Electron Scattering on the Hoyle State and Carbon Production in Stars*

Maksym Chernykh
Institut für Kernphysik, TU Darmstadt

CGS-13
Cologne, 25 August 2008

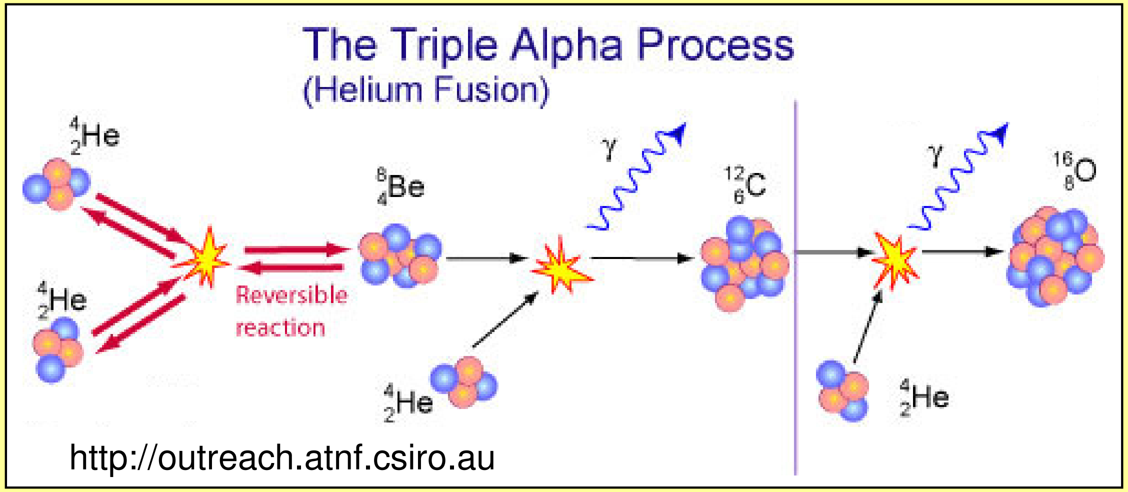
M. Chernykh, H.P. Blok, H. Feldmeier, T. Neff, P. von Neumann-Cosel, A. Richter

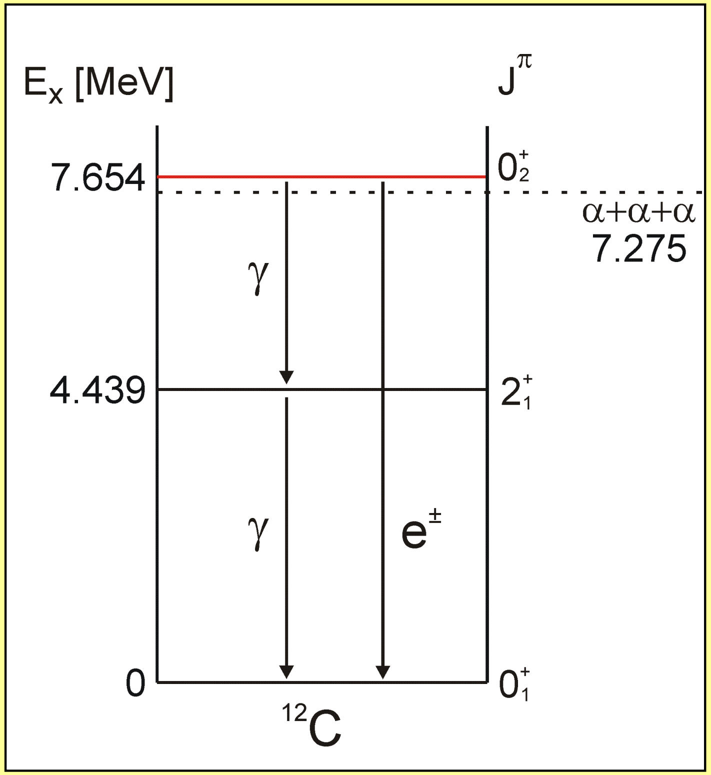
* Supported by DFG under contract SFB 634

Content

- Motivation
- Electron scattering on ^{12}C
- Analysis and results
- Summary

Astrophysical Importance of the Hoyle State





- Triple alpha reaction rate

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

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

(α,α´γγ)
(p,p´γγ)

(p,p´e^+e^-)

