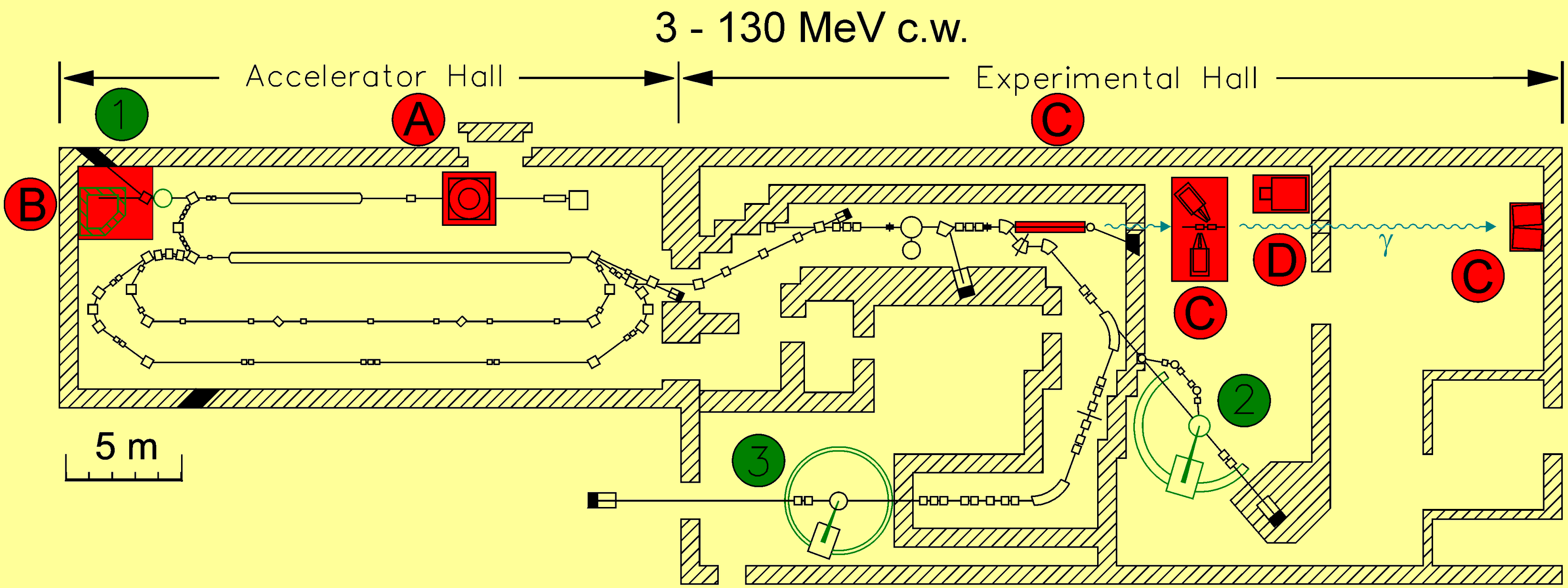
Few-Body Experiments at the S-DALINAC

- S-DALINAC and research program – an overview
- Selected examples:
  - charge radius of the proton remeasured with a new technique
  - deuteron electrodisintegration and its importance for the primordial nucleosynthesis of the lightest nuclei
  - electron scattering on the Hoyle state in ^{12}C and the triple-alpha process

Supported by the DFG within SFB 634

Experiments at the S-DALINAC

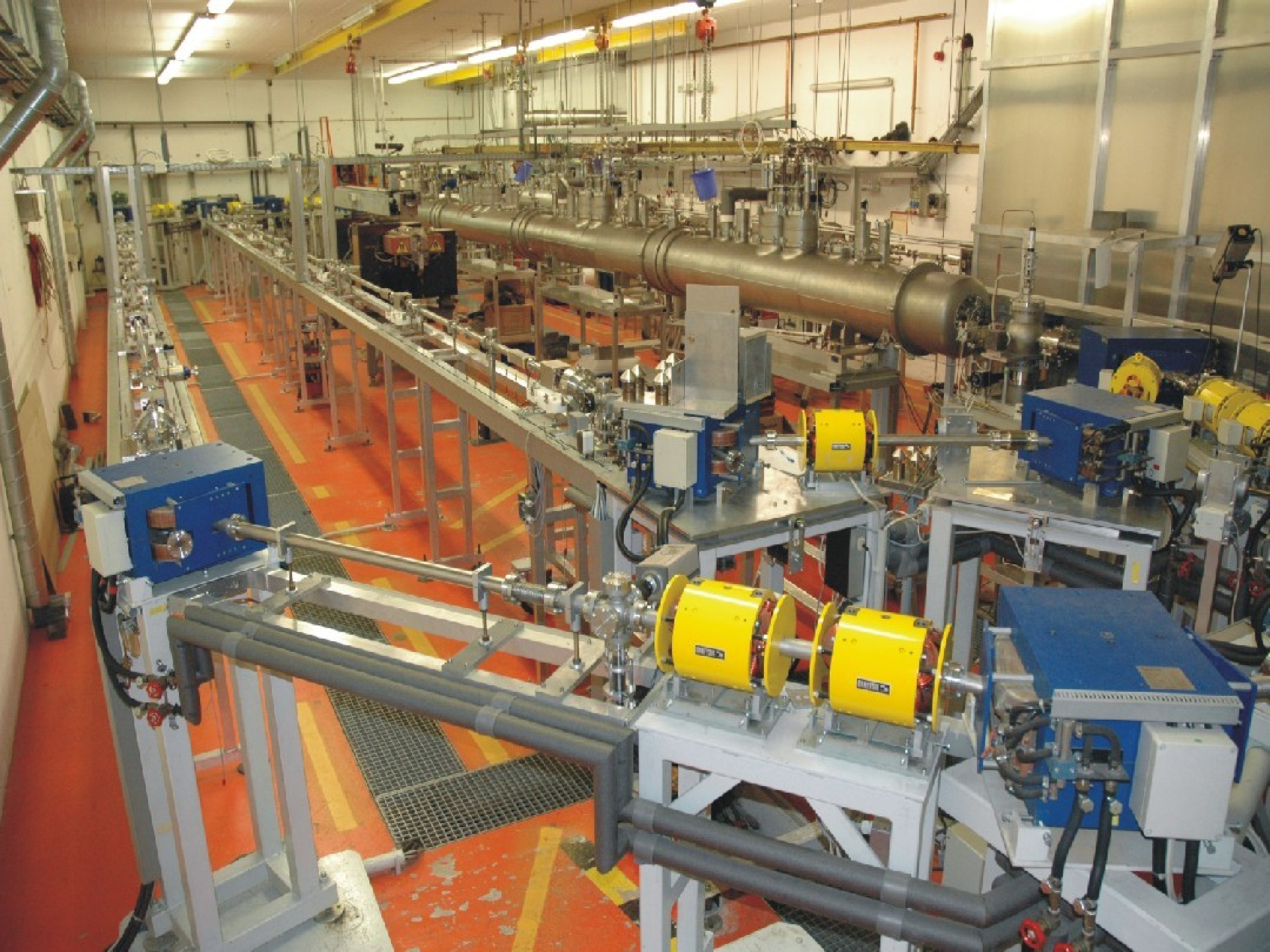


Status

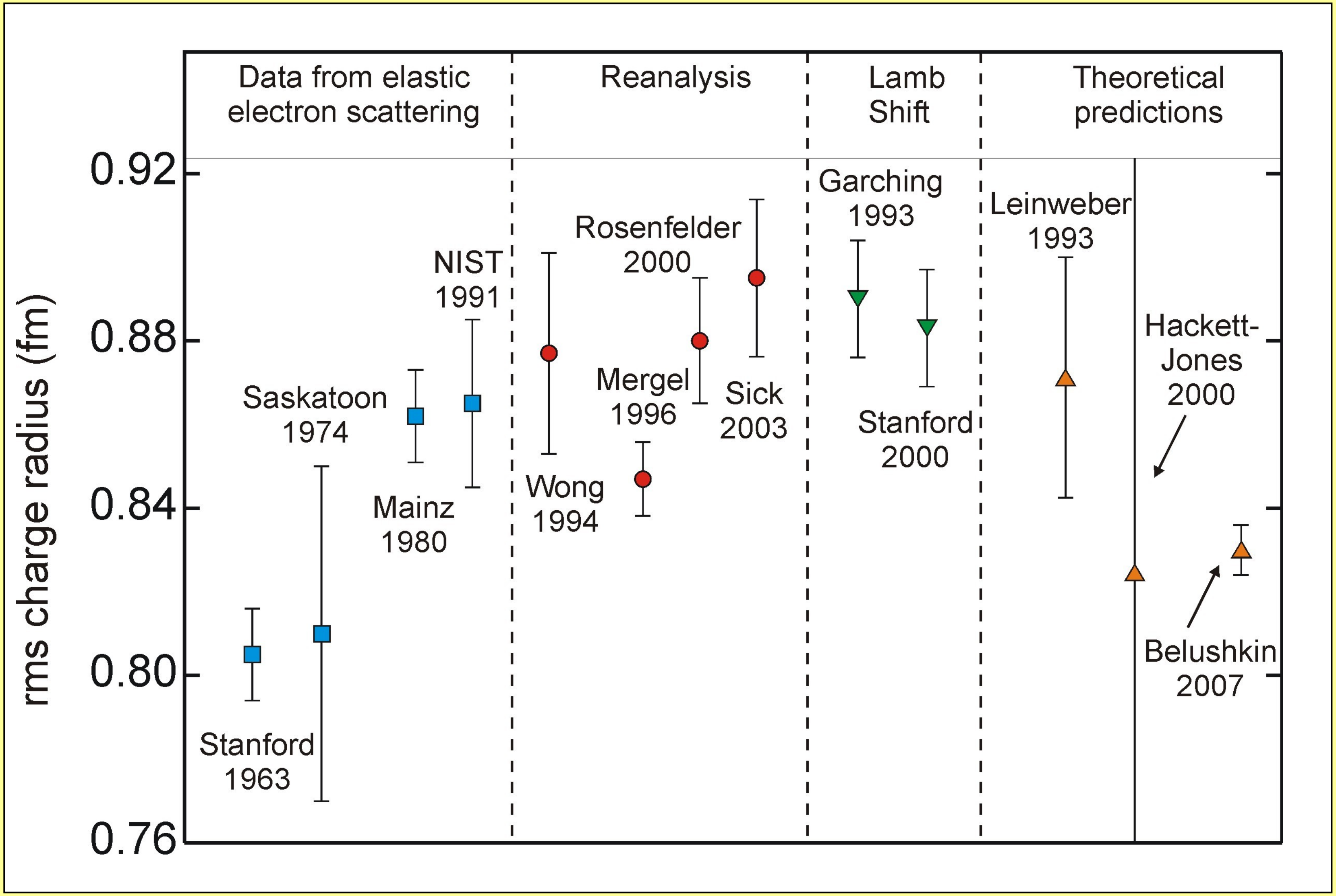
1. Nuclear resonance fluorescence
2. (e,e´) and 180° experiments
3. High-resolution (e,e´) experiments

SFB

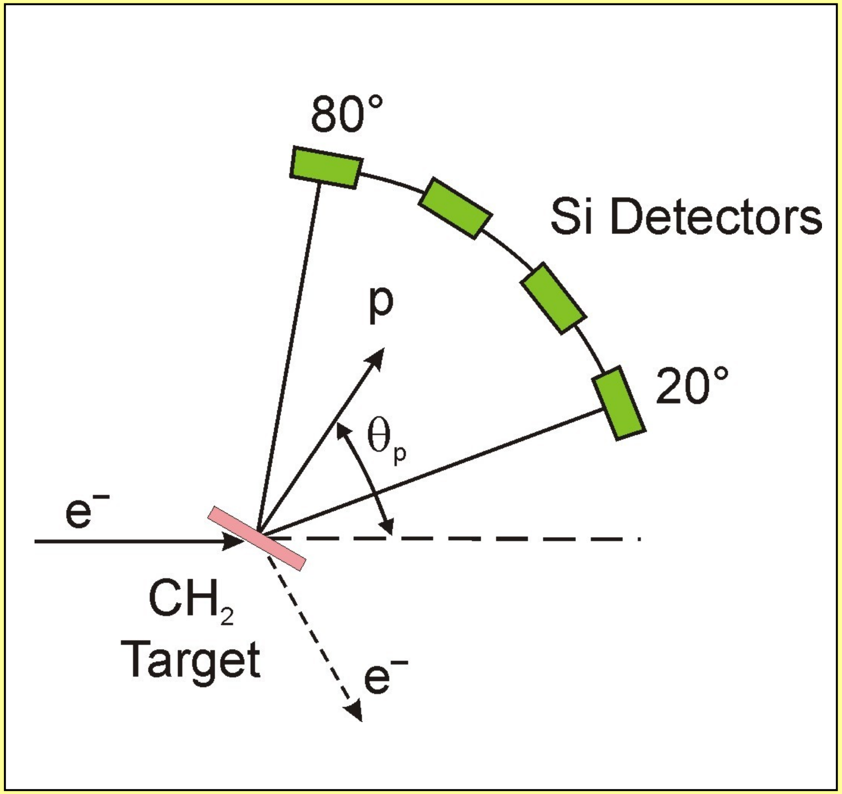
A. Polarized electron source
B. 14 MeV bremsstrahlung
C. 100 MeV bremsstrahlung for polarizability of the nucleon
D. Photon tagger



