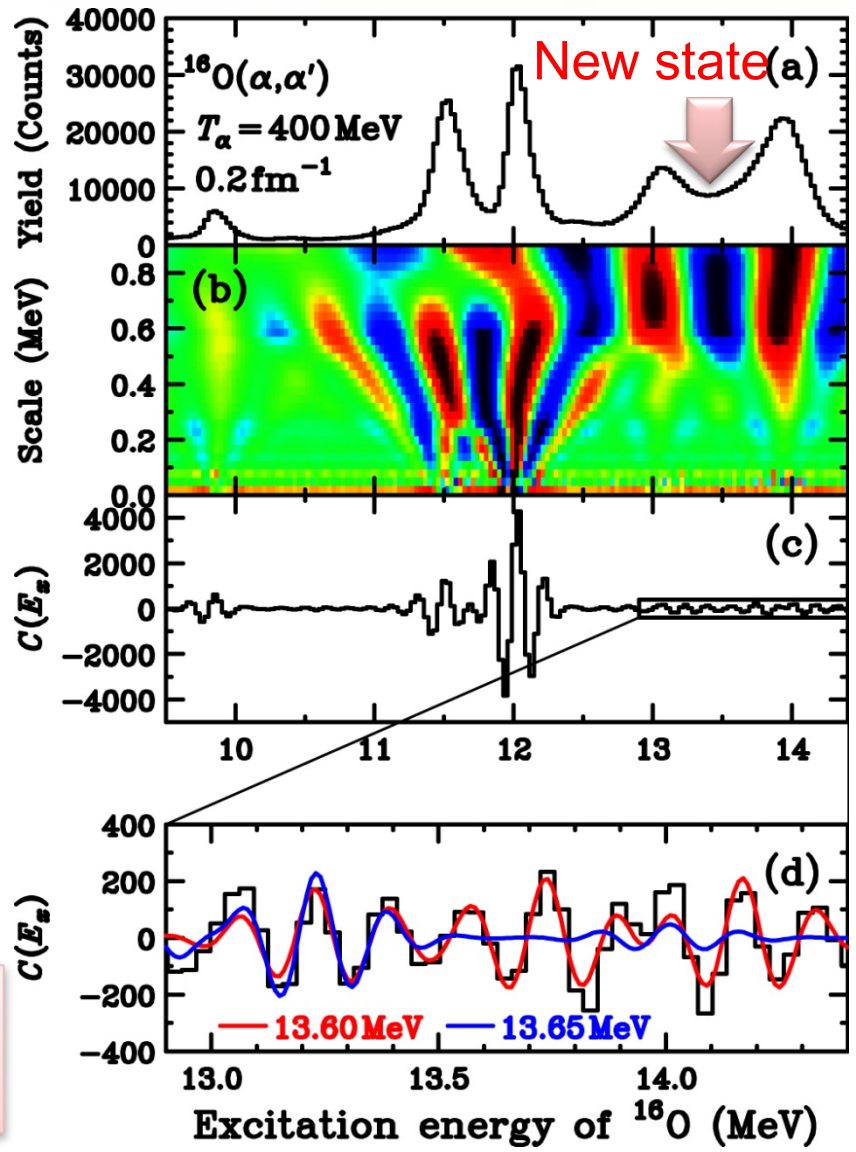
*Performed by Ihara-san*

- *In 13.0 – 14.0 MeV*
  - Maxima at scale = 0.1 MeV
    - Width of each peak (exp. res.)
  - Maxima at scale = 0.7 MeV
    - Total width of the bump
- *In 9.0 – 13.0 MeV*
  - Peaks with Moret type structure at
    - 9.8 MeV (2<sup>+</sup>)
    - 11.5 MeV (2<sup>+</sup>)
    - 12.0 MeV (0<sup>+</sup>)

- *Around 13.6 MeV*
  - Uneven structure of C → New state

◆ Sensitive to position :  $13.6 \pm 0.1$  MeV

◆ Insensitive to width



# Determination of Width

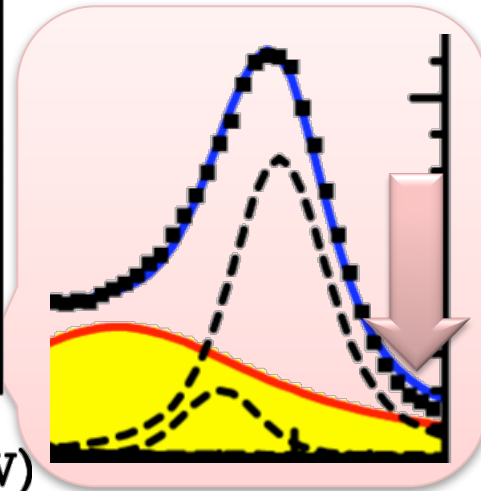
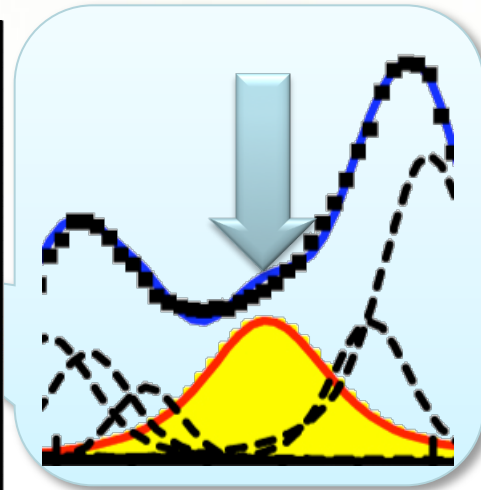
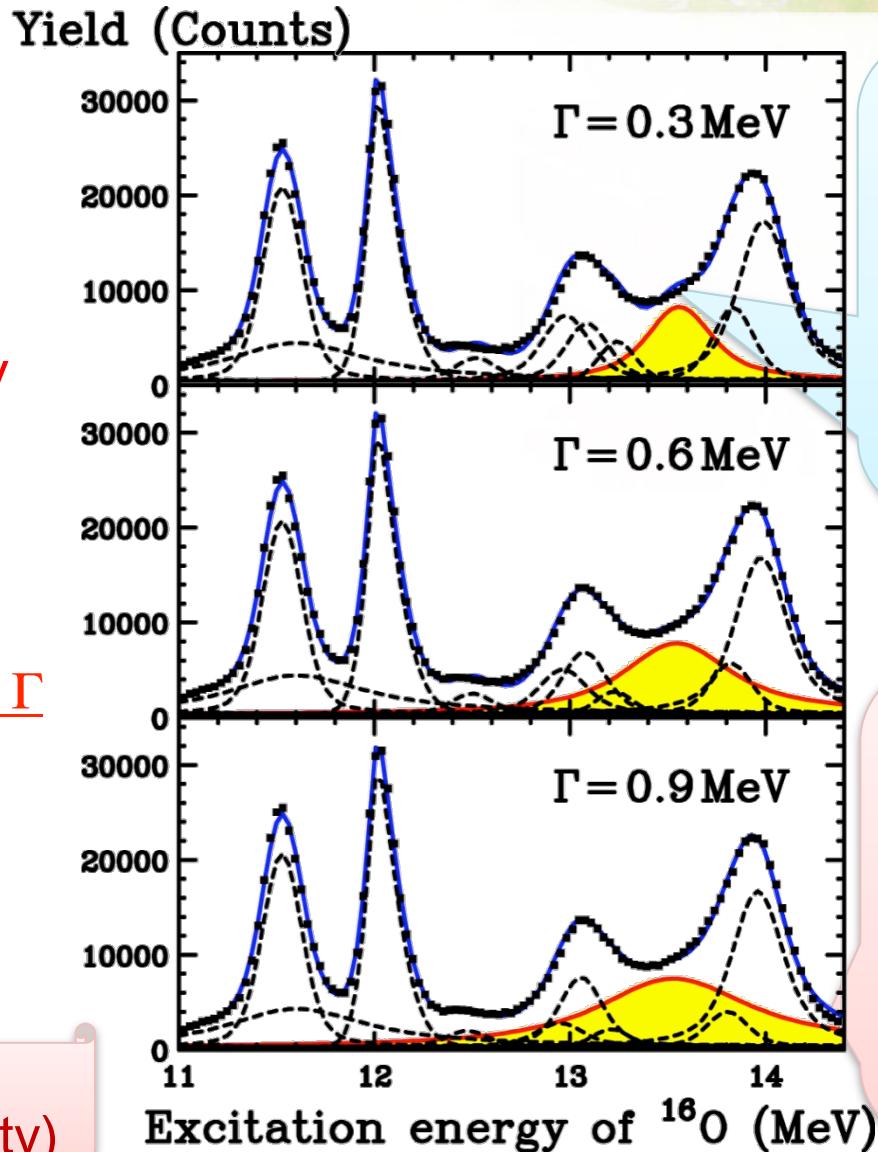


- *Peak fitting (Reproduction)*

- $E_x = 13.6$  MeV (fixed)
- $\Gamma = 0.3\text{--}0.9$  MeV (varied)

- *Quality of reproduction*

- Less sensitive to  $\Gamma$
- Significant overestimation
  - $\Gamma = 0.3$  MeV
  - $\Gamma = 0.9$  MeV