(e,e´) → ME → Γ_π

- Reaction rate with accuracy ±6% needed

S.M. Austin, NPA 758 (2005) 375c

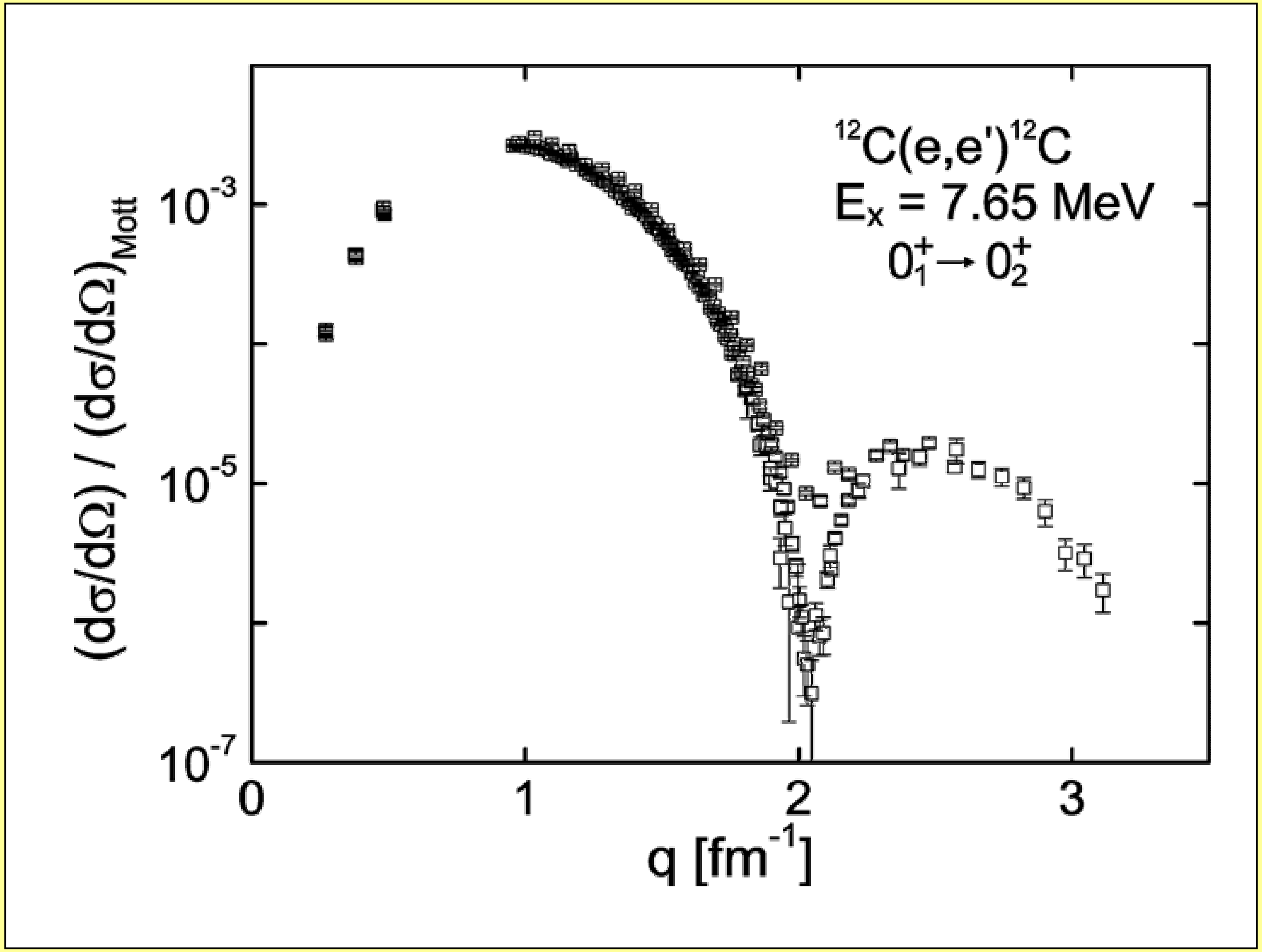
Uncertainties of the Astrophysical Relevant Quantities

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

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 $\Delta r_{3\alpha}/r_{3\alpha} = \pm 11.6\%$ presently