Proton Charge Radius: Results and Predictions

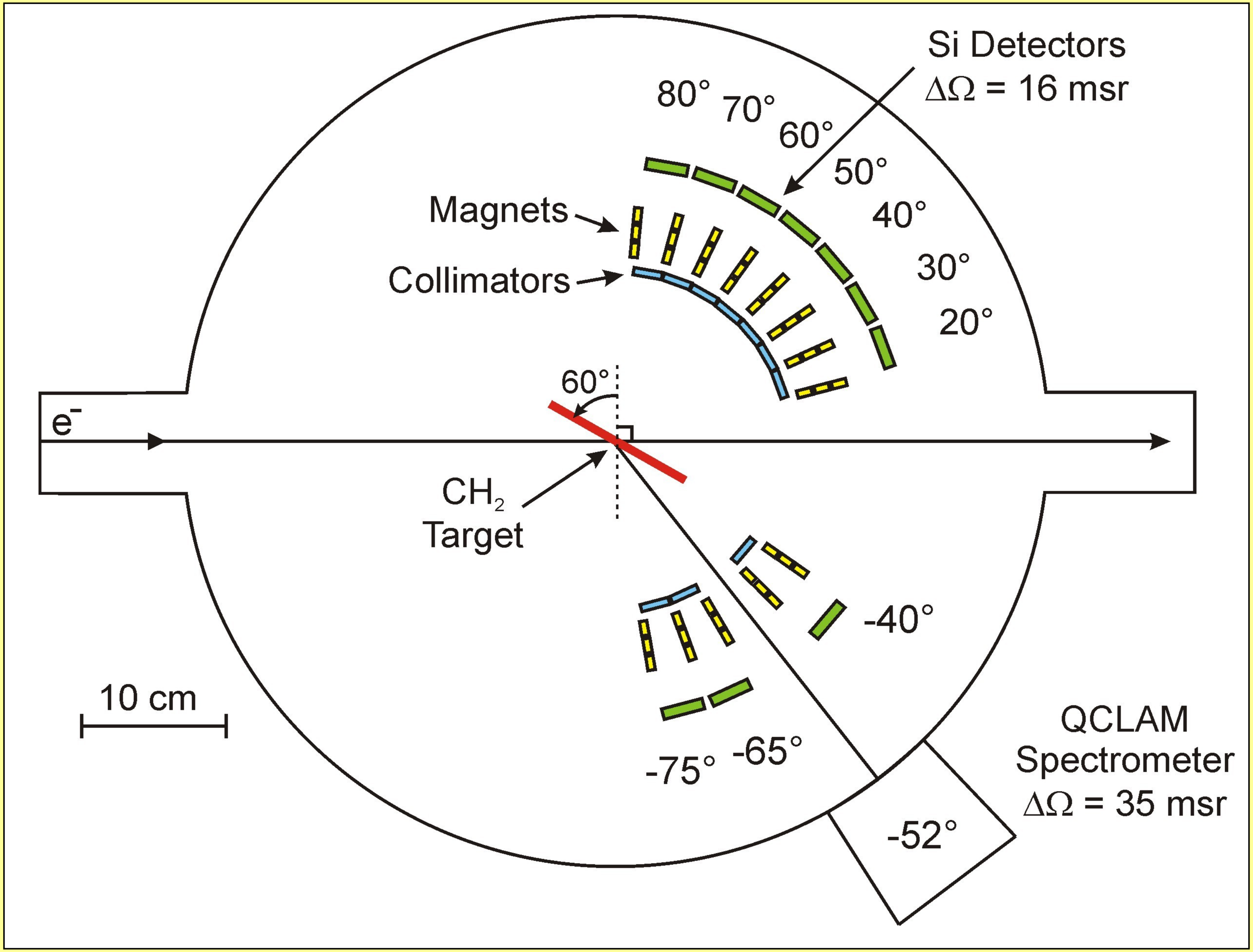


New Idea: Detect Protons rather than Electrons

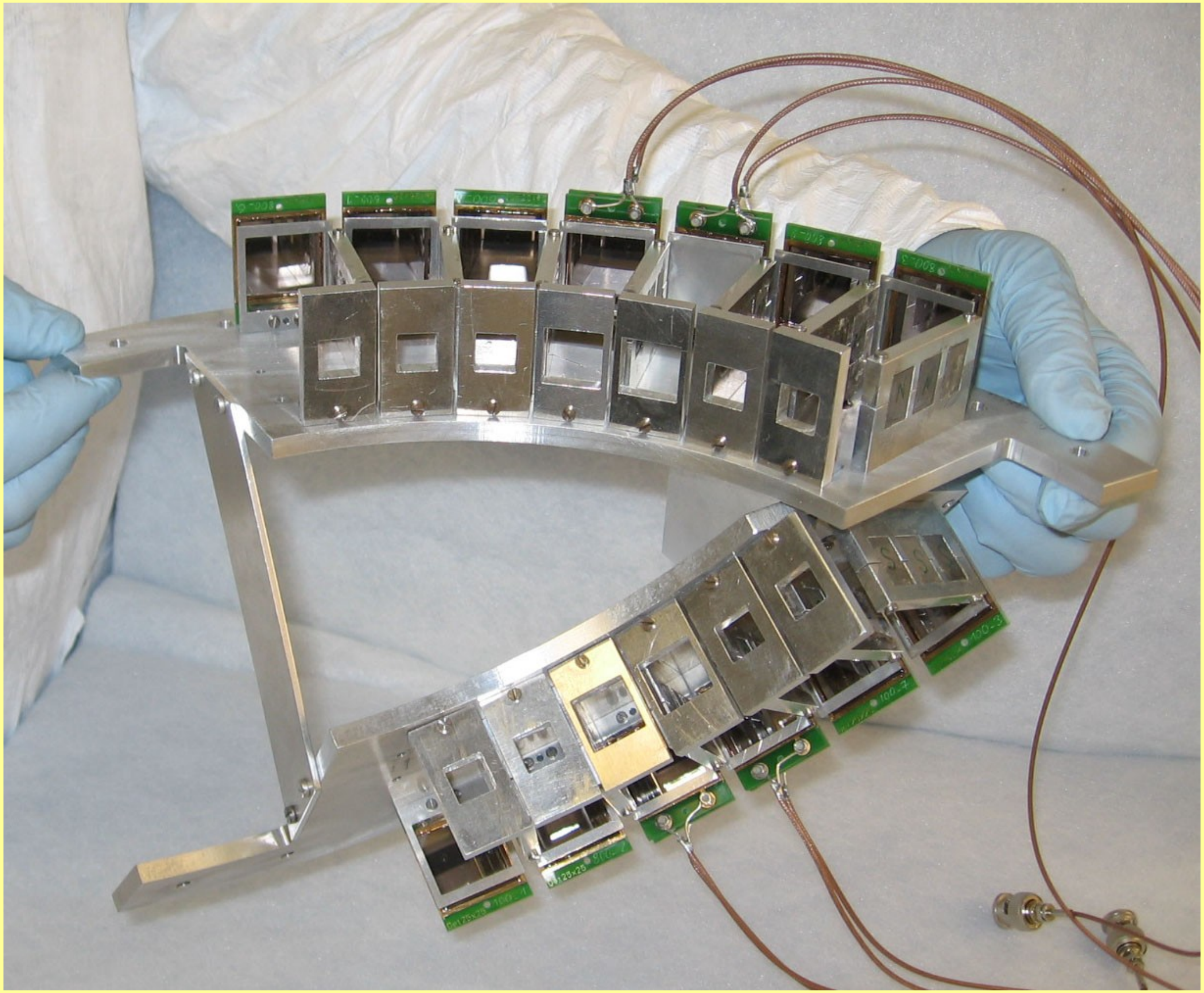


- simultaneous measurement of complete angular distribution
- avoids normalization problems
- well defined detection efficiency