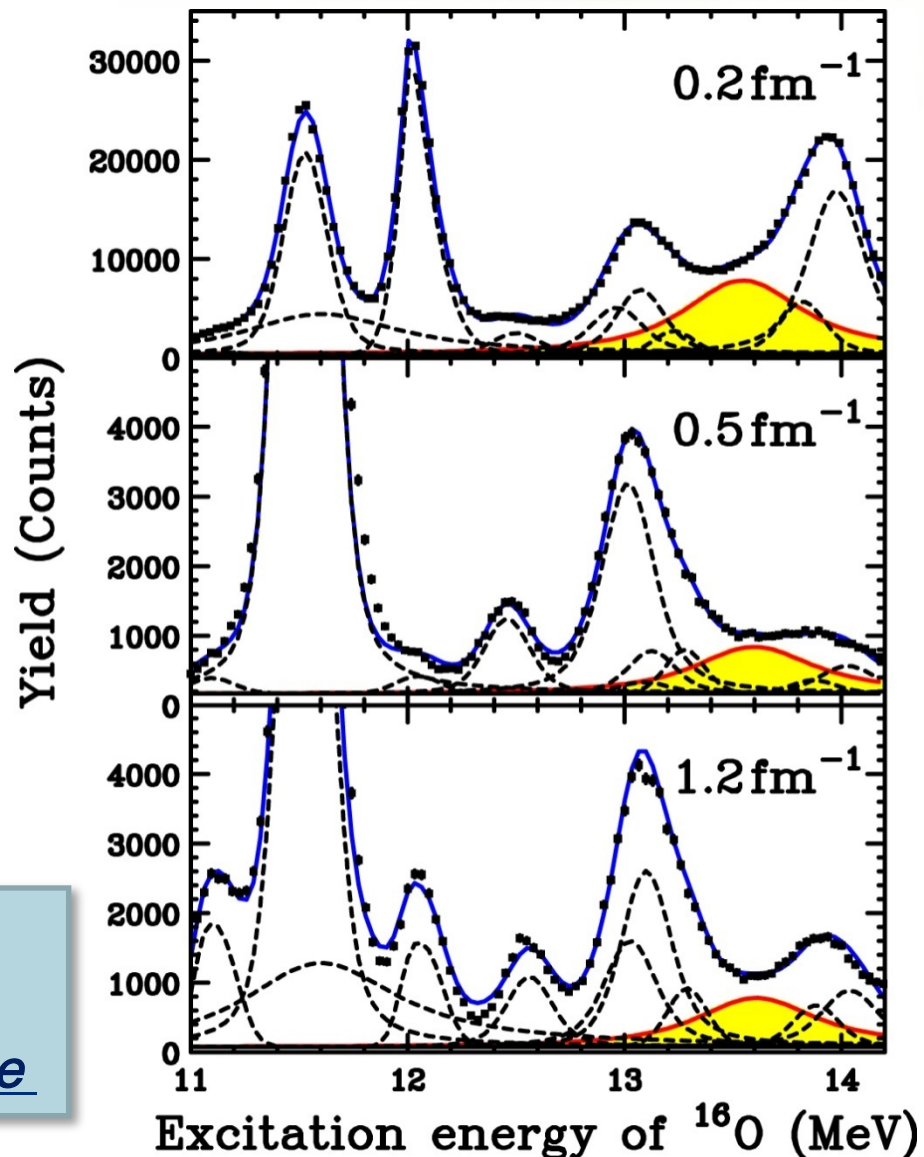
$\Gamma = 0.6 \pm 0.2$  MeV  
(NOT small uncertainty)

# Results of Reproduction at Large $q$

- *New State is identified at all  $q$* -

- *Inelastic scattering data*
  - $q = 0.2 - 2.3 \text{ fm}^{-1}$
  - Significant yield at 13.6 MeV for all momentum-transfer data
    - NOT reproduced with known states
    - Contribution from new state
- *Peak fitting (reproduction) with new state*
  - $E_x = 13.6 \text{ MeV}$
  - $\Gamma = 600 \text{ keV}$

Reasonable reproduction at all momentum transfers with common parameters  $\rightarrow$  New (resonance) state



# Observation of New State with Other Probe

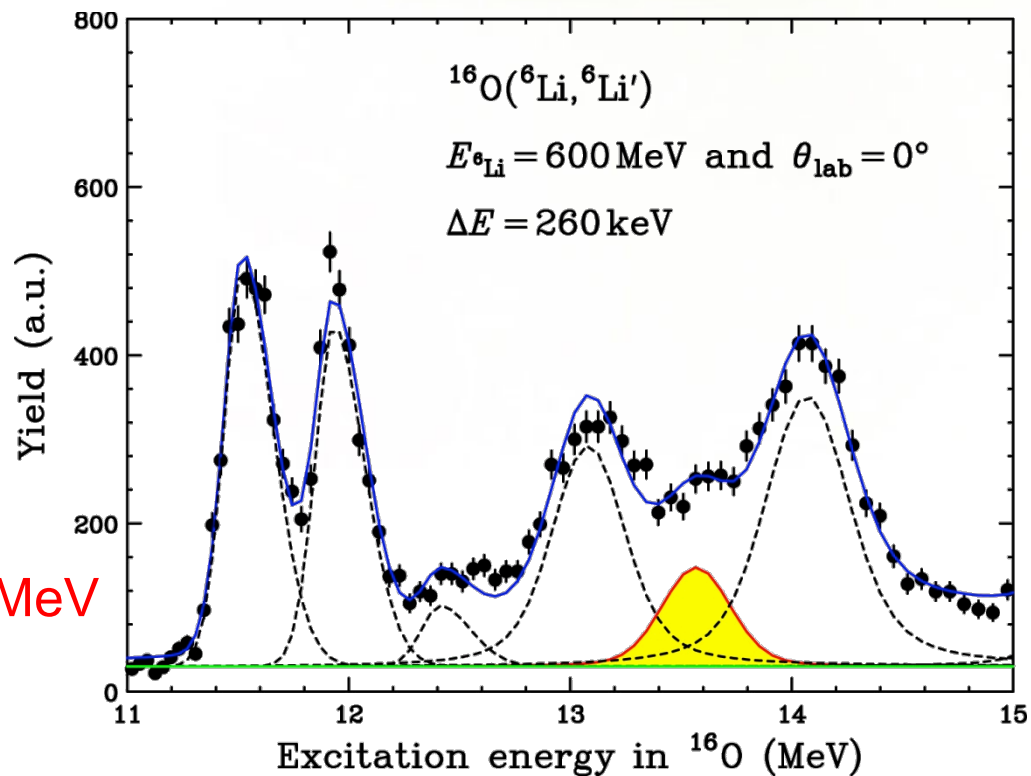
-  $^{16}\text{O}(^6\text{Li},^6\text{Li}') at E_{\text{Li}}=600 \text{ MeV}$  and zero degrees -

- *Energy resolution*

- Spread of  $^6\text{Li}$  beam: 300 keV
- Dispersion matching  
→ 260 keV
- Energy resolution is limited by target effects

- *Signature of new state*

- Significant yield around 13.6 MeV
- Best-fit value
  - $E_x = 13.5 \text{ MeV}$
  - $\Gamma = 0.7 \text{ MeV}$



Consistent with  $^{16}\text{O}(\alpha,\alpha')$  results

- No angular distribution data

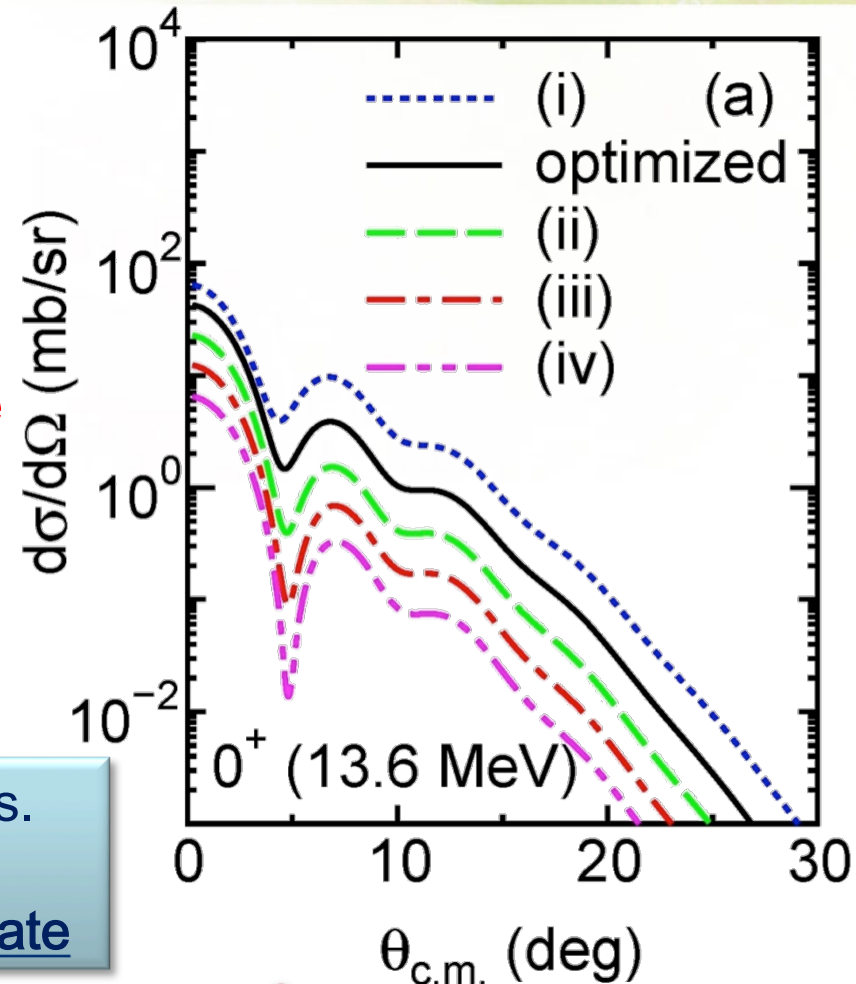
# Microscopic Coupled-Channel Calculations

- *Cross section is sensitive to r.m.s.*-

- *Microscopic Coupled-Channel*
  - Coupling between
    - 2ch: g.s. and ACC state
  - OMP : same as elastic scattering
  - **Transition density from  $\alpha$ -condensate model**
- *R.M.S. Dependence*
  - 3.4, 4.1, 4.7, 5.3, and 5.9 fm
  - 3.4 fm (large)  $\Leftrightarrow$  5.9 fm (small)

High sensitivity of absolute values to r.m.s.  
 $\Rightarrow$  Experimental cross sections give information on the diluteness of new state

R.M.S. could be determined from abs. values of c.s.



