Alpha Inelastic Scattering on ^{16}O and Alpha Cluster States

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Outline

Requirements by the Organizers:
All the contributors are requested to give a presentation including new ideas, interesting topics, and problems in order to promote active discussions and new collaborations.

- New 0^+ state in ^{16}O at E_x=13.6 MeV and Γ=0.6 MeV
  - Previously assumes as a candidate of ACC
  - NOW, not ACC (but with large r.m.s.)
  - **Theoretically, 0^+ at 15.1 MeV seems to be ACC**
- Re-analysis of $^{16}O(\alpha,\alpha')$ data
  - What kind of information can be deduced ?
  - **Provide some very-preliminary results**
    - 15.1MeV state
    - Other 0^+ (cluster) states
- Re-analysis of ^{16}O(p,p') data
  - (p,p') data can provide another information on 0^+ ?
- Comment on (0^+) state at E_x=11.26 MeV and Γ=2.5 MeV
  - Spin-partity assignment seem to be questionable

Prediction of 4α Cluster State ^{16}O

- Prediction of α-particle condensed state -

A.Tohsaki, H.Horiuchi, P.Schuck et al., PRL 87 (2001)192501

	E_{calc} (MeV)	E_{exp} (MeV)	$R.M.S._{calc.}$ (fm)	$R.M.S._{exp.}$ (fm)
1st	-124.8	-127.6 (g.s.)	2.6	2.7
2nd	-116.0	-116.4 (0^+(?) at 11.3 MeV & Γ=2.5MeV?)	3.2	N/A
3rd	-110.7	-113.6 (0^+(?) at 14.0MeV & Γ=4.8MeV?)	4.0	?
4α	-110.0	-113.2		

Suggested by $^{12}C+\alpha$, but NOT experimentally confirmed

Large R_0 value → ACC
- Center of mass momenta P=0 (Condensed state)
- Dilute state

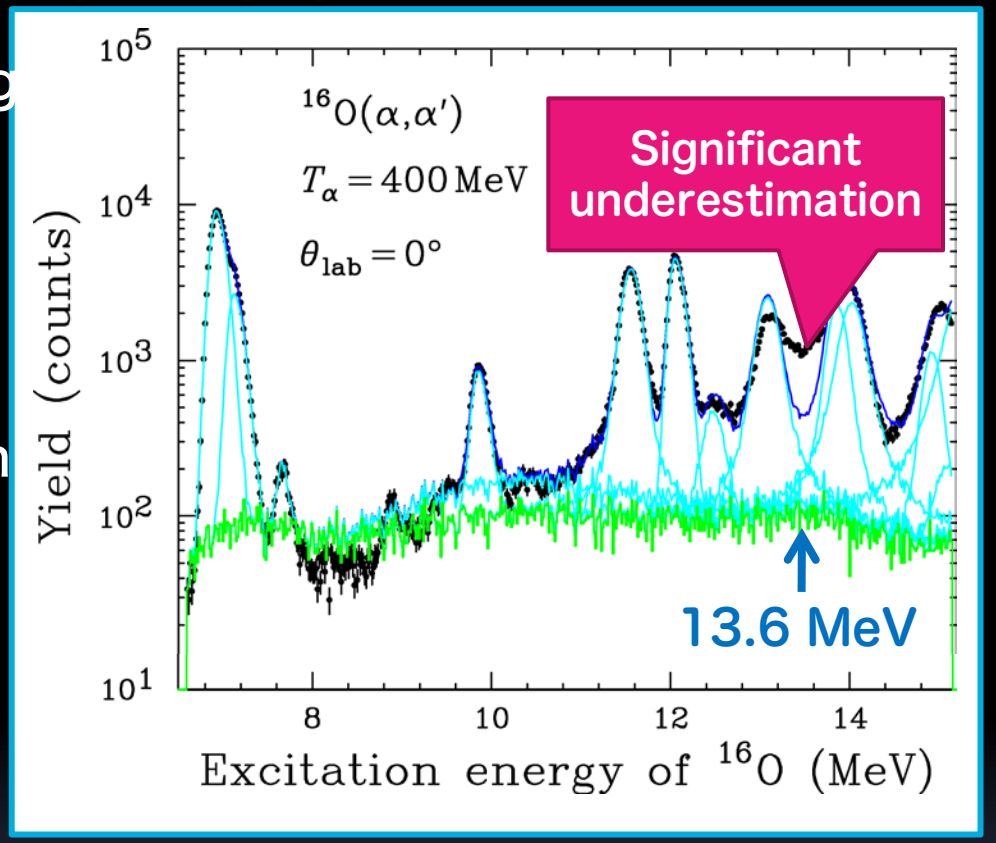
Experimentally "MISSING(?)" 0^+ ACC state
→ Expected large width makes it difficult to be observed ?

E189 Experiment at RCNP

- Search for ACC state in ^{16}O
  - Investigation of 14.0 MeV 0^+ state in ^{16}O
    - Observed only in $^{12}C+\alpha$
    - Not yet confirmed
    - Not yet listed in Table of Isotopes / NNDC
  - Search for new α-cluster 0^+ state as ACC around 4α threshold
    - Search for 0^+ around 14 MeV

Result of Peak Fitting
- Signature of new cluster 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

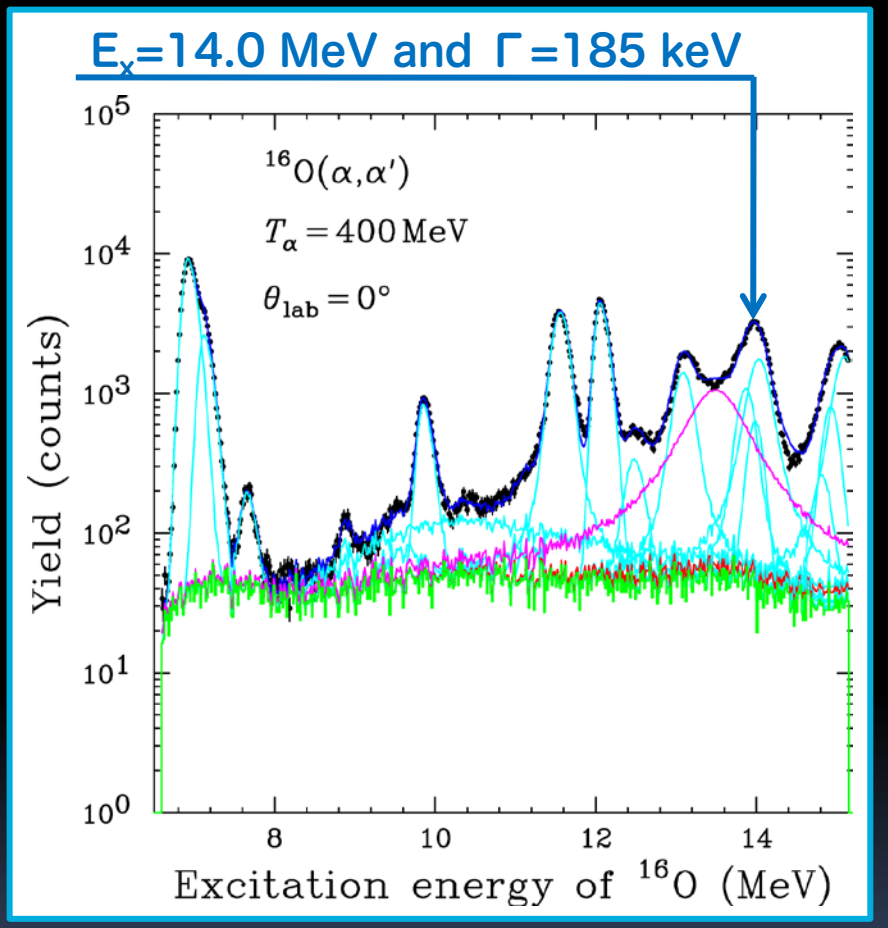


Underestimation at 13.6 MeV is independent of q (common for all data)
⇒ Strong indication for new state

Comment on 0^+ State at 14.0 MeV

- NO clear signature of E_x=14.0 MeV and Γ=4.8 MeV -

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



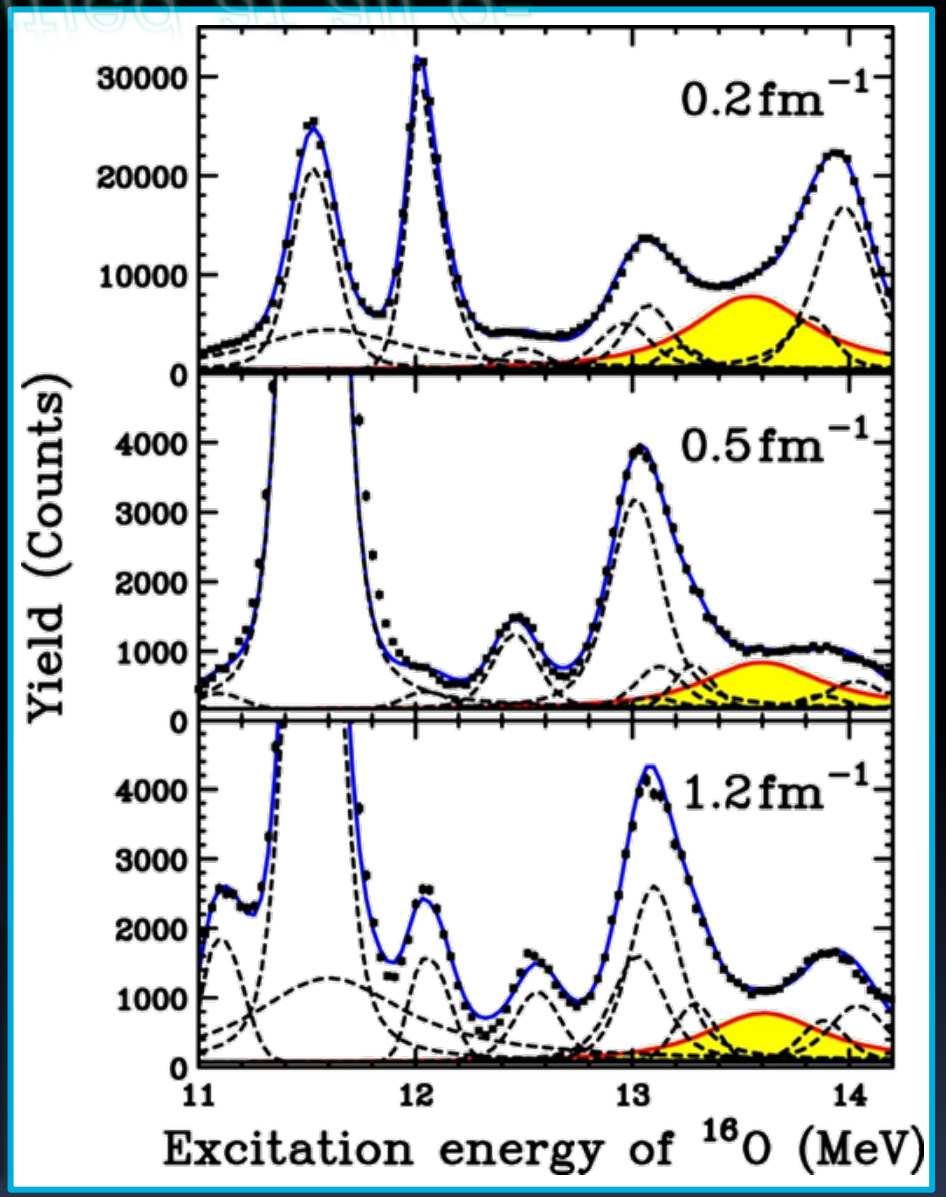
14.0 MeV 0^+ state (red curve) is NOT clearly observed
(0^+ E_x=14.0 MeV and Γ=185 keV is clearly observed)

Results of Reproduction at Large q
- New State is identified at all q-

- Inelastic scattering data
  - q = 0.2 – 2.3 fm^{-1}
  - Significant yield at 13.6 MeV for all q-transfer data
    - NOT reproduced with known states
    - Contribution from new state

- Peak fitting (reproduction) with new state
  - E_x = 13.6±0.1 MeV
  - Γ = 600±200 keV