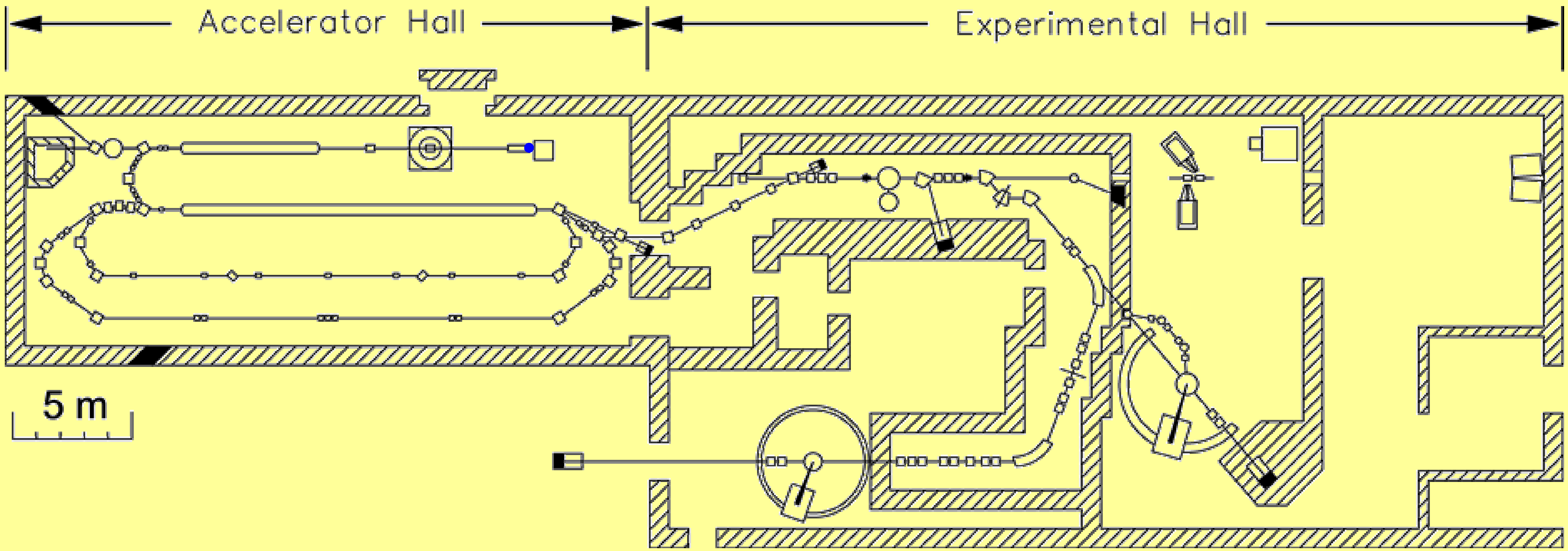
Transition Form Factor to the Hoyle State