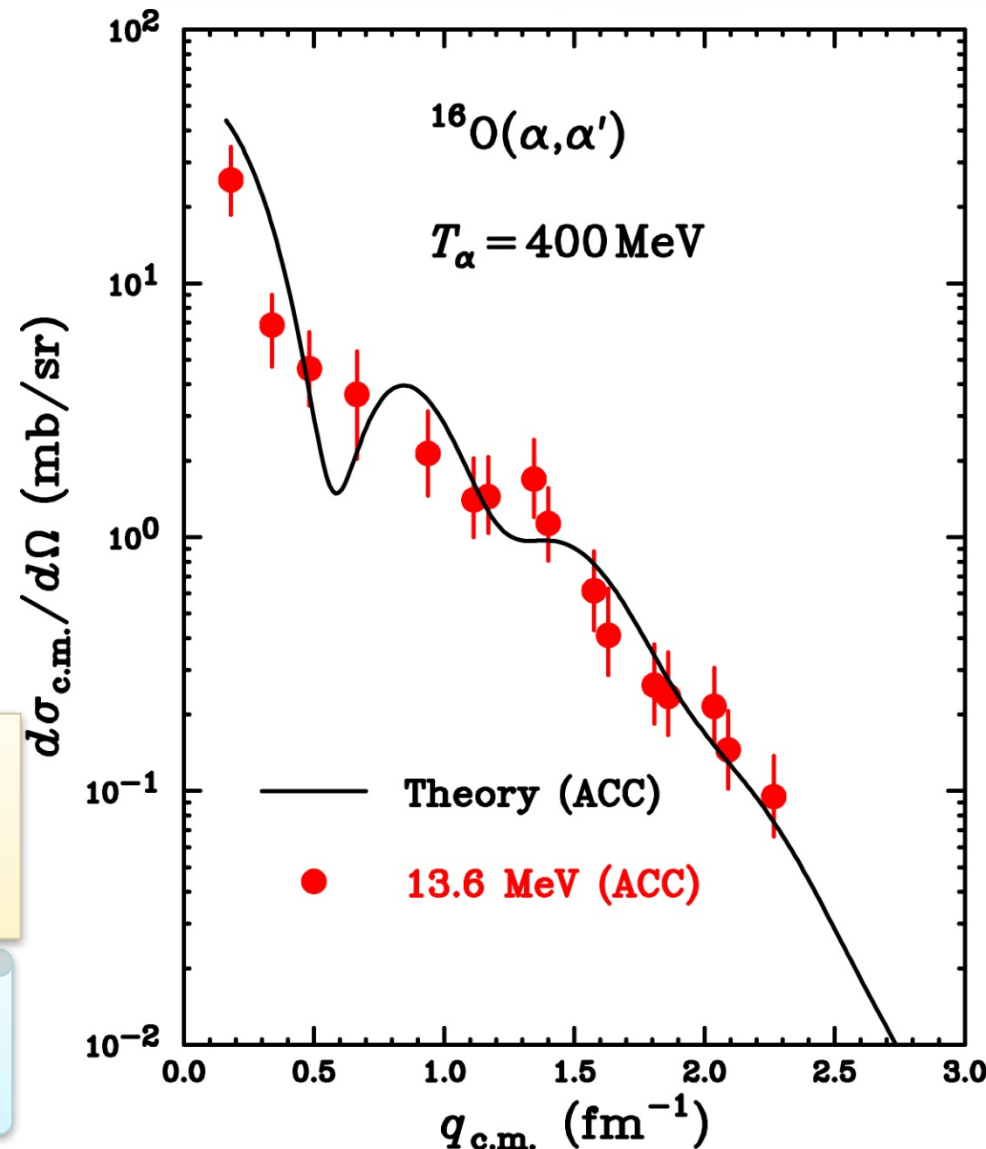
*M. Takashina and Y. Funaki,  
Private communications.*

# Comparison with Coupled-Channel Calculations

- *Cross sections of new state*
  - Clear L=0 ( $0^+$ ) q-dependence
  - Cover  $q=0-2.3 \text{ fm}^{-1}$
  - Error bars: including syst. Uncertainties
- *Theoretical calculations*
  - Couple-channel calculations
  - Transition density is calculated with  $\alpha$ -condensed model

Absolute values of cross sections are reproduced with ACC w.f. with r.m.s.=4.3 fm

New state is a (strong) candidate of ACC state



# Summary



- *Search for  $\alpha$ -cluster condensed state via  $^{16}\text{O}(\alpha, \alpha')$* 
  - Spin-scalar and Iso-scalar → **High sensitivity to ACC (isoscalar  $0^+$ )**
  - Use ice ( $\text{H}_2\text{O}$ ) target → **Background-free clean spectra**
- *$0^+$  state at  $E_x=14.0$  MeV and  $\Gamma=4.8$  MeV*
  - NOT clearly excited in  $(\alpha, \alpha')$
- *New  $0^+$  state*
  - **CLEARLY excited in  $(\alpha, \alpha')$  (ALSO excited in  $(^6\text{Li}, ^6\text{Li}')$ )**
  - Experimental information
    - $E_x=13.6 \pm 0.1$  MeV and  $\Gamma=0.6 \pm 0.2$  MeV
    - $L = (0^+)$
- *Comparison with theoretical calculations*
  - Absolute values of cross sections are sensitive to r.m.s. (diluteness)

Cross sections of new state are consistent with calc. for ACC (r.m.s.=4.3 fm)



*Misc*

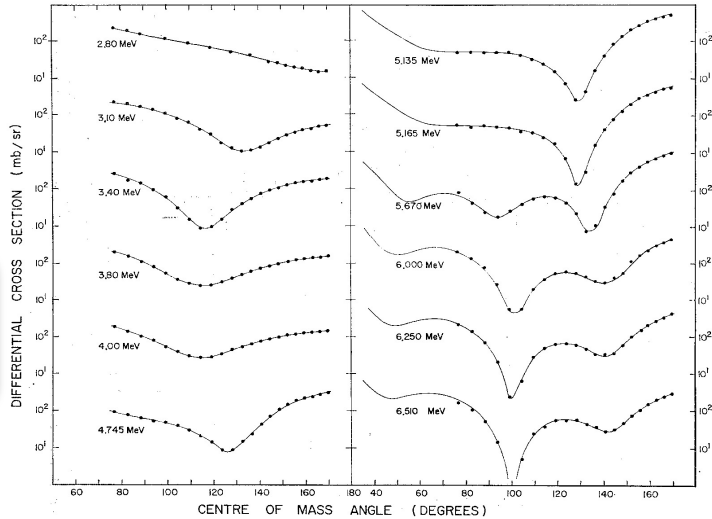
# Signature of the broad $0^+$ state in $^{16}\text{O}$

*G.C.Clark et al., NPA 110,481(1968).*

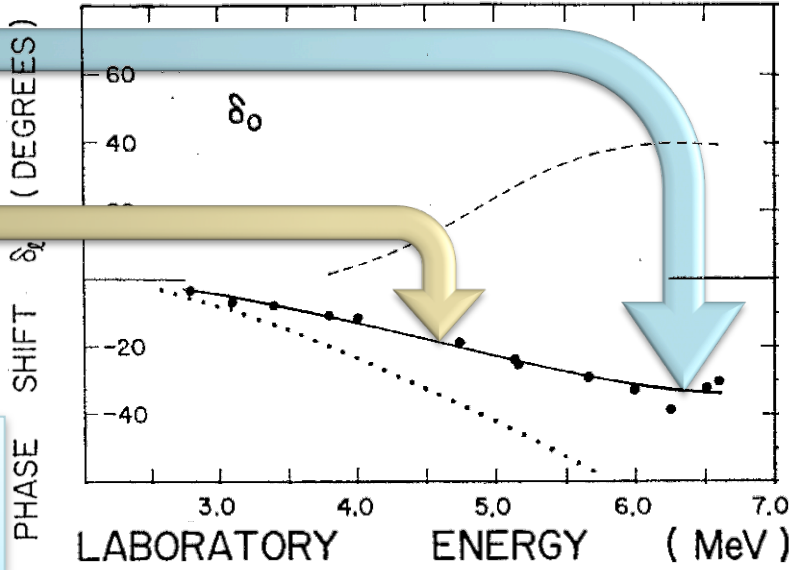
- $^{12}\text{C} + \alpha$  elastic scattering
  - $E = 2.8 - 6.6$  MeV (elastic channel only)

## Phase shift analysis

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \left| -\frac{1}{2}\eta \operatorname{cosec}^2\left(\frac{\theta}{2}\right) \exp(i\eta \ln \operatorname{cosec}^2\left(\frac{\theta}{2}\right)) + \sum_l (2l+1) P_l(\cos \theta) \exp(i(2\alpha_l + \delta_l)) \sin \delta_l \right|^2$$



- Require  $\delta_0 - \delta_5$
- *Dip at  $E = 6.5$  MeV*
  - Contribution from  $^{16}\text{O}(0^+; 12.05 \text{ MeV})$
- *Monotonous decrease of  $\delta_0$* 
  - Contribution from broad  $^{16}\text{O}(0^+)$ 
    - $E_x = 14.0 \text{ MeV}, \Gamma = 4.8 \text{ MeV}$



- ◆ NOT direct measurement (inelastic, decay)
- ◆ NO contribution from  $^{16}\text{O}(0^+; 11.26 \text{ MeV})$