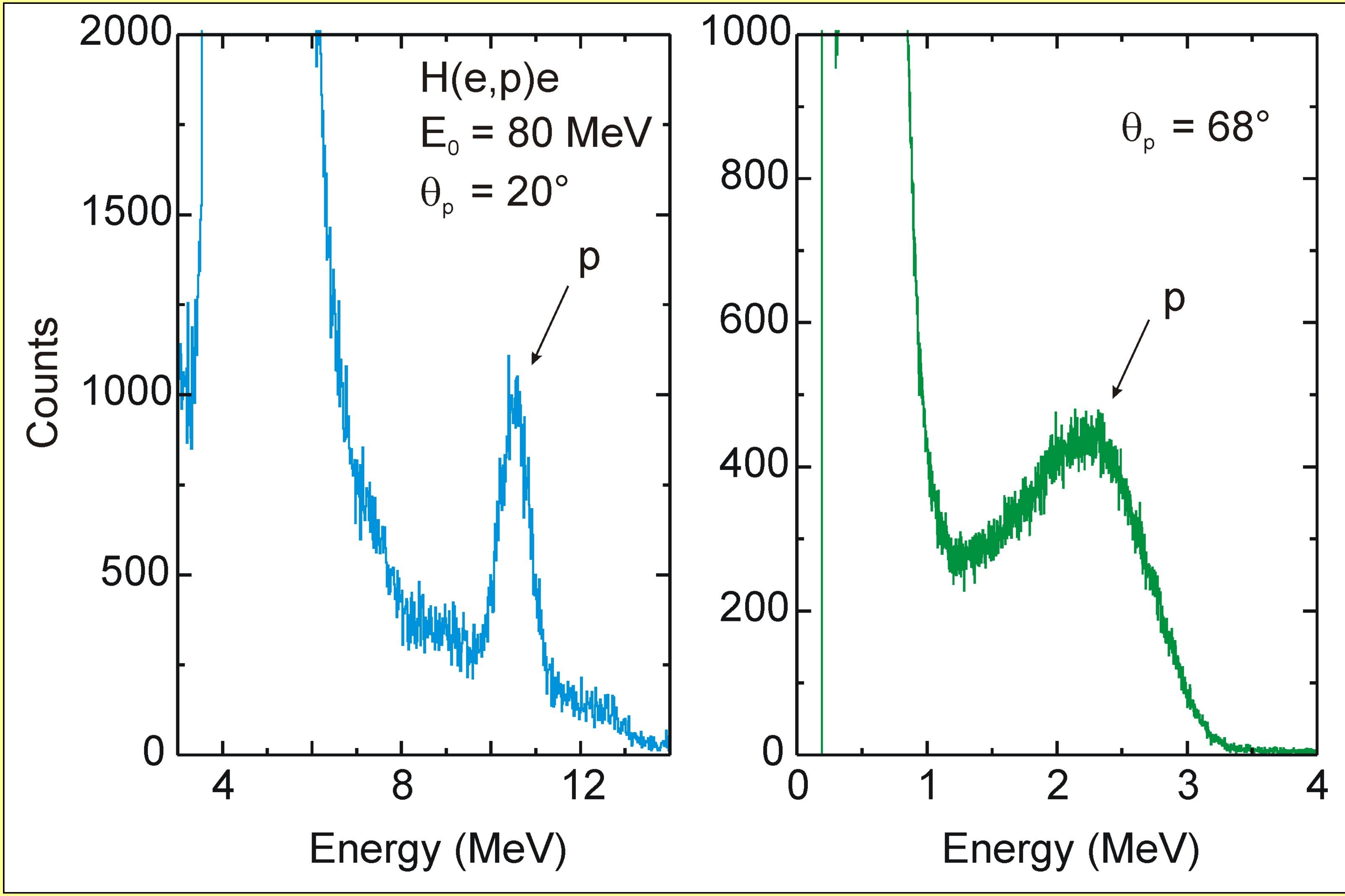
Scheme of Experimental Setup



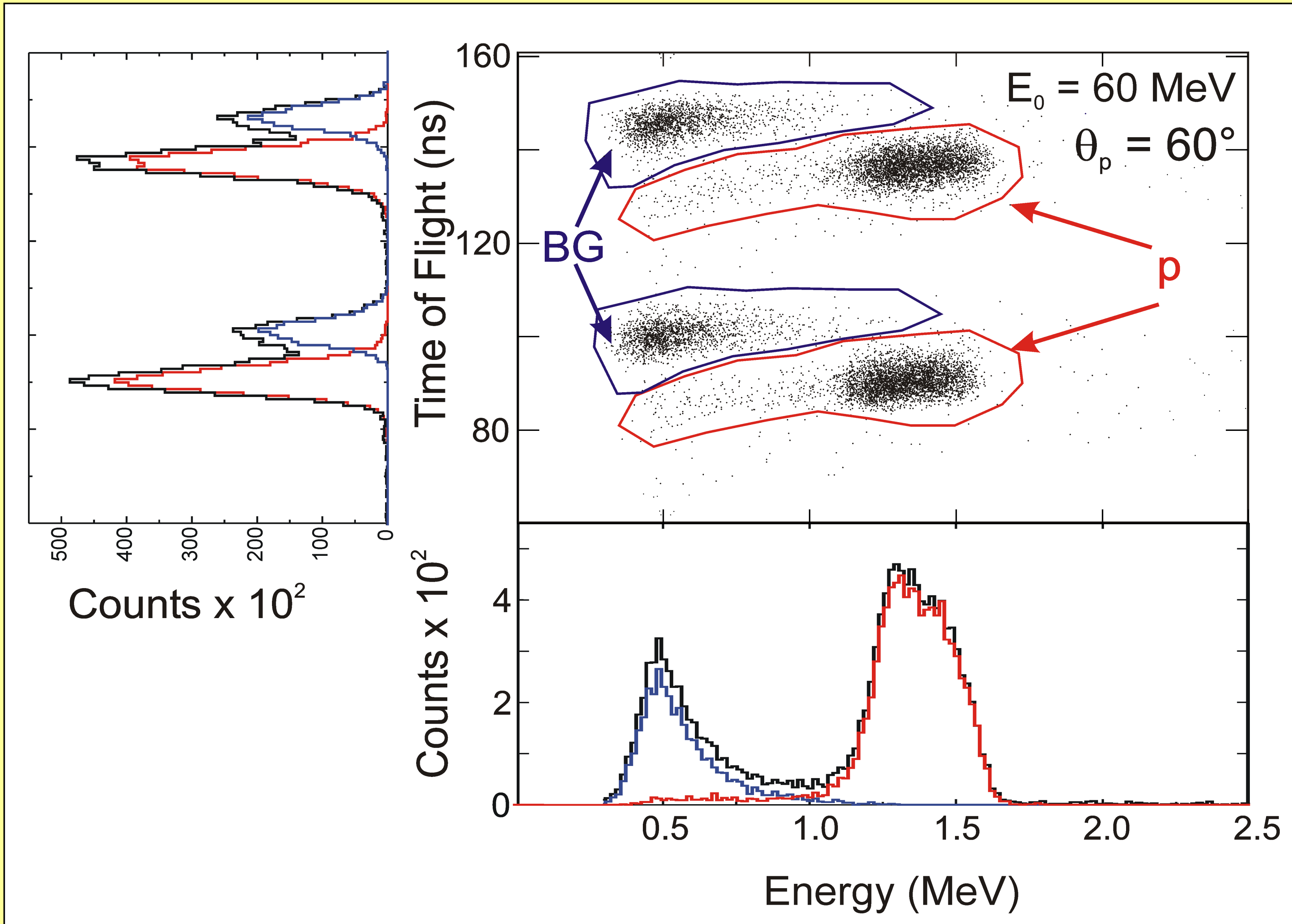
Experimental Setup



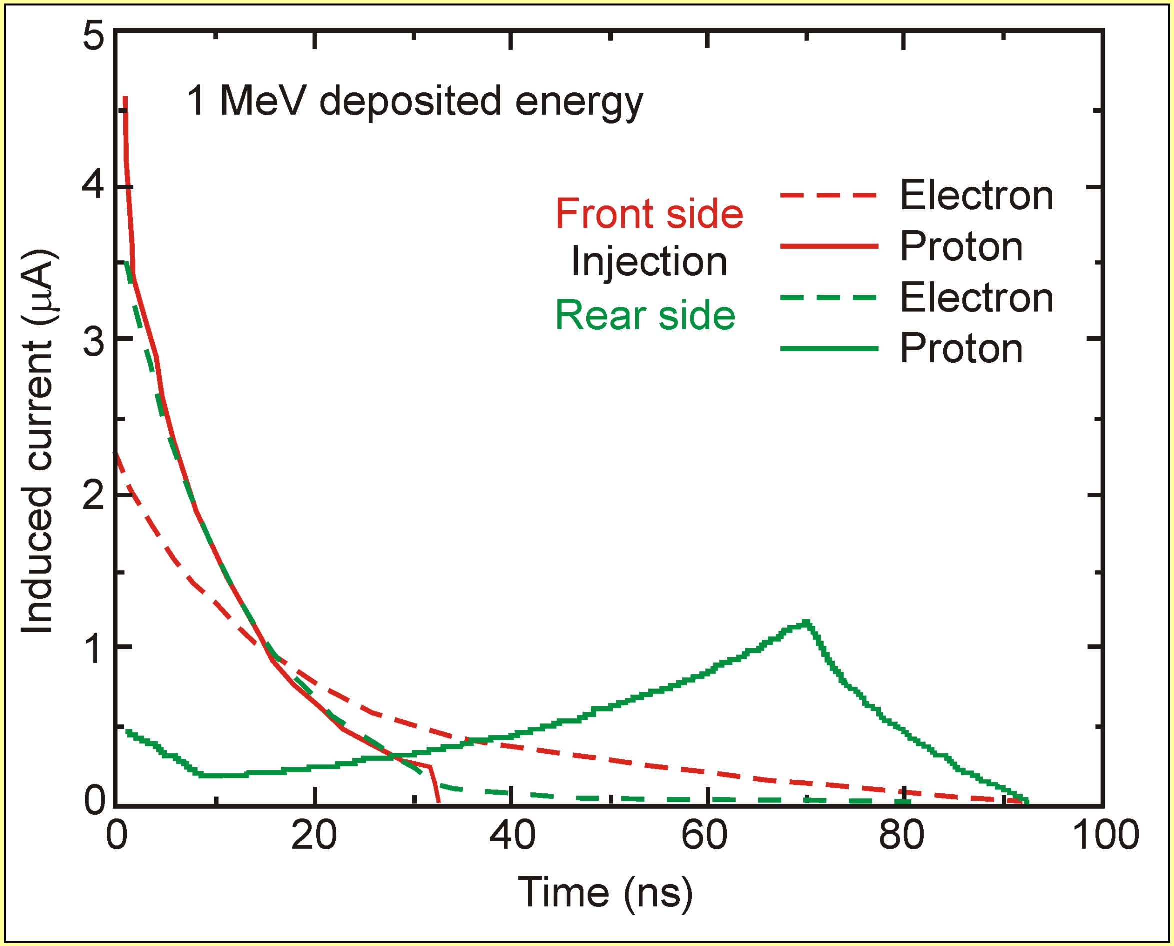
Measured Spectra



Background Suppression by Time-of-Flight



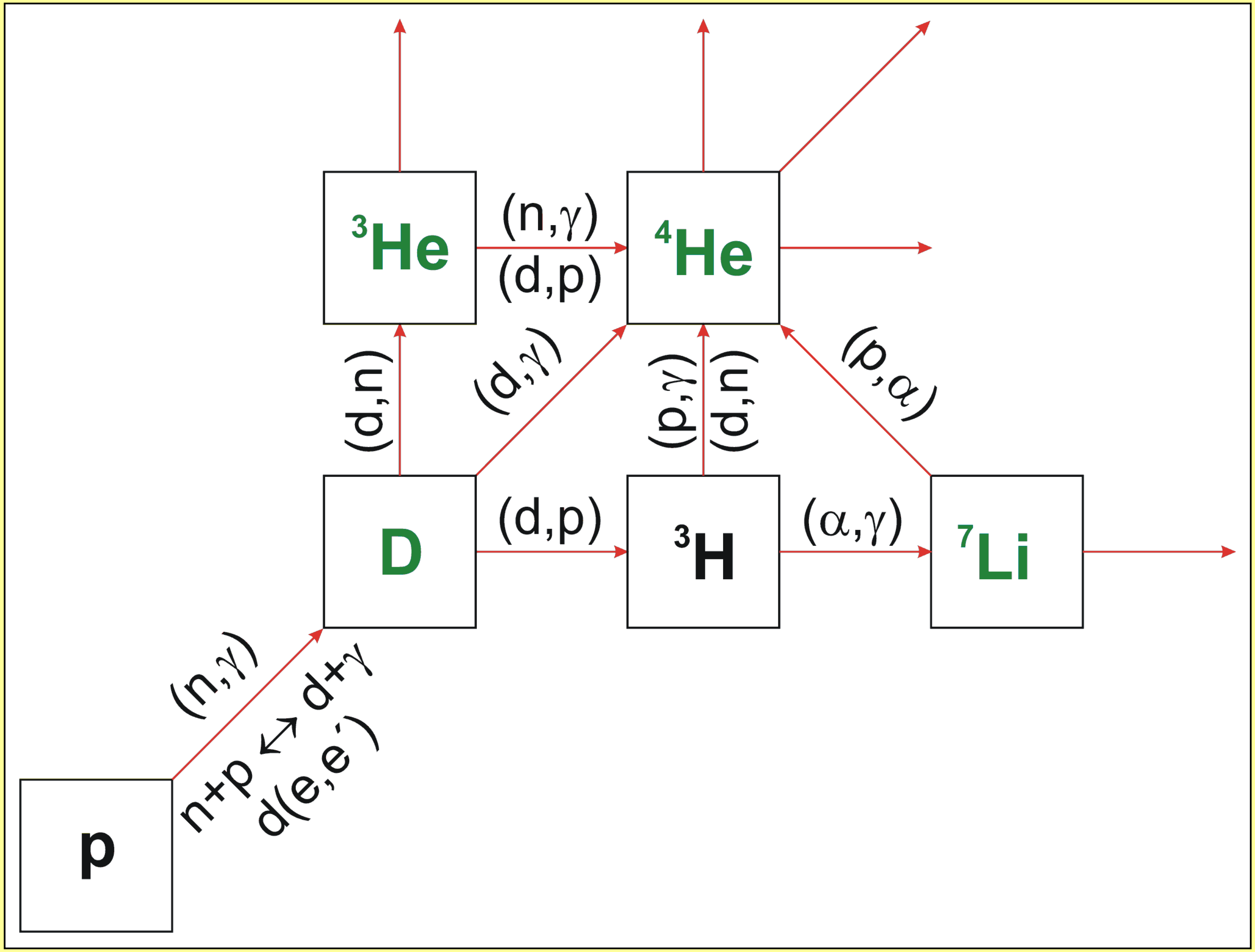
Pulse Shape Discrimination



- Reverse mounting of forward detectors

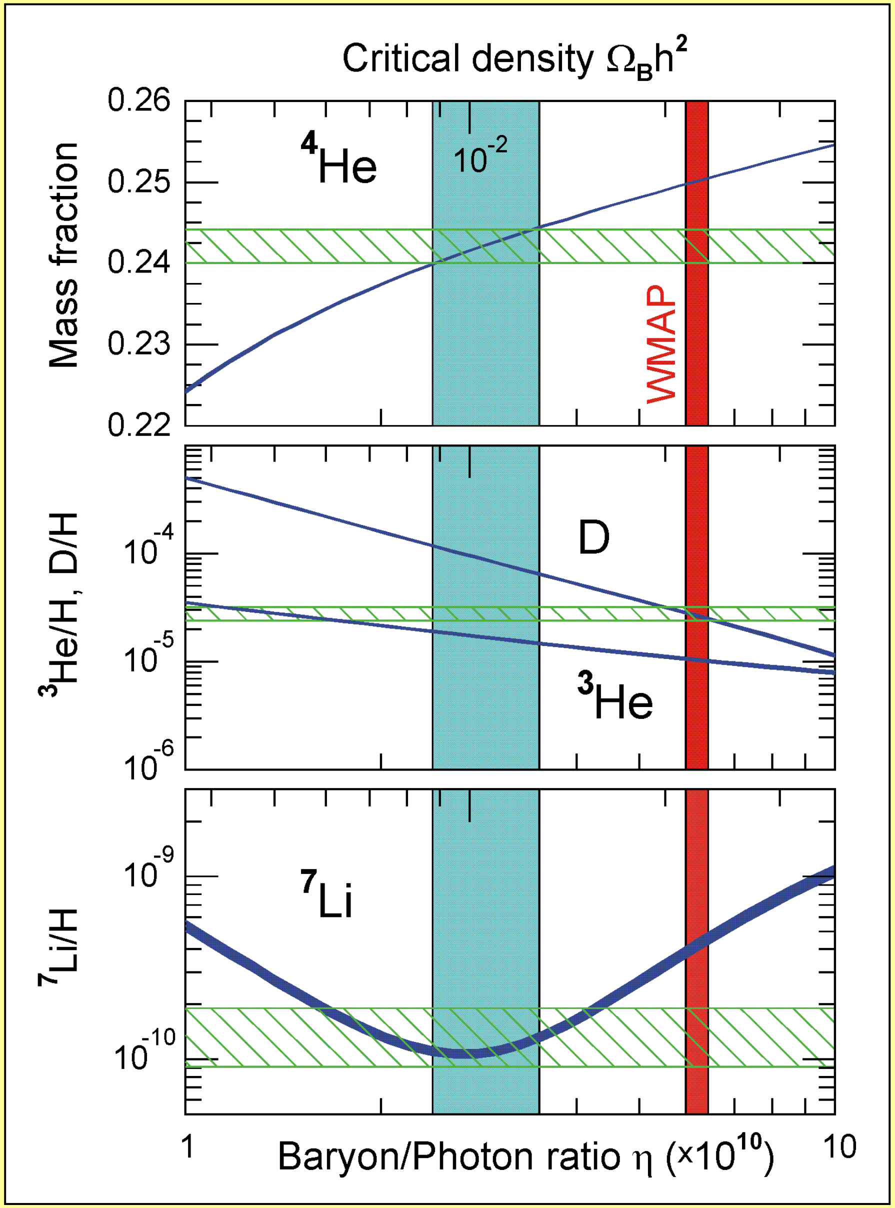
A. Fazzi et al., IEEE Trans. Nucl. Sci. 51, 1049 (2004)