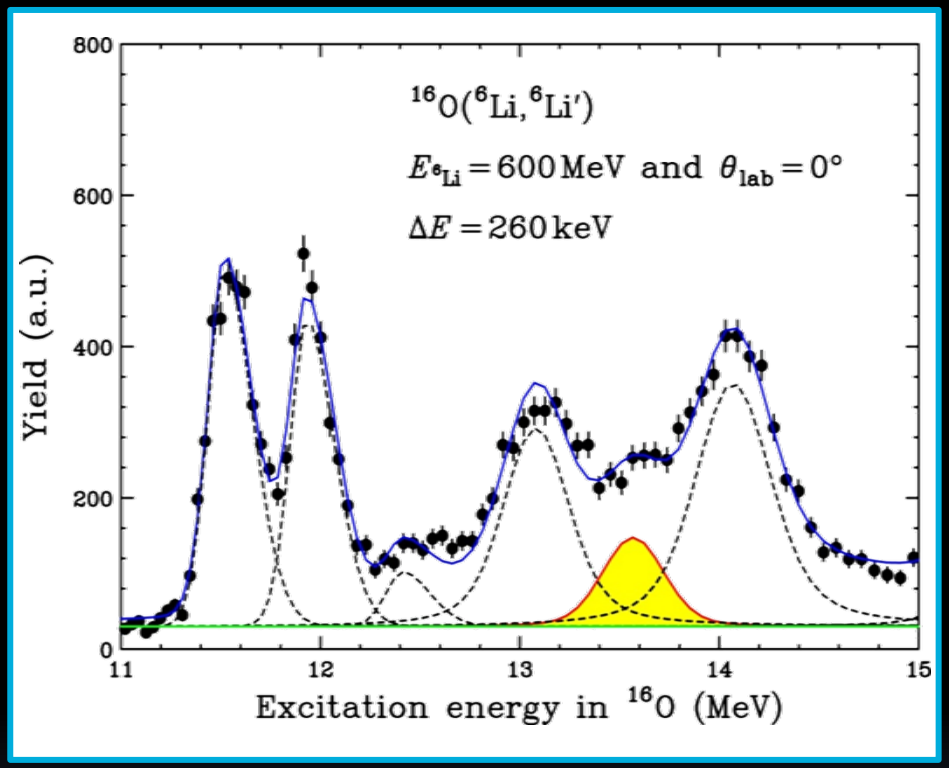
Reasonable reproduction
at all momentum transfers
with common parameters
→ Strong indication of new state



Observation of New State with Other Probe

– $^{16}O(^{6}Li,^{6}Li')$ at E_{Li}=600 MeV and 0° –

- Energy resolution
  - Spread of ^{6}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 MeV
    - Γ = 0.7 MeV

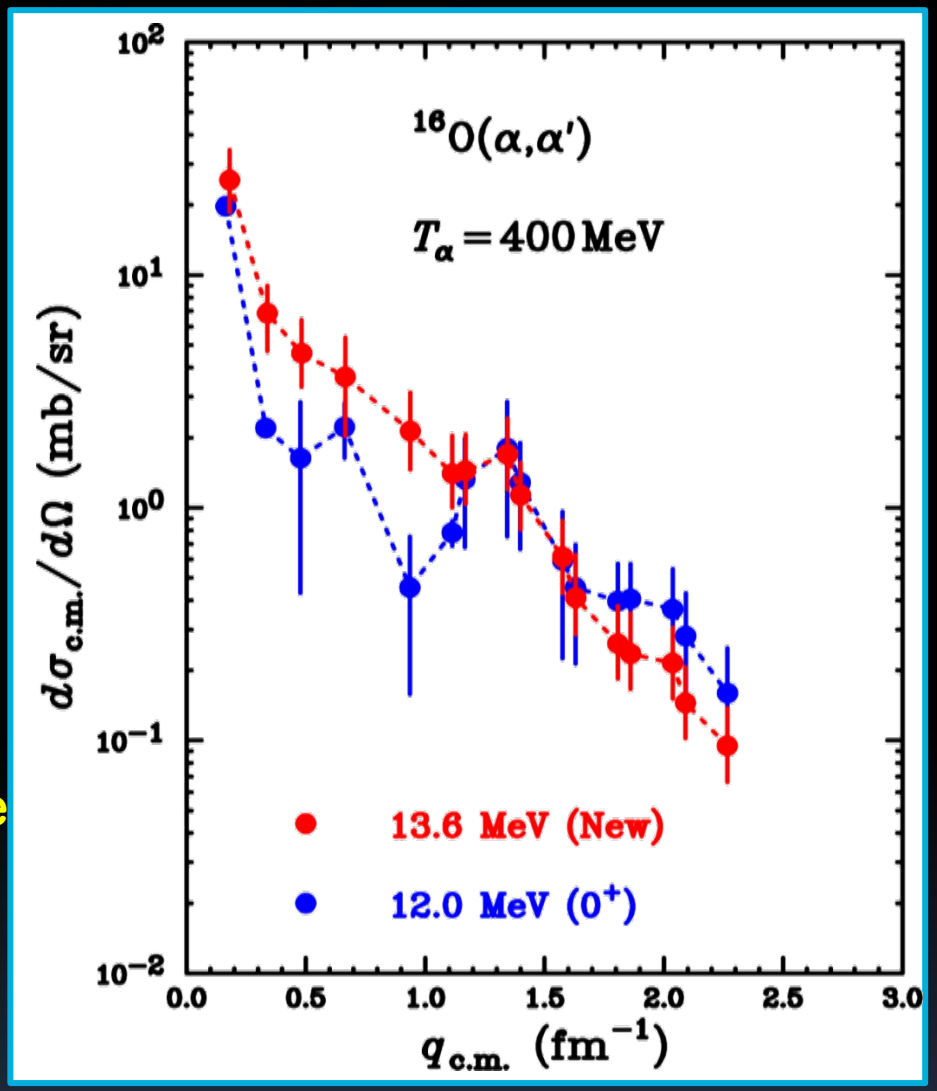


Consistent with $^{16}O(\alpha,\alpha')$ results

- No angular distribution data

Spin and Parity of New State

- Angular distribution of new state
  - Deduced up to 2.3 fm^{-1}
  - Forward peaking
- Comparison with 0^+_3 at 12.0 MeV
  - Similar angular distribution
    - $J^\pi = 0^+$
  - Similar magnitude
    - New state is also well-developed cluster state
    - Would have large B(E0)

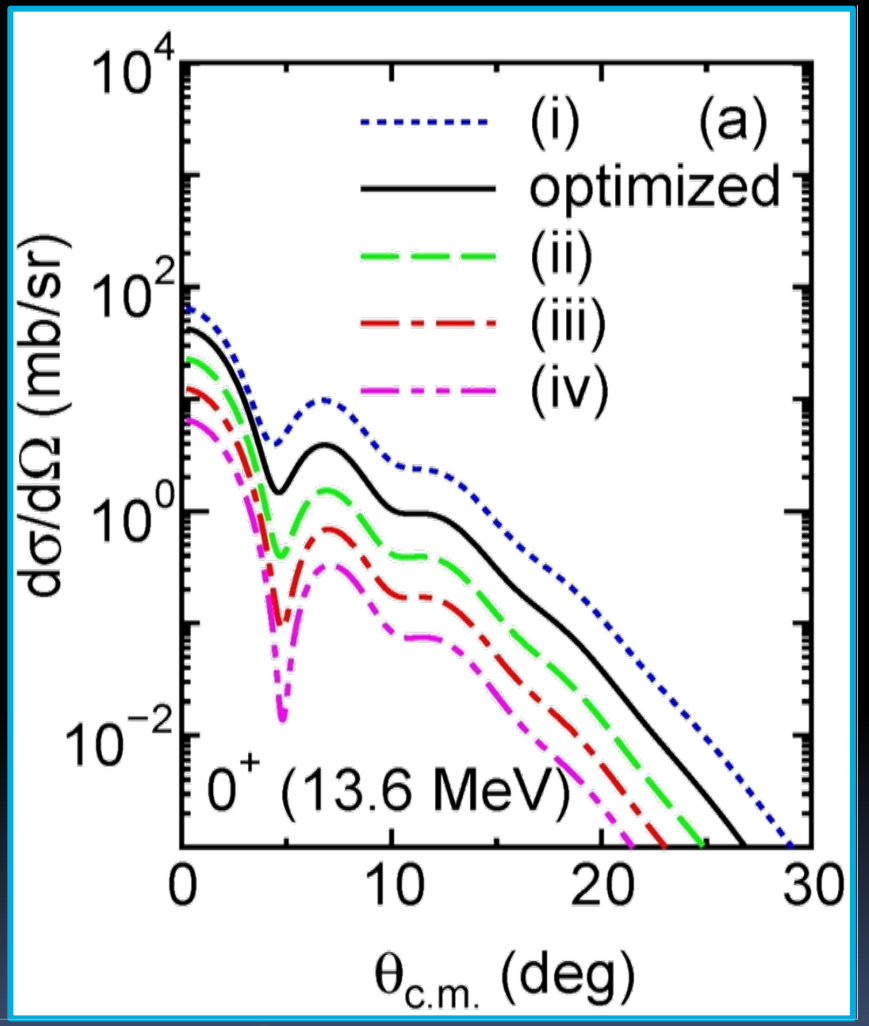


New state at 13.6 MeV is a cluster state with 0^+
(Can be a candidate of ACC)

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 scatt.
  - Transition density from α-condensate model
- R.M.S. Dependence
  - 3.4, 4.1, 4.7, 5.3, and 5.9 fm
  - 3.4 fm (large) ⇔ 5.9 fm (small)



High sensitivity of abs. values to r.m.s.
⇒ Exp. cross sections give information on the diluteness of new state

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

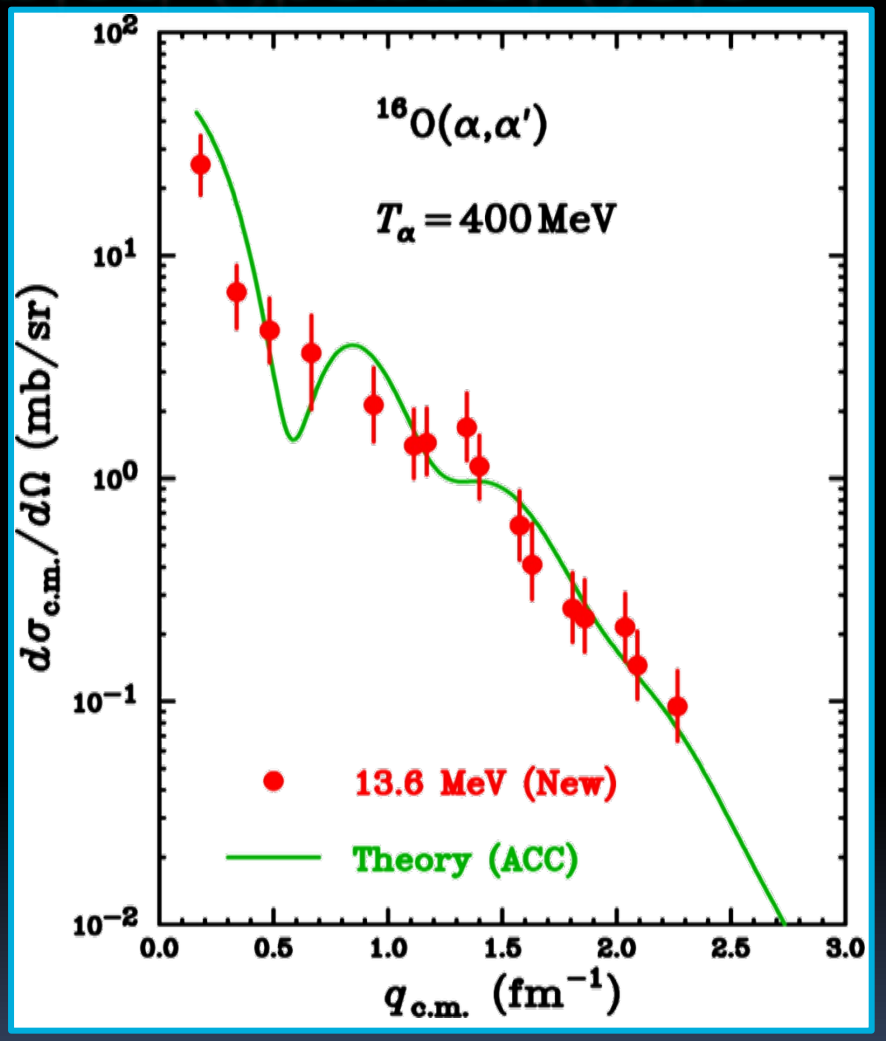
M.Takashina and Y.Funaki, Private communications.

Comparison with Coupled-Channel Calc.

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

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

New state is a candidate of ACC state

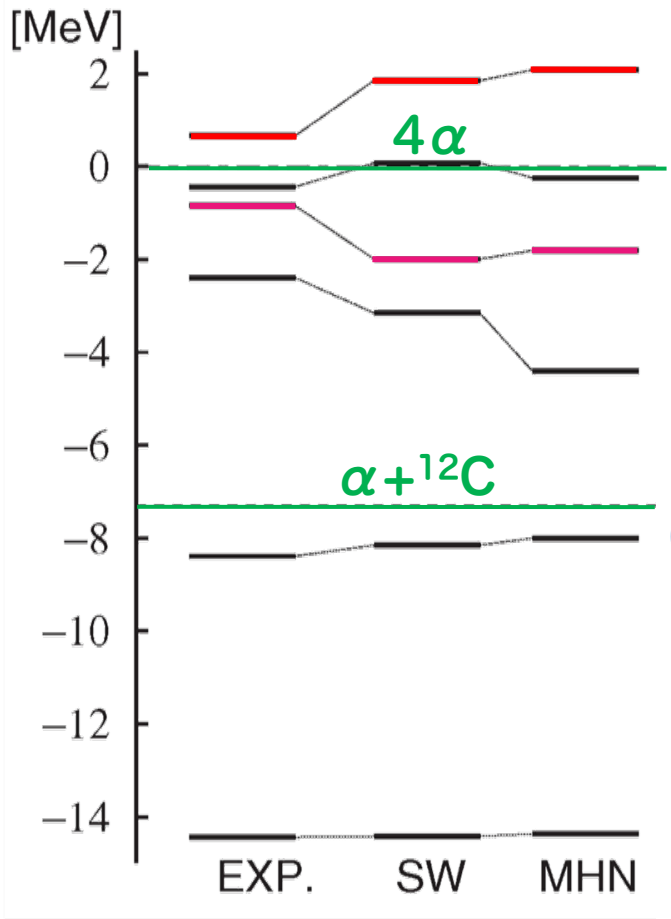


This was the conclusion of our PLB paper

Recent Theoretical Progress and Re-analysis of $^{16}O(\alpha,\alpha')$ Data

Full 4α OCM Calculations

Y.Funaki et al., PRL 101,082502(2008)



0^+_6;4α ACC ← Known 0^+ at 15.1 MeV

0^+_5;α+^{12}C(1^-) in P

0^+_4;α+^{12}C(0^+) w/ higher nodal ← NEW

0^+_3;α+^{12}C(2^+) in D

0^+_2;α+^{12}C(0^+) in S

0^+_1;g.s.