# Microscopic Coupled-Channel Calculations

- Cross section is sensitive to r.m.s.-

*M.Takashina and Y.Sakuragi,  
PRC 74,054006(2006).*

- *Microscopic Coupled-Channel*

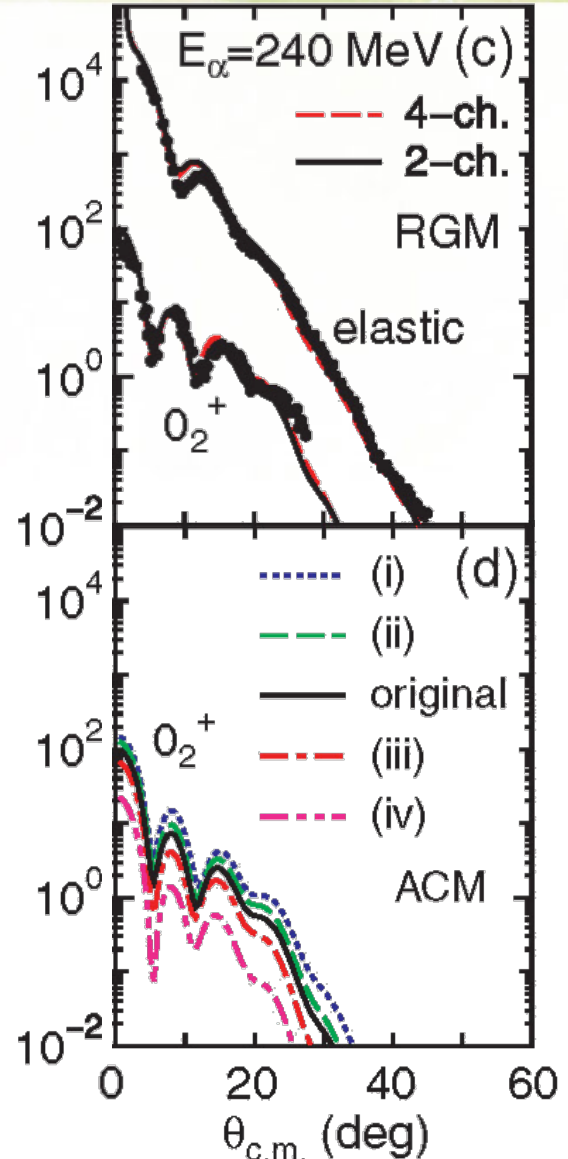
- Coupling between
  - 4ch: g.s., 2<sup>+</sup>, Hoyle, and 3<sup>-</sup>
  - 2ch: g.s. and Hoyle
- Double folding model with DDM3Y
- Transition density from  $\alpha$ -condensate model

Reproduce with ACC w.f. with r.m.s.=3.8 fm

- *R.M.S. Dependence*

- 3.0, 3.5, 3.8, 4.4, and 5.6 fm
- 3.0 fm (large)  $\Leftrightarrow$  5.6 fm (small)

Nuclear radius of excited state (diluteness)  
 $\Rightarrow$  Could determine from absolute values of c.s.



# Experimental condition



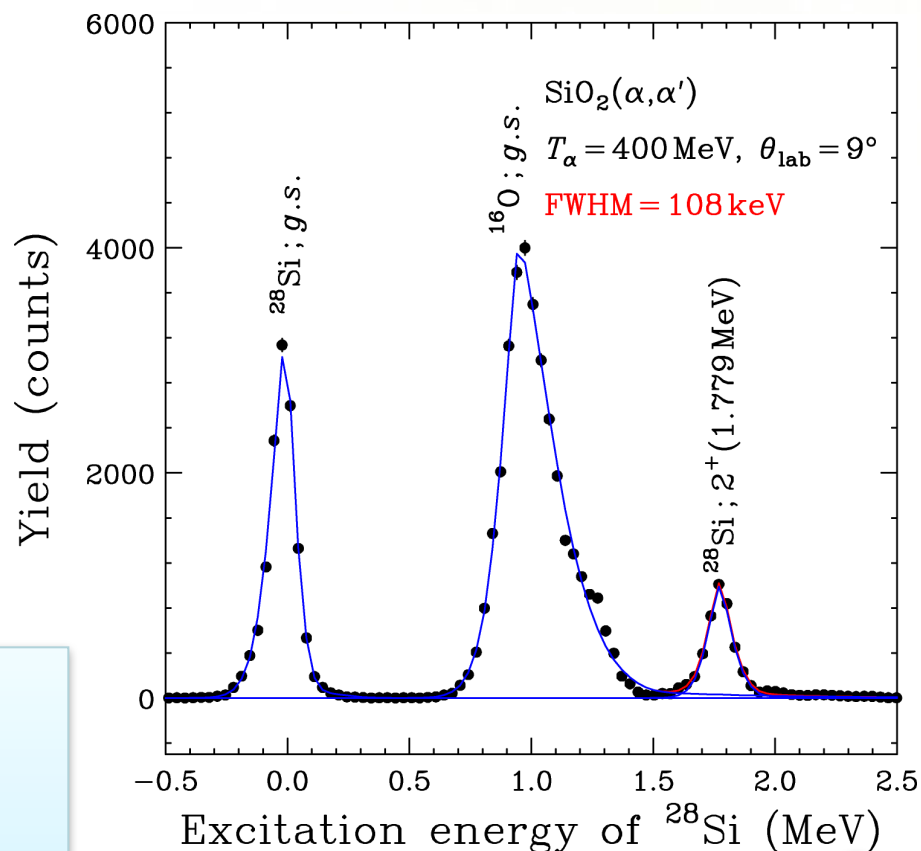
- *Search for  $\alpha$ -cluster condensed state in  $^{16}\text{O}$* 
    - Via spin-scalar and isoscalar ( $\alpha, \alpha'$ ) reaction
    - Large-area ice target for back-ground free clean spectra
      - Thin ice targets with a thickness of  $9 \text{ mg/cm}^2$
      - $\text{SiO}_2$  target with a thickness of  $2.0 \text{ mg/cm}^2$  *for normalization*
    - High-resolution and halo-free beam from WS for clean measurement
- Confirmation with  $^{16}\text{O}(^6\text{Li}, ^6\text{Li}')$  at  $E_{^6\text{Li}}=600 \text{ MeV}$  ( $100 \text{ MeV/A}$ )  
has been also performed
- ( $^6\text{Li}, ^6\text{Li}'$ ) = Isoscalar probe  $\Rightarrow$  Suitable for search for ACC
- *Beam Parameters in production runs*
    - $^4\text{He}$  at  $400 \text{ MeV}$  ( $100 \text{ MeV/A}$ )
    - Beam current:  $40 \text{ enA}$  on target
    - Energy resolution:  $110\text{-}190 \text{ keV}$
  - *Observables in production run with  $\alpha$  beam*
    - Elastic scattering  $1.5 \text{ deg.} \sim 31.0 \text{ deg.}$  in lab. system
    - Inelastic scattering  $0.0 \text{ deg.} \sim 15.0 \text{ deg.}$  in lab. system
    - Excitation energy range up to  $25 \text{ MeV}$

# High Quality $\alpha$ Beam

- High Energy Resolution -

- *Beam energy resolution was measured via  $\text{SiO}_2(\alpha, \alpha')$  scattering*
  - 107 keV for Si(g.s.)
  - 109 keV for Si(1.779 MeV)
  - 108 keV on the average
- $\Delta E/E = 2.7 \times 10^{-4}$ 
  - RCNP best beam energy resolution for  $\alpha$

High energy resolution is essential to resolve broad ACC state in high level-density region



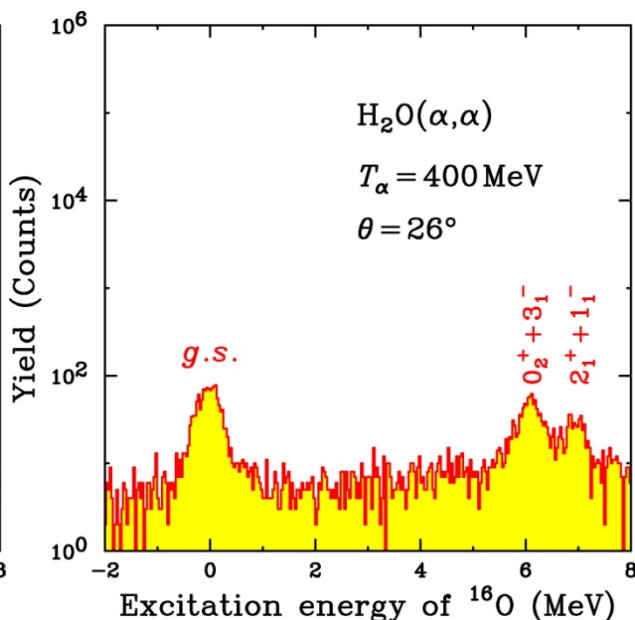
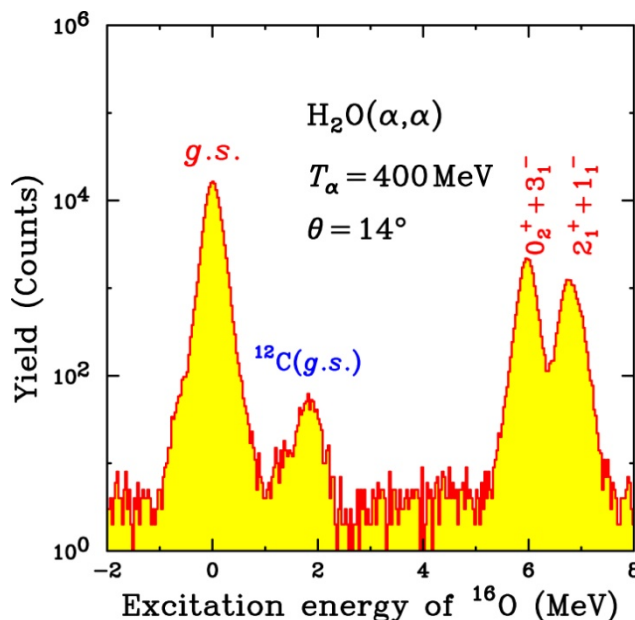
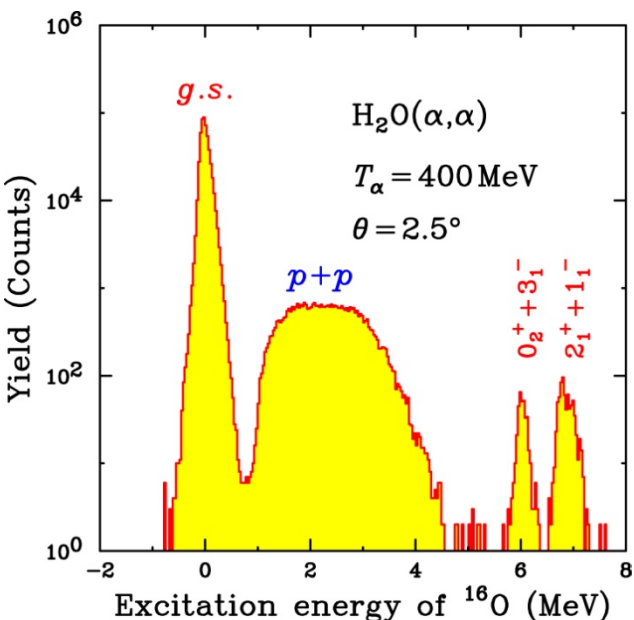
Kinematical corrections were optimized for Si (not for O)