- Extrapolation to zero momentum transfer
- Fourier-Bessel analysis

H. Crannell, data compilation (2005)

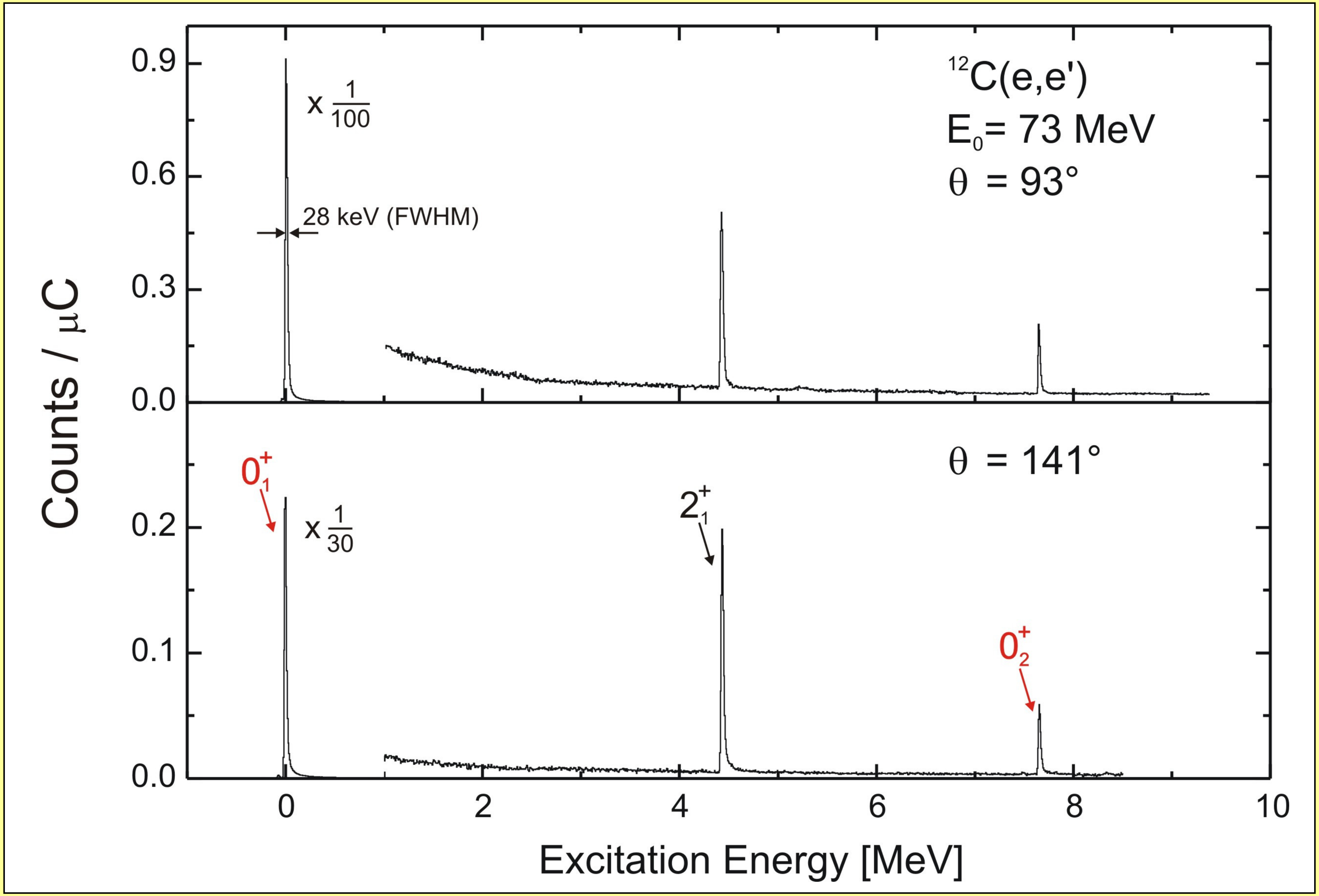
Experiment at the S-DALINAC



- E_0 = 29.3 – 78.3 MeV
- θ = 69° – 141°
- q = 0.2 – 0.7 fm^{-1}
- ΔE = 28 keV (FWHM)

Lintott Spectrometer

Measured Spectra



Model-independent PWBA Analysis