	R		M(E0)	
	SW	MHN	SW	MHN
0^+_1	2.7	2.7		
0^+_2	3.0	3.0	4.1	3.9
0^+_3	2.9	3.1	2.6	2.4
0^+_4	4.0	4.0	3.0	2.4
0^+_5	3.1	3.1	3.0	2.6
0^+_6	5.0	5.6	0.5	1.0

OCM calc. successfully reproduce six 0^+ state in ^{16}O

✓ NEW 0^+ at 13.6 MeV is 0^+_4;α+^{12}C(0^+) w/ higher nodal

✓ KNOWN 0^+ at 15.1 MeV is ACC state !!!

Consistency Check

- Exp./Theor. information on 0^+ state at 13.6 MeV
  - R.M.S. = 4.3 fm
  - Consistent with theoretical prediction of 4.0 fm
    - $\alpha+^{12}C(0^+)$ w/ higher nodal

- Theoretical prediction for 0^+ at 15.1 MeV
  - R.M.S. = 5.6 fm in MHN
    - C.f. 2.7 fm for g.s.
    - ACC state
  - M(E0) = 1.0 in MHN
    - Small compared with other 0^+
    - Large R.M.S.
  - Consistent with exp. data ?

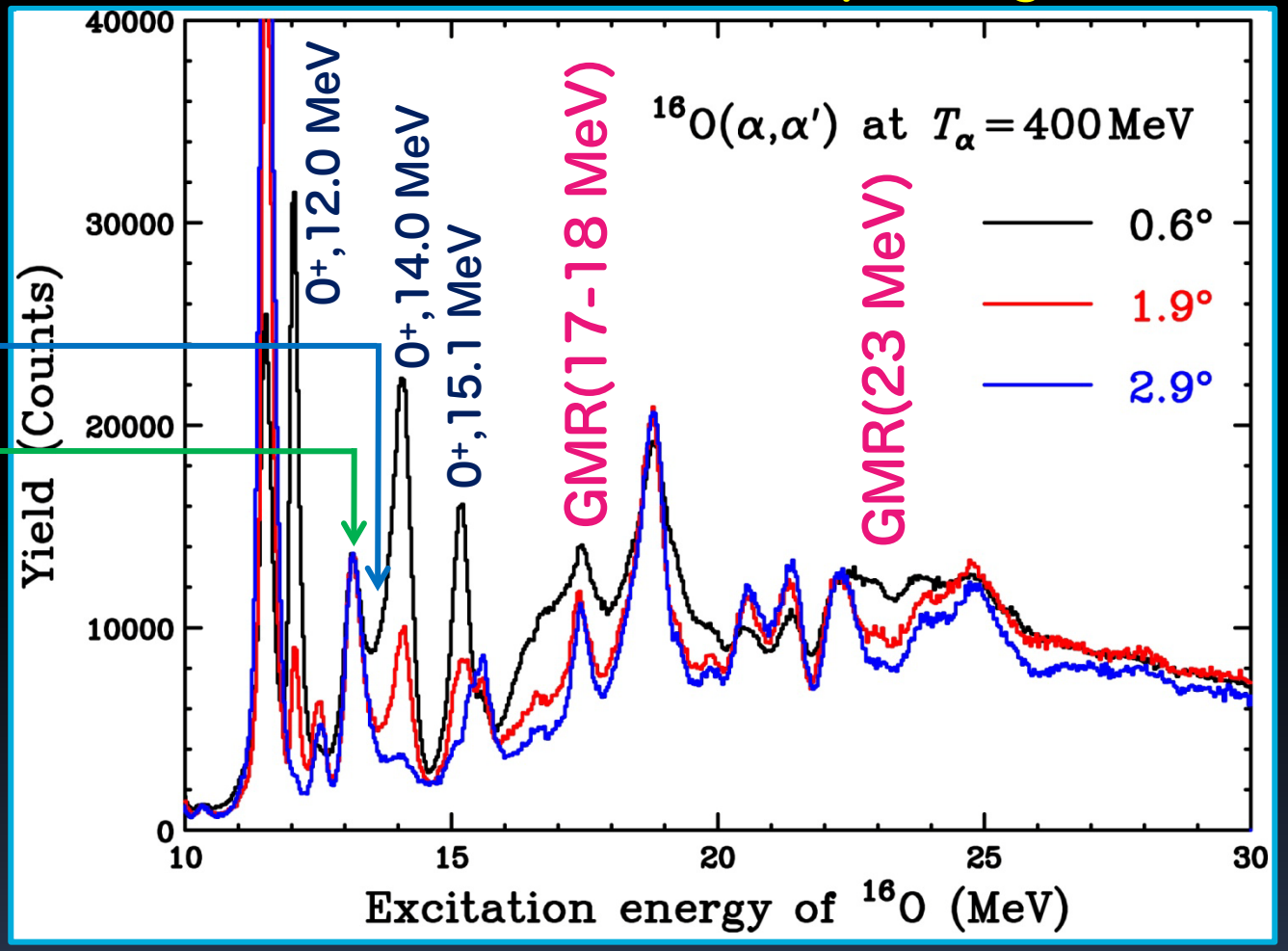
	R		M(E0)	
	SW	MHN	SW	MHN
0_1^+	2.7	2.7		
0_2^+	3.0	3.0	4.1	3.9
0_3^+	2.9	3.1	2.6	2.4
0_4^+	4.0	4.0	3.0	2.4
0_5^+	3.1	3.1	3.0	2.6
0_6^+	5.0	5.6	0.5	1.0

E0 (L=0) Strengths beyond 14 MeV

- Energy spectra at 0.6° ,1.9° ,2.9°
  - Normalized for 2^+ at 13.0 MeV
  - 0.6° > 1.9° ,2.9° for E0 (L=0) [forward peaking]

New 0^+ at 13.6 MeV

Normalized



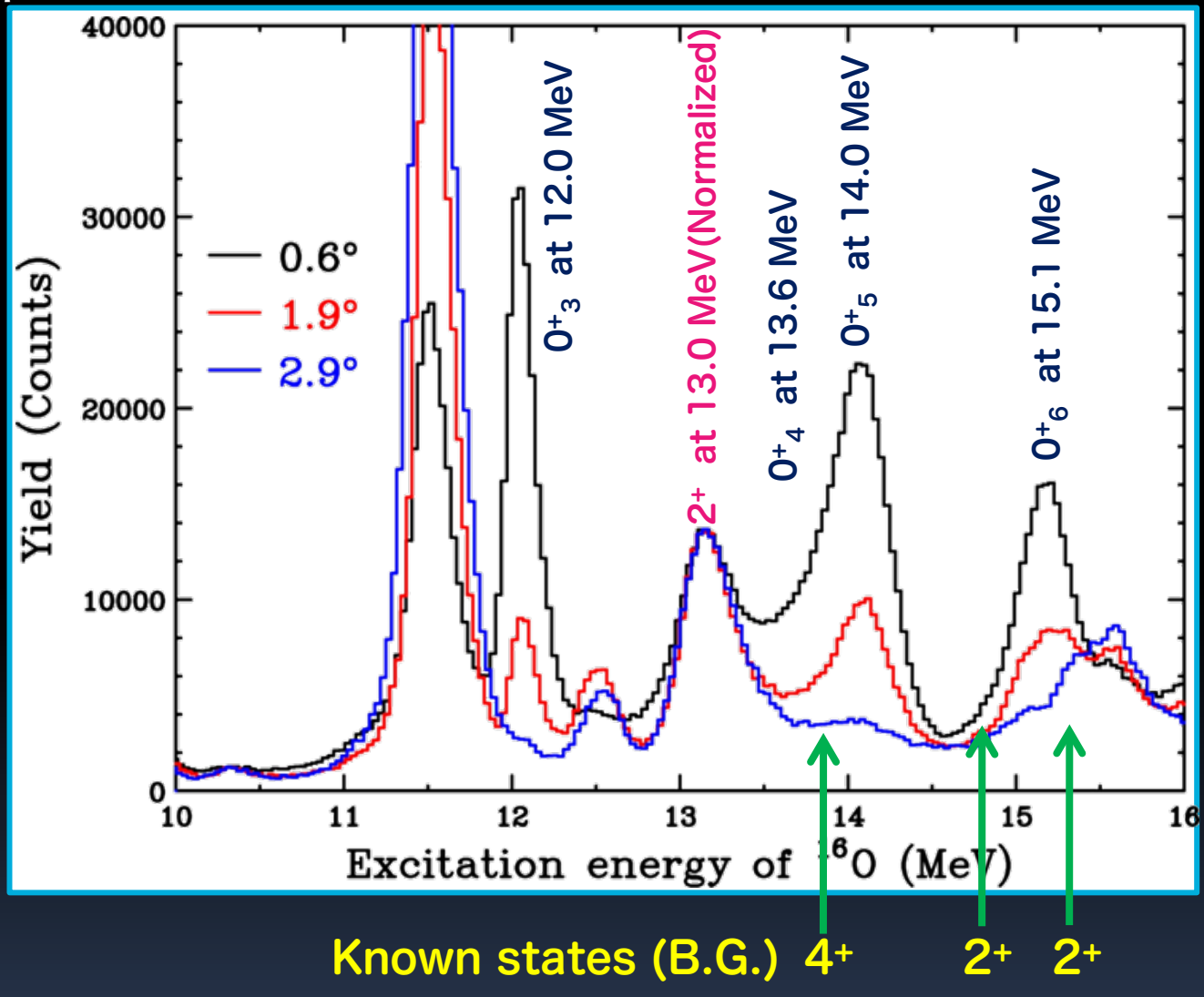
No narrow 0^+ beyond 16 MeV

Possibility for deducing σ of 0^+_5 and 0^+_6

- Data cover $\theta < 14^\circ$
  - 0^+ : $\theta < 3^\circ$
- Physical B.G.
  - For 0^+_5
  - 4^+ at 13.9 MeV
  - For 0^+_6
  - 2^+ at 14.9 MeV
  - 2^+ at 15.3 MeV

σ at $\theta > 3^\circ$ could NOT be deduced reliably.

σ at $\theta < 3^\circ$ (especially 0°) are useful or NOT?



Simple Estimate

Y.Funaki et al.,
PRL 101,082502(2008)

- Ratios of $\sigma(0^\circ)$ for 0^+ can be easily estimated from the yield at 0°
  - $\sigma(0^\circ)$ would be proportional to $|M(E0)|^2$
  - If proportional coefficients are common
    → Ratios of M(E0) can be estimated

Normalized

Consistent

State	Yield (α,α')	M(E0)	M(E0) (e,e')	OCM calc. SW	OCM calc. MHN
0^+_3 (12.0 MeV)	$(2.2\pm0.4)\times10^4$	4.0±0.4	4.0±0.1	2.6	2.4
0^+_4 (13.6 MeV)	$(2.7\pm0.5)\times10^4$	4.4±0.4	N/A	3.0	2.4
0^+_5 (14.0 MeV)	$(2.2\pm0.4)\times10^4$	4.0±0.4	3.3±0.7	3.0	2.6
0^+_6 (15.1 MeV)	$(1.4\pm0.3)\times10^4$	3.2±0.4	N/A	0.5	1.0

MHM gives better description, BUT small

(α,α') c.s. for 0^+_6 is significantly SMALLER than those for other 0^+

✓ Reflect the large R.M.S. as ACC
  ✓C.f. Larger R.M.S. ⇔ Smaller B(E0) ⇔ Smaller c.s.

✓ But c.s. (and M(E0)) seems to be TOO large than expected
  ✓Proportional coefficients are NOT common? (depend on R.M.S.?)

Re-analysis of ^{16}O(*p*,*p*') Data

- ✓ What kind of data we have for 0^+
- ✓ (p,p') can provide comprehensive information ?