# Elastic Scattering Spectra

- $\alpha + {}^{16}\text{O}$  elastic scattering clearly resolved
  - $\alpha+p$  elastic scattering (H<sub>2</sub>O target)
  - $\alpha+{}^{12}\text{C}$  elastic scattering (Oil in vacuum)
  - Inelastic scattering
  - Background

Target thickness:  
H<sub>2</sub>O(p,p)  $\leftrightarrow$  SiO<sub>2</sub>(p,p) with 2.0 mg/cm<sup>2</sup>  
Compare elastic scattering



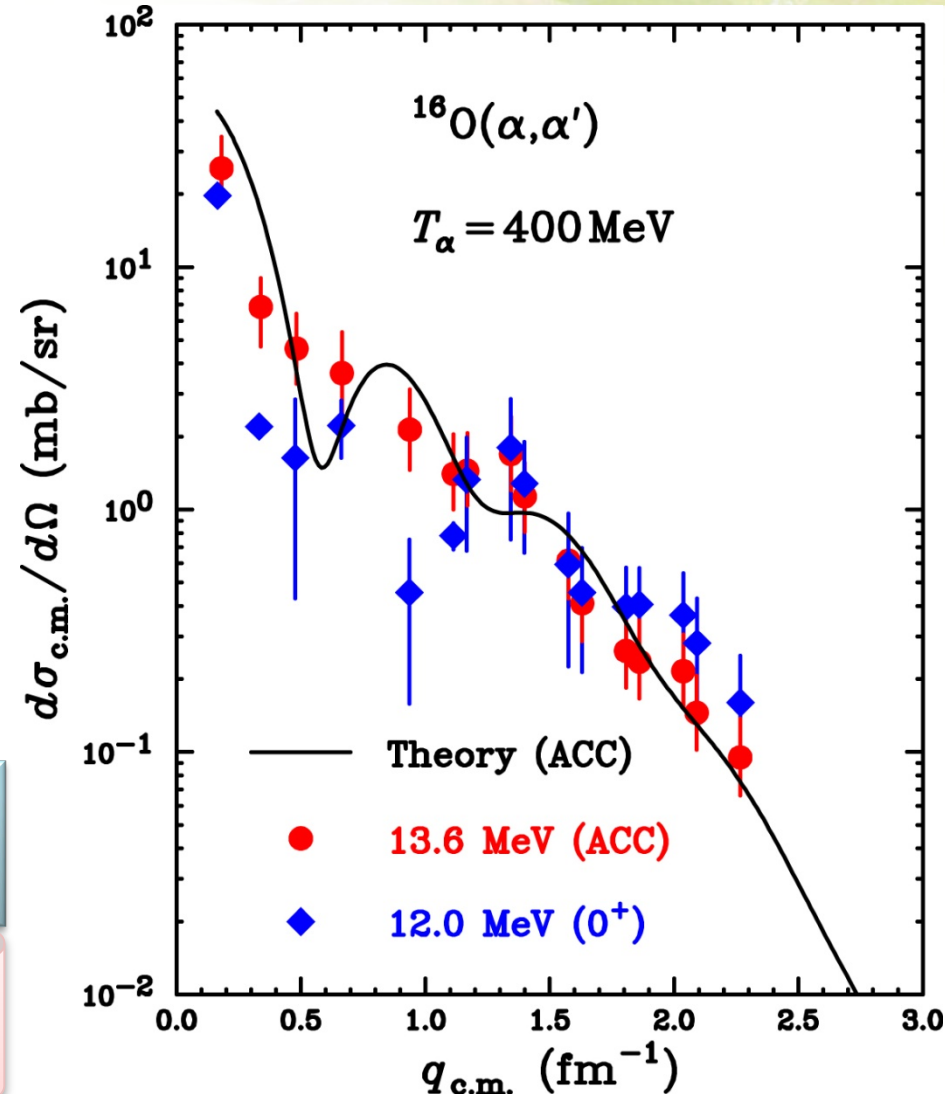
# Comparison with $^{12}\text{C}(2^+)+\alpha$ $0^+$ at 12.0 MeV

## - Evidence of well-developed cluster structure -

- $0^+$  state at 12.0 MeV
  - Cluster state
  - $^{12}\text{C}(2^+)+\alpha$  with  $l=2$
- *q-dependence of cross sections*
  - New state =  $0^+$  at 12.0 MeV
  - Spin-parity of new state =  $0^+$ 
    - Spin-scalar and Iso-scalar
- *Absolute values of cross sections*
  - New state =  $0^+$  at 12.0 MeV

Monopole excitation to cluster states  
= strong as to the s.p. strength

New state  
= Well-developed cluster structure





# Signal of Dilute Extension of ACC

## - Magnitude of Form Factor -

Y.Funaki et al.,EPJ A 28,259(2006).

- *Form factor from g.s. to Hoyle state*

- $\alpha$ -condensed (ACC) w.f.
  - Consistent with exp. Data
  - Consistent with RGM (Resonating Group Method)

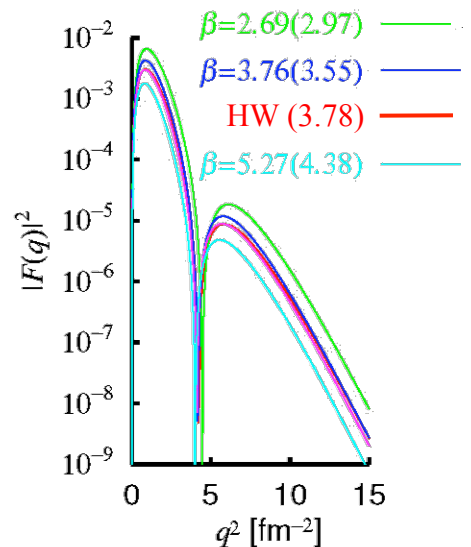
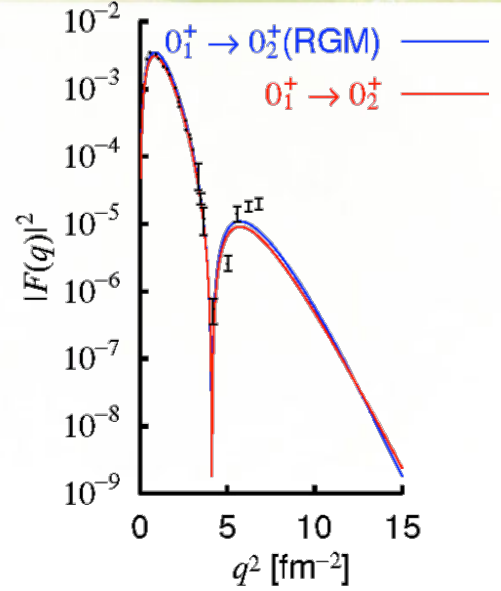
Result with ACC w.f. is highly reliable

- *Sensitivity to diluteness of ACC*

- Magnitude of form factor is sensitive to r.m.s.
  - Original 3.78 fm  $\rightarrow$  Dilute (gas-like) system
  - 2.97 fm (large)  $\Leftrightarrow$  4.38 fm (small)

Spatial extension of  $\alpha$ -cluster state

- ◆ Can be studied by abs. size of cross section (F.F.)
- ◆ Can NOT be studied by q-dependence



# Theoretical Prediction for Cluster States

- Independent of theoretical frameworks -

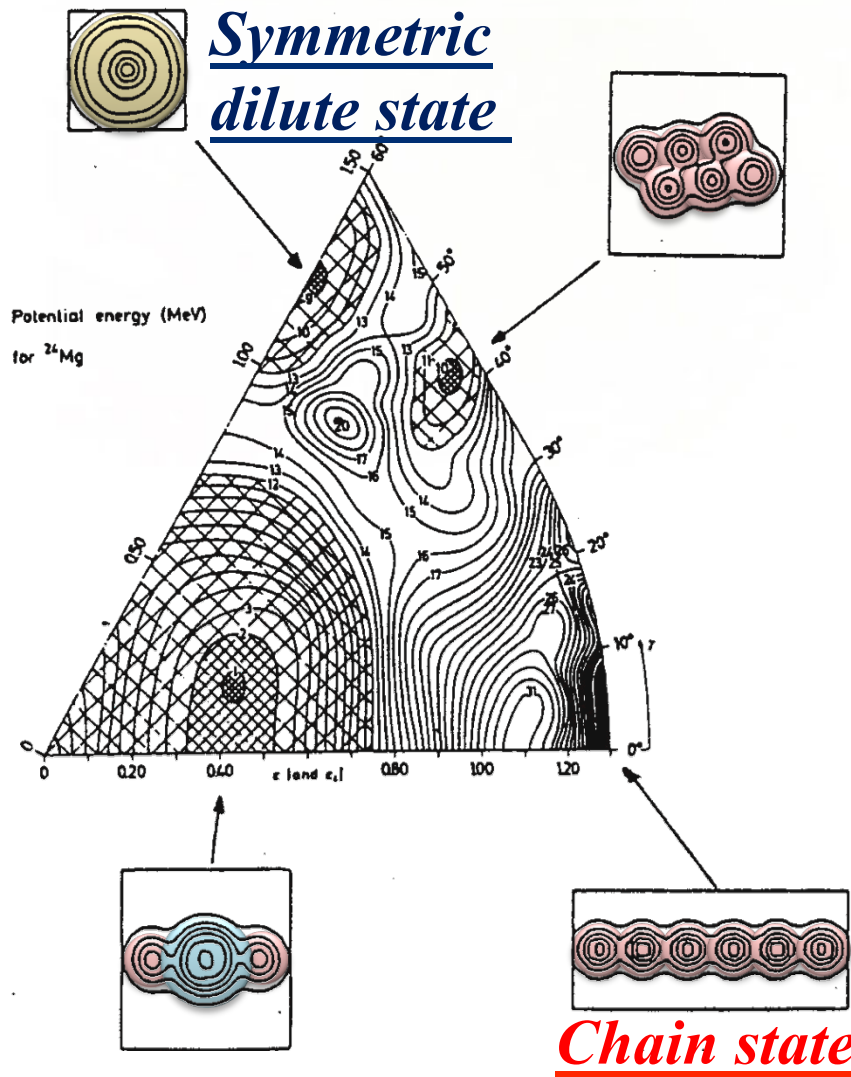
- *Theoretical prediction in  $\alpha$ -cluster model*
  - Several **stable** arrangements for  $\alpha$ -clusters

