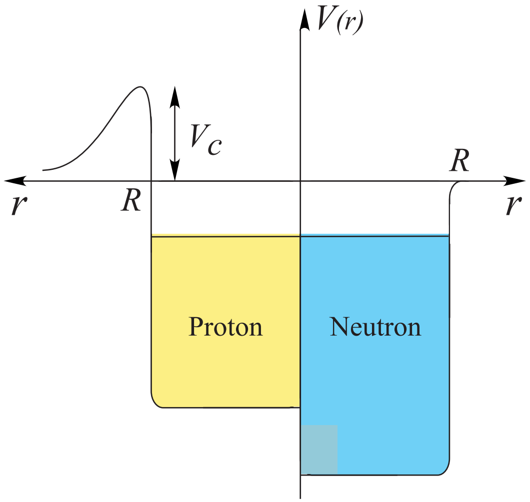
Dilute Cluster States

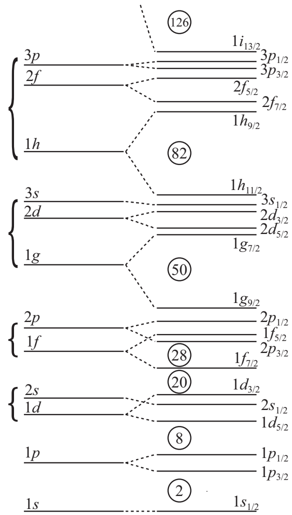
Center for Nuclear Study, University of Tokyo
KAWABATA Takahiro

Introduction

Two different pictures of Nuclear Structure

Shell Model

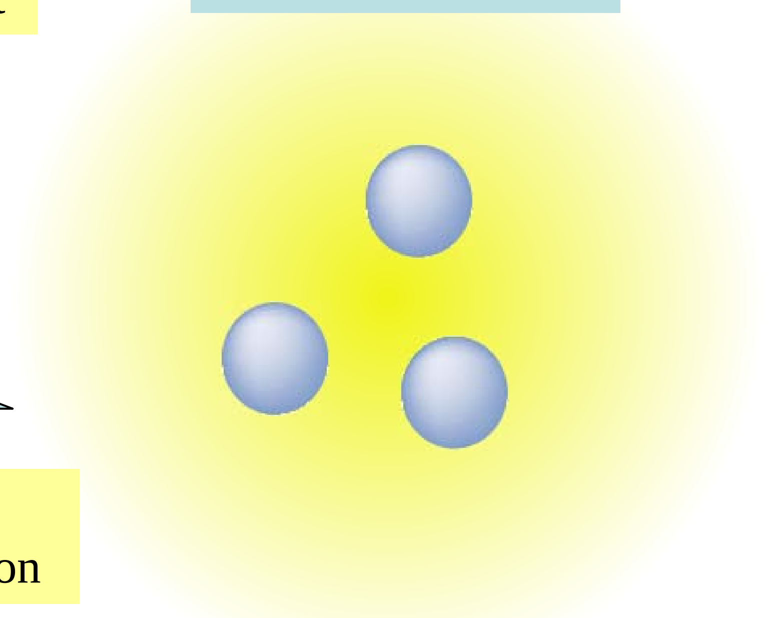




SU(3) Limit

Multi-$\hbar\omega$ Configuration

Cluster Model



Single-particle orbit in the mean-field potential.

Magic numbers (2, 8, 20, ...).

Describes well single-particle excited states.

Strong correlation between nucleons.

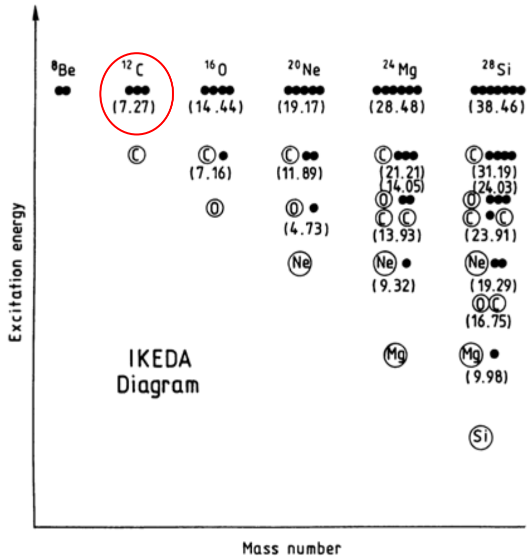
Cluster consists of several nucleons.

Clusters are weakly bound.

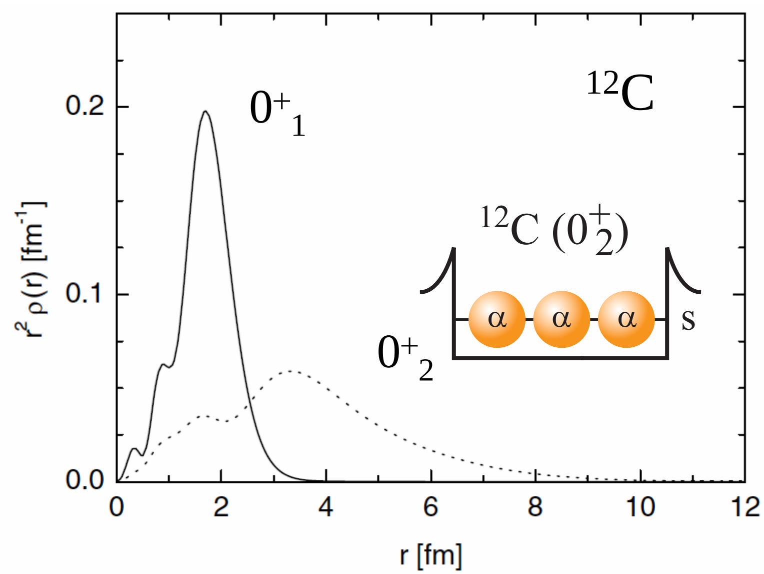
Dilute Cluster States in N=4n Nuclei

Alpha particle cluster is an important concept in nuclear physics for light nuclei.

Alpha cluster structure is expected to emerge near the α-decay threshold energy.



T.Yamada and P. Schuck, Euro. Phys. J. A **26**, 185 (2005).



The 0^+_2 state at E_x = 7.65 MeV in ^{12}C

Famous 3alpha (boson) cluster state.

Dilute-gas state of alpha particles.

(B.E.) Condensed state where three alpha particles occupy the lowest s-orbit.

Similar dilute-gas-like states have been predicted in self-conjugate N = 4n nuclei.

^{16}O (4α), ^{20}Ne (2α+^{12}C), ^{24}Mg (2α+^{16}O) ......