$^{16}O(p,p')$ data from RCNP

- Forward angles data T.Kawabata et al., PRC 65, 064316 (2002).
  - $^{16}O(p,p')$ at 400 MeV
    - $q = 0 - 1.2$ fm^{-1}
    - $\theta = 0 - 14°$
  - $\Delta E = 80 - 150$ keV → Could NOT resolve 0^+_6 state from
    - ✓ 2^+ at 14.9 MeV (Γ=54 keV)
    - ✓ 2^- at 15.2 keV (Γ=63 keV)
- Backward angles data T.W. et al., PLB 632, 485 (2006).
  - $^{16}O(p,p')$ at 300 MeV
    - $q = 0.9 - 2.1$ fm^{-1}
    - $\theta = 14 - 30°$
  - $\Delta E = 30$ keV

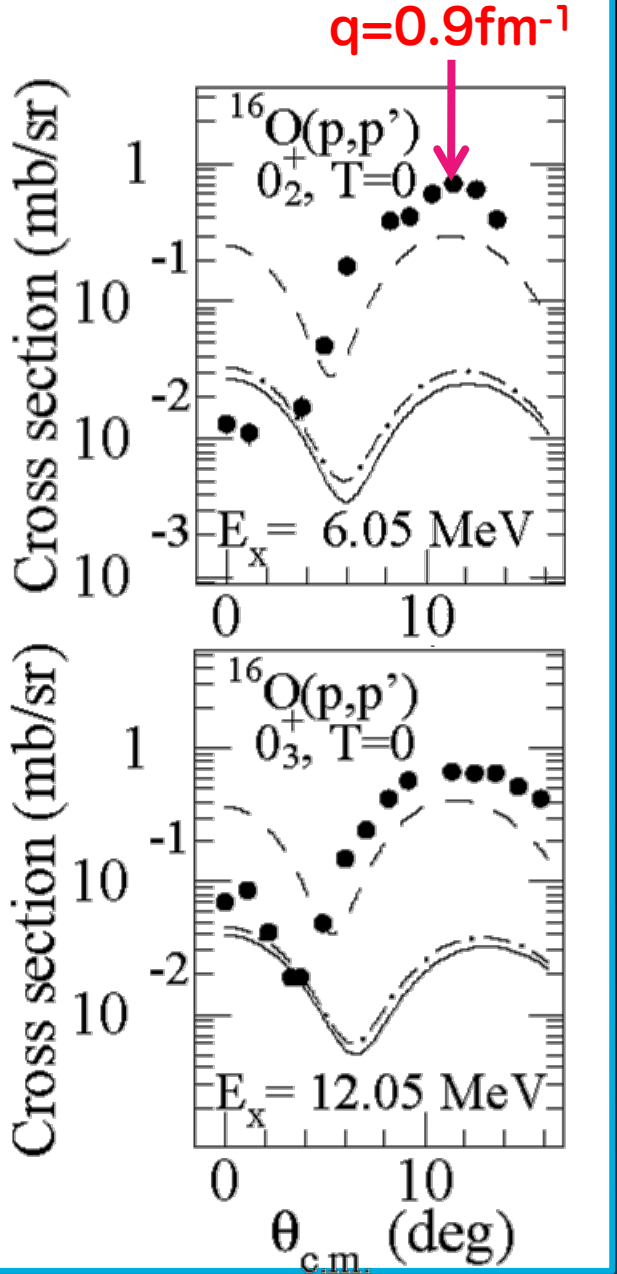
- ✓ Are the 0^+ states observed clearly in (p,p') ?
- ✓ How about angular distributions of 0^+ states ?
- ✓ Are the backward angles data useful ?

Angular Distributions of 0^+ States

- Well-resolved 0^+
  - 0^+_2 at 6.0 MeV
  - 0^+_3 at 12.0 MeV

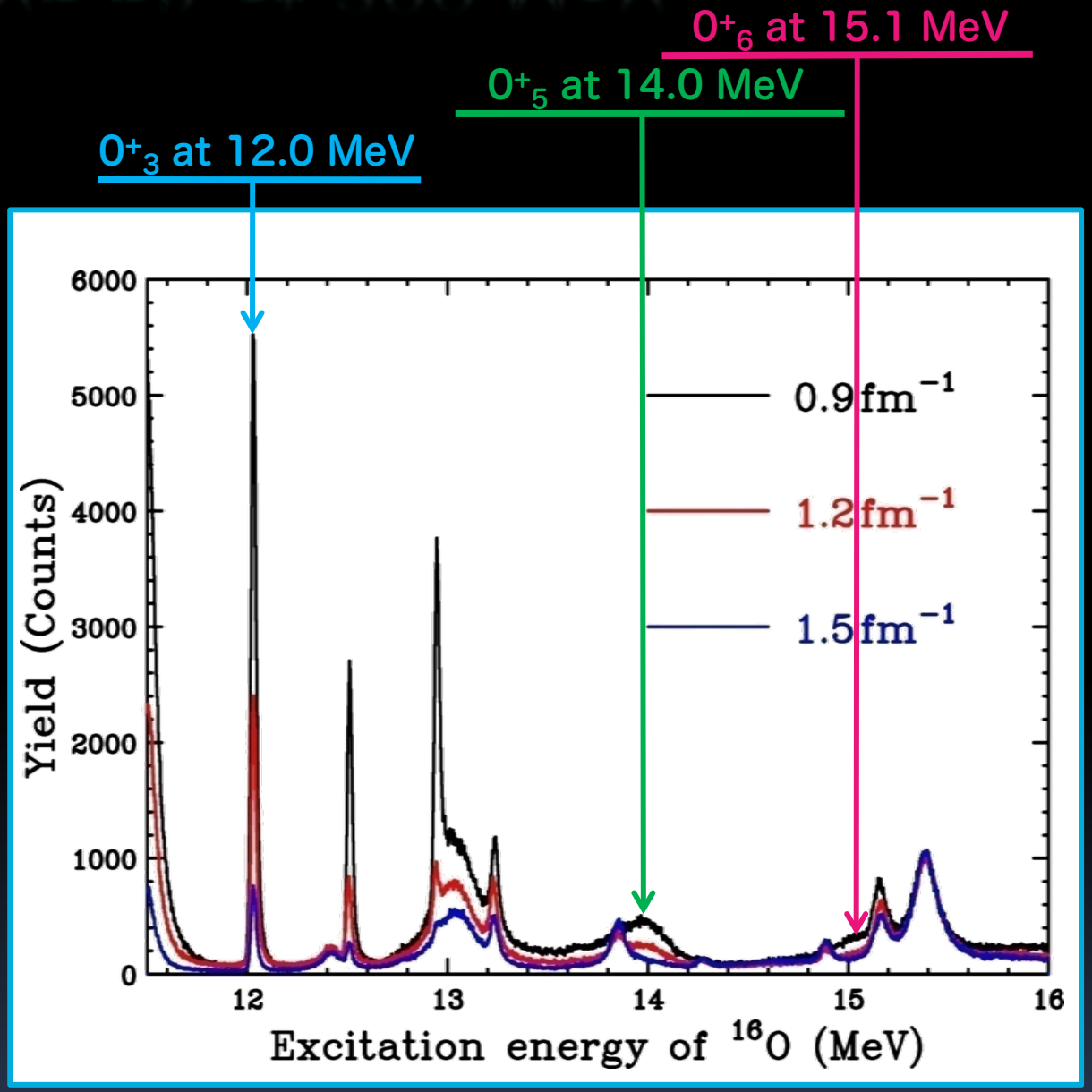
- Cross sections are NOT forward peaking
  - Maximum at q=0.9 fm^{-1}
  - Different from (α,α')
  - (p,p') data are sensitive to interior region and /or r-dependence of form factor ?

Significant 0^+ strengths are expected in backward angles data (q=0.9-2.1 fm^{-1})



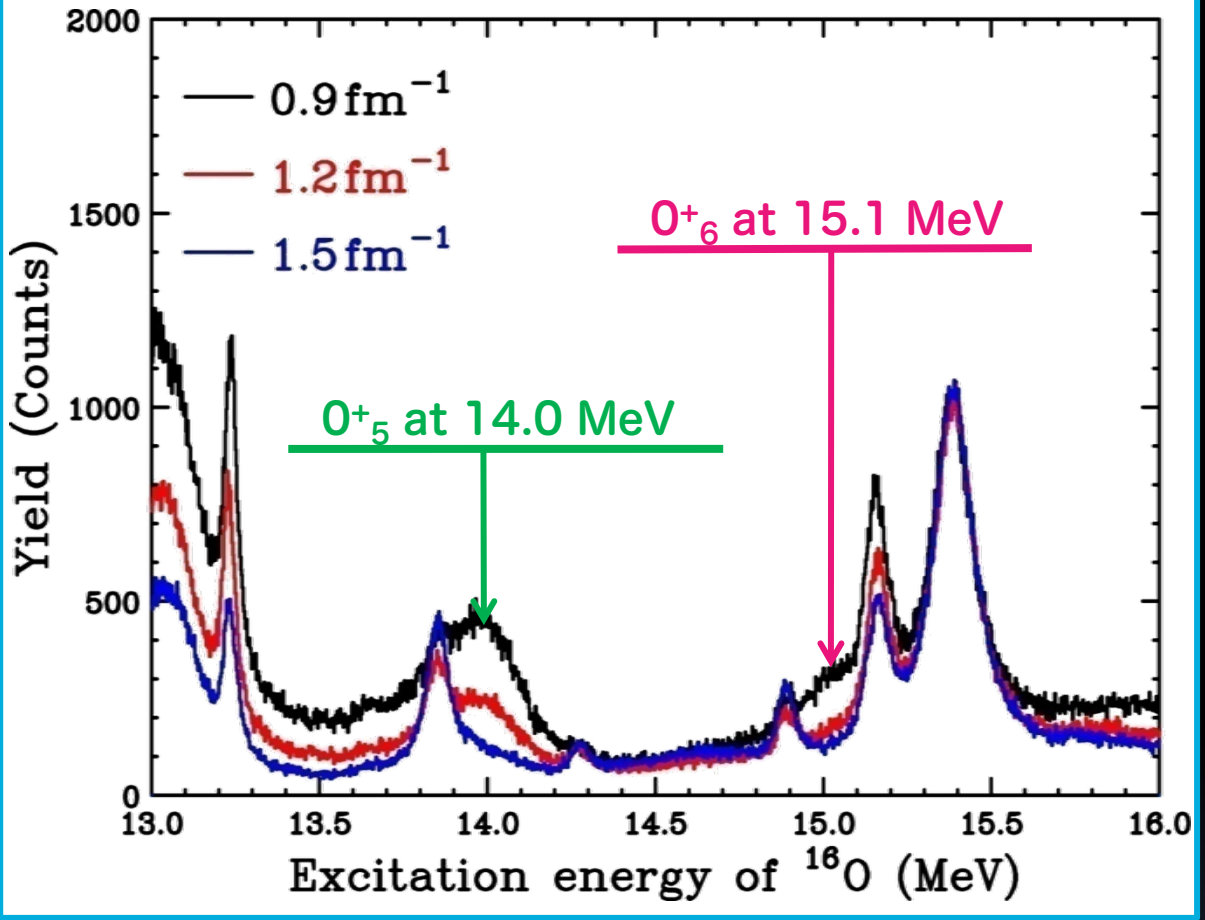
High Res. ^{16}O(p,p') at 300 MeV

- Angular distributions
  - $0^+_3 \fallingdotseq 0^+_5$
  - Similar form factor(?)
- What about 0^+_6?



High Res. ^{16}O(p,p') at 300 MeV

- For 0^+_5
  - 0.9>1.2>1.5 fm^{-1}
- For 0^+_6
  - 0.9≫1.2≒1.5 fm^{-1}
- Angular distributions
  - $0^+_5 \neq 0^+_6$
  - Different form factor(?)



DWBA with realistic W.F. for 0^+ should be performed
→ Is the cross section for ACC 0^+ characteristic in (p,p) ?
→ Experimental data at forward angles (q < 0.9 fm^{-1}) is helpful ?

Comment on 11.26 MeV state

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

0^+_1;ground state

0^+_2;$^{12}C(0^+)+\alpha$ in S

0^+?,Custer?

