α-Cluster States in Electron Scattering *

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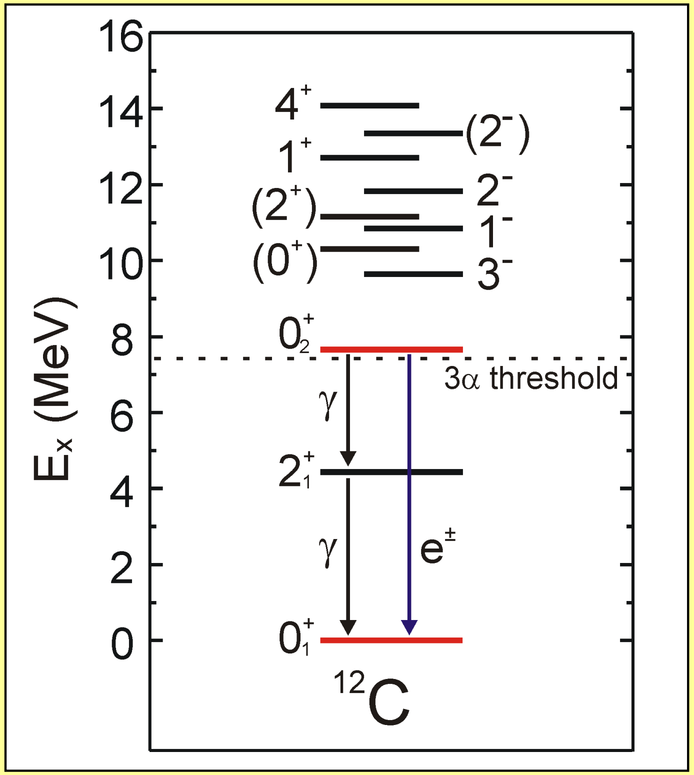
Motivation: structure of the Hoyle state

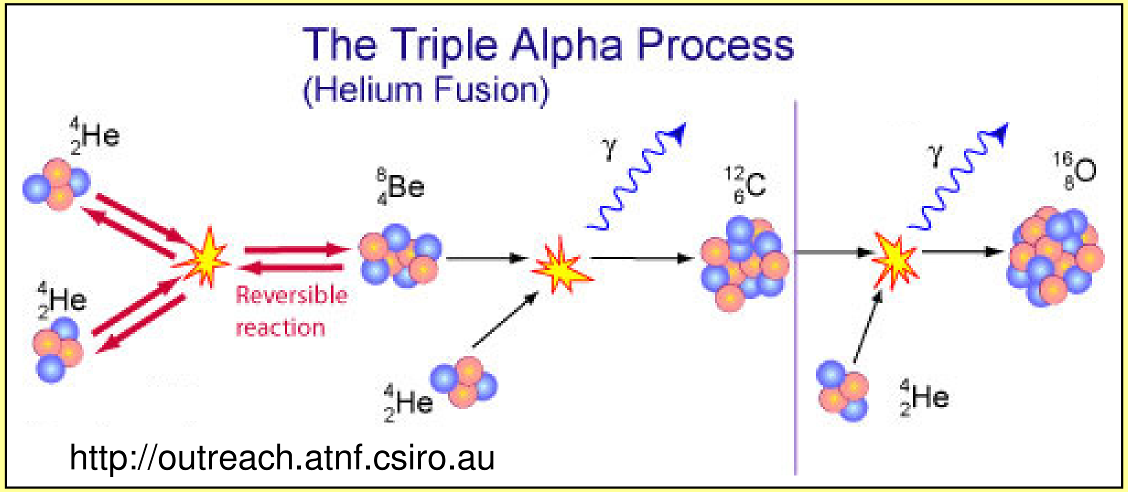


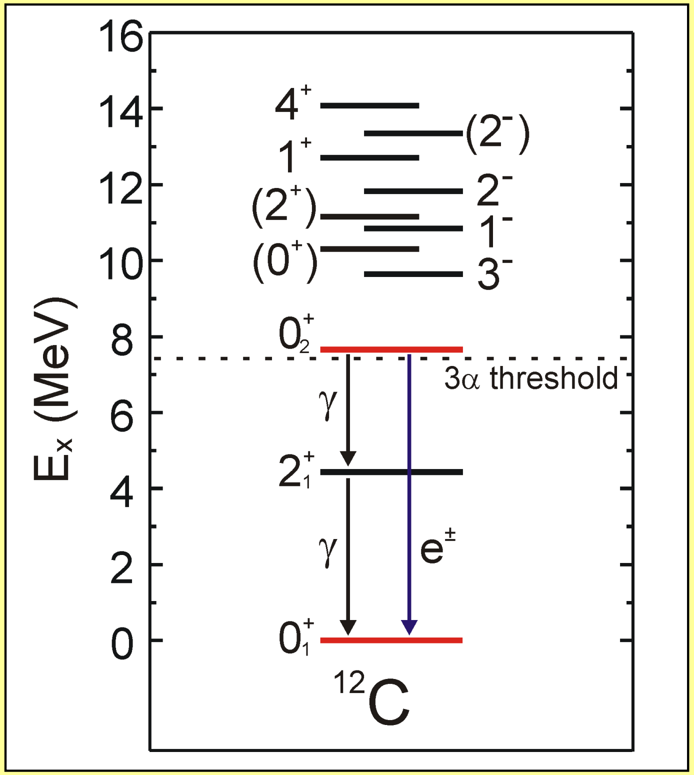
- Hoyle state is a prototype of α-cluster states in light nuclei
- Cannot be described by shell-model approaches
- α-cluster models predict Hoyle state as a dilute gas of weakly interacting α particles resembling the properties of a Bose-Einstein Condensate (BEC)
- Comparison of high-precision electron scattering data with predictions of FMD and α-cluster models

➡ Hoyle state cannot be understood as a true Bose-Einstein Condensate !