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

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

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

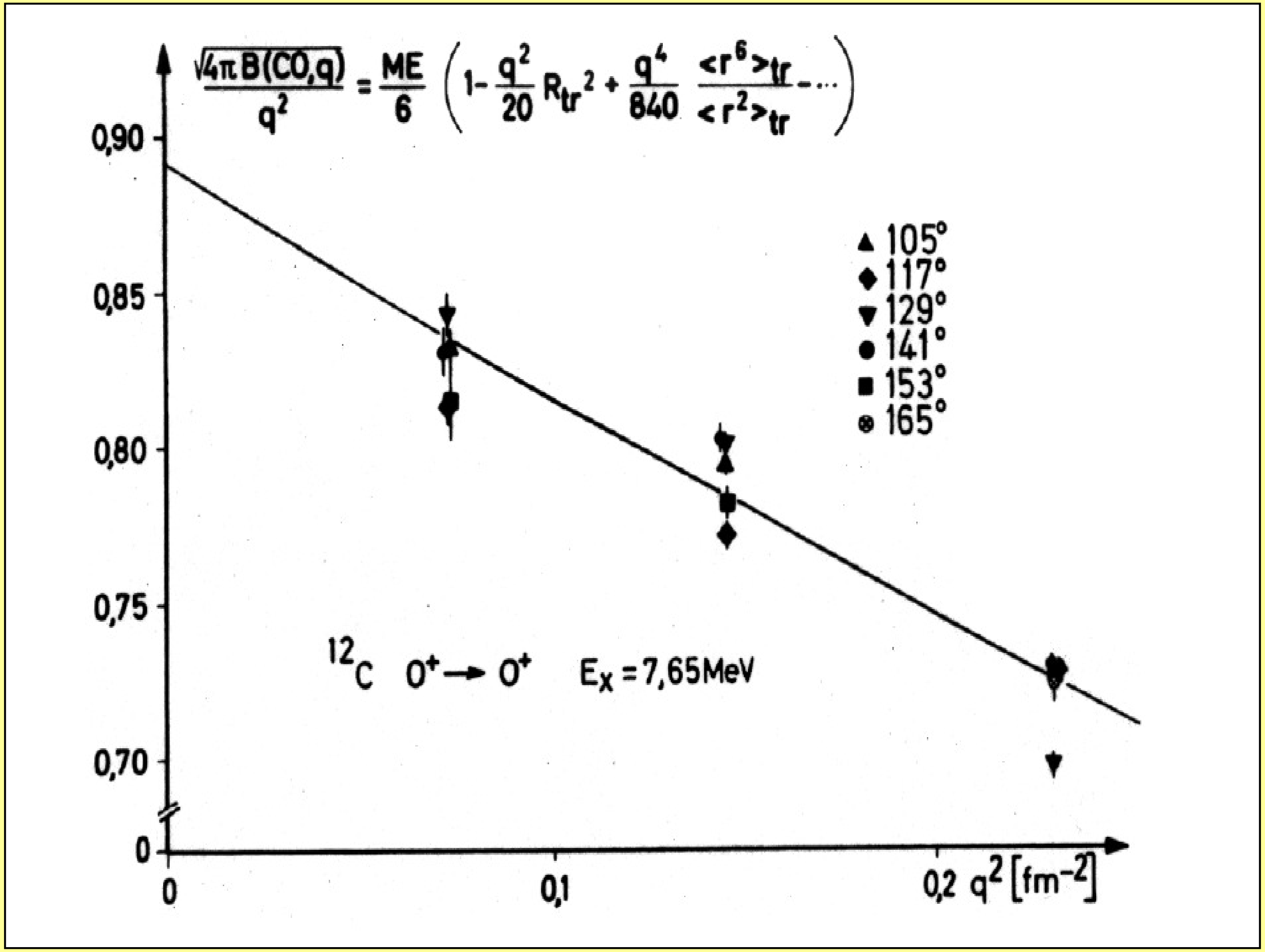
$$ME = \langle r^2\rangle_{tr}\,, \qquad R_{tr}^2 = \frac{\langle r^4\rangle_{tr}}{\langle r^2\rangle_{tr}}$$