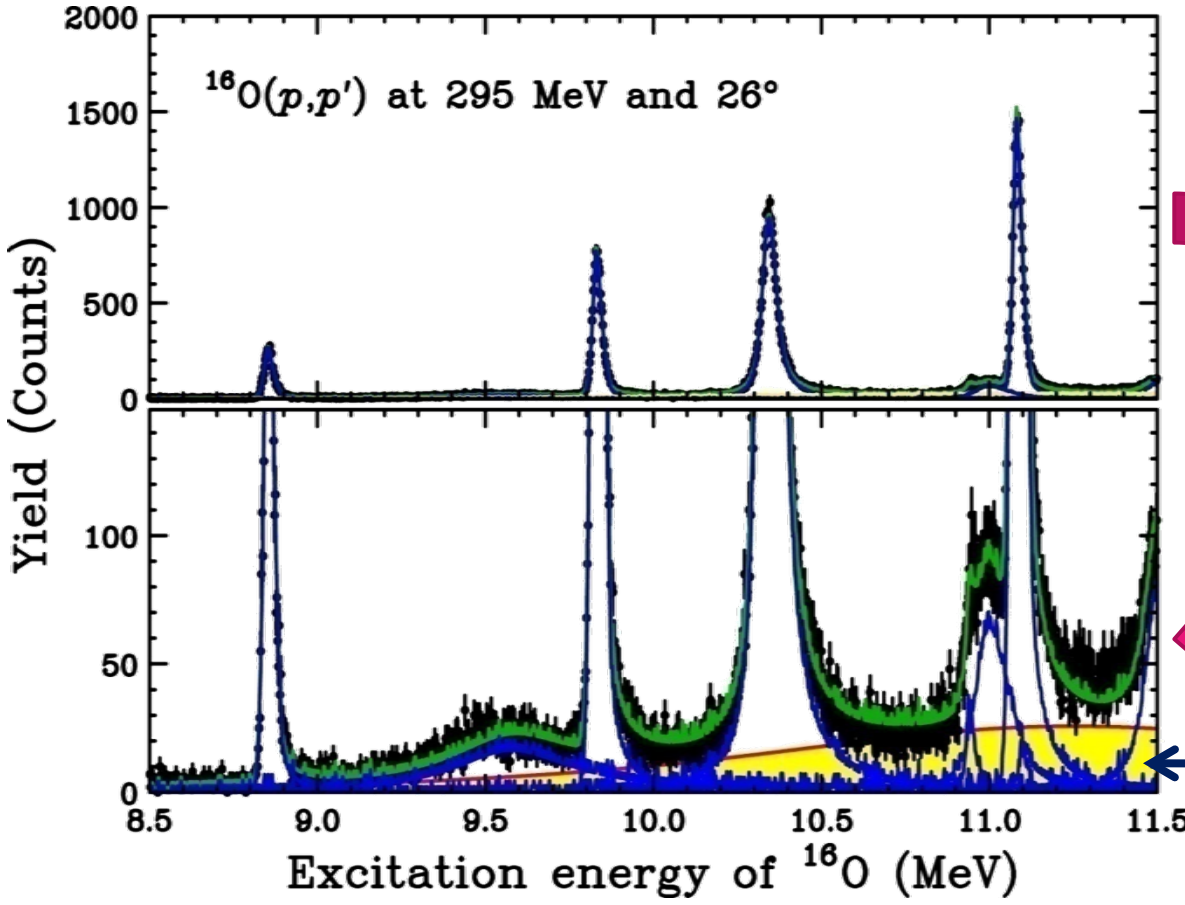
0^+_3;$^{12}C(2^+)+\alpha$ in D

- ✓11.26 MeV state is observed in (p,p')?
- ✓Spin-parity ?

0^+_5;4α Cluster (NOT ACC)

Comment on (0^+) state at E_x=11.26 MeV and Γ=2.5 MeV

State at 11.26 MeV with Γ=2.5 MeV



ZOOM

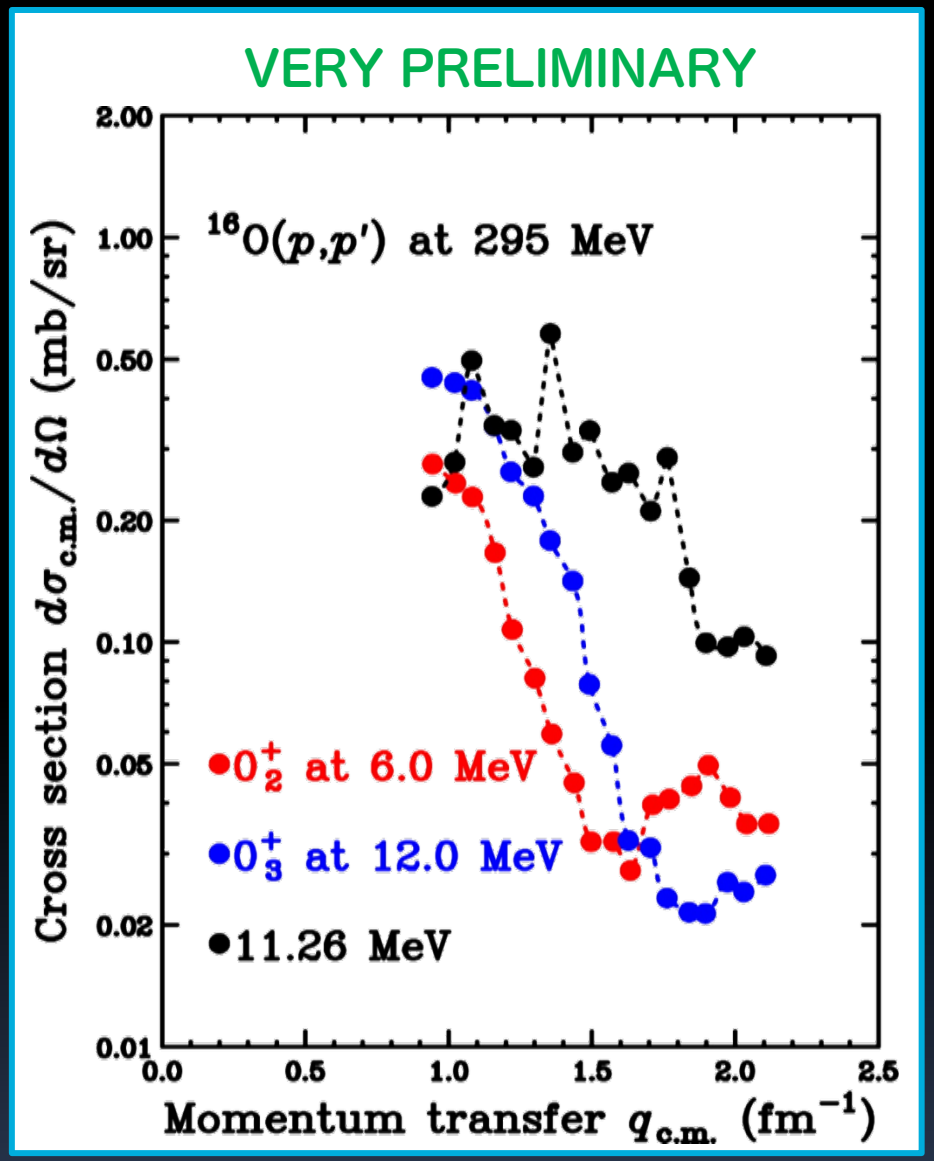
E_x = 11.26 MeV
Γ = 2.5 MeV

- ✓ Experimental data are well-reproduced by considering state at 11.26 MeV and Γ=2.5 MeV
- ✓ Its existence is NOT conclusive because its strength is NOT large

Cross Section of 11.26 MeV State

- Known 0^+ states
  - 0^+_2 at 6.0 MeV
  - 0^+_3 at 12.0 MeV
  - Clear q-dependence
  - Consistent with results at 400 MeV
- 11.26 MeV state
  - Weak q-dependence
  - q-dependence seems to be different (NOT conclusive)

✓ J^π is NOT 0^+ ?
✓ Different structure ?



Summary (ToDo List)

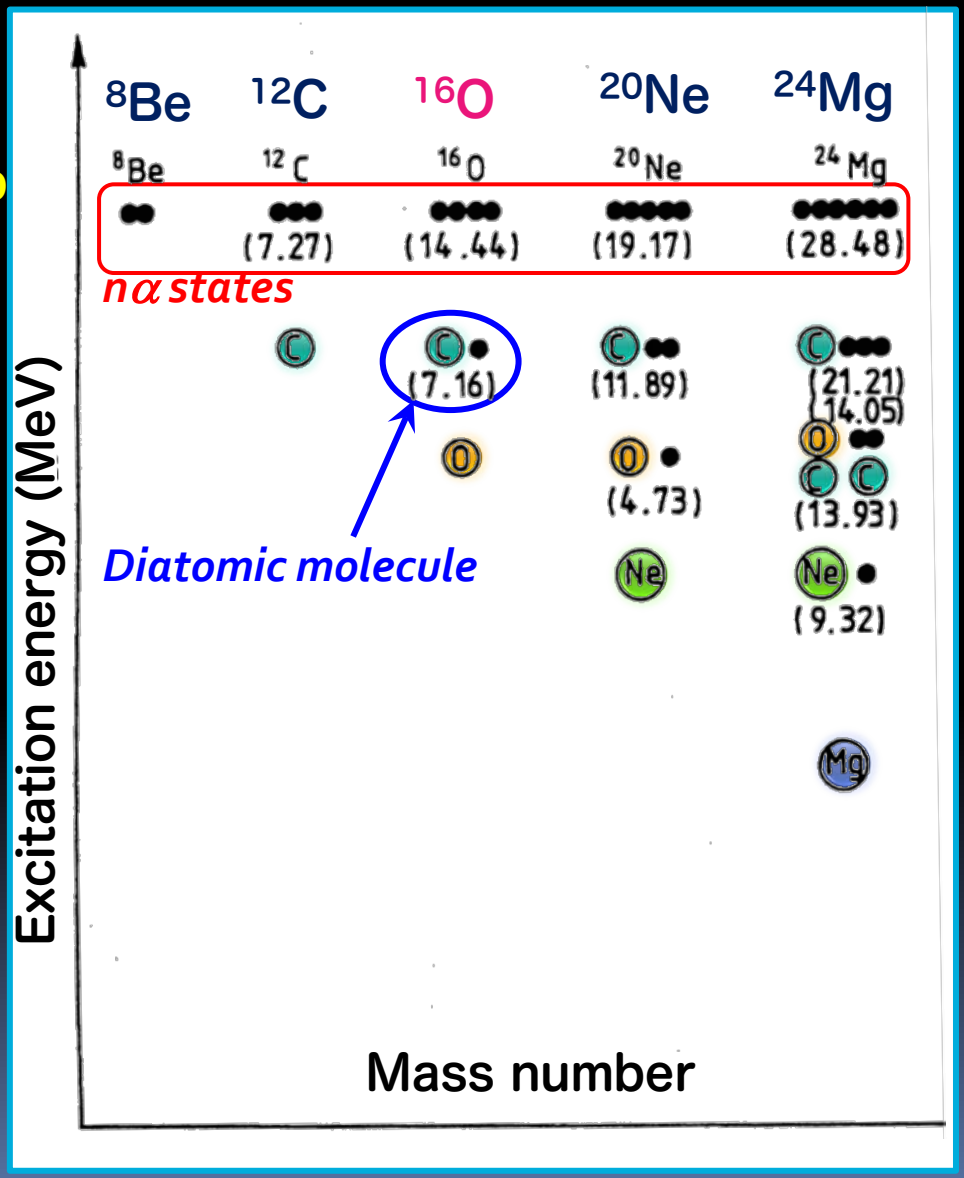
- New 0^+ state in ^{16}O at E_x=13.6 MeV and Γ=0.6 MeV
  - Large Γ than other 0^+ states (c.f. 166 keV for 0^+_6)
  - Can be theoretically explained/reproduced "quantitatively"?
- Re-analysis of $^{16}O(\alpha,\alpha')$ data
  - Cross sections for 0^+ are limited at forward angles
    - The data at 0 degrees are reliable
  - Cross sections are simply proportional to relevant R.M.S./B(E0)?
    - Theoretical investigations are required
  - The data support that 0^+_6 has a large R.M.S. as ACC
- Re-analysis of ^{16}O(p,p') data
  - Angular distribution of 0^+_6 seems to be different
  - (p,p') data can provide information on interior region ?
    - Theoretical investigations are required
    - YES → High res. data for separating 2^- at 15.2 MeV from 0^+_6 at 15.1 MeV would be required at forward angles
- (0^+) state at E_x=11.26 MeV and Γ=2.5 MeV
  - Angular distribution seems to be different
    - Different Spin-partity or different structure ?