Primordial Nucleosynthesis



- D, ^{3}He, ^{4}He, ^{7}Li are synthesized

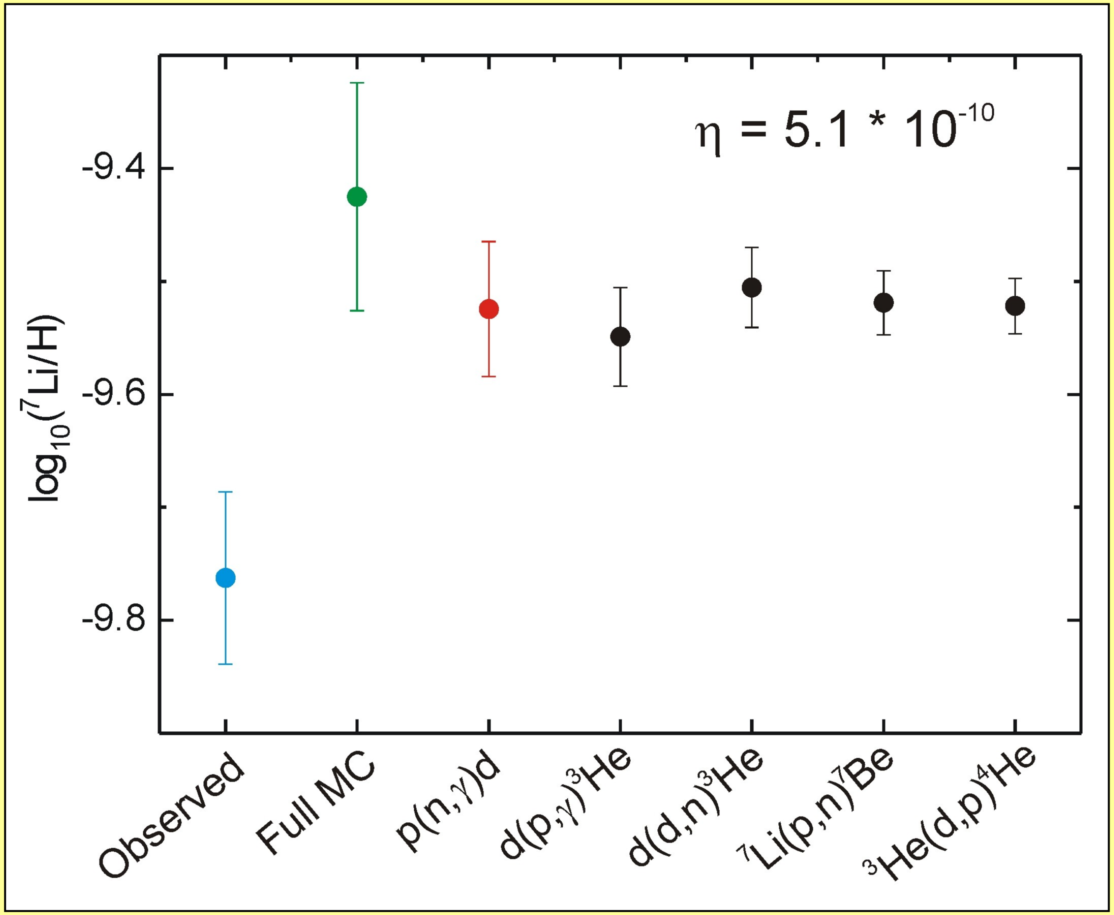
Test of Cosmological Standard Model



- Abundances depend on baryon/photon ratio (baryon density)
- Observational constraints: WMAP disagrees with spectroscopic information and/or BBN

Adopted from A. Coc et al., Astroph. J. 600, 544 (2004)

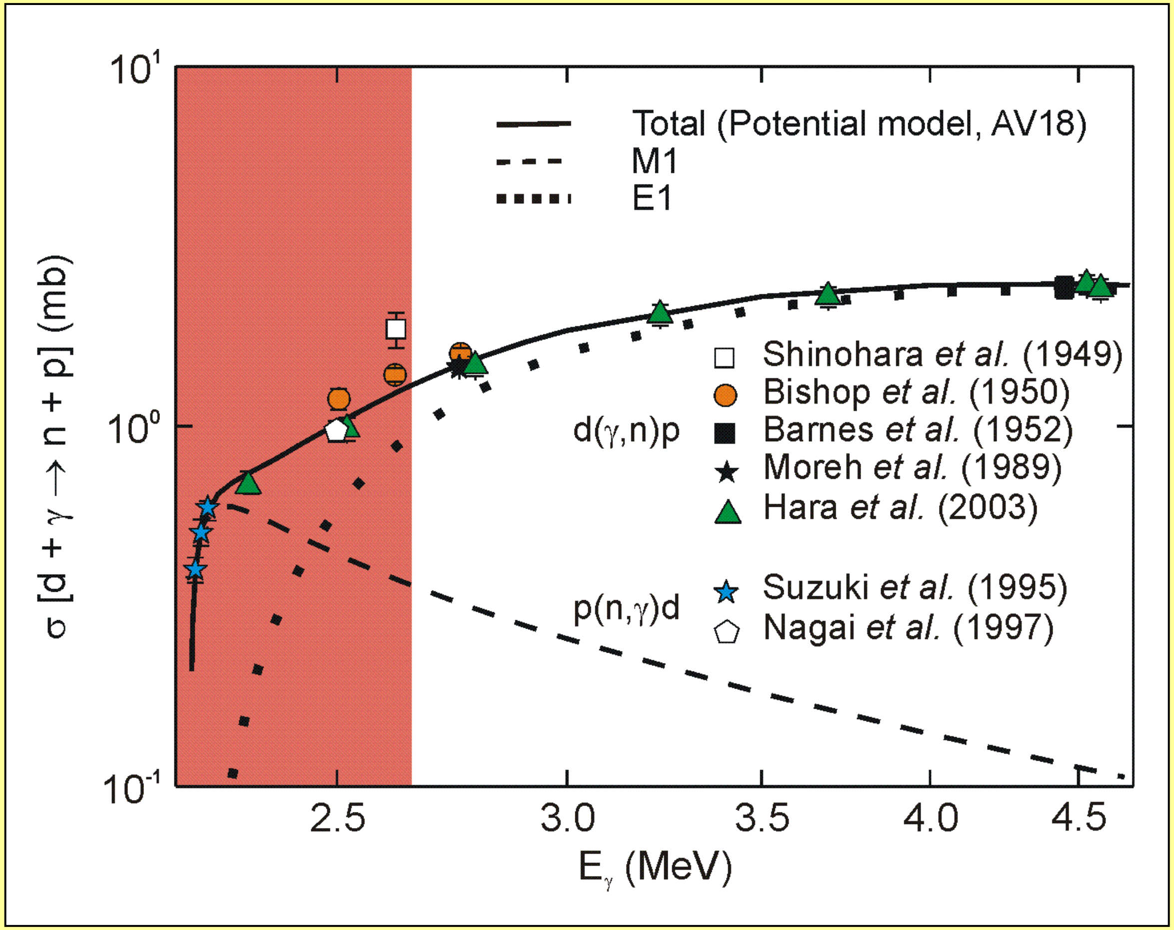
Uncertainty of ^{7}Li Abundance



- Largest uncertainty from *p(n,γ)d* reaction
- Relevant energy window 15 - 200 keV above threshold

S. Burles et al., Phys. Rev. Lett. 82, 4176 (1999)

$d(\gamma,n)p$: Data and Predictions

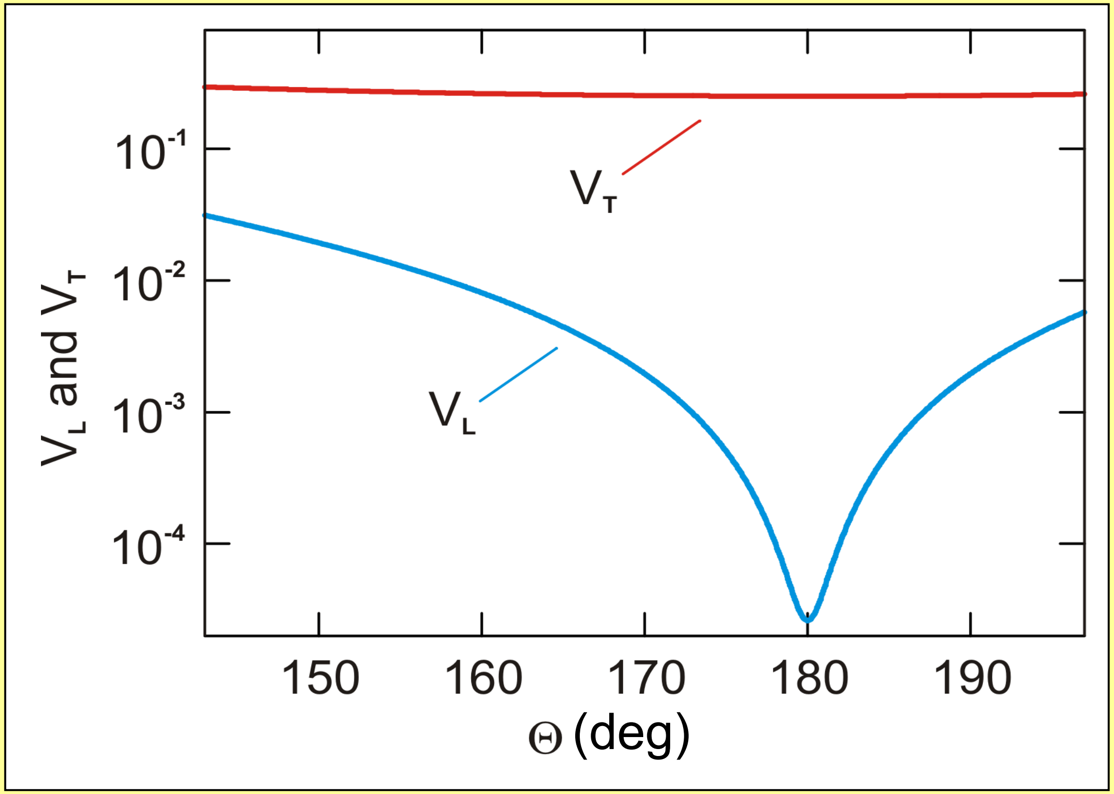


- Potential model (AV18) calculations by H. Arenhövel
- EFT calculations (J.-W. Chen and M.J. Savage, S. Ando et al.) are very similar
- Scarce and scattering data close to the threshold
- M1 dominates → D(e,e´) at 180°

Why Electron Scattering under 180°?