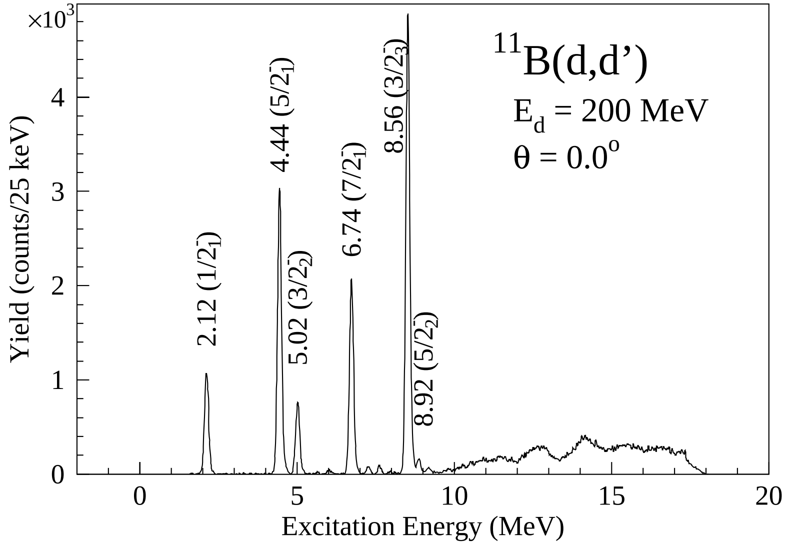
Does such a dilute state of clusters exists in the other N≠4n nuclei ?

Condensation in Boson + Fermion mixture ??

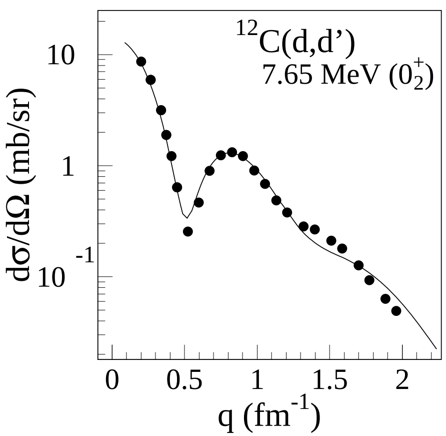
Cluster State in ^{11}B

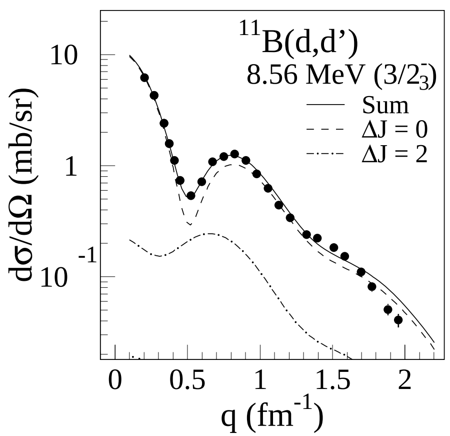
A 2α + t cluster state has been observed in ^{11}B(*d*,*d'*) reaction.

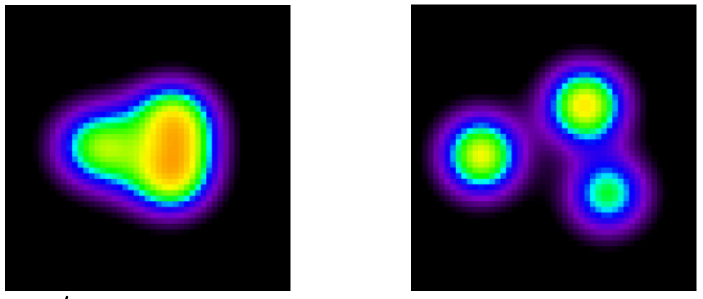
T. Kawabata *et al.*, Phys. Lett. B **646**, 6 (2007).



- $3/2^-_3$ state in ^{11}B is strongly excited by the $\Delta J^\pi = 0^+$ transition.
- Analogies between the $3/2^-_3$ state and the 0^+_2 state in ^{12}C (dilute-gas-like 3α cluster state) has been observed.
  - ➢Similar excitation energies and monopole strengths.
  - ➢Not predicted in SM calculations.
- AMD (VAP) successfully describes the $3/2^-_3$ state with a 2α + t cluster wave function.







$3/2^-_1$ (g.s.) $\langle r^2 \rangle^{1/2}$ = 2.5 fm

$3/2^-_3$ $\langle r^2 \rangle^{1/2}$ = 3.0 fm

AMD (VAP) Calculation by Y. Kanada-En'yo

Comparison with AMD and SM

	Experiment		SM (SFO)		AMD (VAP)	
J^π	B(GT)	B(σ)	B(GT)	B(σ)	B(GT)	B(σ)
$1/2^-_1$	0.401±0.032	0.037±0.007	0.782	0.051	0.43	0.040
$5/2^-_1$	0.453±0.029		0.616	0.032	0.70	0.045
$3/2^-_2$	0.487±0.029	0.035±0.005	0.745	0.047	0.67	0.047
$3/2^-_3$	< 0.003	< 0.003			0.02	0.002
$5/2^-_2$	0.398±0.031	0.012±0.003	0.483	0.025	0.56	0.039

J^π	B(E0;IS) (fm4)	B(E2;IS) (fm4)	B(E2) (e^2fm^4)	B(E2;IS) (fm^4)	B(E2) (e^2fm^4)	B(E0;IS) (fm4)	B(E2;IS) (fm^4)	B(E2) (e^2fm^4)
$1/2^-_1$		11±2	2.6±0.4	12.0	1.8		12.3	2.3
$5/2^-_1$		56±6	21±6	49.5	16.5		66.5	19.2
$3/2^-_2$	< 9	4.7±1.5	< 1.3	14.2	1.7	7	2.3	0.02
$7/2^-_1$		38±4	3.7±0.9	42.0	4.4		34.4	3.6
$3/2^-_3$	96±16	< 6	(9.4±0.2)			94	5.3	0.84
$5/2^-_2$		0.4±0.3	1.6±1.2	0.012	0.014		0.66	0.15

AMD (VAP) successfully predicts the experimental data.

E0 and M1 strengths for the $3/2^-_3$ state are well described by a 2α + t cluster w.f.

AMD (VAP) suggests a dilute-gas-like structure of the $3/2^-_3$ state in ^{11}B.

✓The $3/2^-_3$ state might be an α condensed state in the N≠4n (boson-fermion) system.

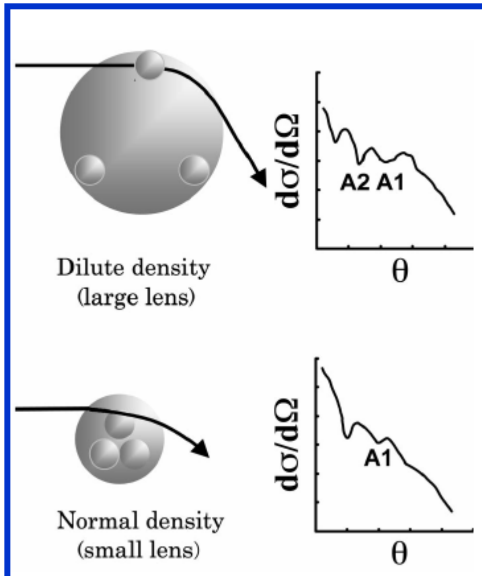
✓Large monopole strengths might be a signature of α cluster states.