Backup

Ikeda Diagram

- Threshold rule
  - Several cluster types will appear around threshold energy of breakup into constituent clusters (threshold rule)
  - Example for ^{16}O
    - C+α at 7.2 MeV
    - 4α at 14.4 MeV
- Experimental investigations
  - Identify ALL cluster states
    - Especially 0^+ (g.s. of cluster state)
  - Cluster properties
    - C+α or 4α
    - Cross section (B(E0))
  - 4α ACC state
    - Hoyle (ACC) state in ^{12}C

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



E189 Experiment at RCNP

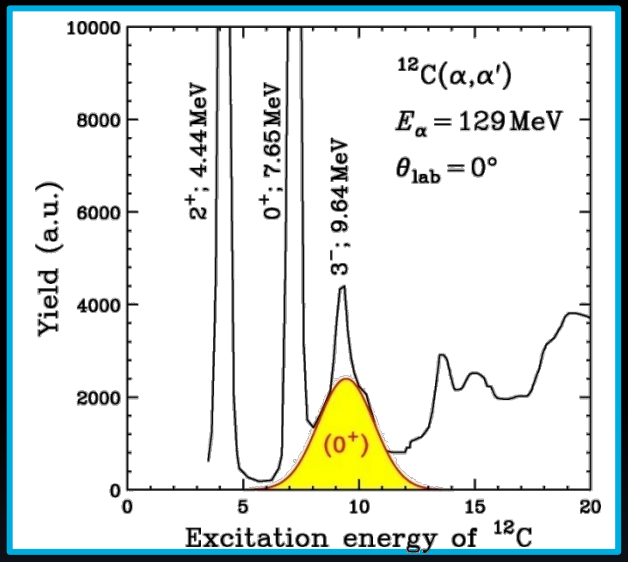
- Search for ACC state in ^{16}O
  - Investigation of 14.0 MeV 0^+ state in ^{16}O
    - Observed only in $^{12}C+\alpha$
    - Not yet confirmed
    - Not yet listed in Table of Isotopes / NNDC
  - Search for new α-cluster 0^+ state as ACC around 4α threshold
    - Search for 0^+ around 14 MeV
  - NEW!! Investigation of 2^{nd}-6^{th} 0^+ states in ^{16}O
    - We have just started data re-analysis (Very preliminary)

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 at ~14 MeV → Selective excitation of 0^+ is important

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



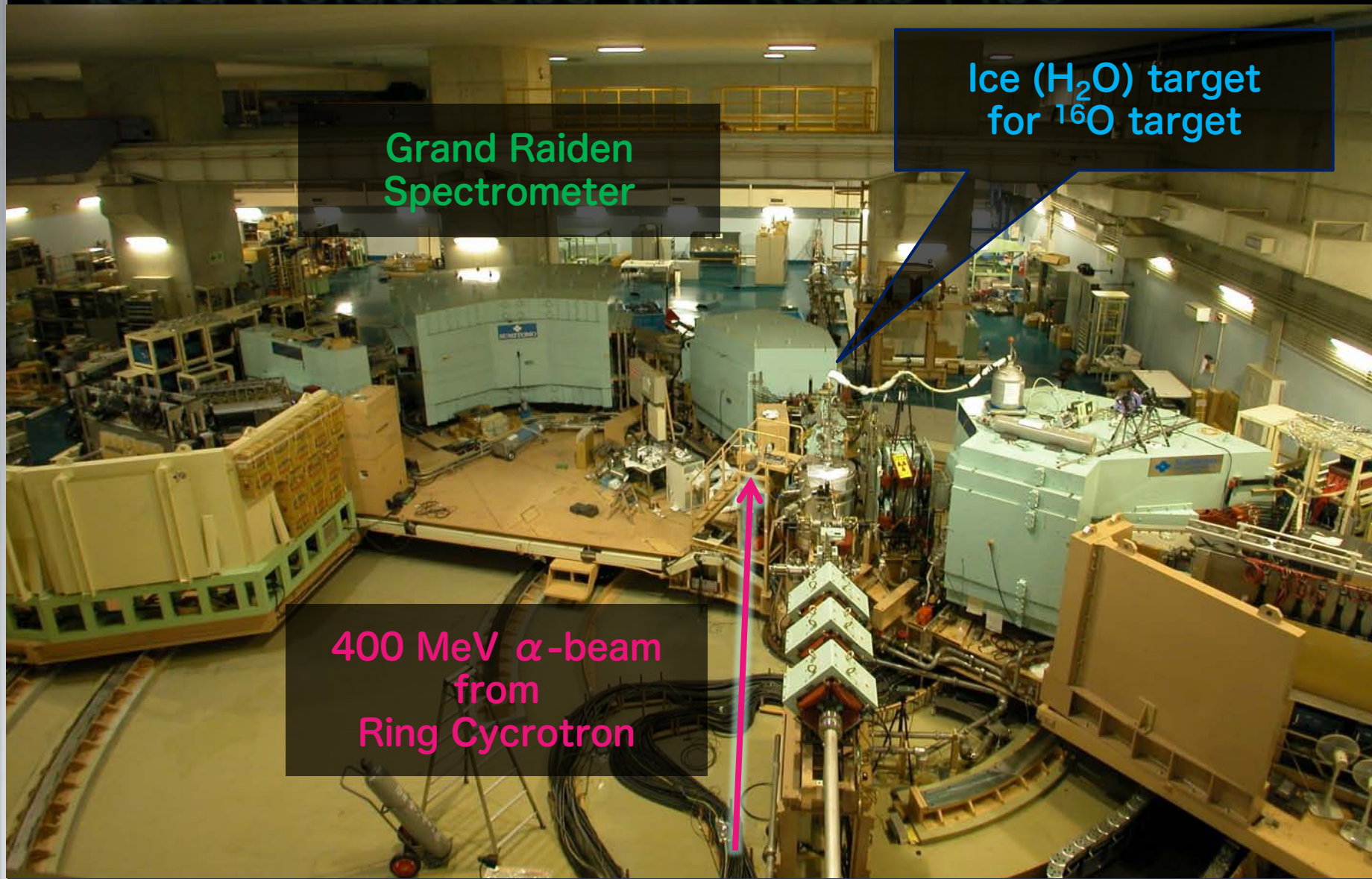
- High resolution measurement
  - Clearly resolve ACC from neighboring states

- Measure angular distribution
  - Distinctive assignment of L

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

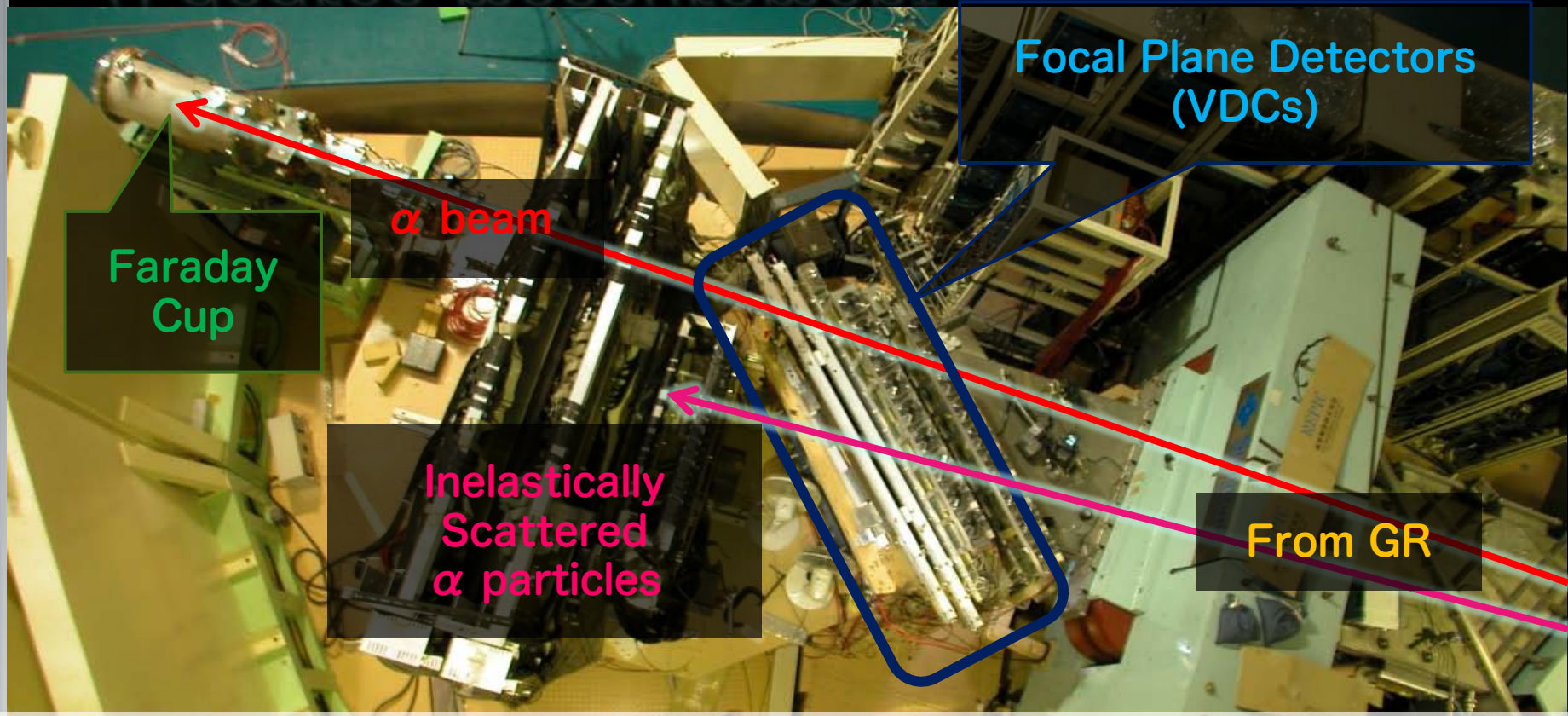
Experimental Setup

Grand Raiden and WS Beam Line



Experimental Setup

- 0 degree measurement -

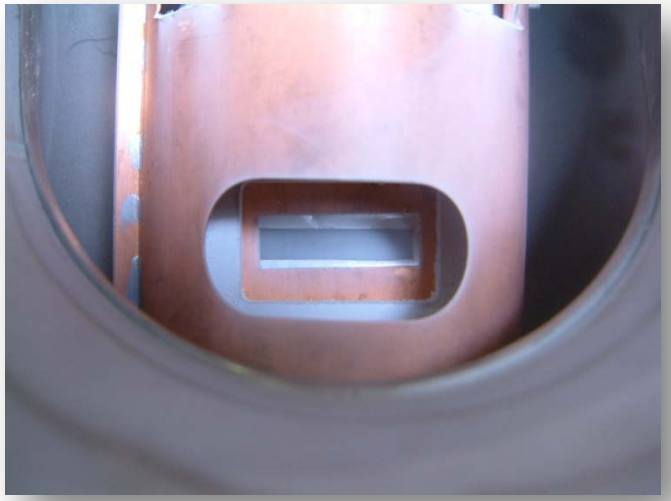


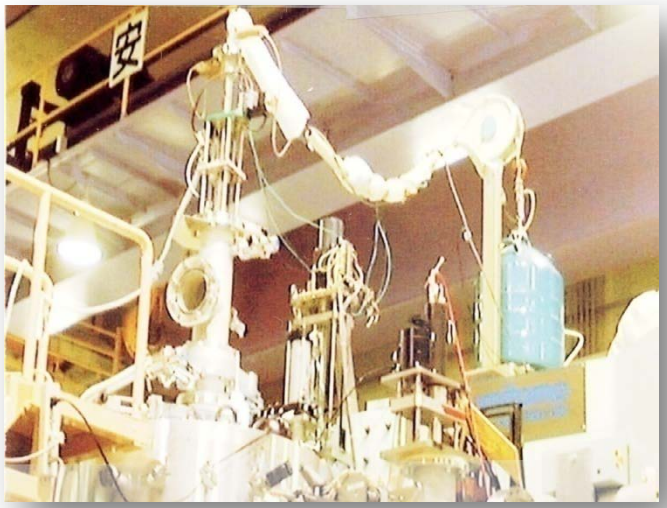
ACC state with L=0 is most strongly excited at 0 degrees (q=0)

→ *0 degree measurement is essential to identify ACC*

Ice Target for Pure ^{16}O Target

- Ice (H_2O) target
  - Pure ^{16}O target
    - p+α events can be clearly separated kinematically
  - H_2O is cooled down to 77 K (Liquid N_2)
  - Thickness: 9 mg/cm2
  - Area: 30 mm × 6mm (Very large)
    - For Background-free spectra