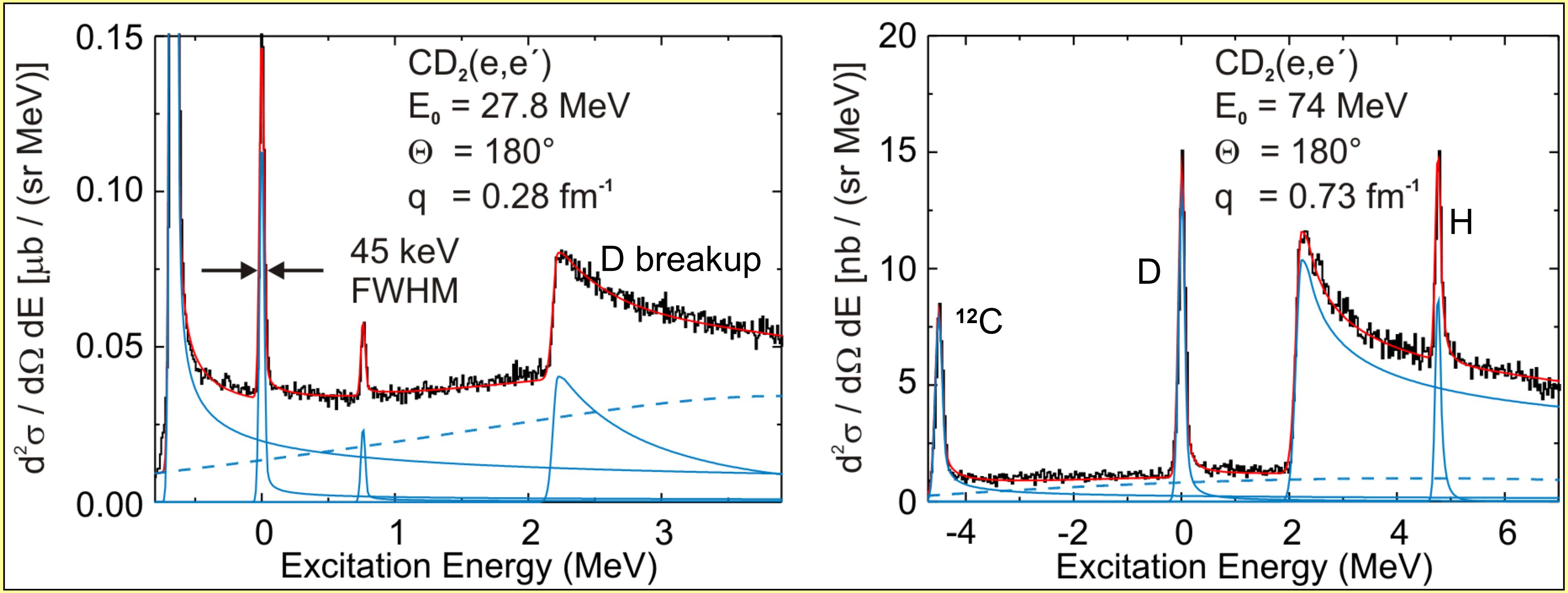
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_L + \left(\frac{d\sigma}{d\Omega}\right)_T$$

$$V_L \times |F_L(q)|^2 \qquad\qquad V_T \times |F_T(q)|^2$$



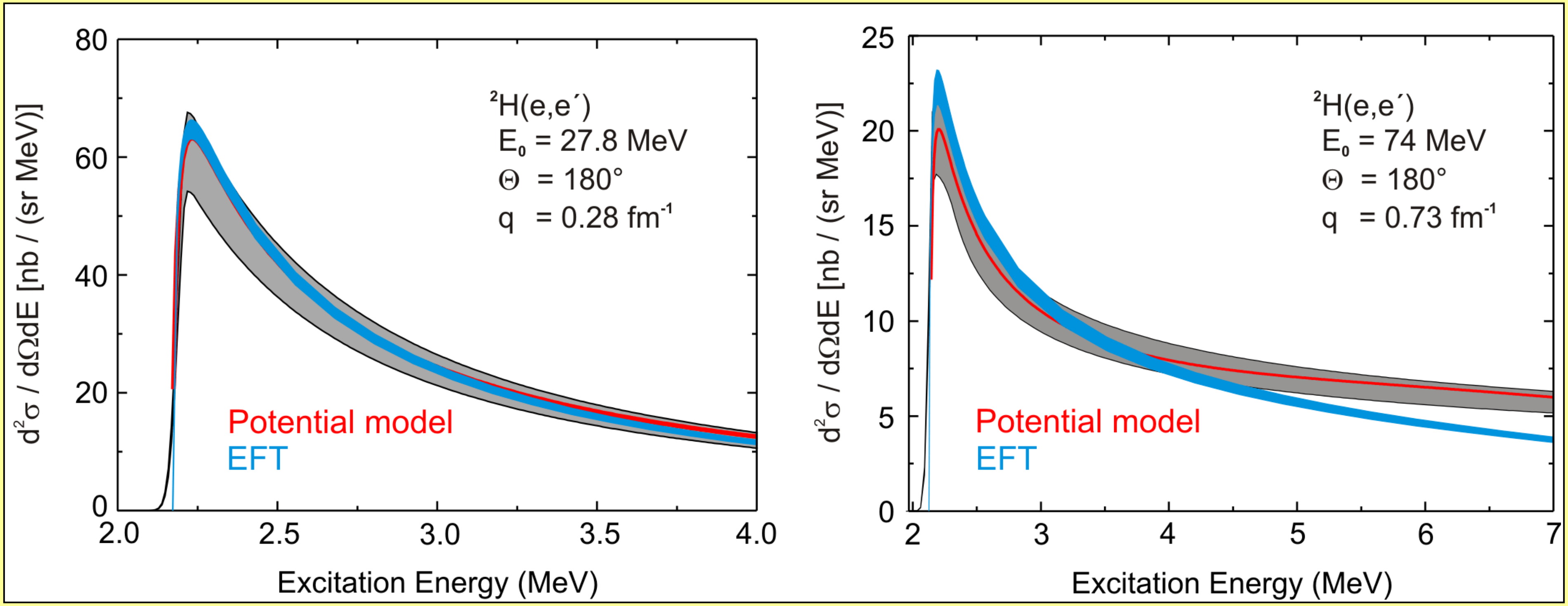
- Scattering at 180° is ideal for measuring transverse excitations: M1 enhanced

Spectra and Decomposition



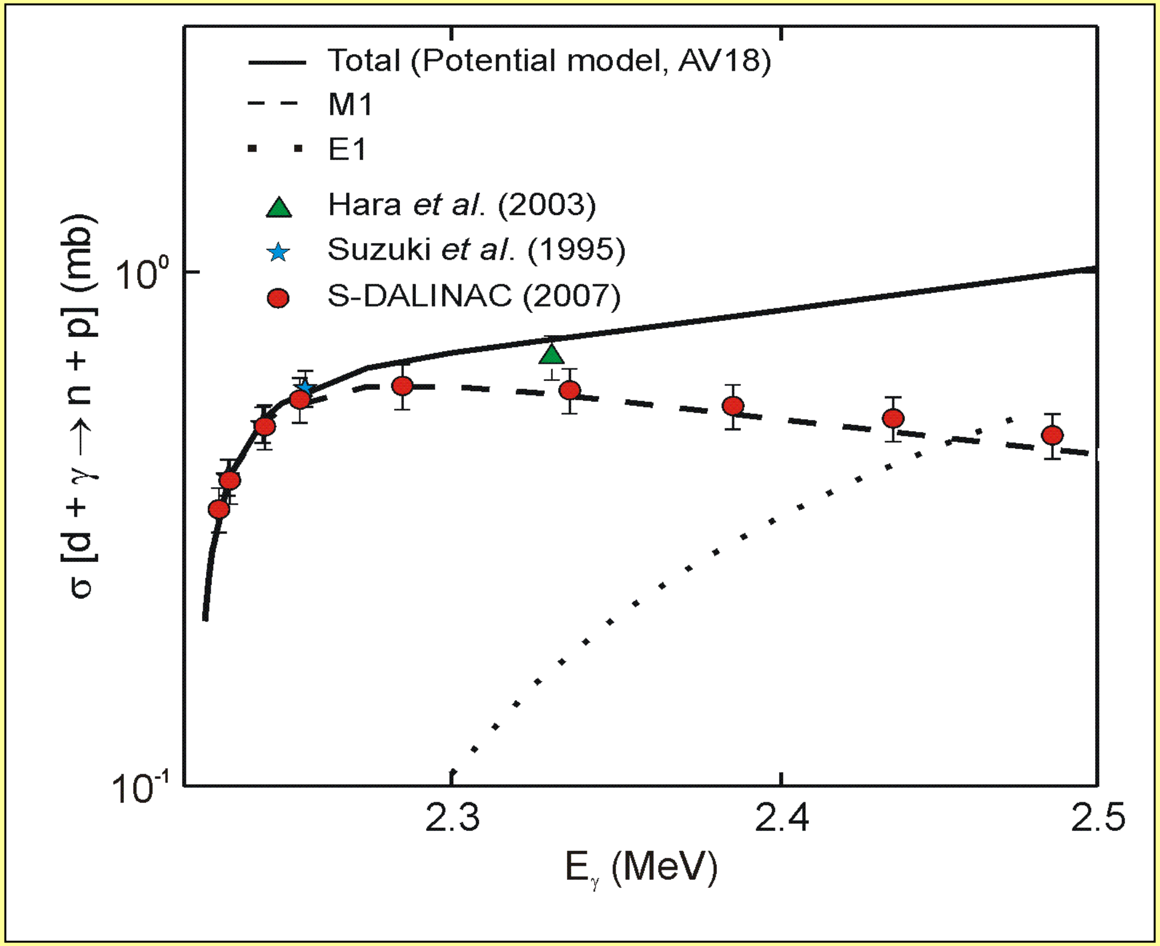
- Absolute and relative normalization agree within 5 %

Comparison to Potential Model and EFT Calculations



- Excellent agreement with potential model (H. Arenhövel)
- Deviations of EFT (H. Griesshammer) at higher momentum transfer
- Extrapolation to photon point → equivalent (γd → np) cross sections

Importance for Big-Bang Nucleosynthesis



- BBN relevant energy window

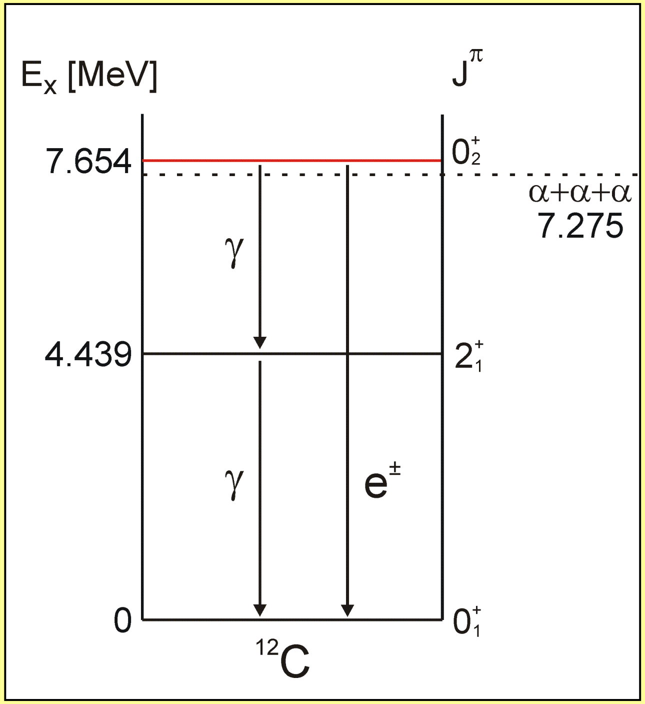
N. Ryezayeva et al., Phys. Rev. Lett. 100, 172501 (2008)

Structure of the Hoyle State in ^{12}C

- The Hoyle state is a prototype of α-cluster states in light nuclei

- Cannot be described within the shell-model but within α-cluster models

- Some α-cluster models predict the Hoyle state to consist of a dilute gas of weakly interacting α particles with properties of a Bose-Einstein Condensate (BEC)

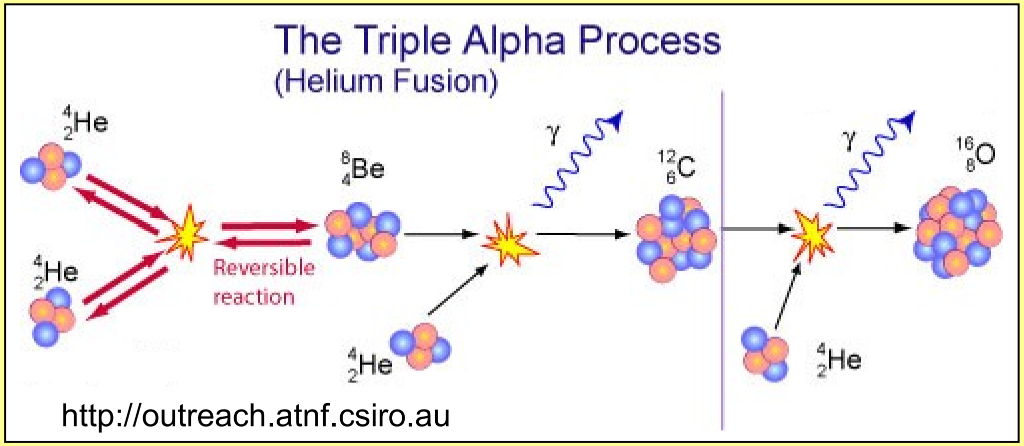


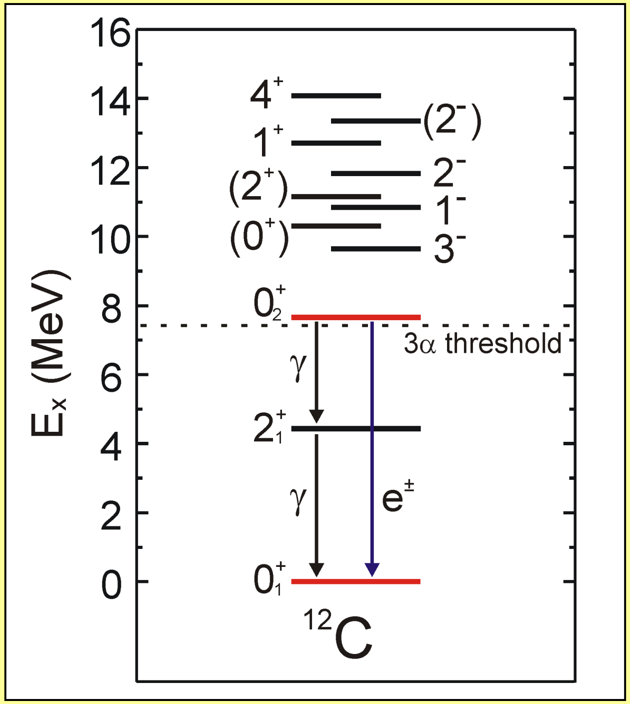
A. Tohsaki et al., Phys. Rev. Lett. 87,192501 (2001)