- M. Chernykh, H. Feldmeier, T. Neff, P. von Neumann-Cosel, and A. Richter, Phys. Rev. Lett. 98 (2007) 032501

Motivation: astrophysical importance





- Triple alpha reaction rate

$$r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\tfrac{Q_{3\alpha}}{kT}\right)$$

$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

(α,α’) (p,p’) (p,p’) (e,e’)

- Reaction rate with accuracy ~ 6% needed

S.M. Austin, Nucl. Phys A758 (2005) 375c

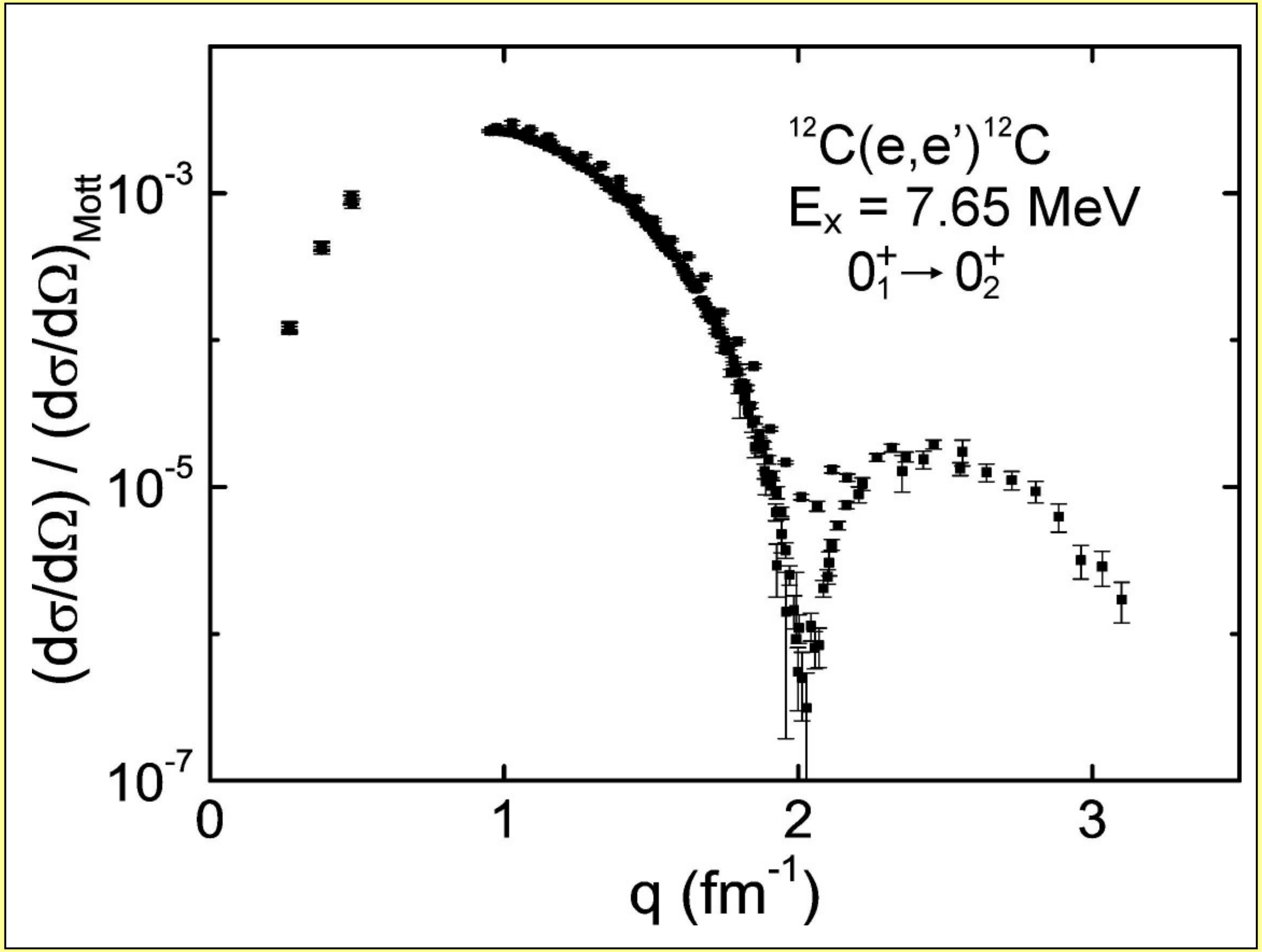
Motivation: astrophysical importance

$$r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q_{3\alpha}}{kT}\right) \qquad \Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

Quantity	Value	Error (%)
$Q_{3\alpha}$	379.38 ± 0.20 keV	1.2 ($T_9 = 0.2$)
Γ_{rad}/Γ	$(4.12 \pm 0.11) \times 10^{-4}$	2.7
Γ_π/Γ	$(6.74 \pm 0.62) \times 10^{-6}$	9.2
Γ_π	$(62.0 \pm 6.0) \times 10^{-6}$ eV	9.7 Crannell *et al.* (1967)
Γ_π	$(59.4 \pm 5.1) \times 10^{-6}$ eV	8.6 Strehl (1970)
Γ_π	$(52.0 \pm 1.4) \times 10^{-6}$ eV	2.7 Crannell *et al.* (2005)

- Total uncertainty $\Delta r_{3\alpha}/r_{3\alpha}$ = 11.6% only

Transition form factor to the Hoyle state



- Fourier-Bessel analysis: Crannell (2005)
- Extrapolation to zero momentum transfer: Crannell (1967), Strehl (1970)

H. Crannell, data compilation

Model-independent PWBA analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{PWBA} = 4\pi\left(\frac{e^2}{E_0}\right)^2 f_{rec}\ V_L(\theta)\ B(C0,q)$$

$$4\pi B(C0,q) = \left[\langle 0_2^+|\int \hat{\rho}_N\, j_0(qr)\, d^3r|0_1^+\rangle\ \right]^2$$

$$\langle r^\lambda\rangle_{tr} = \langle 0_2^+|\int \hat{\rho}_N\, r^\lambda\, d^3r|0_1^+\rangle$$