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

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

- Model-independent extraction of the partial pair width Γ_π

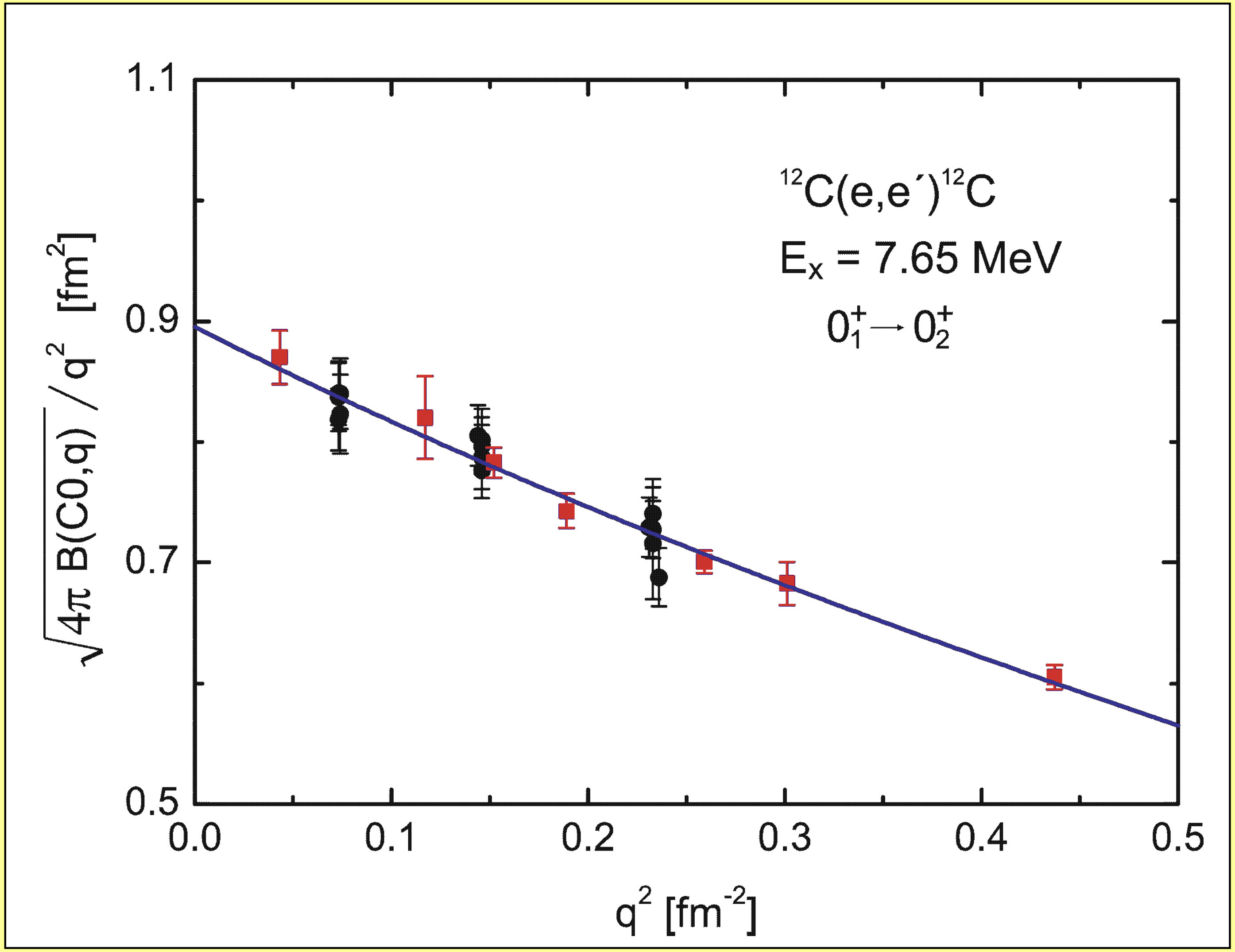
Model-independent PWBA Analysis



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

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

Model-independent PWBA Analysis



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

- *ME* = 5.37(7) fm², R_{tr} = 4.30(12) fm

Fourier-Bessel Analysis

- Transition form factor is the Fourier-Bessel transform of the transition charge density

$$F(q) = 4\pi \int_0^\infty \rho_{tr}(r)\, j_0(qr)\, r^2\, dr$$

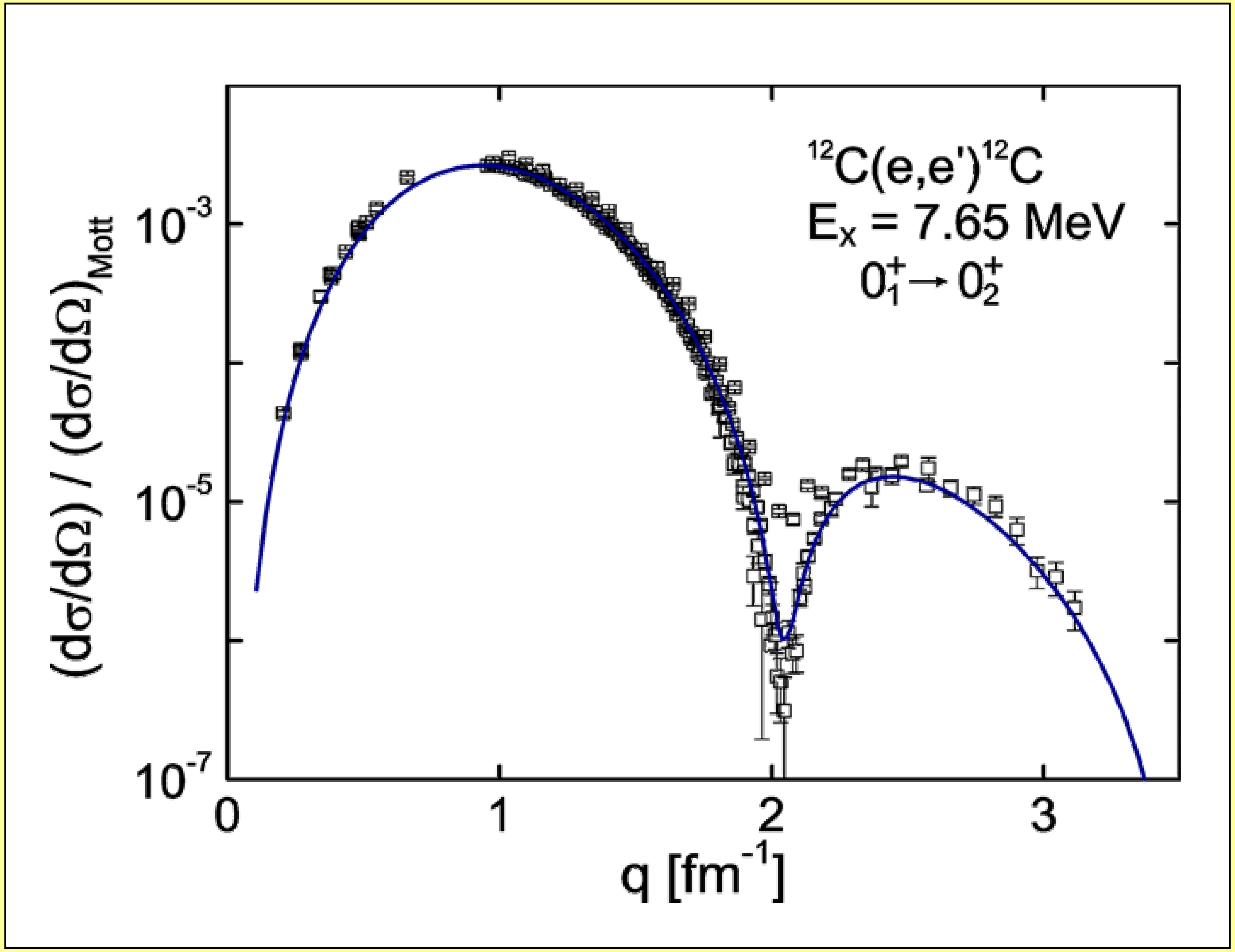
$$\rho_{tr}(r) = \begin{cases} \sum\limits_{\mu=1}^{\infty} a_\mu\, j_0(q_\mu r) & \text{for } r < R_c \\ 0 & \text{for } r \geq R_c \end{cases}$$