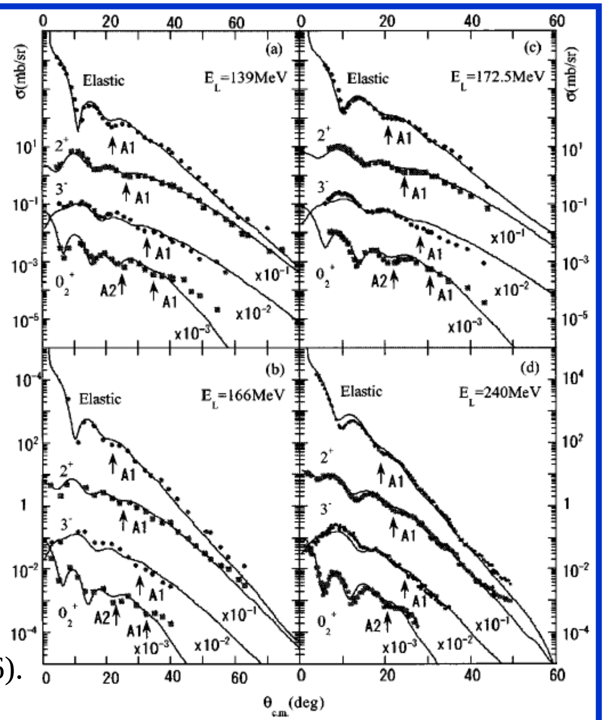
Questions

✓ Are the monopole excitations really associated with the cluster structure?

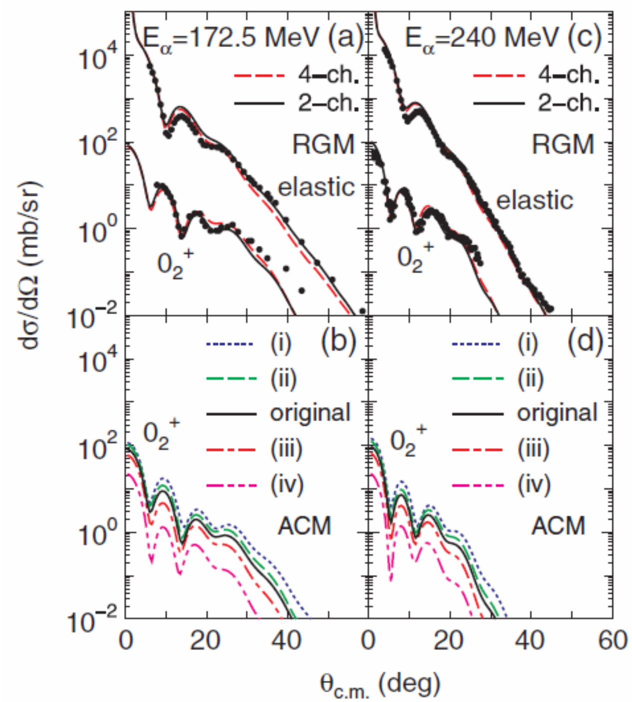
✓ Can we directly determine a rms radius of the dilute-gas-like state via precise measurement of the angler distribution ?

→ Rainbow Scattering ??





S. Ohkubo and Y. Hirabayashi, Phys. Rev. C **70**, 041602(R) (2006).

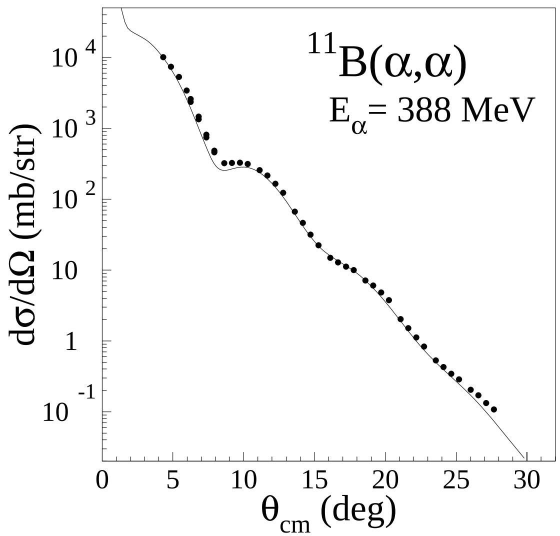


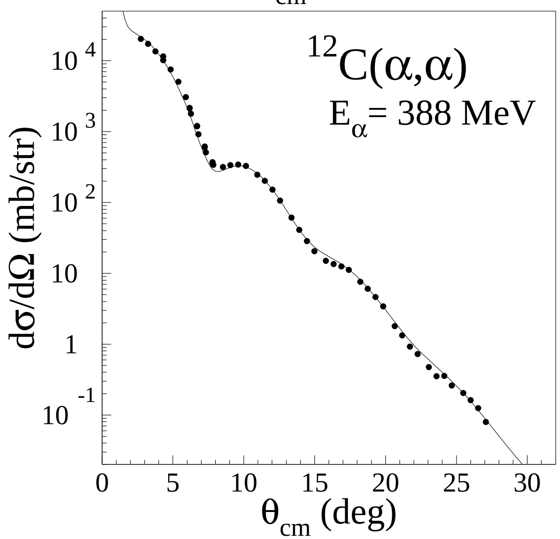
M. Takashina and Y. Sakuragi, Phys. Rev. C **74**, 054606 (2006).

Still controversial !

Single Folding Calculation

Single folding model successfully reproduces α elastic scattering.





GS density ρ_0 is folded by density-dependent αN interaction.

$$U_0(r) = \int d\vec{r}' \rho_0(r') V\left(|\vec{r} - \vec{r}'|, \rho_0(r')\right)$$

- GS density is obtained from
  ^{12}C: RGM calculation by Kamimura
  ^{11}B: ρ_{0p} from Electron Scatterting
  $\rho_{0n}(r) = \rho_{p0}(\alpha r)$, $\alpha=(N/Z)^{1/3}$
- αN interaction is taken from Itoh et al.

$$V\left(|\vec{r}-\vec{r}'|, \rho_0(r')\right) = -V\left(1+\beta_V \rho_0(r')^{2/3}\right)\exp\left(-|\vec{r}-\vec{r}'|/\alpha_V\right) \\ -iW\left(1+\beta_W \rho_0(r')^{2/3}\right)\exp\left(-|\vec{r}-\vec{r}'|/\alpha_W\right)$$

$$V = 36.73\,\text{MeV},\ W = 25.90\,\text{MeV},\ \alpha_V = \alpha_W = 3.7,\ \beta_V = \beta_W = -1.9$$

Transition Potential

TP is obtained from ACM based TD by the single folding model.