- Comparison of high-precision electron scattering data with predictions of FMD and α-cluster models

M. Chernykh, H. Feldmeier, T. Neff, PvNC, A. Richter, Phys. Rev. Lett. 98, 032501 (2007)

The Hoyle State in ^{12}C: Astrophysical Importance





- 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’)
(p,p’)

(p,p’)

(e,e’)

- Reaction rate needed with accuracy ~ 5%

S.M. Austin, Nucl. Phys. A 758, 375c (2005)

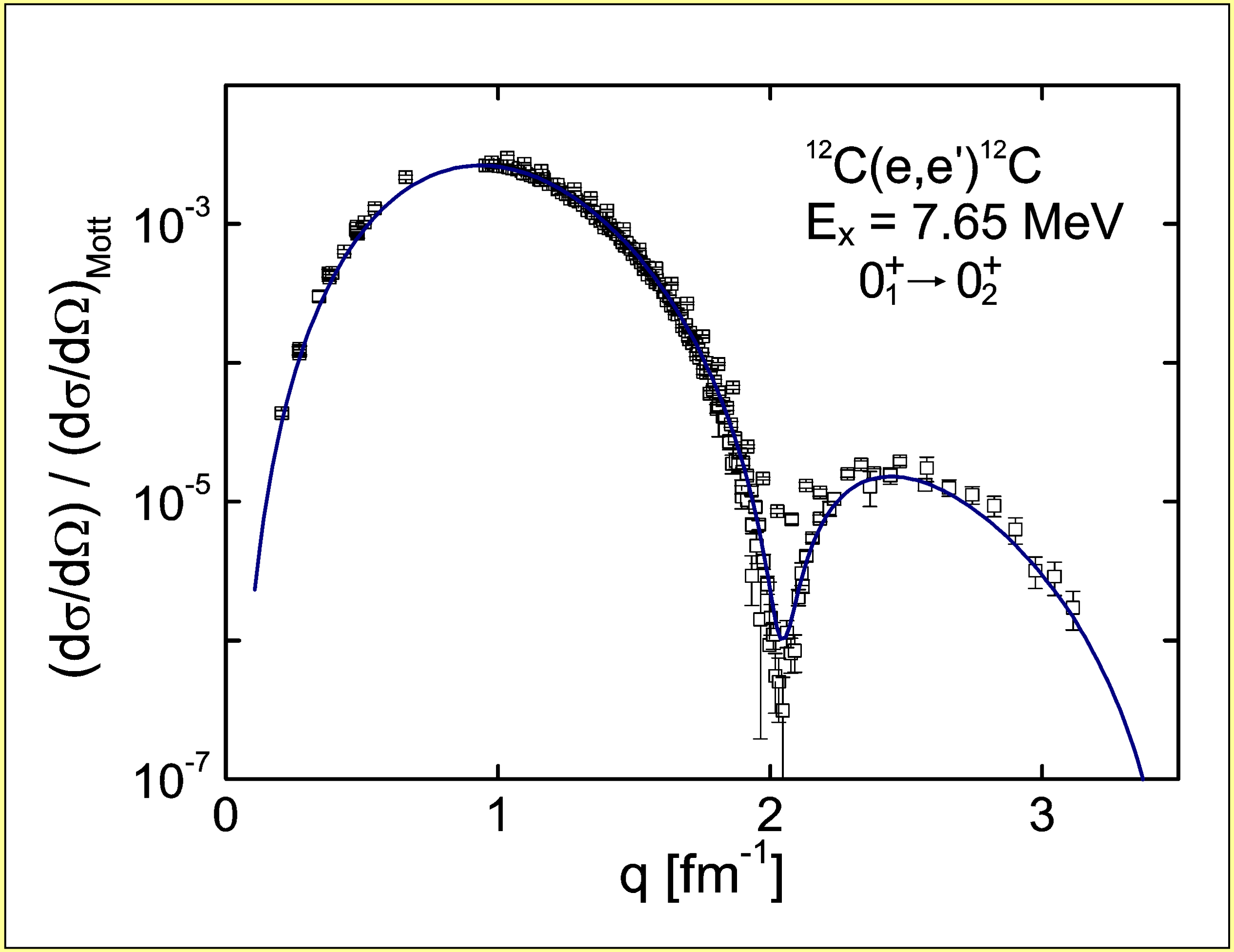
Motivation: Astrophysical Importance

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

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)

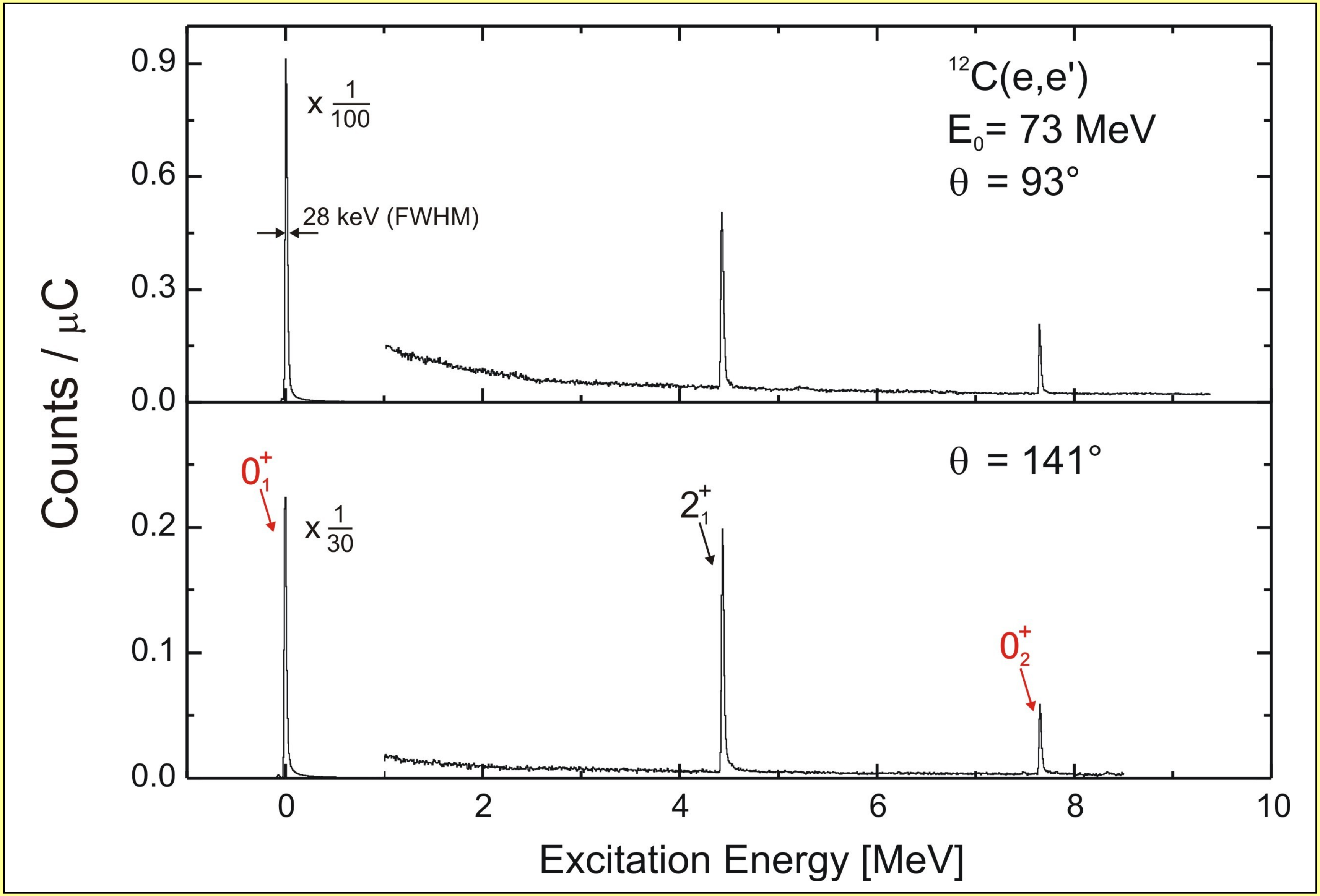
- Pair decay width determined by E0 transition matrix element

Fourier-Bessel Analysis

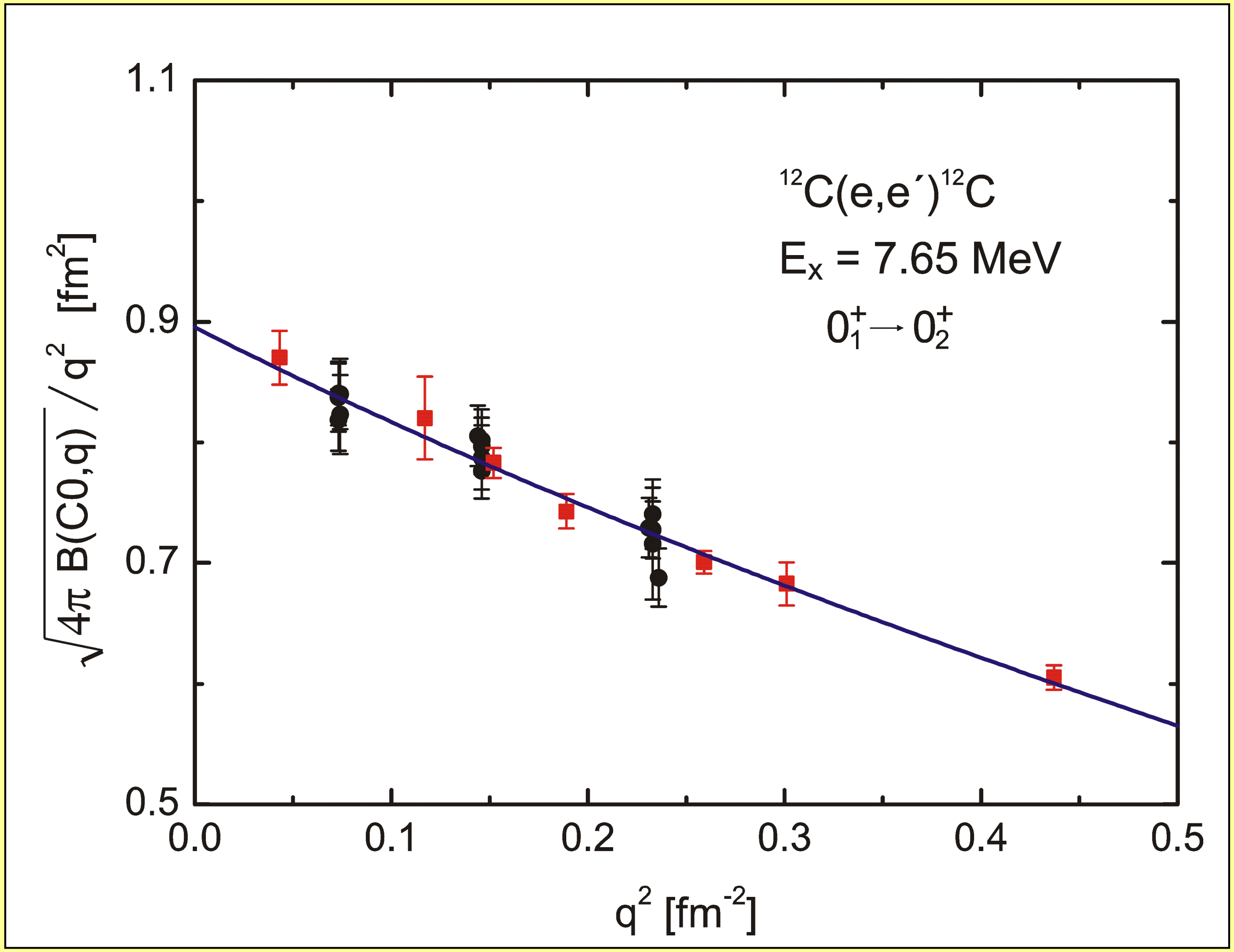


- Large momentum transfer range: q = 0.2 – 3.1 fm^{-1}
- *ME* = 5.54(6) fm^2 as compared to 5.02(7) fm^2 from Crannell