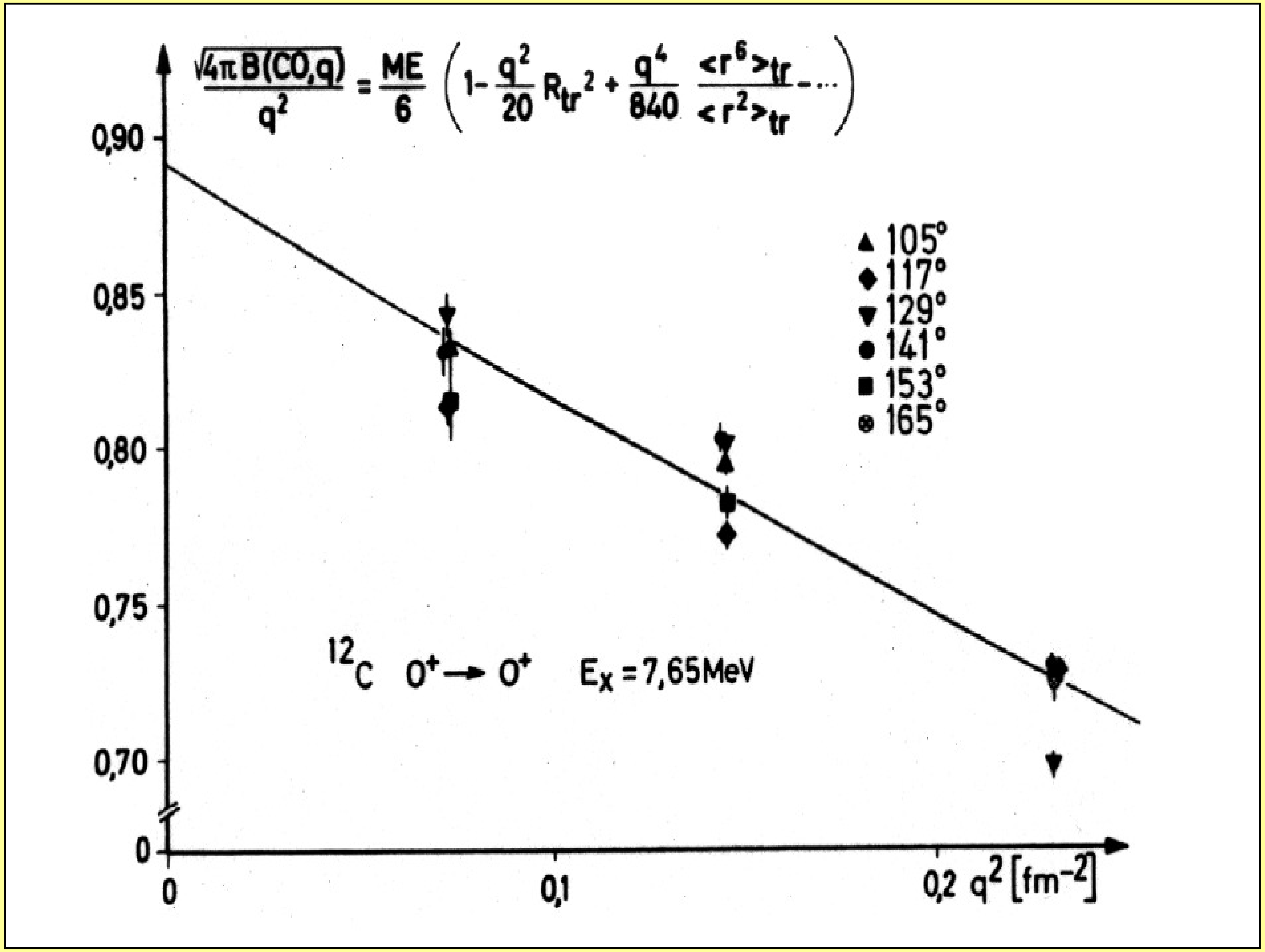
$$ME = \langle r^2\rangle_{tr}\,, \qquad R_{tr}^2 = \frac{\langle r^4\rangle_{tr}}{\langle r^2\rangle_{tr}}$$

$$\sqrt{4\pi\, B(C0,q)} = \frac{q^2}{6}(ME)\left[1 - \frac{q^2}{20}R_{tr}^2 + \ \cdots\right]$$