Supported also by Nilsson-Strutinsky calculations

- *(Linear) chain states have aroused much interest*
  - **Exotic shape** (extremely large deformation)
  - **New degree of freedom**

- Rotation
- Band-head of rotational band

Search for chain states and corresponding rotational bands





# Signature of 4 $\alpha$ Chain State in $^{16}\text{O}$

- *Produce  $^{16}\text{O}$  by  $^{12}\text{C} + \alpha$*

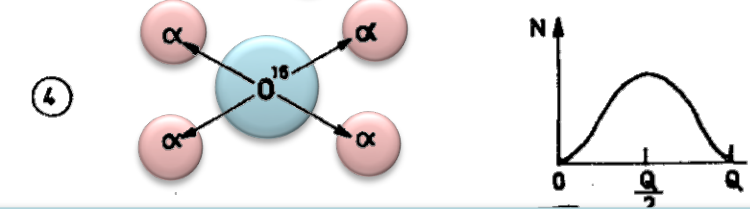
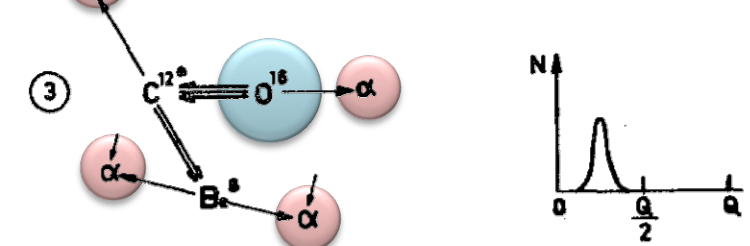
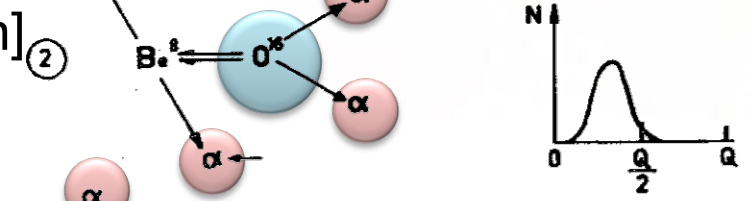
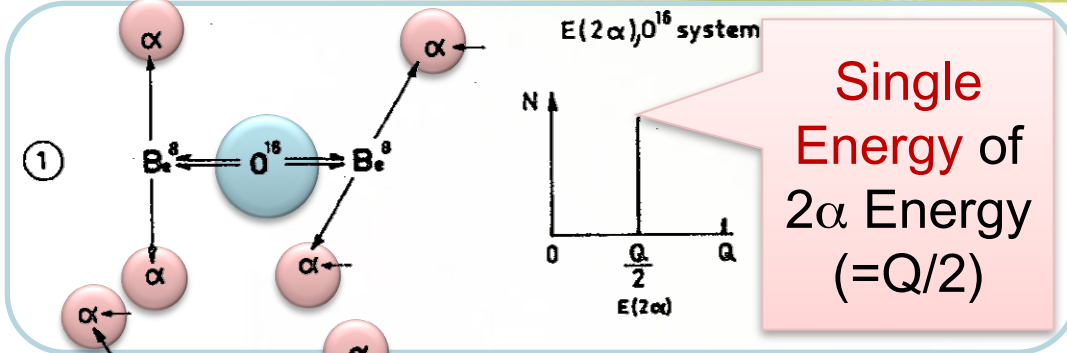
- $E_\alpha$ : 11.85-19.4 MeV
- $E_x$  in  $^{16}\text{O}$ : 16-20 MeV

- *Chain state in  $^{16}\text{O}$*

- Decay to 2  $^8\text{Be}(0^+)$  [2 $\alpha$  chain]

- *Decay modes of  $^{16}\text{O}$*

- $^{16}\text{O} \rightarrow ^8\text{Be} + ^8\text{Be}$   
↘ 2 $\alpha$  ↗  
↘ 2 $\alpha$  ↗
- $^{16}\text{O} \rightarrow ^8\text{Be} + 2\alpha$   
↘ 2 $\alpha$  ↗
- $^{16}\text{O} \rightarrow ^{12}\text{C}(0^+; 7.6\text{MeV}) + \alpha$   
↘  $^8\text{Be} + \alpha$  ↗  
↘ 2 $\alpha$  ↗
- $^{16}\text{O} \rightarrow 4\alpha$

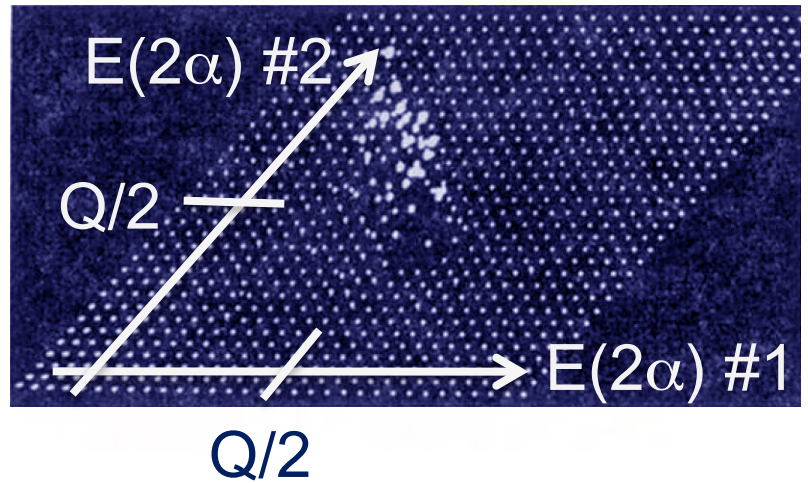


Measure 2 $\alpha$  energy  $\rightarrow$  Select  $^{16}\text{O} \rightarrow ^8\text{Be} + ^8\text{Be}$

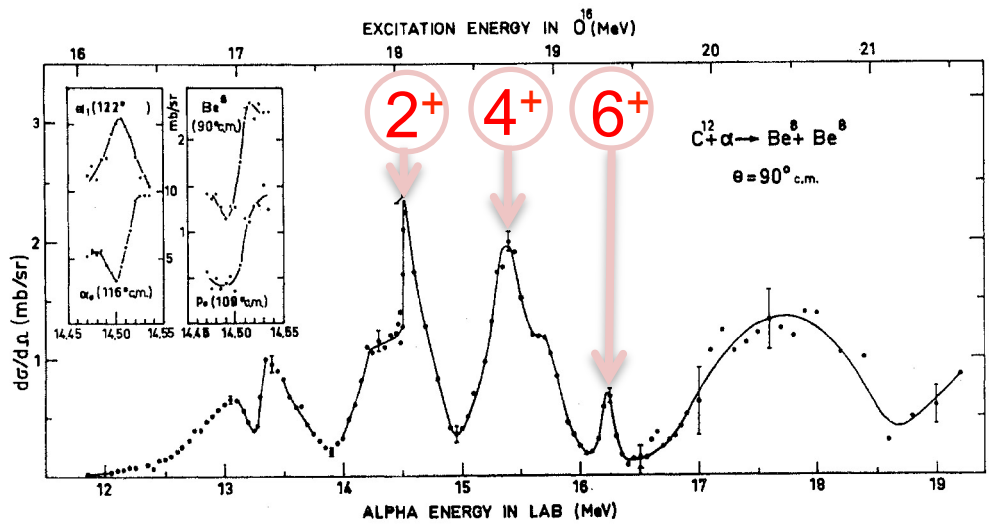
# Signature of $4\alpha$ Chain State in $^{16}\text{O}$



- *Select  $\alpha$ -detection angles*
  - Enhance  $^{16}\text{O} \rightarrow ^8\text{Be} + ^8\text{Be}$  events
- *Angular distribution of  $2\alpha$ - $2\alpha$* 
  - Enable  $J^\pi$  assignment
- *Excitation function*
  - Several resonances in  $E_x=16$ - $21$  MeV of  $^{16}\text{O}$
  - $J^\pi=2^+, 4^+, 6^+$  states were found



Rotational band of chain state?



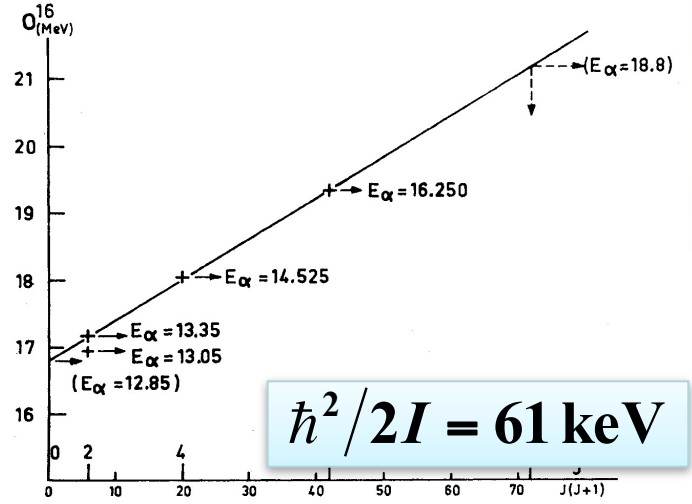
# 4α Chain State in <sup>16</sup>O


## - Rotational Band of Chain State -

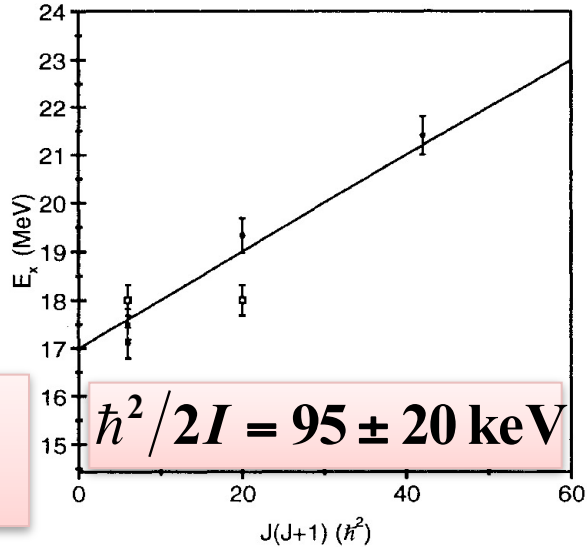
*P. Chevallier et al., PR 160, 160 (1967).  
M. Freer et al., PRC 51, 1682 (1995).*