New Measurements at low Momentum Transfer



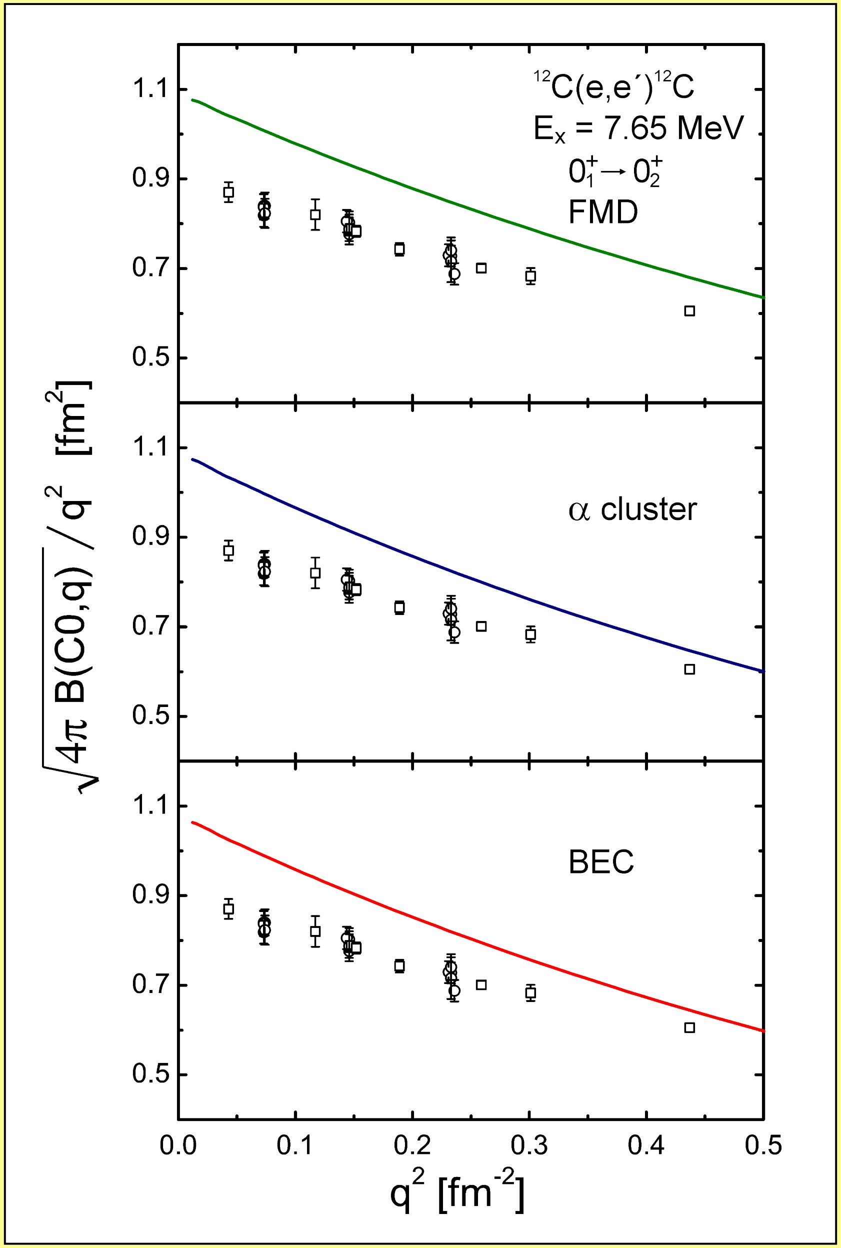
Model-Independent PWBA Analysis



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

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

Model Predictions at Low Momentum Transfer

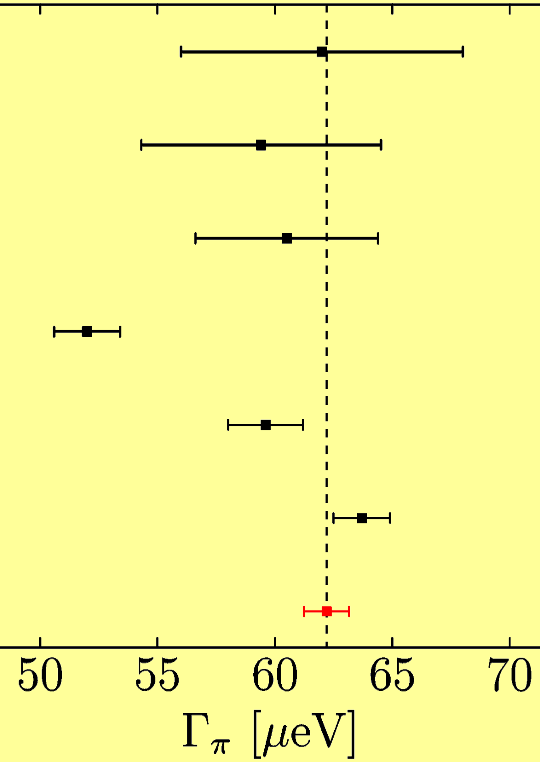


- Theory systematically overpredicts experiment

Results

Year	Analysis	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

Pair width



- Only Γ_π/Γ needs still to be improved (experiment at MSU in progress)
- Refined form factor analysis with Laguerre polynomials under way

Collaboration

- TU Darmstadt

  O. Burda
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  Y. Kalmykov
  A. Krugmann
  P. von Neumann-Cosel
  I. Poltoratska
  I. Pysmenetska
  S. Rathi
  A. Richter
  A. Sheik Obeid
  A. Shevchenko
  O. Yevetska

- GSI Darmstadt

  H. Feldmeier
  T. Neff

- Universität Mainz

  H. Arenhövel

- George Washington University

  H.W. Griesshammer

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 pair decay width Γ_π

Fourier-Bessel Analysis

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

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

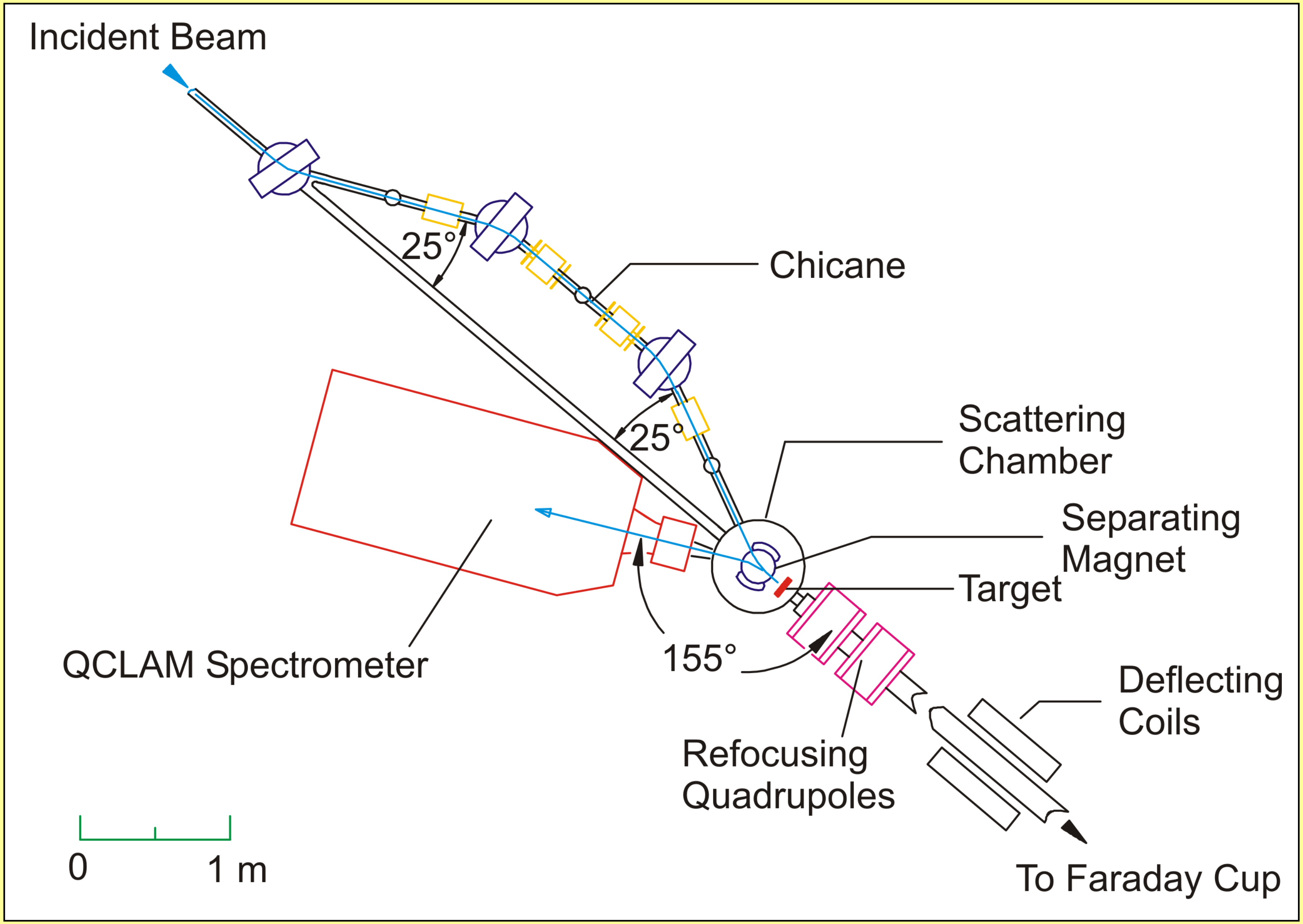
$$\rho_{tr}(r) = \begin{cases} \sum_{\mu=1}^{\infty} a_\mu\, j_0(q_\mu r) & \text{for } \; r < R_c \\ 0 & \text{for } \; r \geq R_c \end{cases}$$

with

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

- Data should be measured over a broad momentum transfer range

180° System at the S-DALINAC



Some Theoretical Approaches Towards the Hoyle State: FMD model

- Antisymmetrized A-body state

$$|Q\rangle = \mathcal{A}(|q_1\rangle \otimes |q_2\rangle \otimes \ldots \otimes |q_A\rangle)$$

Single-particle states

$$\langle \mathbf{x}|q\rangle = \sum_i c_i \exp\Big[-\frac{(\mathbf{x}-\mathbf{b}_i)^2}{2a_i}\Big] \otimes |\chi_i^{\uparrow}, \chi_i^{\downarrow}\rangle \otimes |\xi\rangle$$

Gaussian wave packets in phase space (a_i is width, complex parameter $\mathbf{b}_i$ encodes mean position and mean momentum), spin is free, isospin is fixed

Describes α-cluster states as well as shell-model–like configurations

- UCOM interaction

Derived form the realistic Argonne V18 interaction

Adjusted to reproduce binding energies and charge radii of some "closed-shell" nuclei

Theoretical Approaches: α-Cluster and "BEC" Models

- α-cluster model

  FMD wave function restricted to α-cluster triangle configurations only

- "BEC" model

  System of 3 ^{4}He nuclei in 0s state (like α condensate)