Transition density $\delta\rho_L$ from ACM is folded by density-dependent αN interaction.

$$\delta U_L(r) = \int d\vec{r}'\delta\rho_L(r)\left(V\left(|\vec{r}-\vec{r}'|,\rho_0(r')\right) + \rho_0(r')\frac{\partial V\left(|\vec{r}-\vec{r}'|,\rho_0(r')\right)}{\partial\rho_0(r')}\right)$$

$$V\left(|\vec{r}-\vec{r}'|,\rho_0(r')\right) = -V\left(1+\beta_V\rho_0(r')^{2/3}\right)\exp\left(-|\vec{r}-\vec{r}'|/\alpha_V\right) -iW\left(1+\beta_W\rho_0(r')^{2/3}\right)\exp\left(-|\vec{r}-\vec{r}'|/\alpha_W\right)$$

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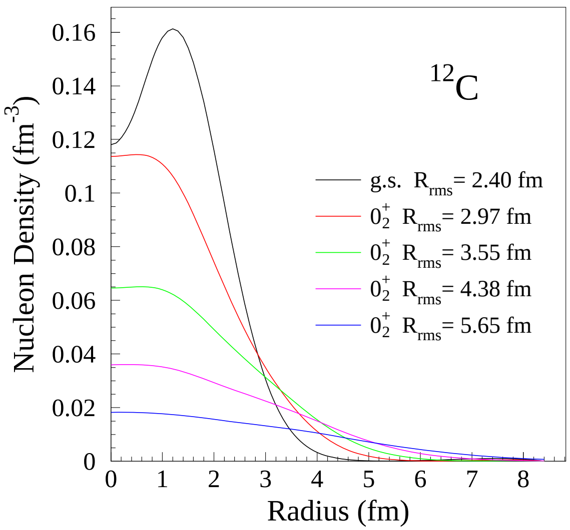
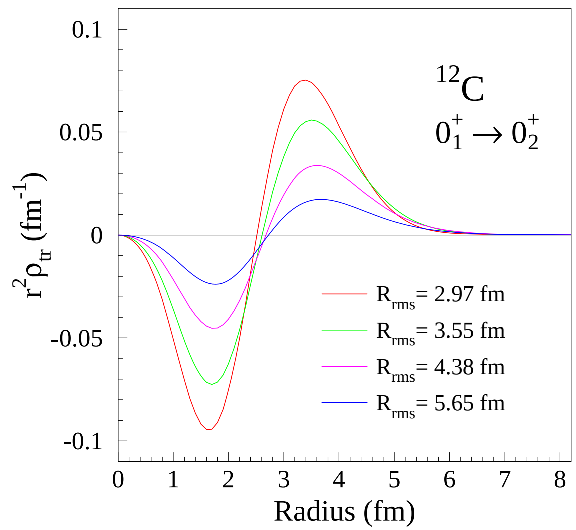
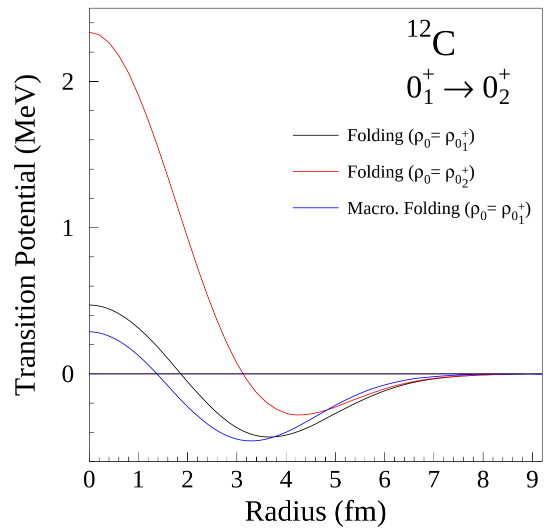
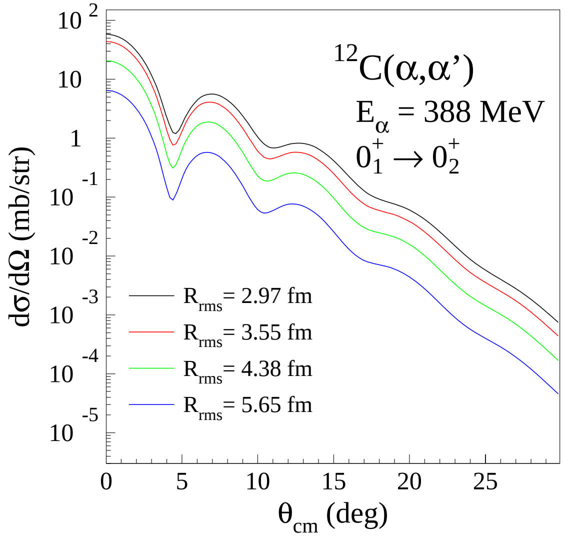


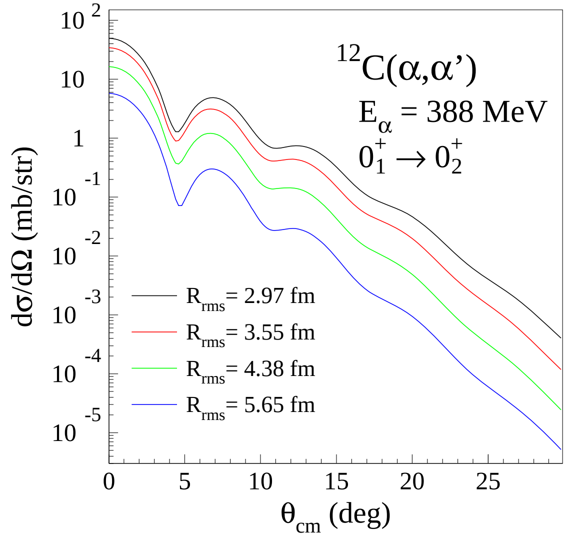




Inelastic Alpha Scattering

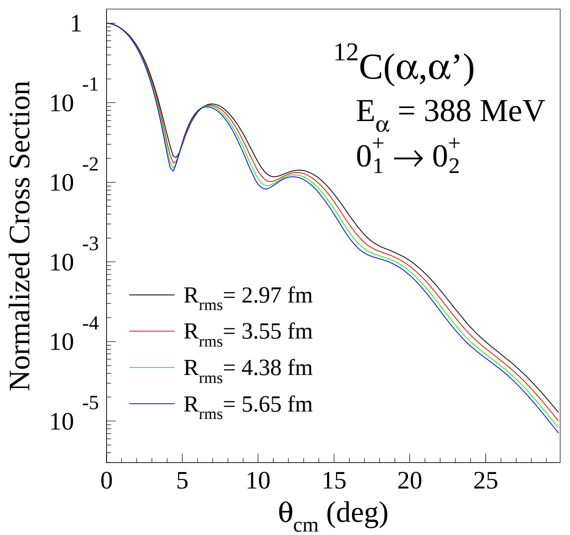
Can we determine a rms radius from the anguler distribution ?