$$\Gamma_\pi \propto ME^2$$

- Model-independent extraction of the partial pair width Γ_π

Monopole matrix element

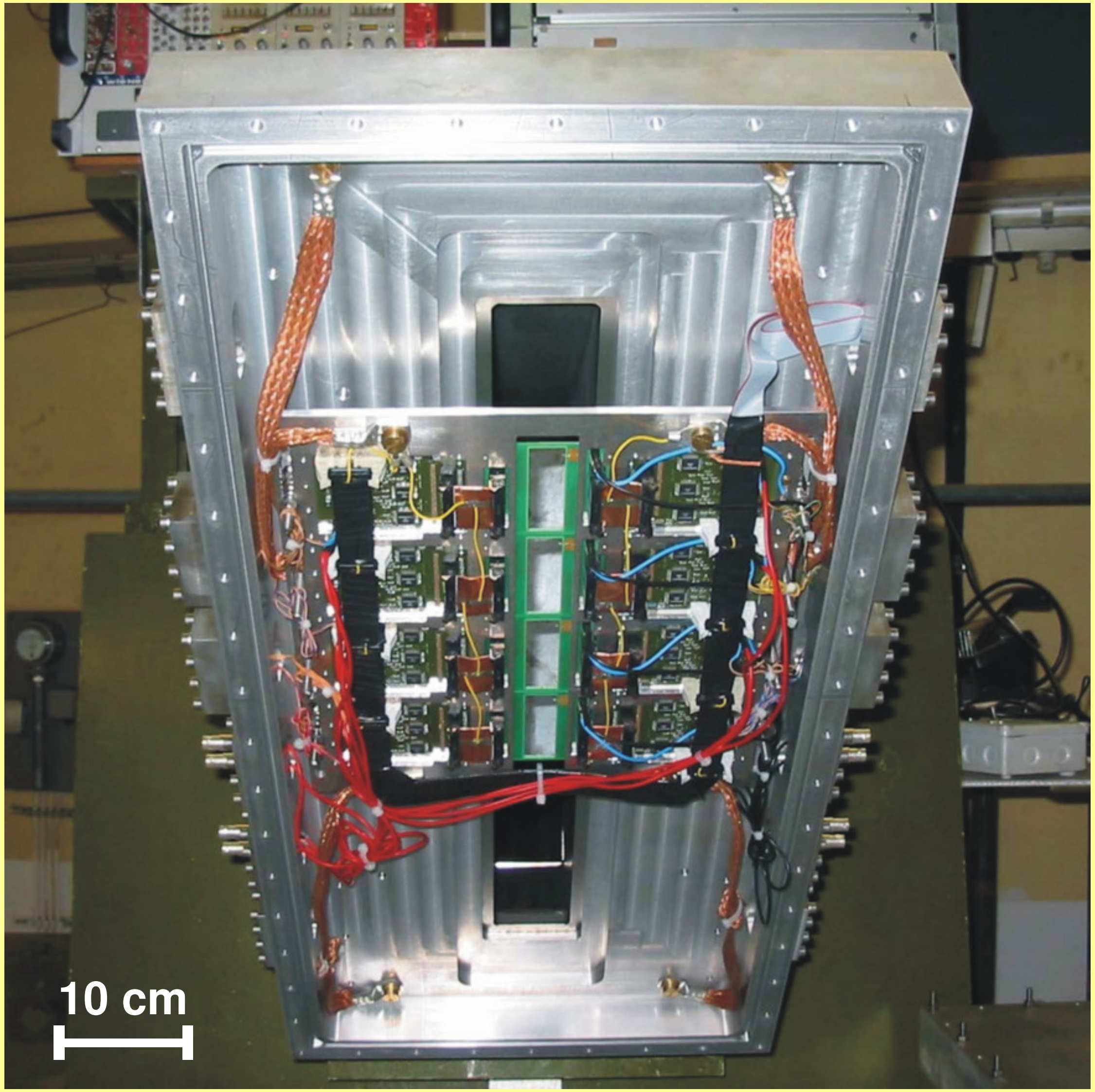


- ME = 5.37(22) fm^2, R_{tr} = 4.24(30) fm
- Large uncertainty because of narrow momentum transfer region