with

$$q_\mu = \frac{\mu\pi}{R_c}$$

- Data should be measured over a broad momentum transfer range

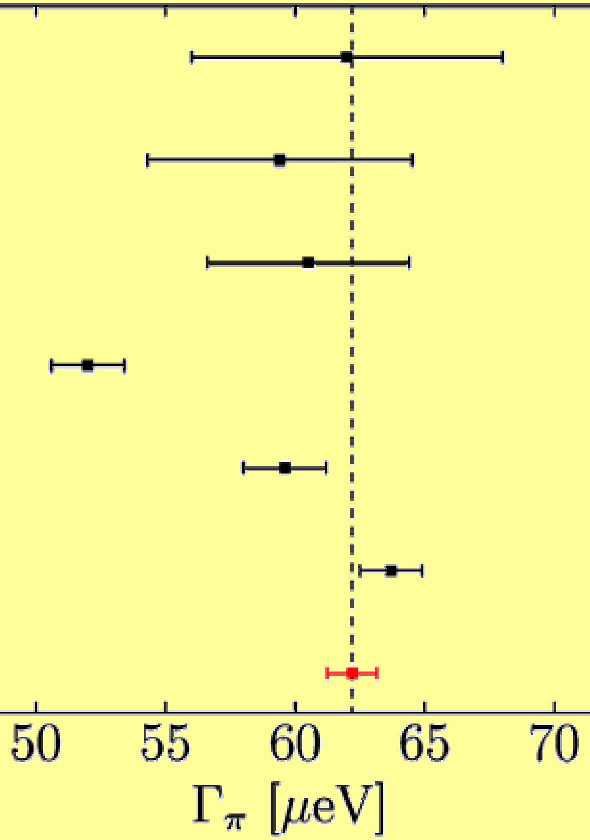
Fourier-Bessel Analysis



- $q = 0.2 – 3.1\ fm^{-1}$
- $ME = 5.55(5)\ fm^2$

Results

Year	Analysis	Pair width	Ref.
1967	PWBA		Crannell *et al.*
1970	PWBA		Strehl
1970	Old average		Ajzenberg-Selove
2005	Fourier-Bessel		Crannell *et al.*
2008	PWBA		Present work
2008	Fourier-Bessel		Present work
2008	New average		Present work