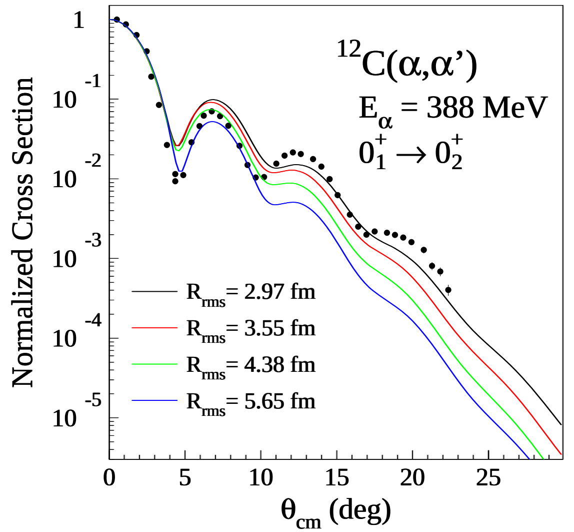


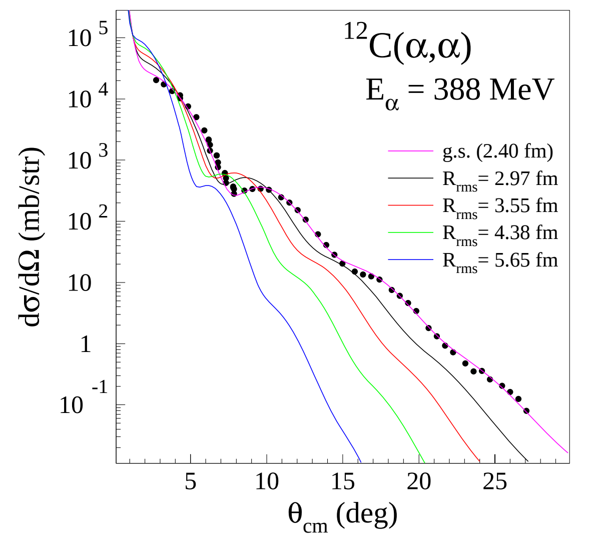


No significant difference in the angular distribution ??

The distorting potentials should be different between the *normal* and *dilute* states.





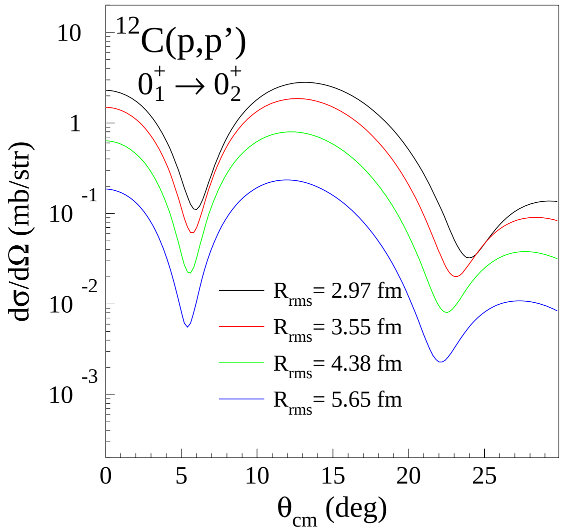


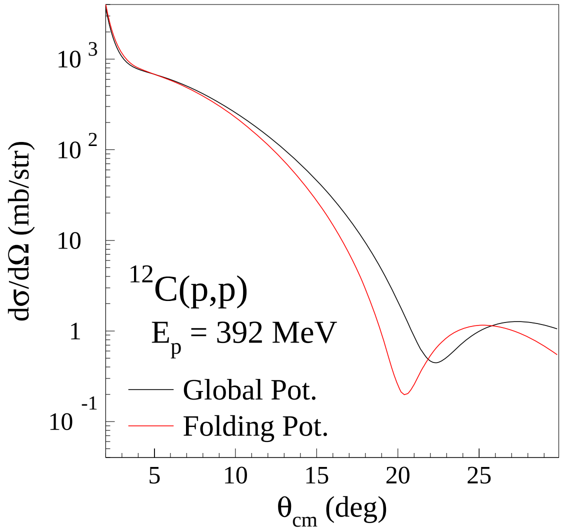
Different distorting pots. for the ground and excited states.

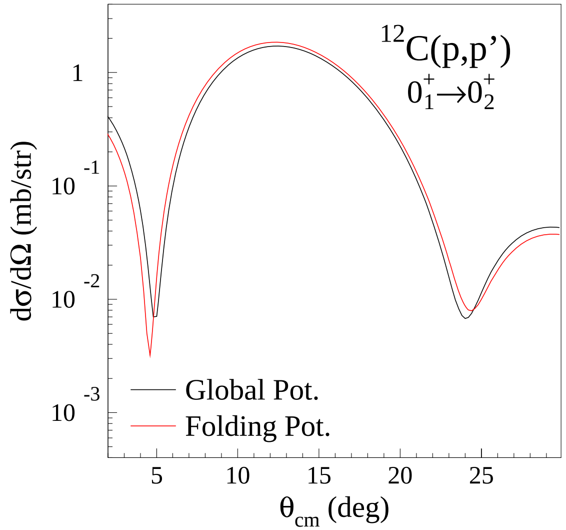
Anguler dist. exhibits the signature... but the accurate calculation is required.

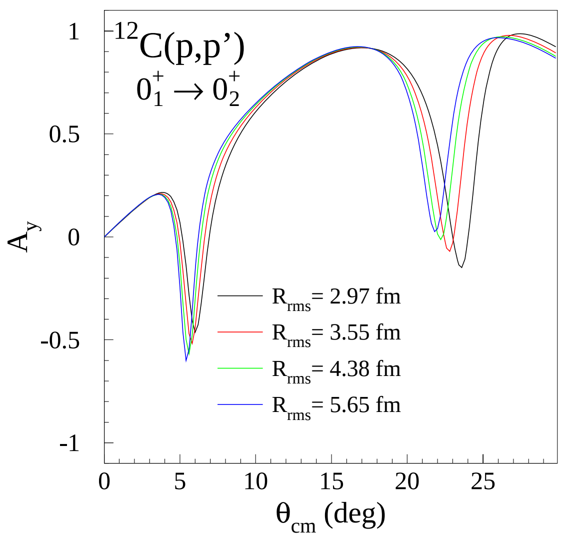
Proton Scattering

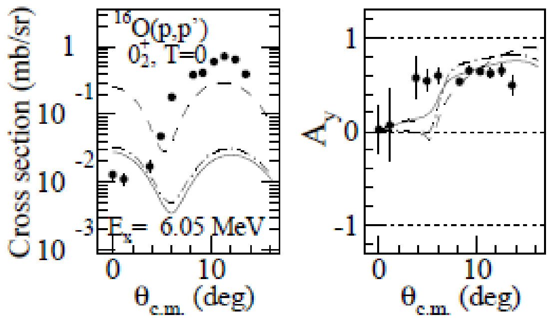
Proton scattering might be sensitive to the inner region of nuclei.