P. Strehl, Z. Phys. 234 (1970) 416

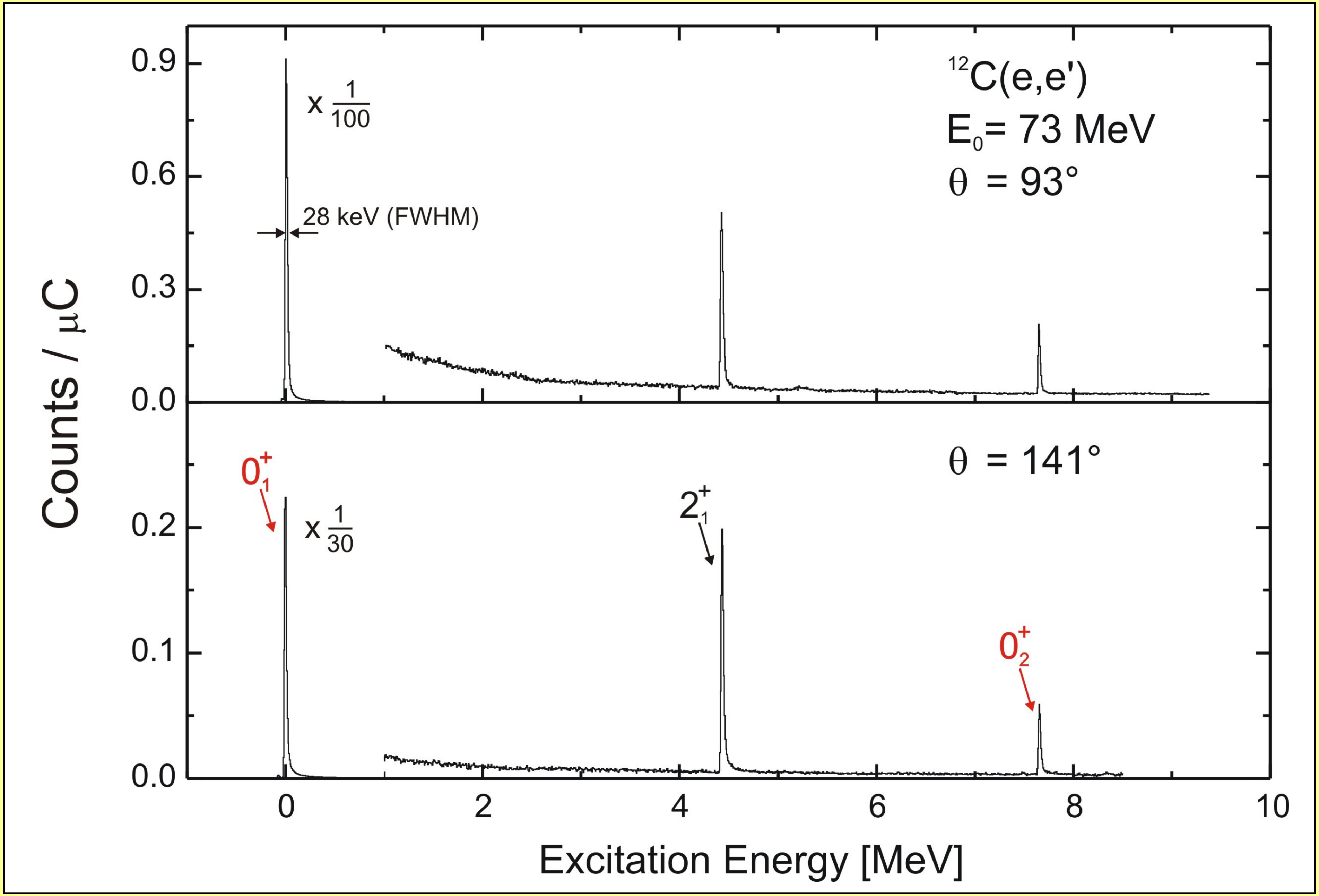
Lintott spectrometer

Detector system

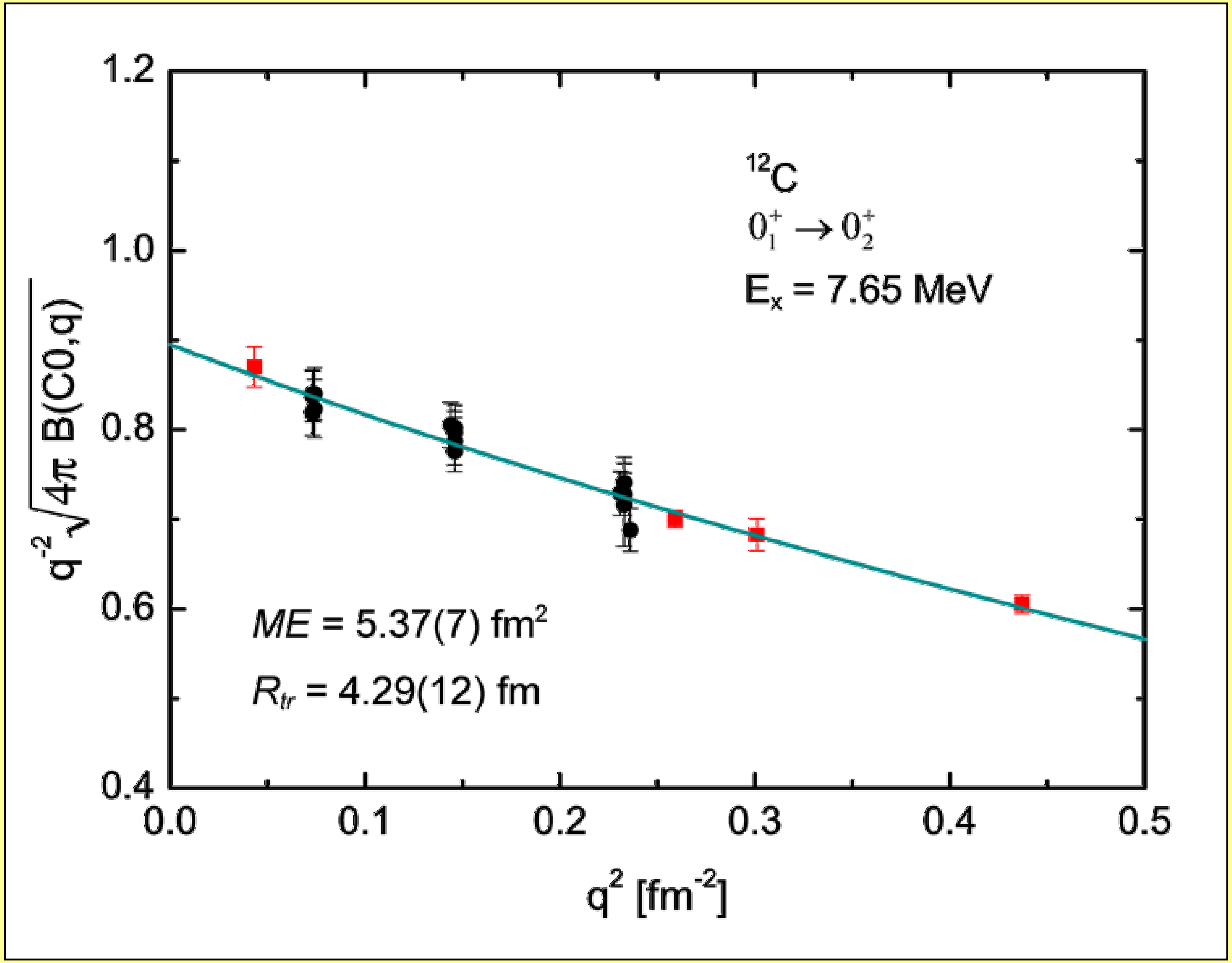


- Si microstrip detector system: 4 modules, each 96 strips with pitch of 650 μm
- Count rate up to 100 kHz
- Energy resolution 1.5×10^{-4}

Measured spectra



Monopole matrix element



$$\sqrt{4\pi\, B(C0,q)} = \frac{q^2}{6}(ME)\left[1 - \frac{q^2}{20}R_{tr}^2 + \cdots\right]$$

Triple alpha reaction rate

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Γ_π	$(59.6 \pm 1.5)\times 10^{-6}$ eV	2.5	Present work

- Total uncertainty $\Delta r_{3\alpha}/r_{3\alpha}$ = 10%
- Only Γ_π/Γ need to be improved

Summary and outlook

- Hoyle state is important for stellar nucleosynthesis
- Monopole matrix element can be extracted by extrapolation of cross section to zero momentum transfer
- Γ_π for decay of the Hoyle state with uncertainty 2.5% extracted

- Outlook
  - Hoyle state: independent Fourier-Bessel analysis
  - ^{16}O: broad 0^+ state at 15 MeV

Thank you!