- *Observed 2<sup>+</sup>, 4<sup>+</sup>, 6<sup>+</sup>*
  - **Consistent with rotational band**
    - Band head: 16.8 MeV E<sub>x</sub> in <sup>16</sup>O
    - $\hbar^2/2I = 61 \text{ keV}$

◆ Large moment of inertia  
 $= 3 \times [M(^{16}\text{O}) \cdot R(^{16}\text{O})^2]$   
 ◆ 4α liner chain structure  
 → Distance between αs = 4.1 fm



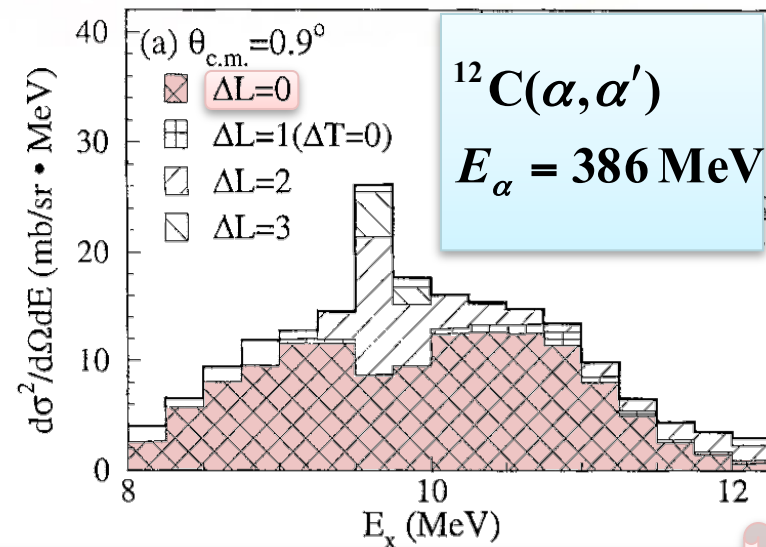
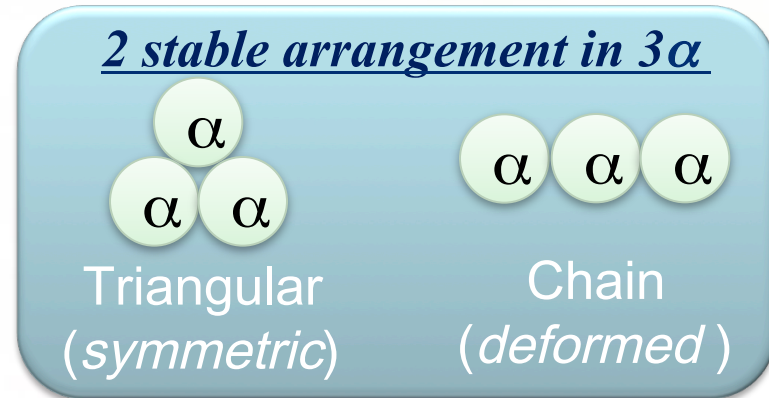
- *Later study*
    - <sup>12</sup>C(<sup>16</sup>O, <sup>16</sup>O\*)<sup>12</sup>C at 99 MeV  
 4α
    - Similar rotational band, but
      - $\hbar^2/2I = 95 \pm 20 \text{ keV}$
- Significant difference between exp. data  
 → **Existence of 4a chain state is NOT settled**



# Excited $0^+$ states in $^{12}\text{C}$

## - Chain State? Dilute Symmetric State? -

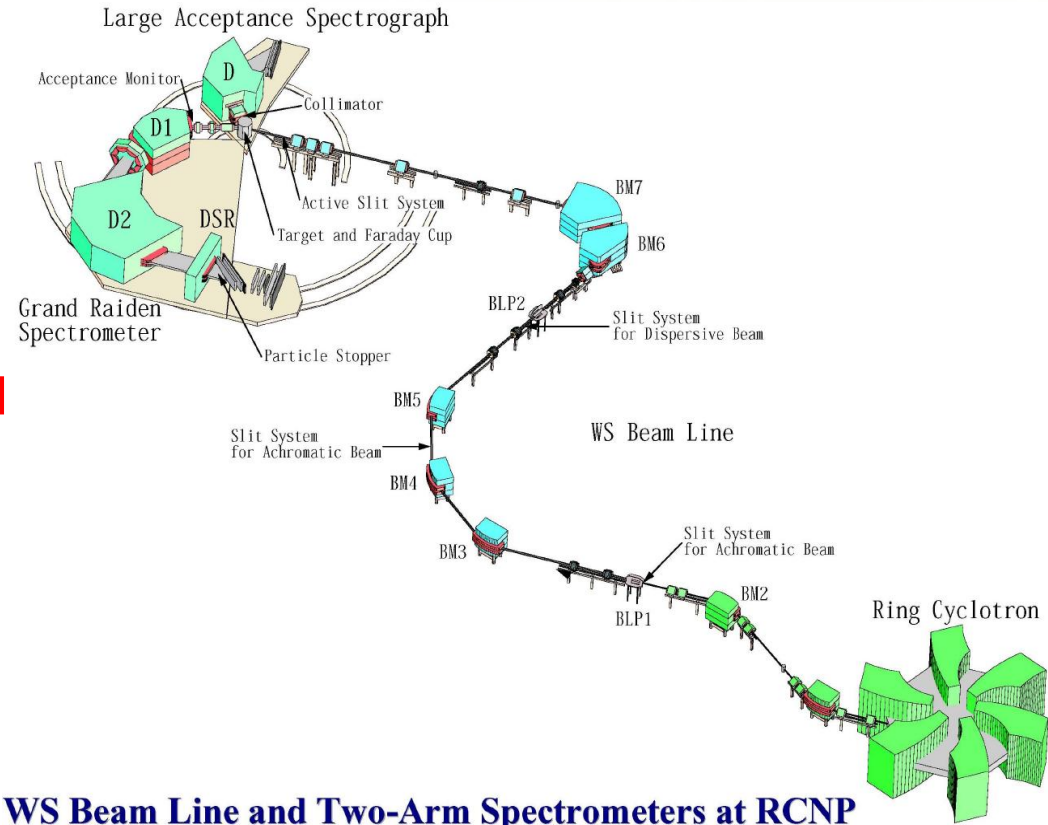
- *Search for chain state in  $^{24}\text{Mg}$* 
  - Observe two  $^{12}\text{C}(0^+; 7.6 \text{ MeV})$ 
    - Hoyle state
    - Assume  $3\alpha$  linear chain
- *If  $^{12}\text{C}(0^+; 7.6 \text{ MeV})$  is a chain state*
  - There should be a rotational band
  - There is NO  $2^+$  member
- *Recent exp./theoretical works*
  - Broad 10.3 MeV state is identified as
    - $0^+$  at  $E_x = 10.0 \text{ MeV}$  and  $\Gamma = 2.7 \text{ MeV}$
    - $2^+$  at  $E_x = 9.9 \text{ MeV}$  and  $\Gamma = 1.0 \text{ MeV}$
  - New a-cluster (cond.-type) w.f.
    - 7.6 MeV state is dilute and symmetric (a-cluster cond. state)



$0^+$  at 10.0 MeV  
 $2^+$  at 11.2 MeV } Rotational band?

# Specifications of WS

- *Total length: 65.46m*
- *Total bending angle: 270°*
- *Five double-focus points (Two for BLP)*
- *Dispersive mode*
  - Dispersion: 37.1 m
  - Angular dispersion: 20.0 rad
  - Compete matching with GR
- *Achromatic mode*
  - Lateral dispersion: 0 m
  - Angular dispersion: 0 rad
  - Double achromatic beam

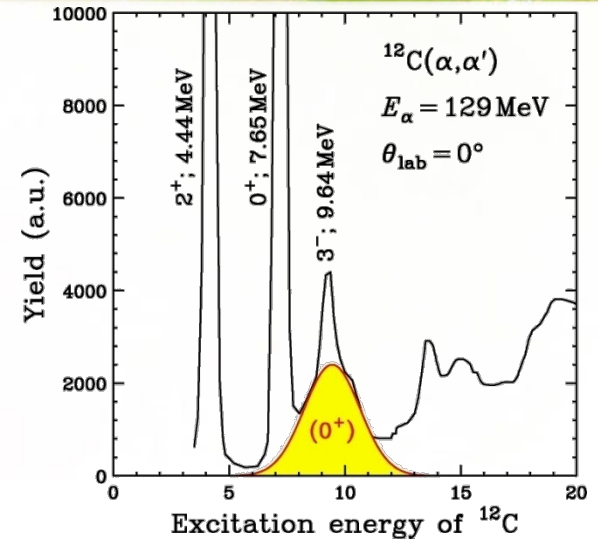


WS Beam Line and Two-Arm Spectrometers at RCNP

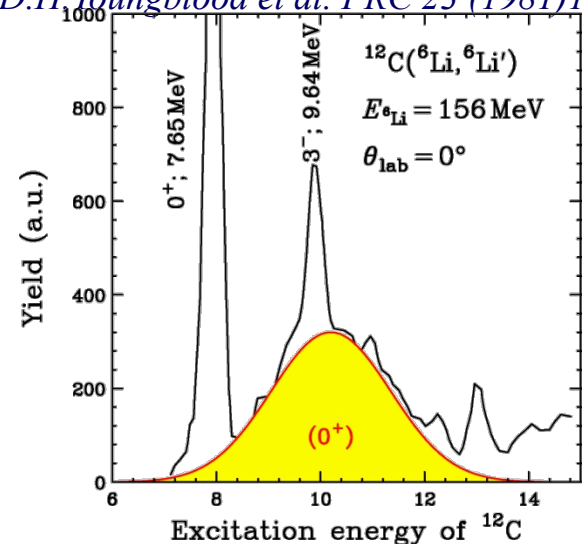
# Experimental Procedure



- *Excite  $\alpha$ -cluster condensed  $0^+$  state via*
  - $^{16}\text{O}(\alpha, \alpha')$ 
    - Isoscalar only
    - Spin-scalar only
    - Clearly excite 10.2 MeV  $0^+$  state in  $^{12}\text{C}$
  - $^{16}\text{O}(^6\text{Li}, ^6\text{Li}')$ 
    - Isoscalar only
    - Spin-scalar and spin-vector
    - Projectile excitation
    - Favorable S/N ratio at high excitations due to the low binding energy of  $^6\text{Li}$
    - Clearly excite 10.2 MeV  $0^+$  state in  $^{12}\text{C}$
- *Optimize probe*
  - $\alpha$  or  $^6\text{Li}$
- *Measure angular distribution*
  - Distinctive assignment of L