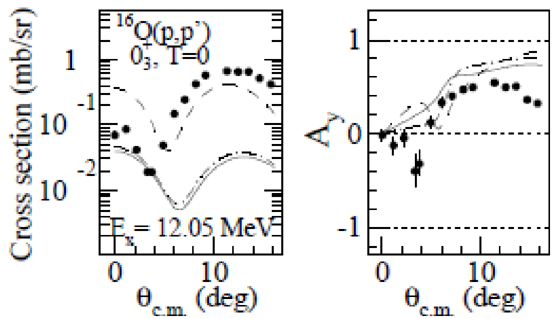












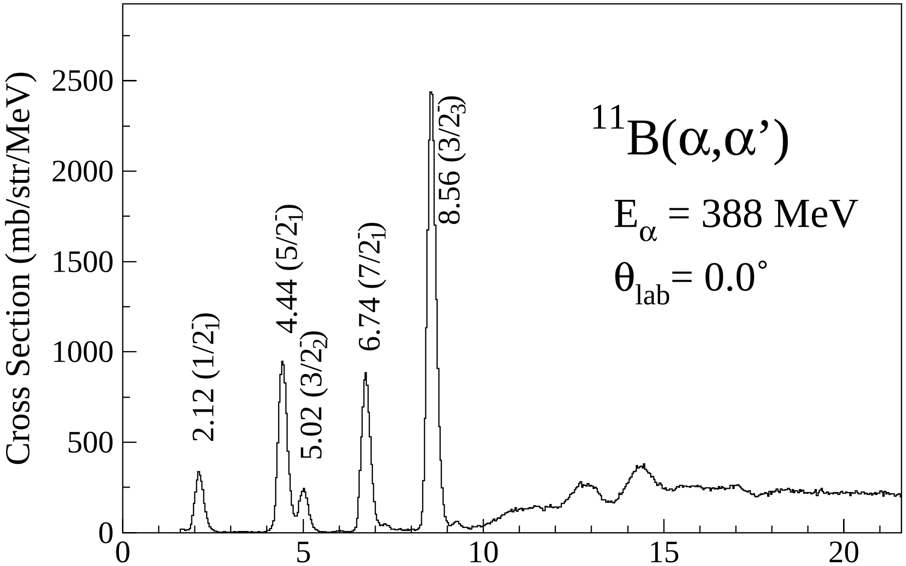
$^{16}O(p,p')@T_p$= 392 MeV

Dependence on the rms radius is strong.....,
but the accurate calculation is still desired.

Summary

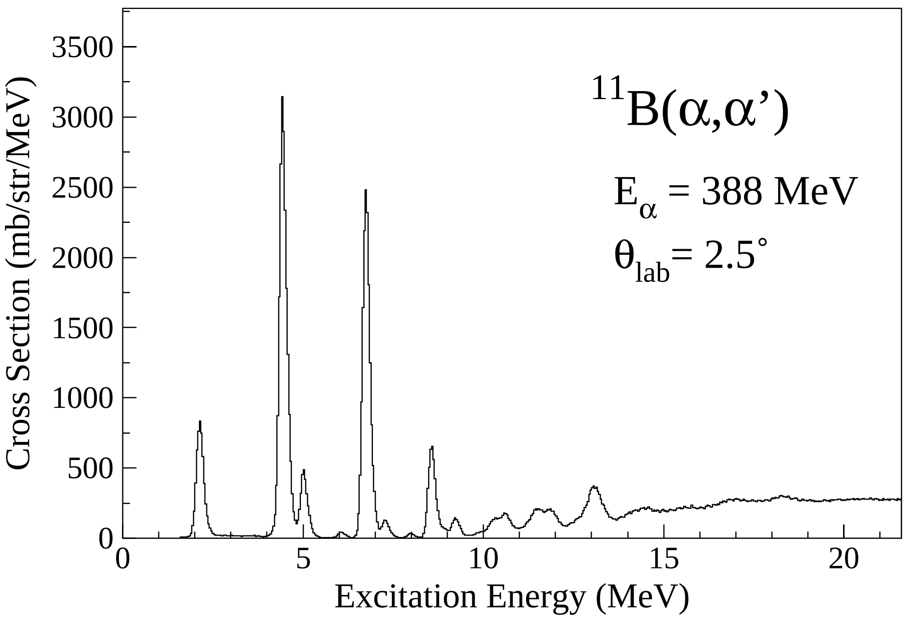
- Dilute cluster states in the p- and sd-shell nuclei are of interest.
  - B.E. condensates might appear.
- Precise measurements of the inelastic scattering are possible at RCNP.
- Dilute nature is slightly reflected to the angular distribution of the cross section.
  - Single folding calculations are performed for the (α,α’) and (p,p’) reactions.
  - Accurate calculation is desired.