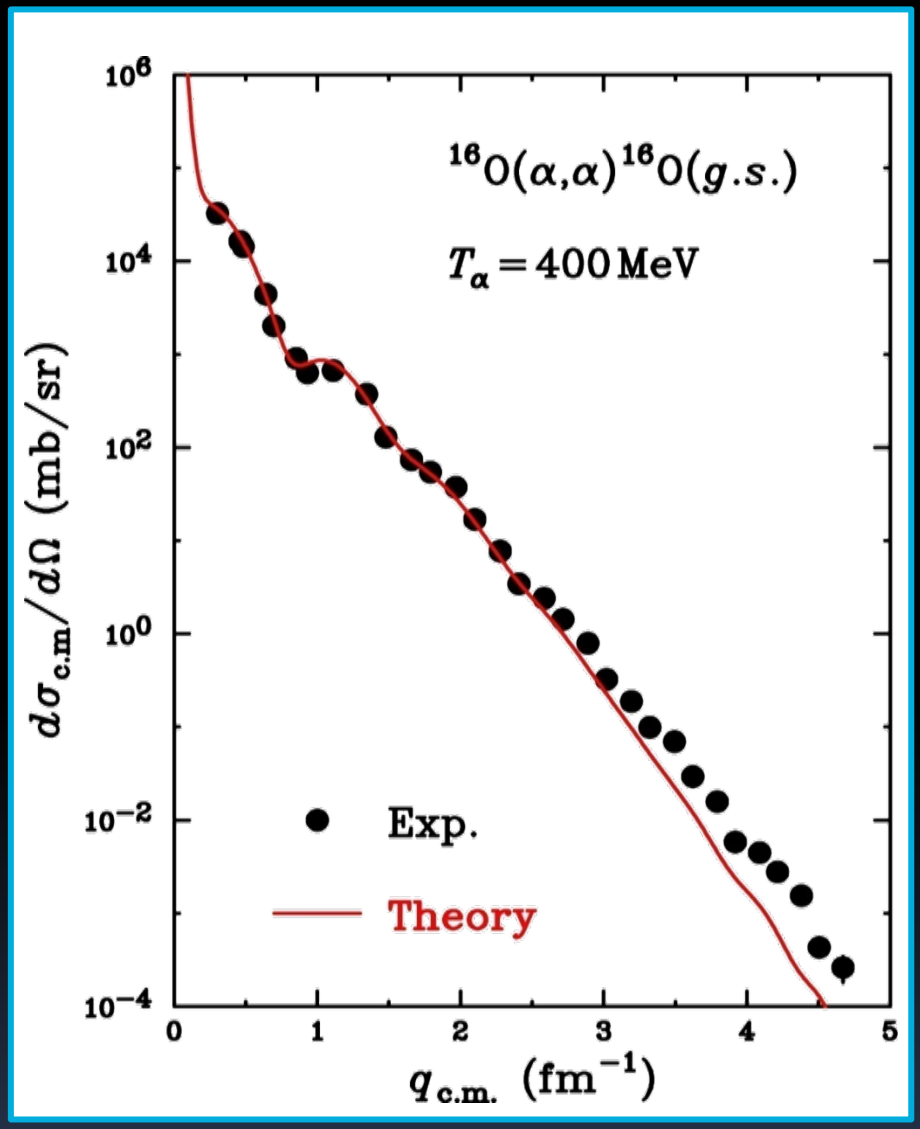


T. Kawabata et al.
Nucl. Instrum, Methods
Phys. Res. A 459, 171 (2001)

Elastic Scattering Cross Section

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

OMPs are reliable for analysis of inelastic data

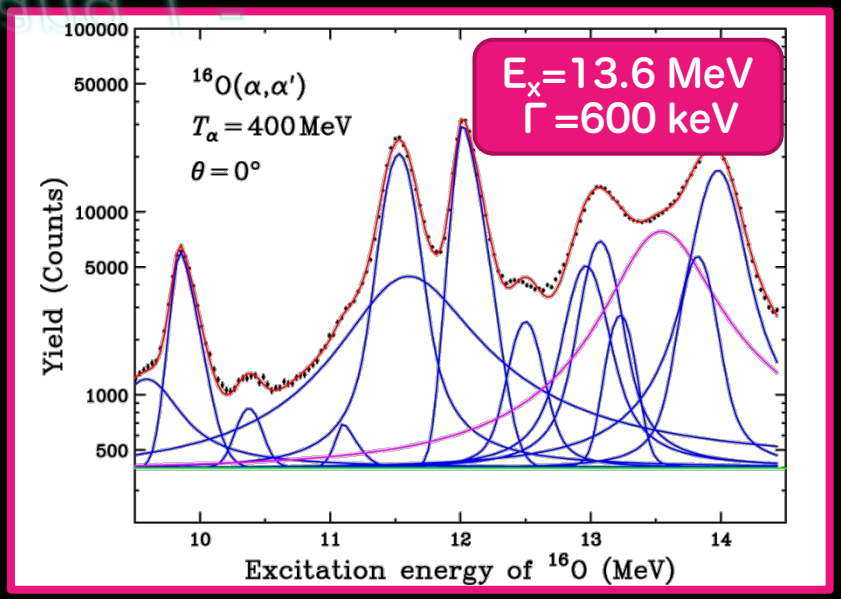


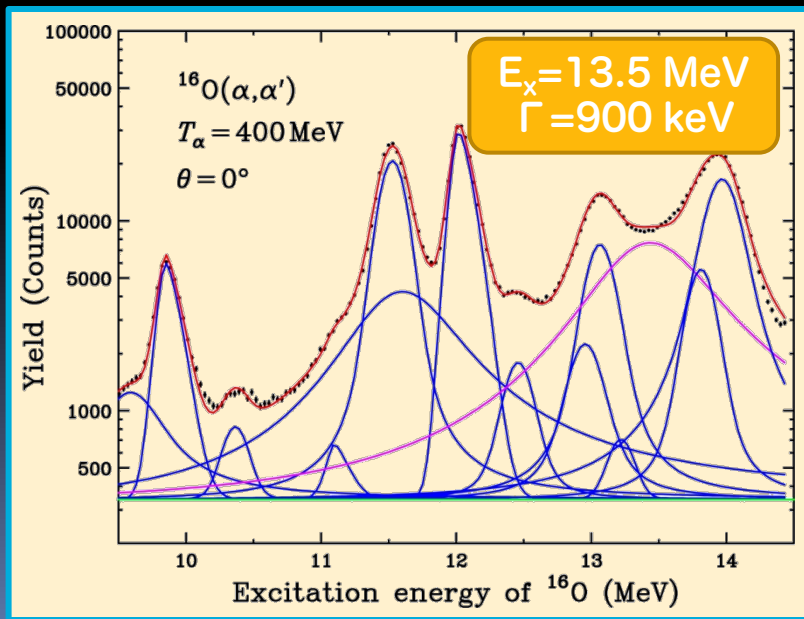
Peak Fitting with New State

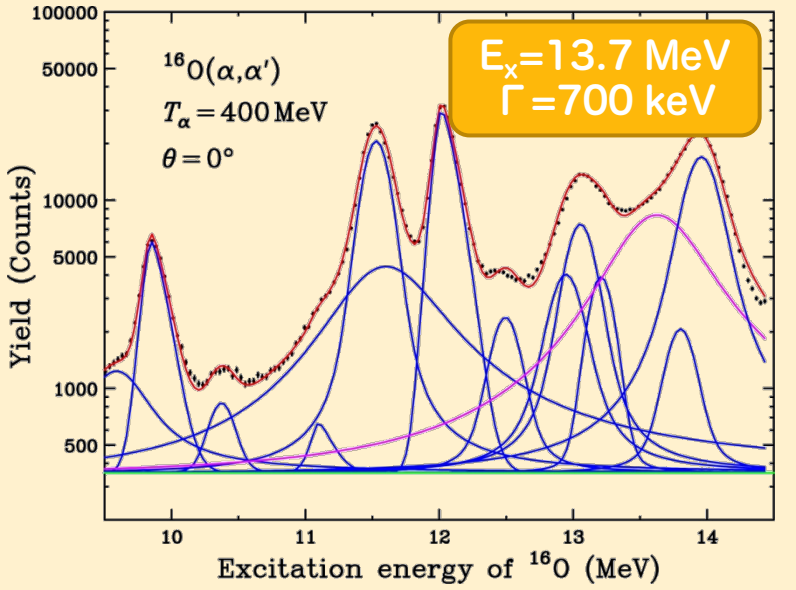
- Correlation between E_x and Γ -

- Reproduction with new state
  - Best reproduction
    - E_x=13.6MeV, Γ=600 keV
  - Strong correlation between E_x and Γ

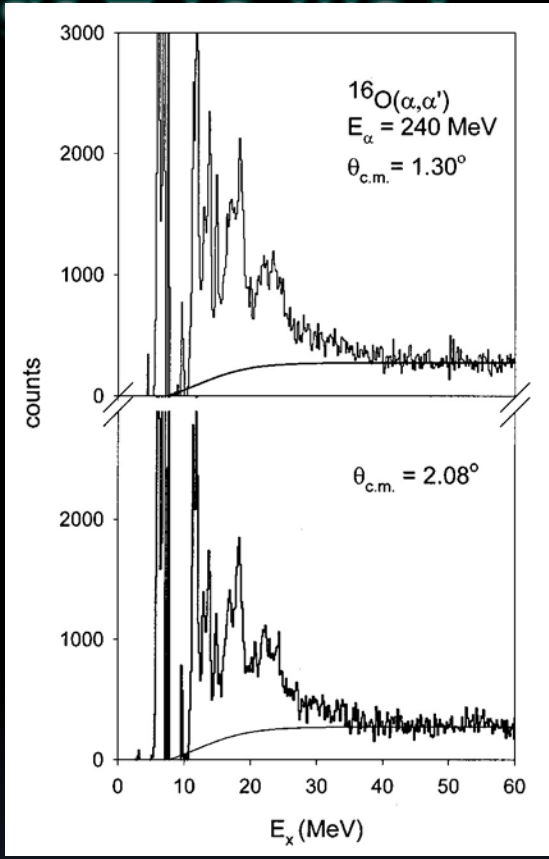
Difficult to deduce precise values of E_x and Γ simultaneously





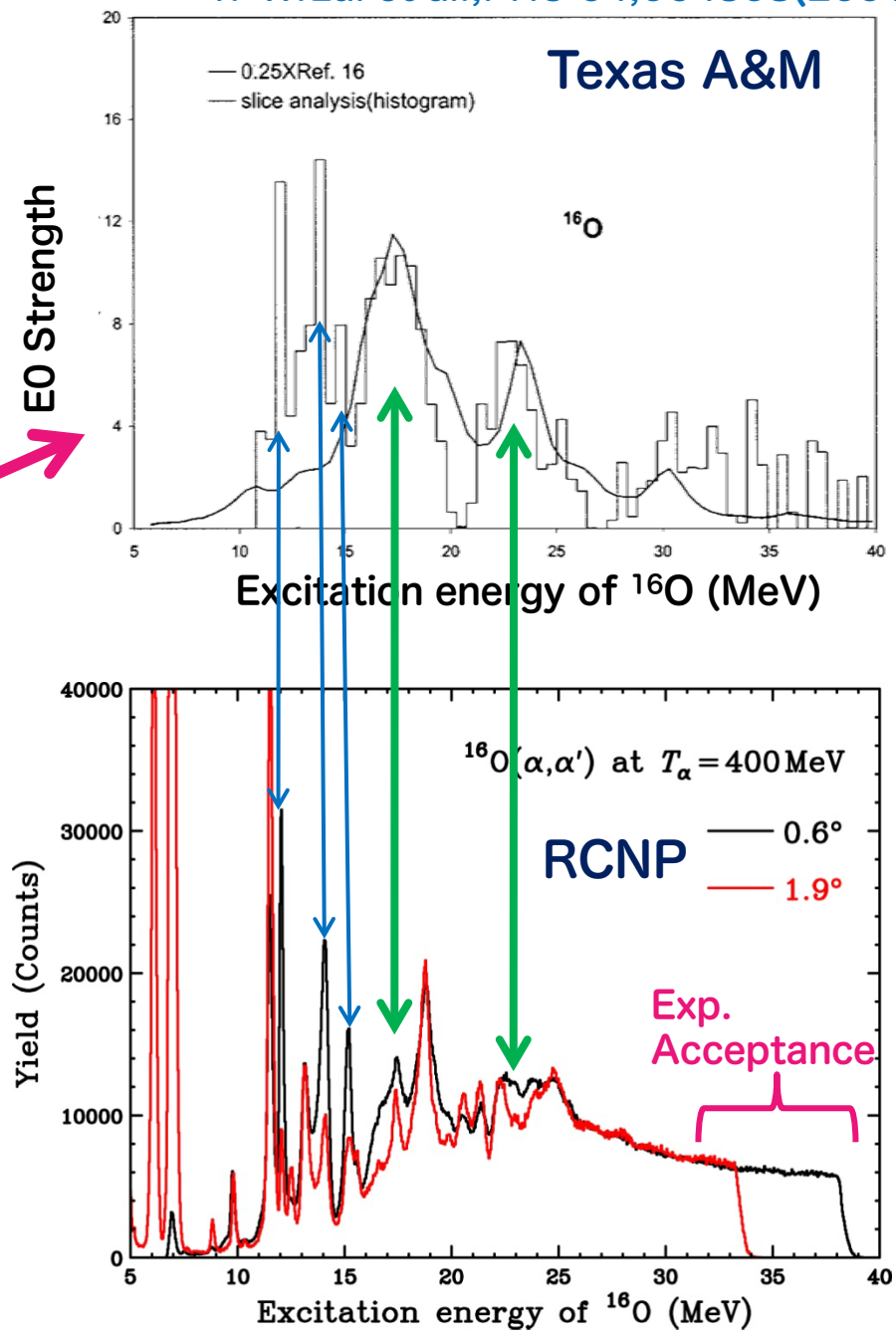


Comparison with $^{16}O(\alpha,\alpha')$ data at 240 MeV



MDA

Y.-W.Lui et al.,PRC 64,064308(2001)