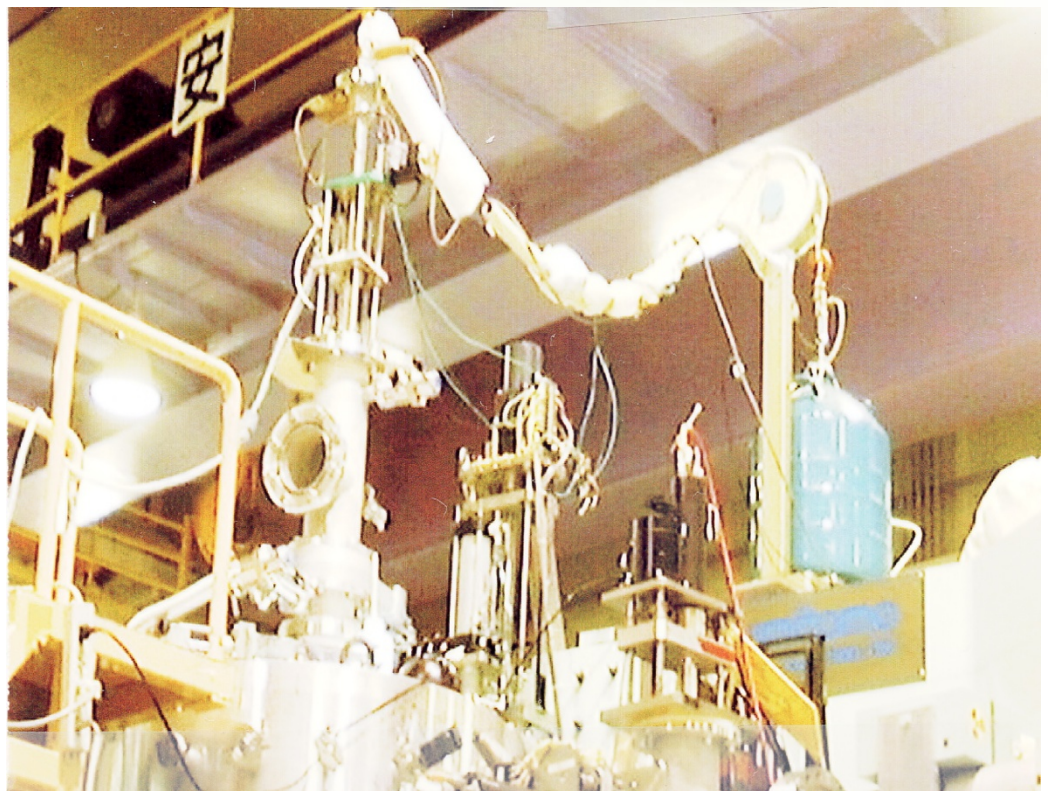
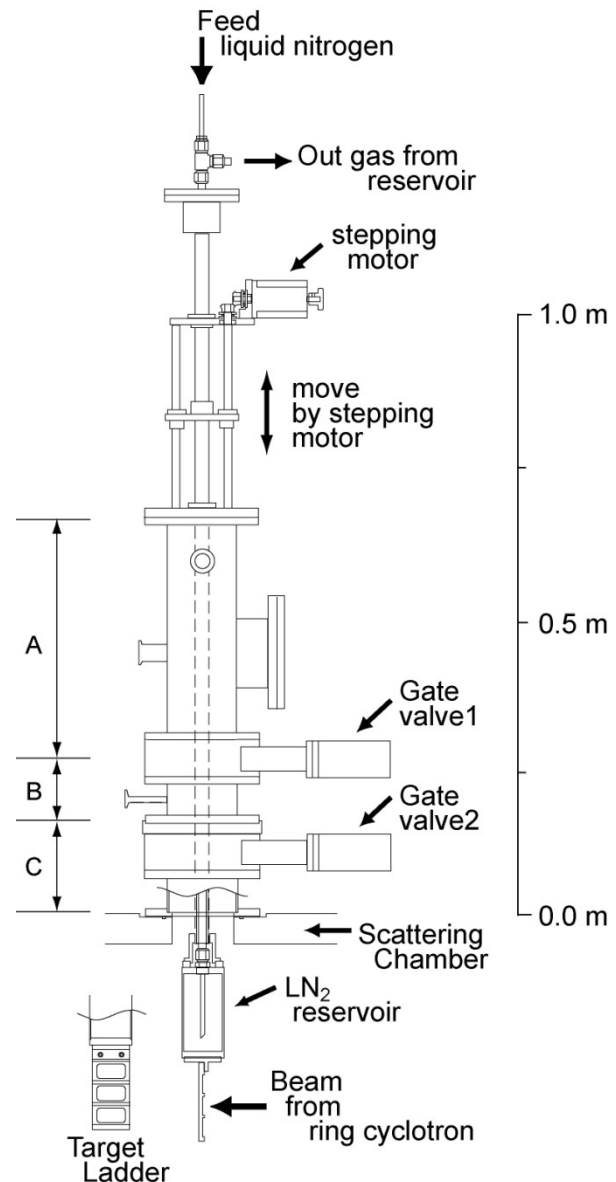


*D.H. Youngblood et al. PRC 23 (1981)1997.*



*W.Eyrich et al. PRC 36 (1987)416.*

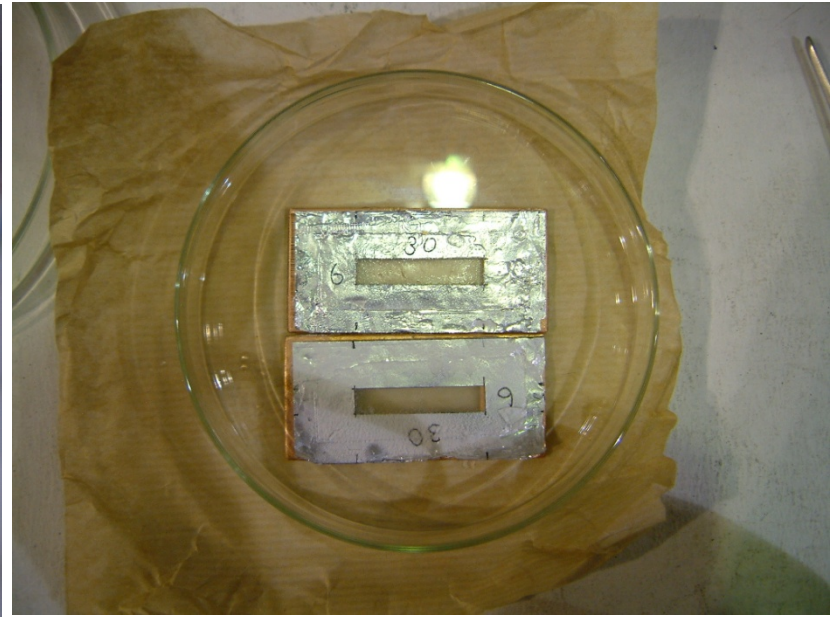
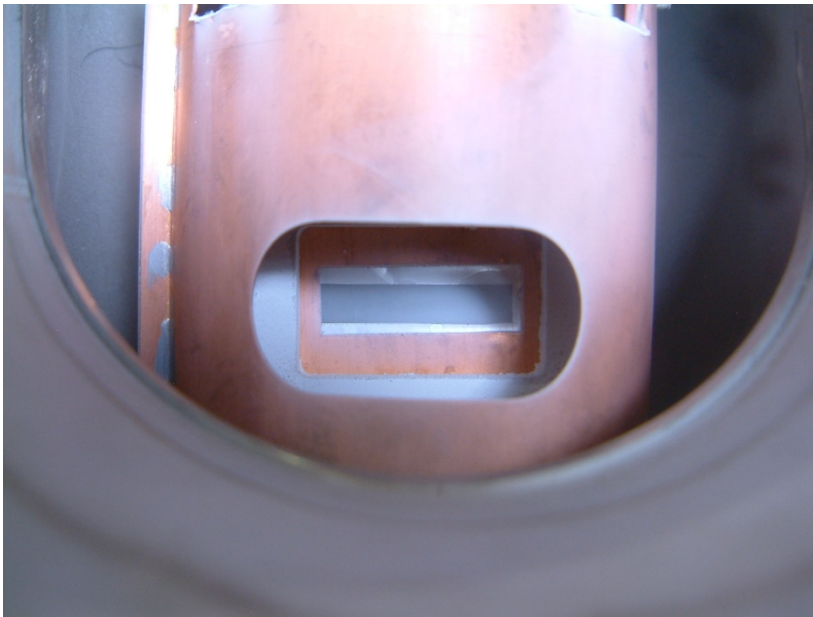
# Cooling System for Ice Target



T. Kawabata et al.  
Nucl. Instrum, Methods  
Phys. Res. A 459, 171 (2001)

# Ice Targets

- 9 mg/cm<sup>2</sup>
- 30 mm × 6 mm  
(for dispersive beam and background-free spectra)



# High Quality $\alpha$ Beam

## - Halo-free -

- *Contributions from background events (beam halo, etc.) can be estimated by using the y-position spectrum in the focal plane*
  - Peak around  $y=0$  corresponds to the true events from the ice target
  - Background events make continuum (flat) y-position spectrum
- *Background events are very small*
- *Background events make almost flat continuum in the excitation-energy spectrum*