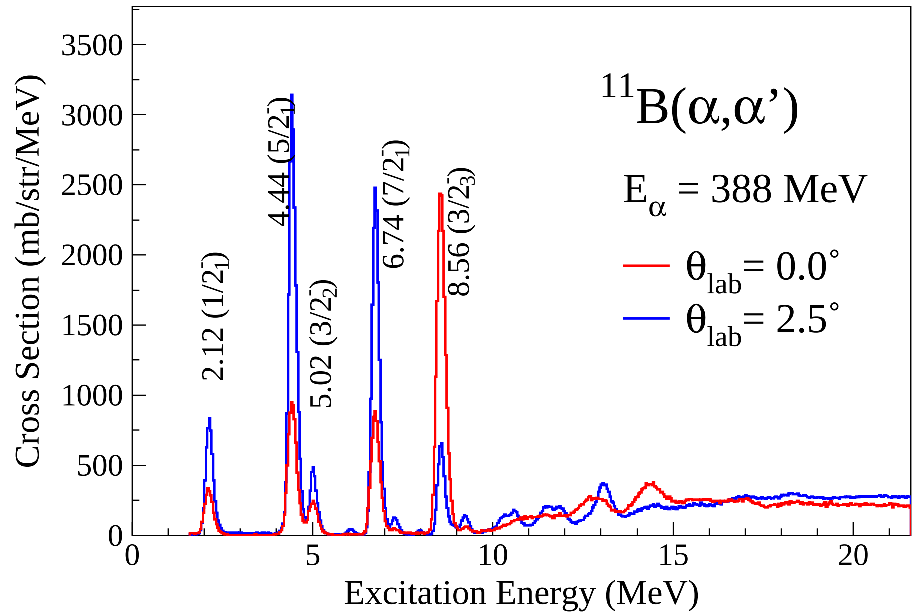
Measured Spectra



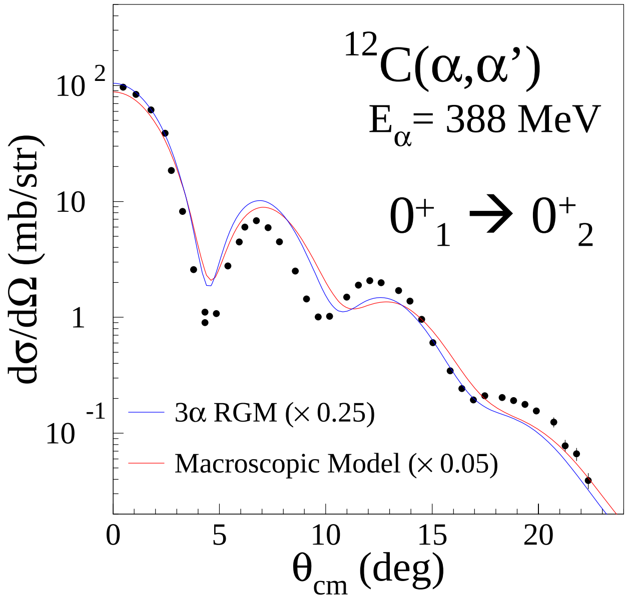
Background-free measurement at extremely forward angles was successfully performed.

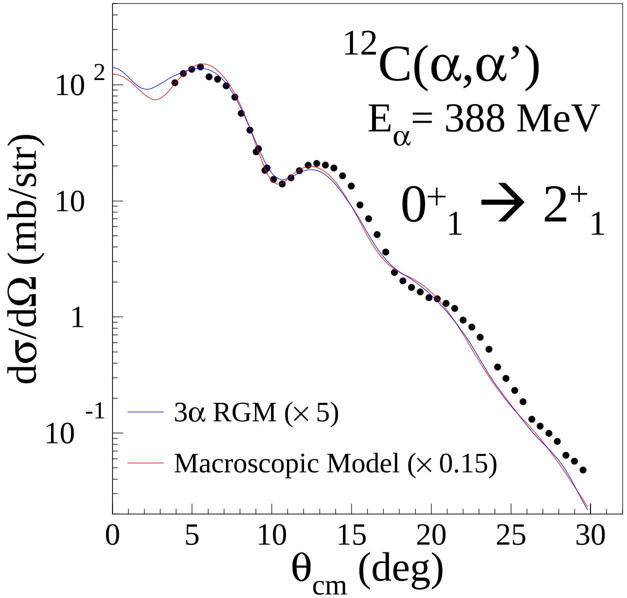
E0 transitions are dominant at 0 deg.





Inelastic Scattering from ^{12}C





- Transition potential is obtained by a single folding model.

$$\delta U_L(r) = \int d\vec{r}' \delta\rho_L(r) \left(V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right) + \rho_0(r') \frac{\partial V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right)}{\partial \rho_0(r')} \right)$$

- Transition densities
  - ➢ From RGM
  - ➢ From Macroscopic Model

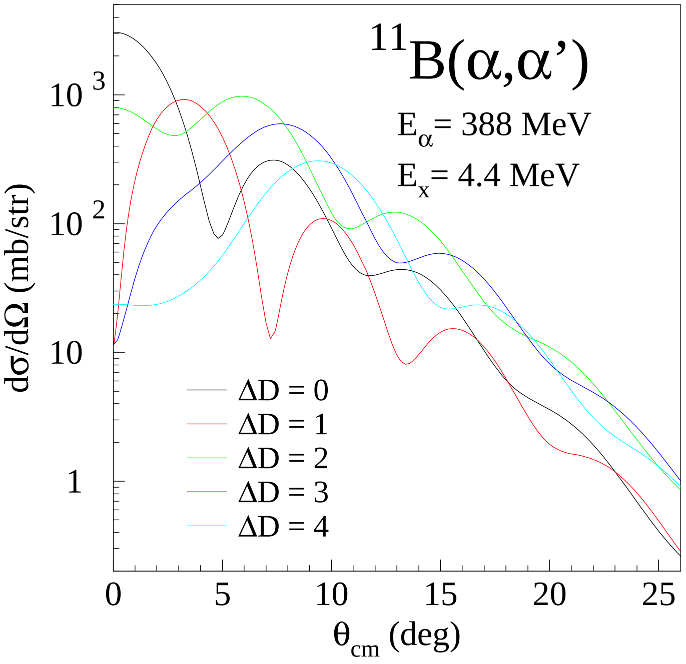
$$\delta\rho_{L=0} = -\beta_{L=0}\left(3 + r\frac{d}{dr}\right)\rho_0(r)$$

$$\delta\rho_{L=2} = -\beta_{L=2}\frac{d}{dr}\rho_0(r)$$

Calculated cross sections are not satisfactory .....

.... but not so bad.