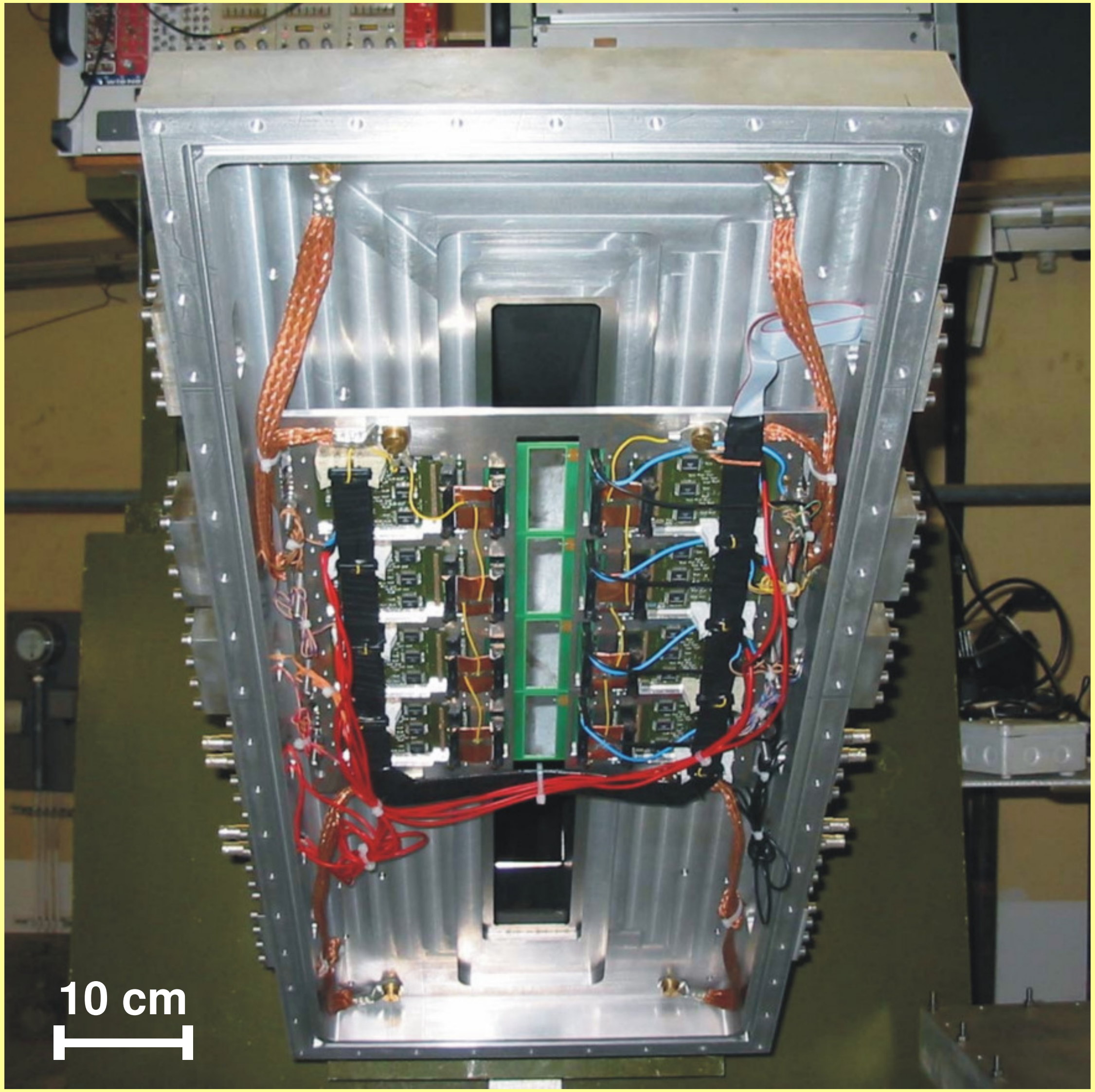


- $\Gamma_\pi = 62.2(10) \times 10^{-6}\,\mathrm{eV}$
- Total uncertainty $\Delta r_{3\alpha}/r_{3\alpha} = \pm 10\%$
- Only Γ_π/Γ needs still to be improved now

Summary

- Hoyle state is very important in astrophysics
- High-resolution electron scattering measurements have been performed
- Monopole matrix element has been determined by low-q extrapolation and Fourier-Bessel analysis
- Pair width Γ_{π} for decay of the Hoyle state with uncertainty 1.6% has been extracted

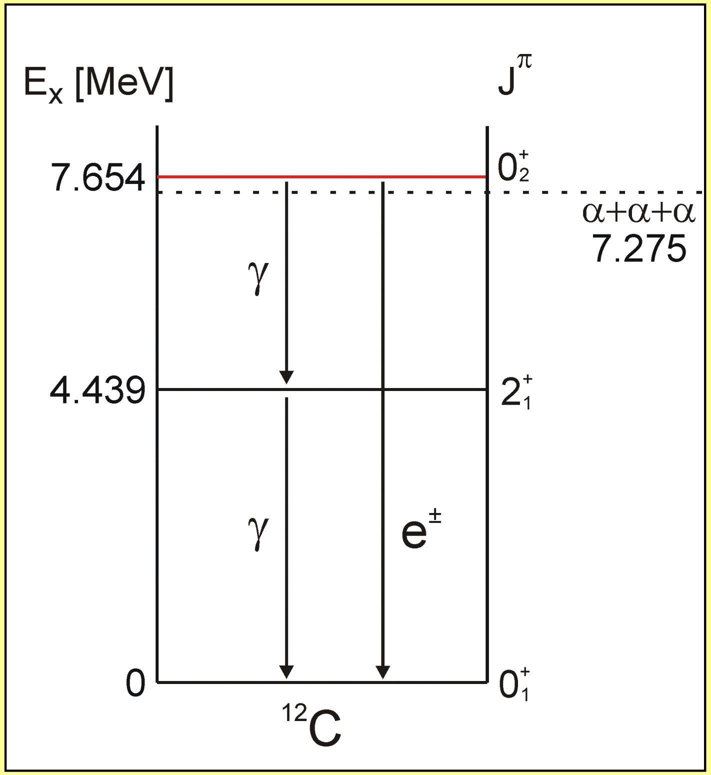
Detector System



- 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}

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