Outline

- Motivation:
  - Astrophysical importance
- Model-independent PWBA analysis
- High-resolution electron scattering measurements
- Results
  - Extraction of monopole matrix element ME
  - Comparison with FMD and α-cluster model predictions
- Summary and outlook

Model-independent PWBA analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{PWBA} = 4\pi\left(\frac{e^2}{E_0}\right)^2 f_{rec}\;\; V_L(\theta)\;\; B(C0,q)$$

$$4\pi B(C0,q) = \left[\langle 0_2^+ |\int \hat{\rho}_N\, j_0(qr)\, d^3r | 0_1^+\rangle\;\right]^2$$

$$\langle r^\lambda\rangle_{tr} = \langle 0_2^+ |\int \hat{\rho}_N\, r^\lambda\, d^3r | 0_1^+\rangle$$

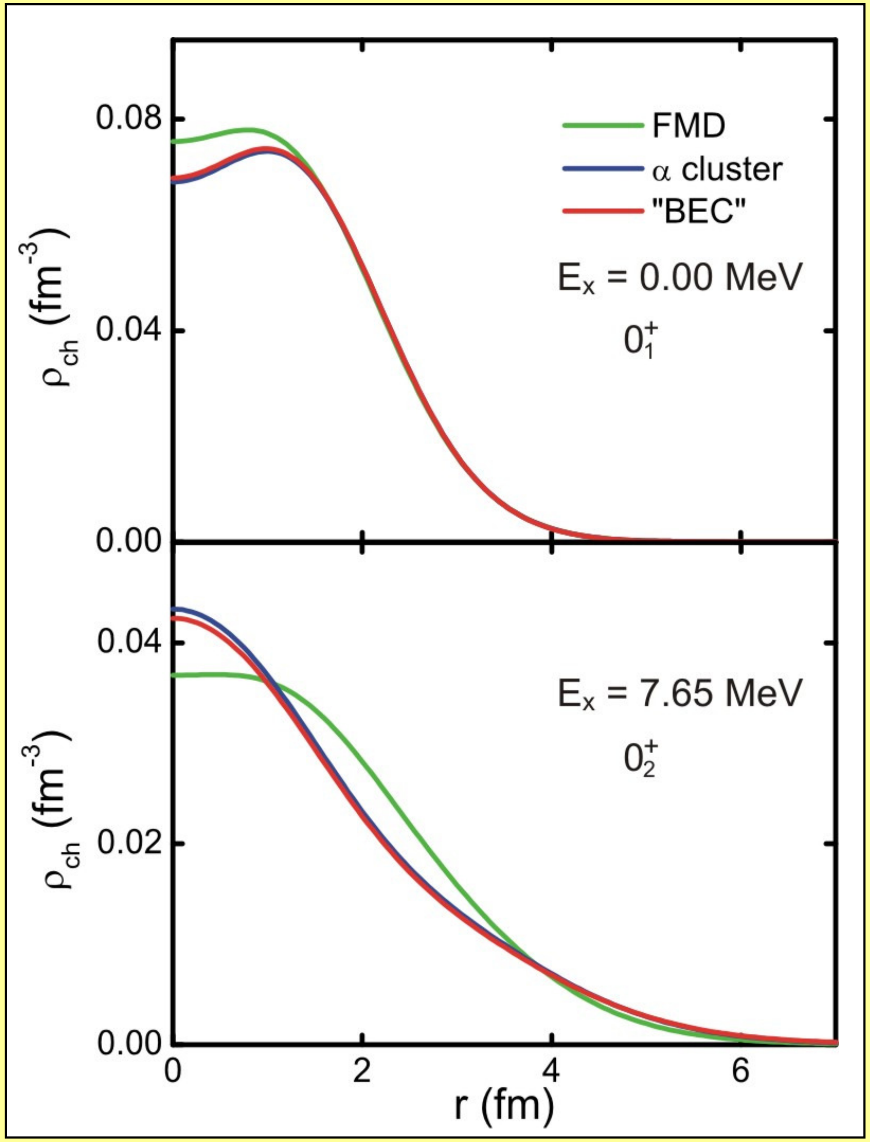
$$ME = \langle r^2\rangle_{tr}\,, \qquad R_{tr}^2 = \frac{\langle r^4\rangle_{tr}}{\langle r^2\rangle_{tr}}$$

$$\sqrt{4\pi\, B(C0,q)} = \frac{q^2}{6}(ME)\left[1 - \frac{q^2}{20}R_{tr}^2 + \frac{q^4}{840}\frac{\langle r^6\rangle_{tr}}{\langle r^2\rangle_{tr}} - \frac{q^6}{60480}\frac{\langle r^8\rangle_{tr}}{\langle r^2\rangle_{tr}} + \cdots\right]$$

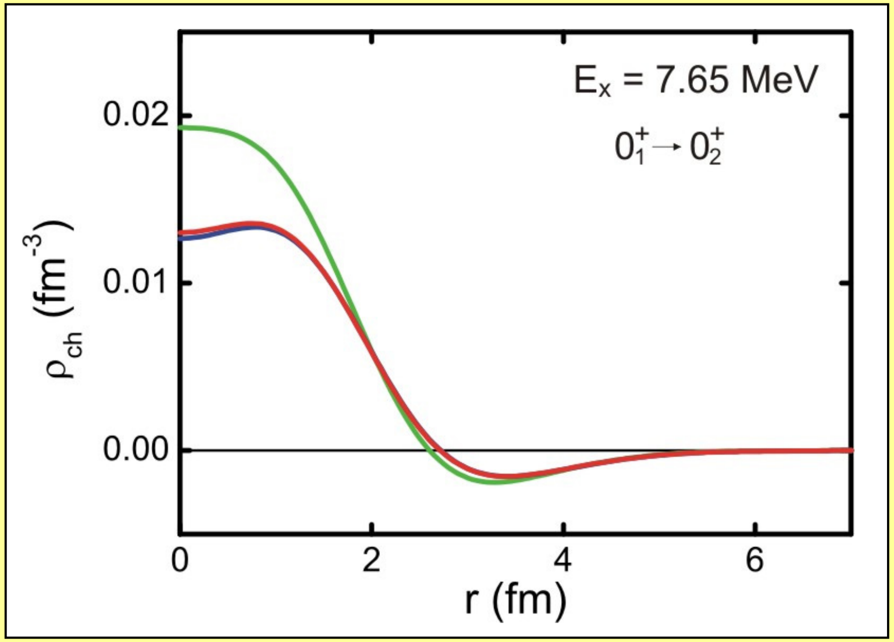
$$\frac{\langle r^6\rangle_{tr}}{\langle r^2\rangle_{tr}} = x_1\,(R_{tr}^2)^2, \quad \frac{\langle r^8\rangle_{tr}}{\langle r^2\rangle_{tr}} = x_2\,(R_{tr}^2)^3, \quad \ldots$$