Multipole Decomposition Analysis

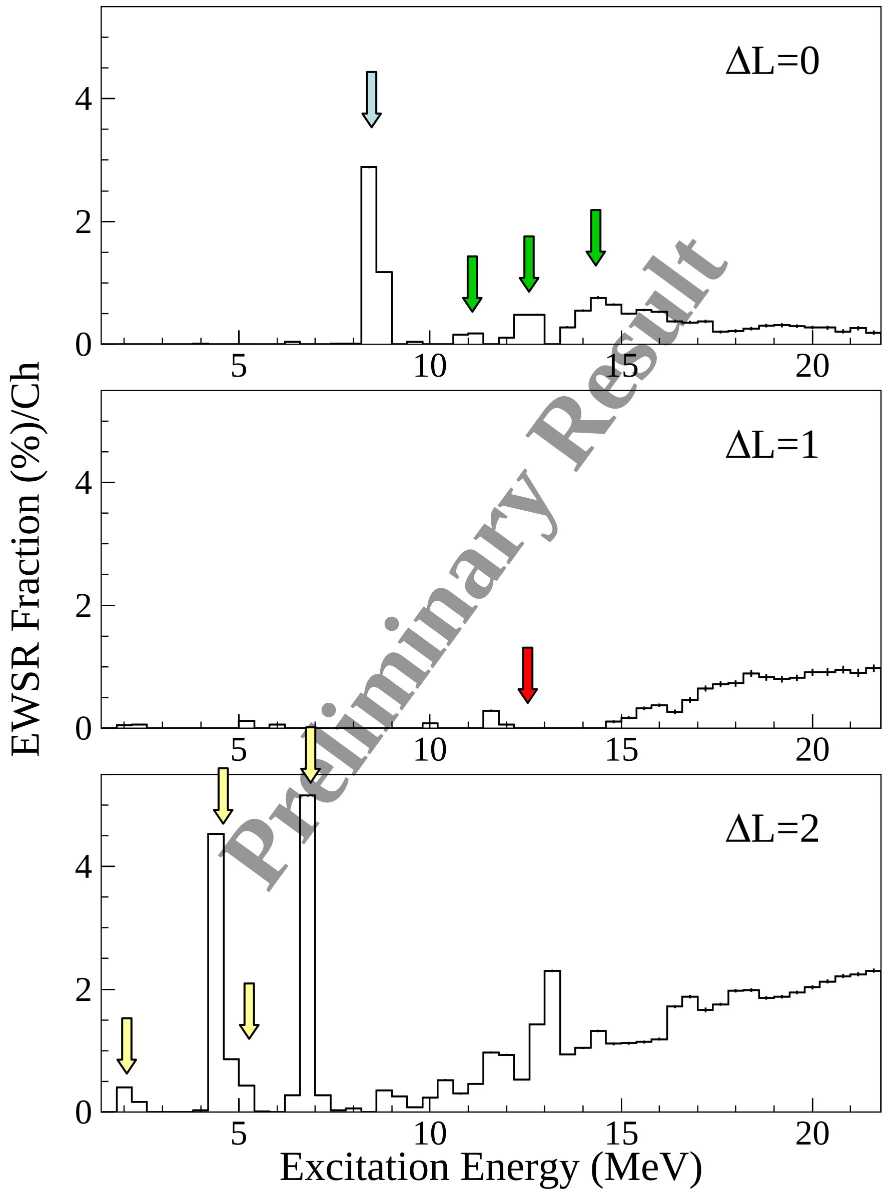


- Multipole decomposition analysis has been performed to separate each ΔL.

$$\frac{d\sigma}{d\Omega}^{\exp} = \sum_{\Delta L} \alpha_{\Delta L} \frac{d\sigma}{d\Omega}^{DWBA}_{\Delta L}$$

- Each mutipole cross section was calculated using the macroscopic transition densities.
- Transitions with ΔL≤ 4 were taken into account.

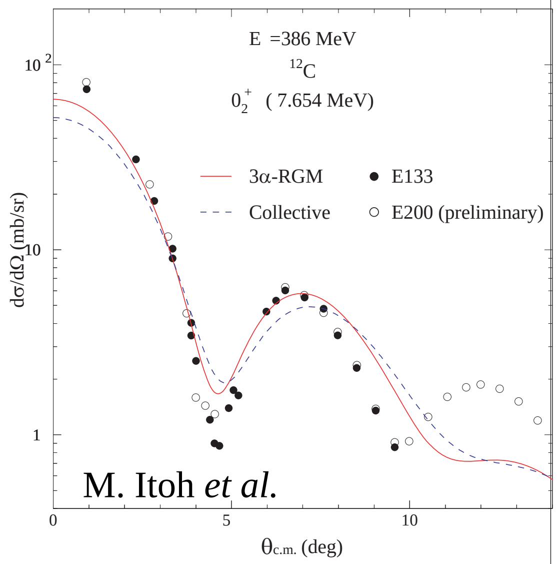
Multipole Strengths in ^{11}B

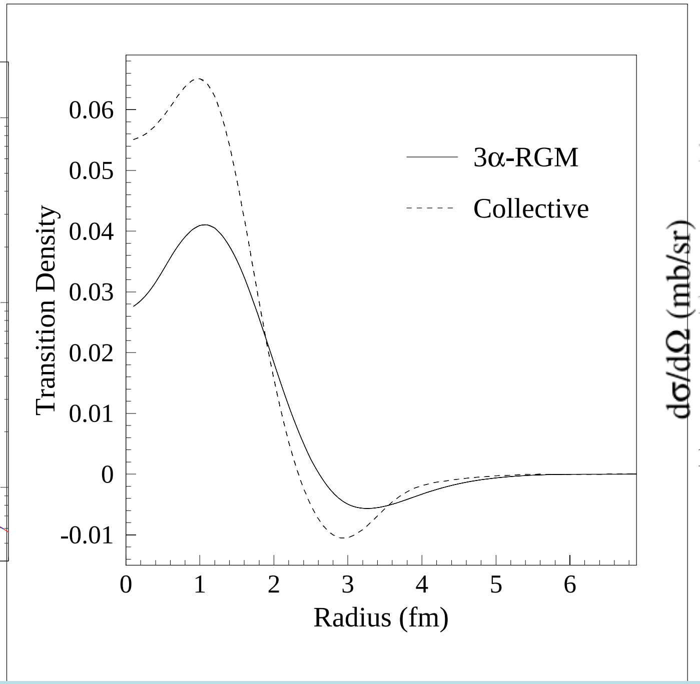


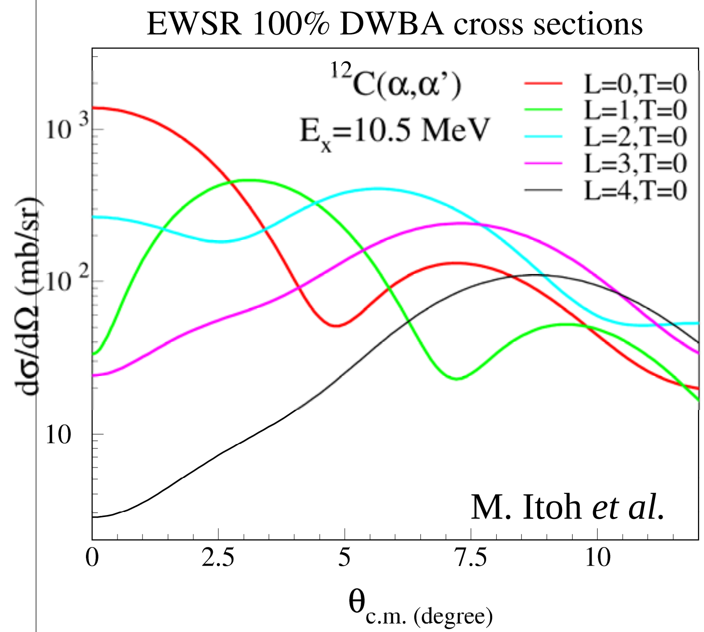
- Successfully identified.
  - ➢Monopole strength
    - ✓E_x=8.56 MeV
  - ➢Quadrupole strengths
    - ✓E_x=2.12 MeV
    - ✓E_x=4.44 MeV
    - ✓E_x=5.02 MeV
    - ✓E_x=6.74 MeV
- No significant E1 strength at 12.5 MeV
- Sizable monopole strengths
  at E_x~11.0, 12.5, 14.5 MeV
  - ➢No $3/2^{-}$ state reported in TOI.
    - ✓New Cluster States ??
    - ✓Fragmented GMR ??

Inelastic Alpha Scattering

- Alpha scattering is suitable to investigate molecular states.
  - Simple reaction mechanism.
  - Only central interaction V_0 contributes.
- Extract transition densities in the surface region for discrete states.
- Search for analog states of 0^+_3 in continuum region by means of MDA.
- Precise measurement of B(E2;IS) for the $5/2^-_2$ state.







Beam time is scheduled in October.