E0 (L=0) strengths are consistent between Texas A&M and RCNP data

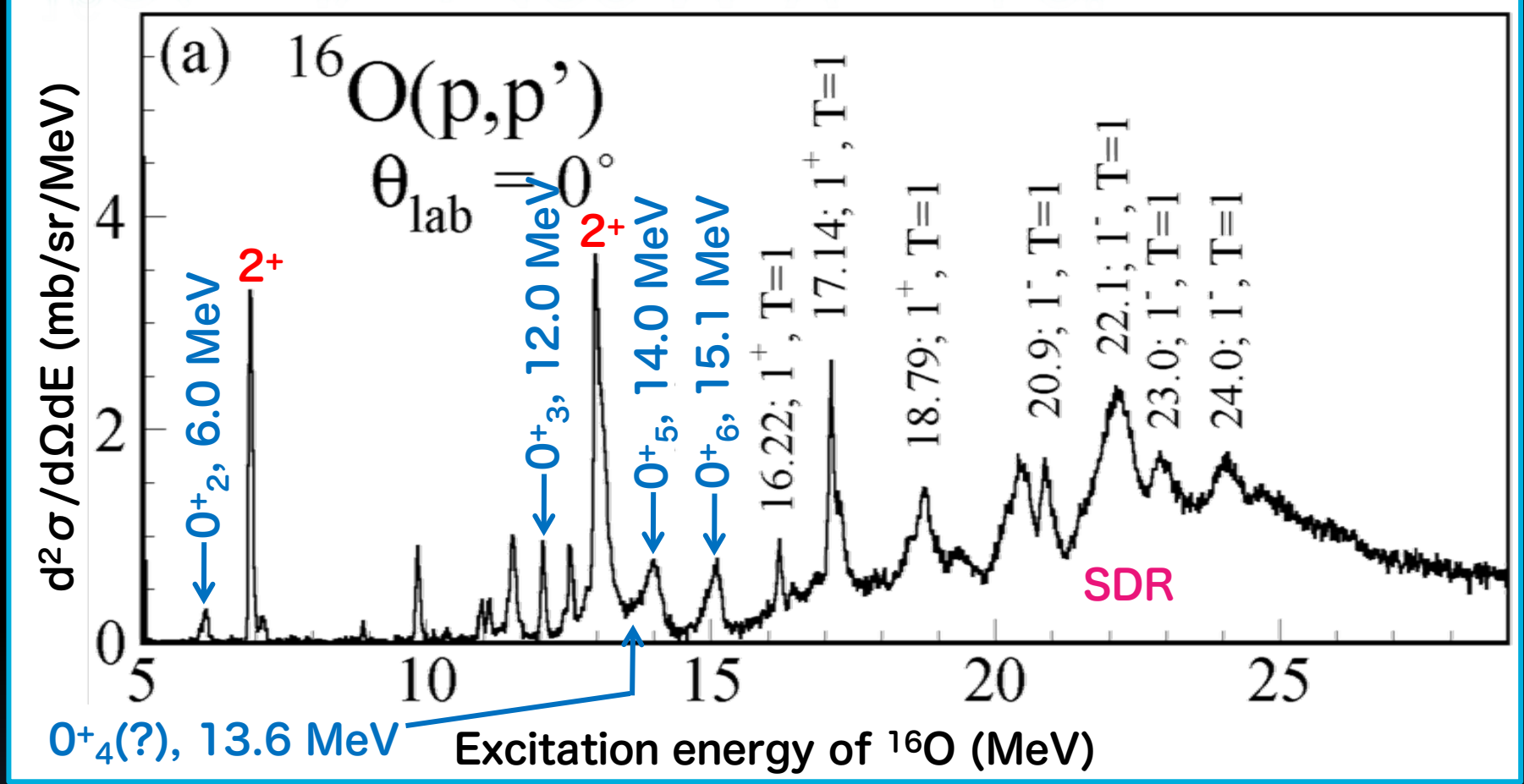
Proton Inelastic Data for ^{16}O

- Advantage of (p,p') [compared with (α,α')]
  - Relatively high energy resolution
    - ΔE=20-30 keV for 300 MeV p-beam
    - ΔE=100-200 keV for 400 MeV α-beam
  - Can probe interior region at intermediate energies
    - Distortion effects are minimum at T_p=200-400 MeV
    - α-beam can ONLY probe surface region
    - Sensitivity for r-dependence of form factor (sensitive to radial wave function for excited state ?)
- Disadvantage
  - Excite both $\Delta S=\pm 1$ and $\Delta T=\pm 1$
    - α-beam excites ONLY spin-scalar and isospin-scalar ($\Delta S=\Delta T=0$)
    - Require enough energy resolution for discrete states
  - Angular distributions are NOT simply specified by ΔL
    - Cross section for 0^+ states are NOT forward-peaking

Disadvantage seems to be overcome by advantage

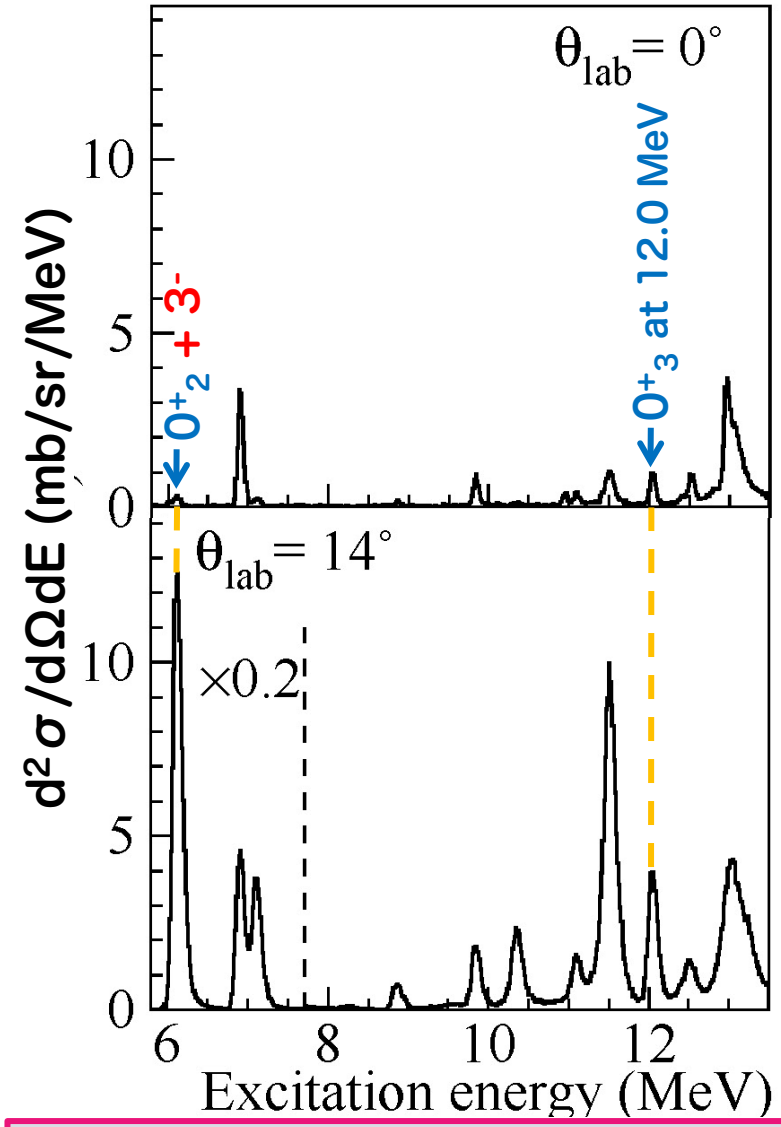
$^{16}O(p,p')$ at 400 MeV and 0°

T. Kawabata, PH.D thesis.

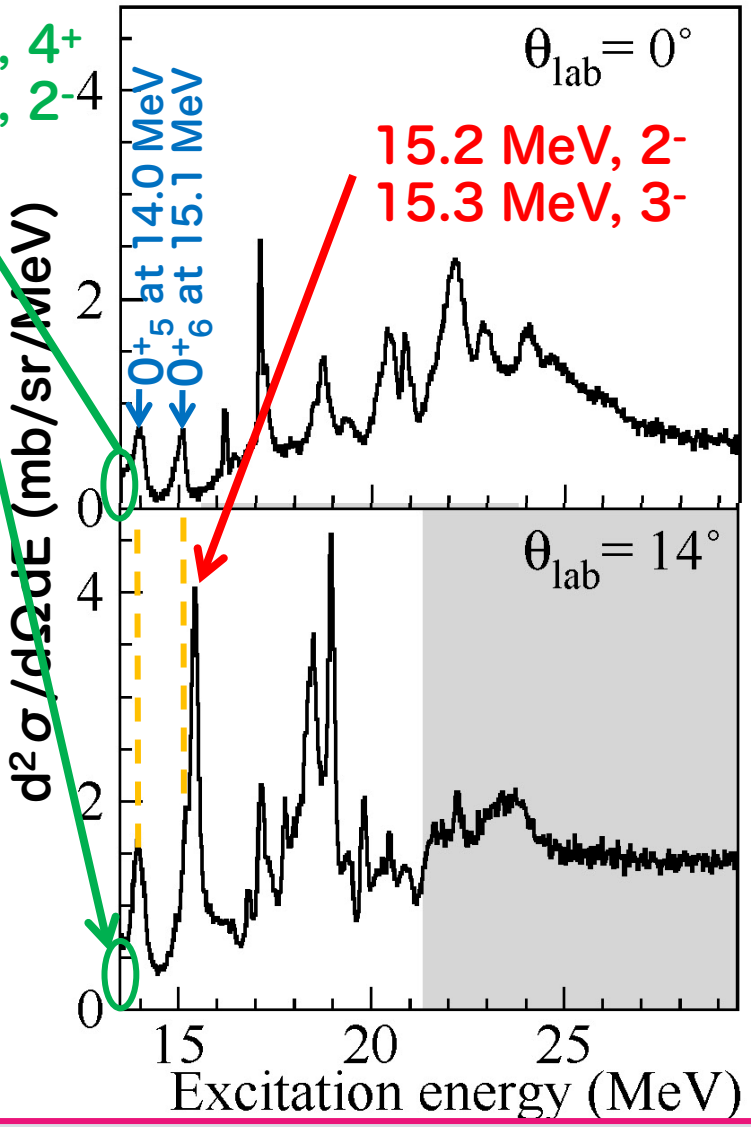


- ✓ The 0^+ states are clearly observed
  (Excess by 0^+_4 at 13.6 MeV is also observed)
- ✓ The 0^+ states are NOT prominent at 0°
  (2^+ at 6.9 and 13.0 MeV are prominent)

Comparison between 0° and 14° Data

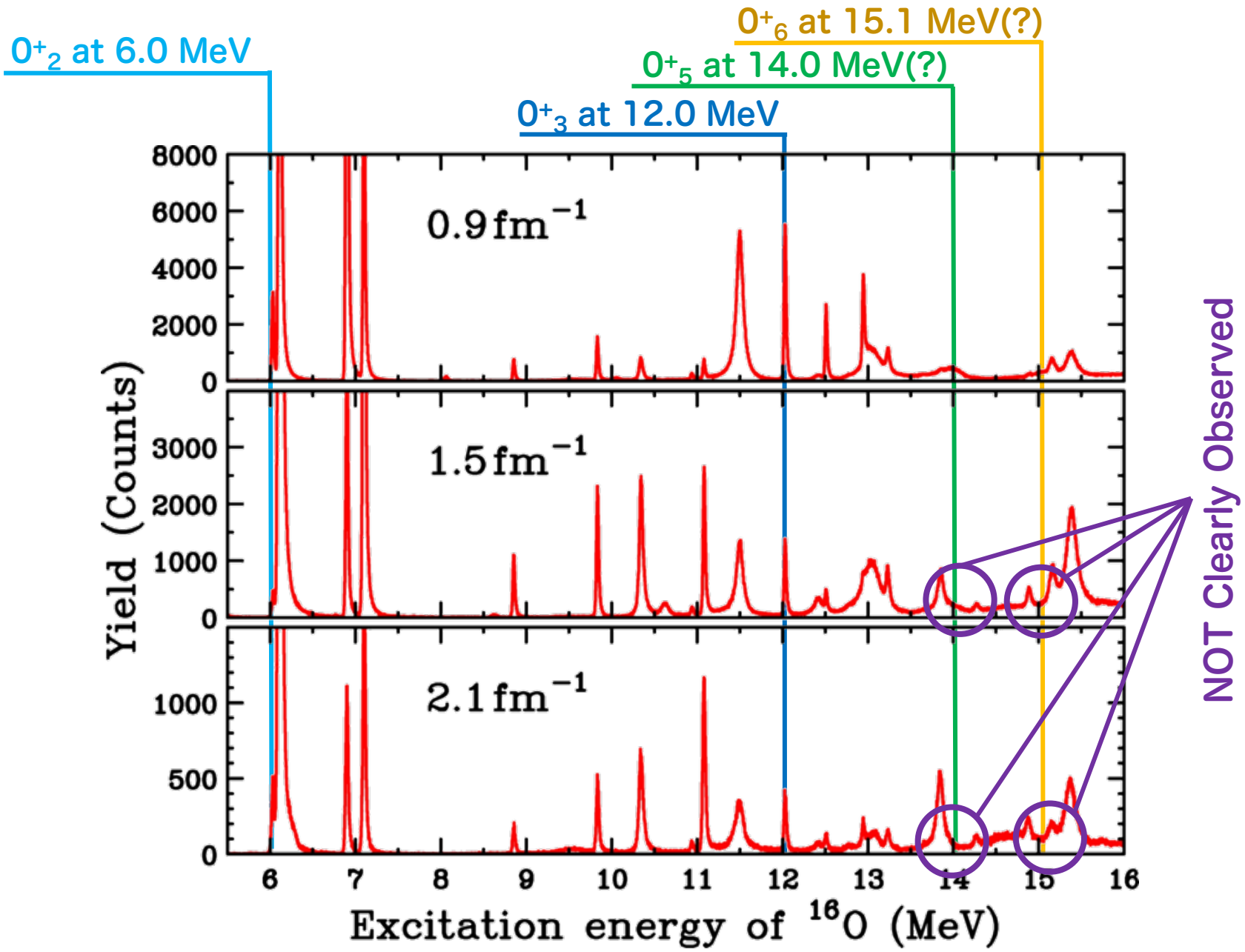


13.9 MeV, 4+
14.0 MeV, 2-



- ✓ 0+ cross sections at 14° are larger than those at 0° → High res. data are useful
- ✓ Physical B.G. are significant for 0^+_5 and 0^+_6

High Res. ^{16}O(p,p') at 300 MeV



High Res. ^{16}O(p,p') at 300 MeV