- Model-independent extraction of monopole matrix element *ME*

^{12}C densities



↔ • Ground state density can be tested via elastic form factor

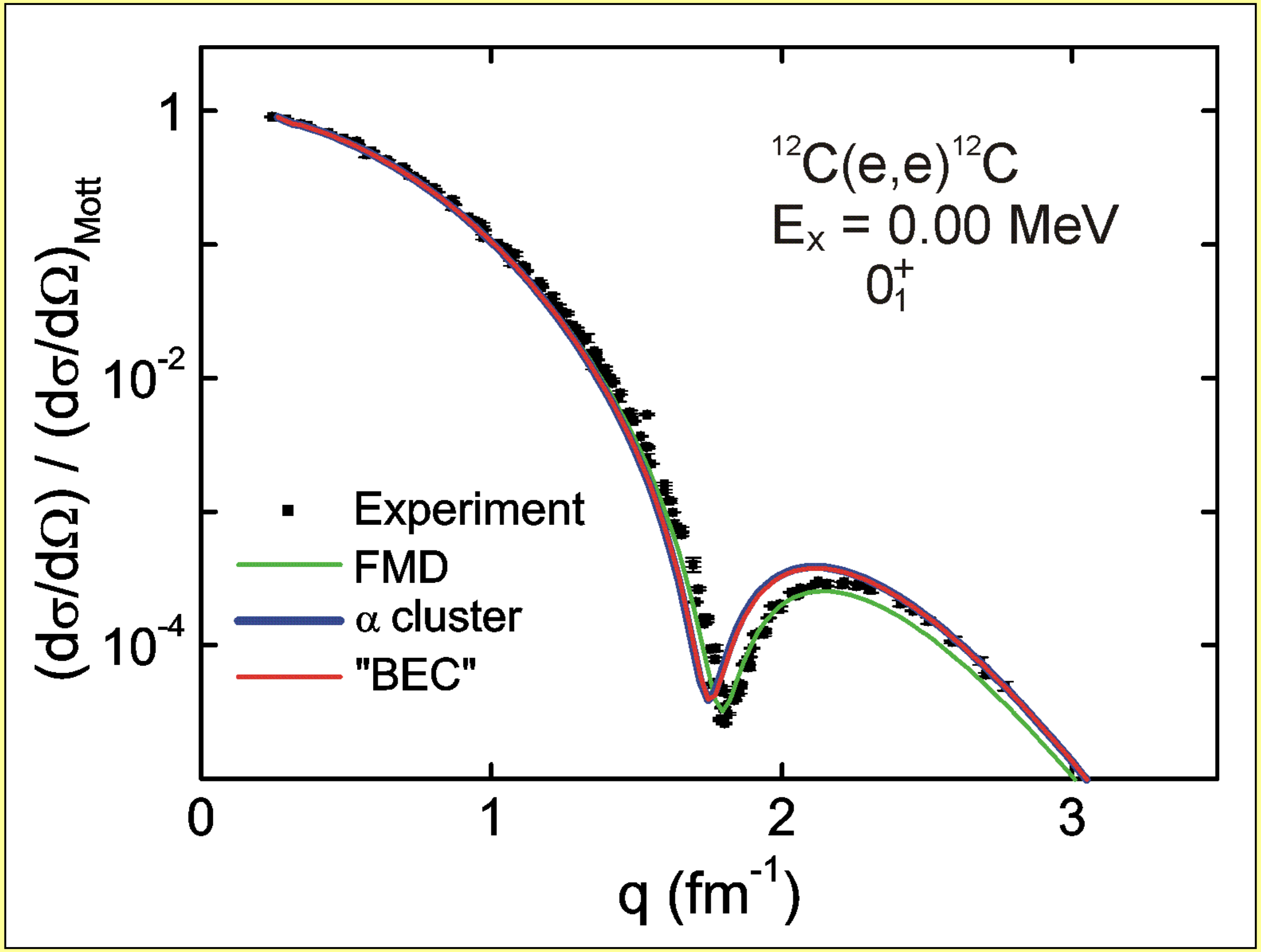


↕ • Transition density can be tested via transition form factor

FMD : R. Roth, T. Neff, H. Hergert, and H. Feldmeier, Nucl. Phys. **A745** (2004) 3

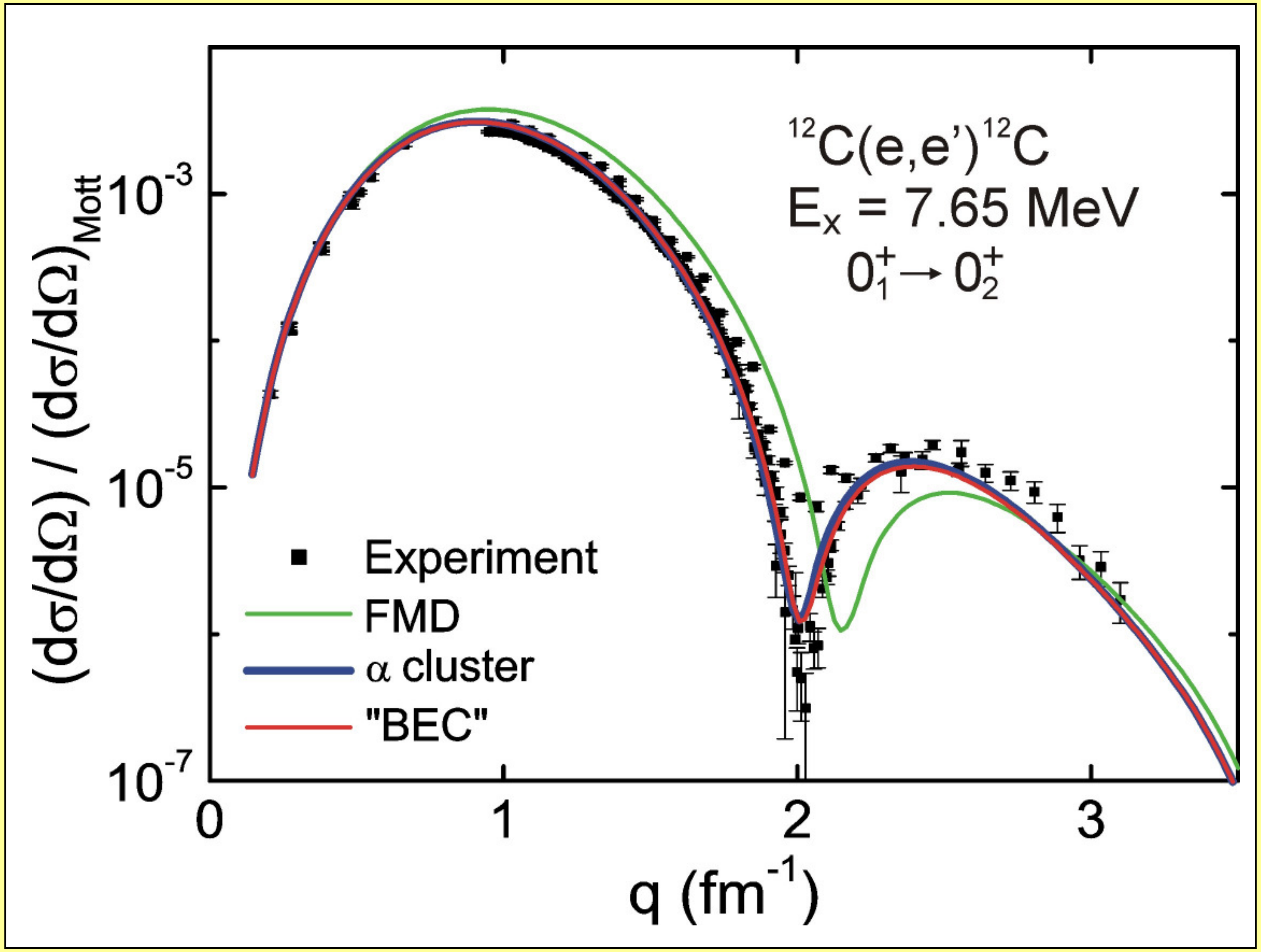
“BEC”: Y. Funaki *et al.*, Phys. Rev. C **67** (2003) 051306(R)

Elastic form factor



- Described well by FMD

Transition form factor to the Hoyle state

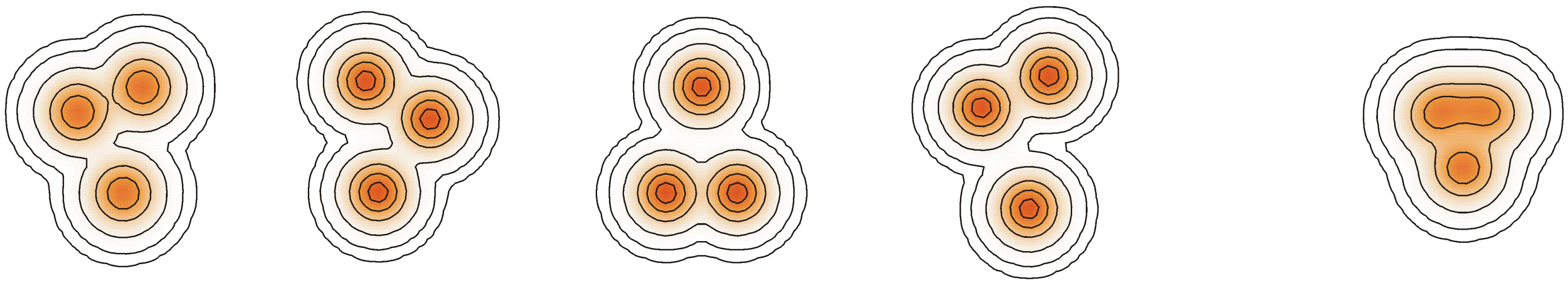


- H. Crannell, data compilation
- Described better by α-cluster models

What is actual structure of the Hoyle state ?

- In the "BEC" model the relative positions of α clusters should be uncorrelated

- Overlap with FMD basis states



$\vert\langle 1\vert 0^+_1\rangle\vert = 0.30$	$\vert\langle 2\vert 0^+_1\rangle\vert = 0.25$	$\vert\langle 3\vert 0^+_1\rangle\vert = 0.15$	$\vert\langle 4\vert 0^+_1\rangle\vert = 0.08$	$\vert\langle 5\vert 0^+_1\rangle\vert = 0.94$
$\vert\langle 1\vert 0^+_2\rangle\vert = 0.72$	$\vert\langle 2\vert 0^+_2\rangle\vert = 0.71$	$\vert\langle 3\vert 0^+_2\rangle\vert = 0.61$	$\vert\langle 4\vert 0^+_2\rangle\vert = 0.61$	$\vert\langle 5\vert 0^+_2\rangle\vert = 0.04$

- But in the FMD and α-cluster model the leading components of the Hoyle state are cluster-like and resemble ^{8}Be + ^{4}He configurations

Summary and outlook

- Summary
  - Γ_π for decay of the Hoyle state with uncertainty 2.5% extracted
  - Hoyle state is not a true Bose-Einstein condensate
  - ^{8}Be + α structure
- Outlook
  - Hoyle state: Fourier-Bessel analysis of all available data
  - ^{12}C: 0_3^+ and 2_2^+ states
  - ^{16}O: broad 0^+ state at 15 MeV