  Hoyle state is a "dilute gas" of α particles

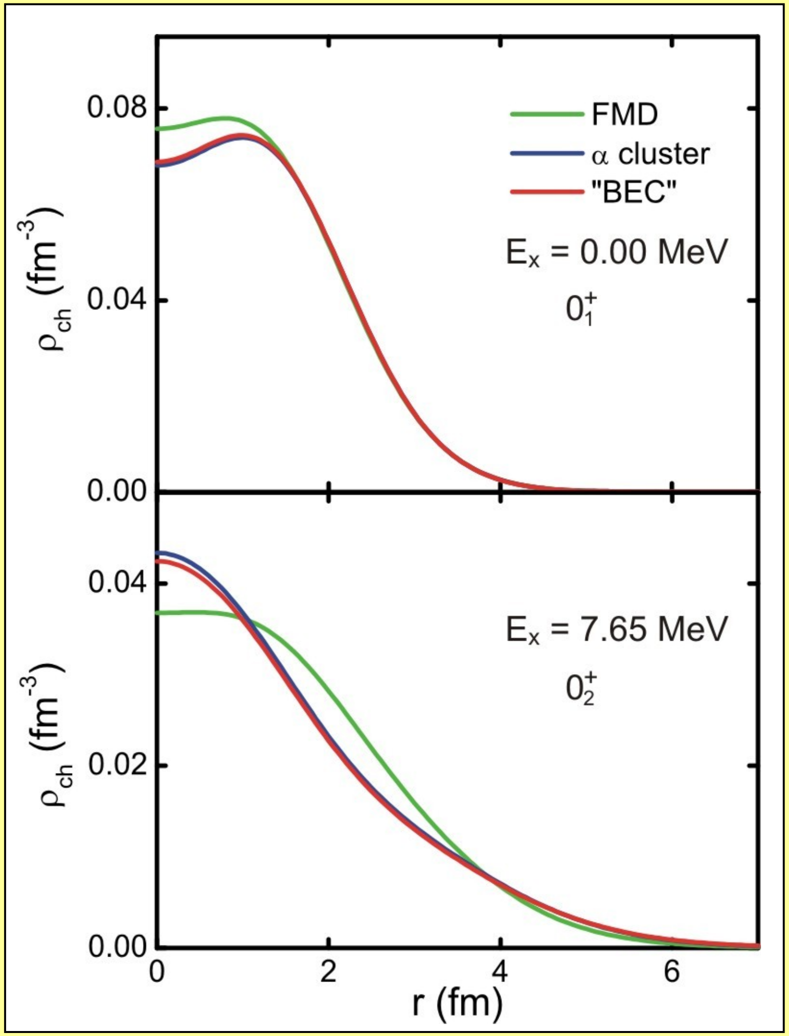
- Volkov interaction

  Simple central interaction

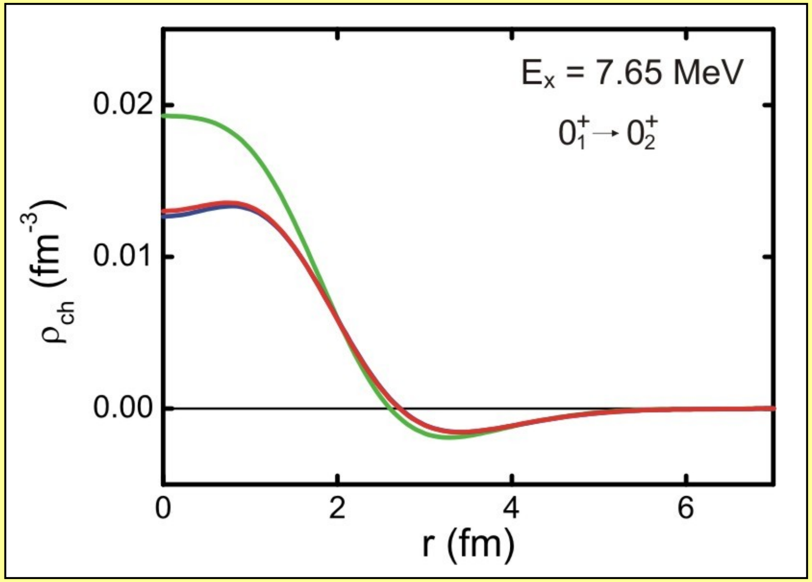
  Parameters adjusted to reproduce α binding energy, radius,
  α–α scattering data and ground state energy of ^{12}C

  Only reasonable for ^{4}He, ^{8}Be and ^{12}C nuclei

^{12}C Densities



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

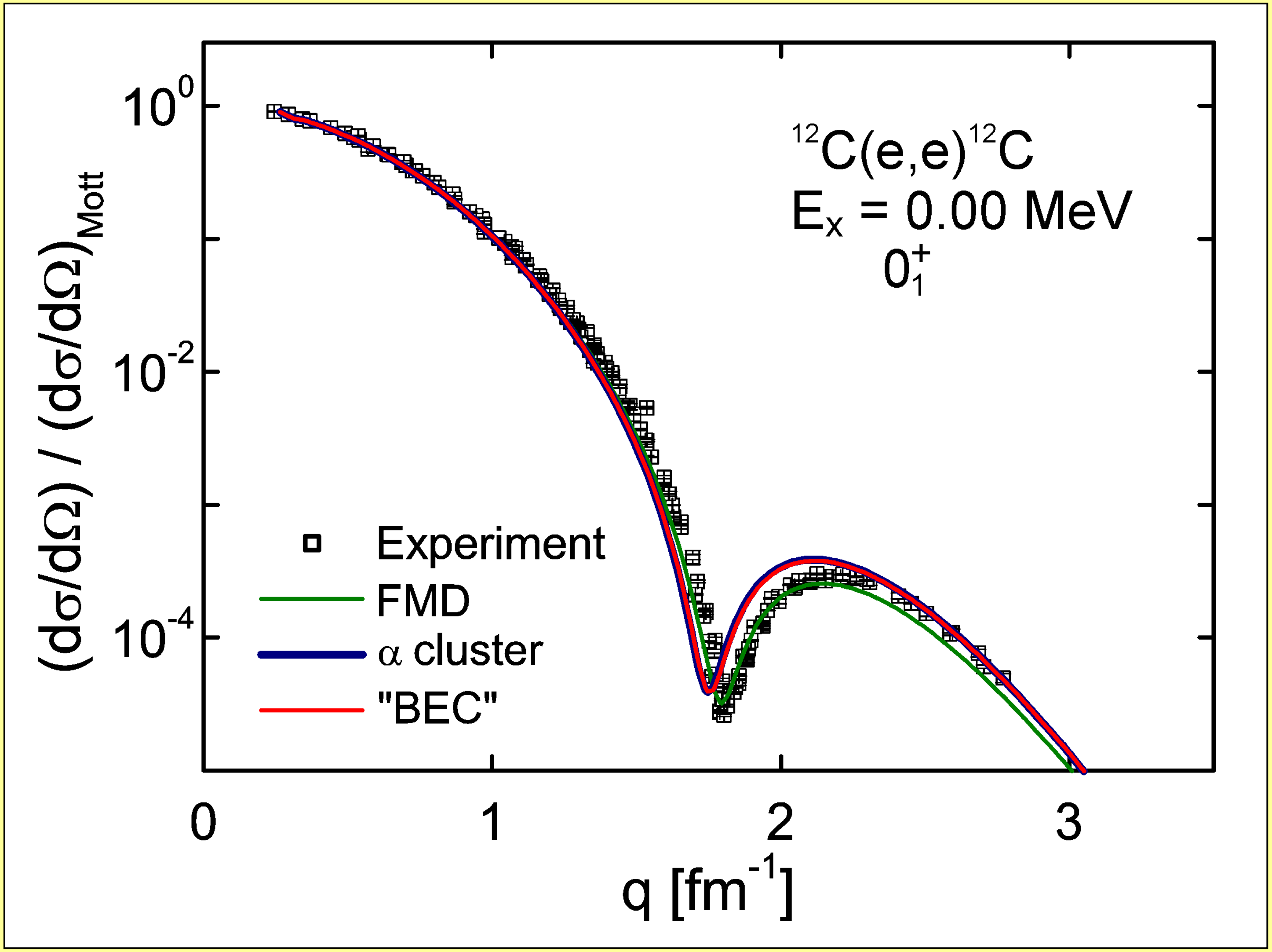


↕

- Transition density can be tested via transition form factor

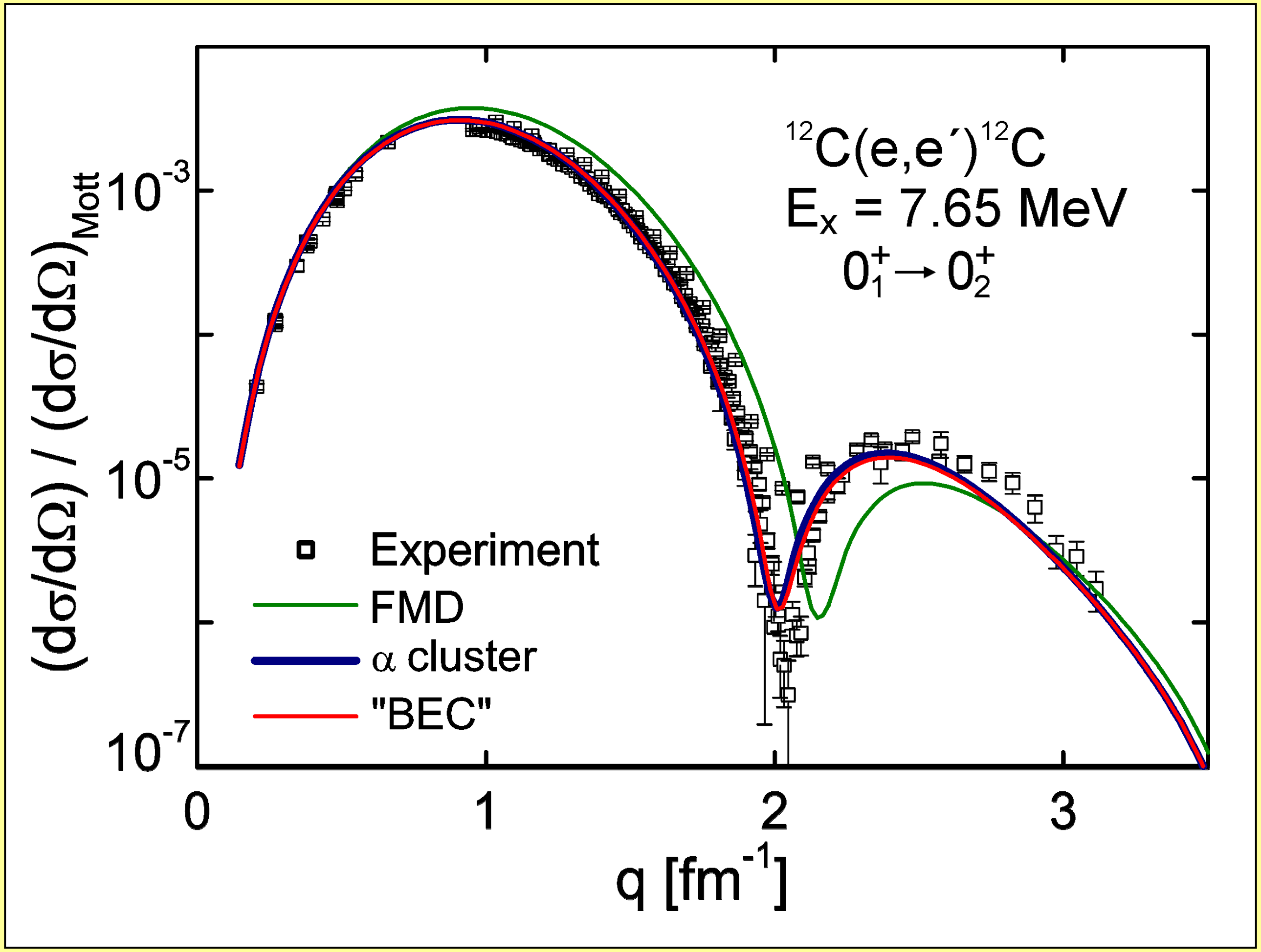
- Note the depression of the central density
- Electron scattering as test of theoretical predictions

Elastic Form Factor



- Described well by FMD

Transition Form Factor to the Hoyle State

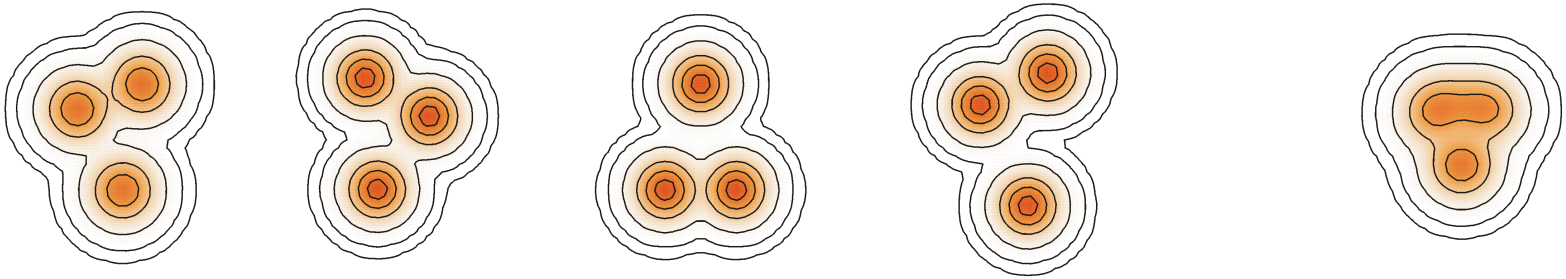


- Described better by α-cluster models
- FMD might be improved by taking α-α scattering data into account

H. Crannell, data compilation (2005)

What is the Actual Structure of the Hoyle State ?

- Overlap with FMD basis states

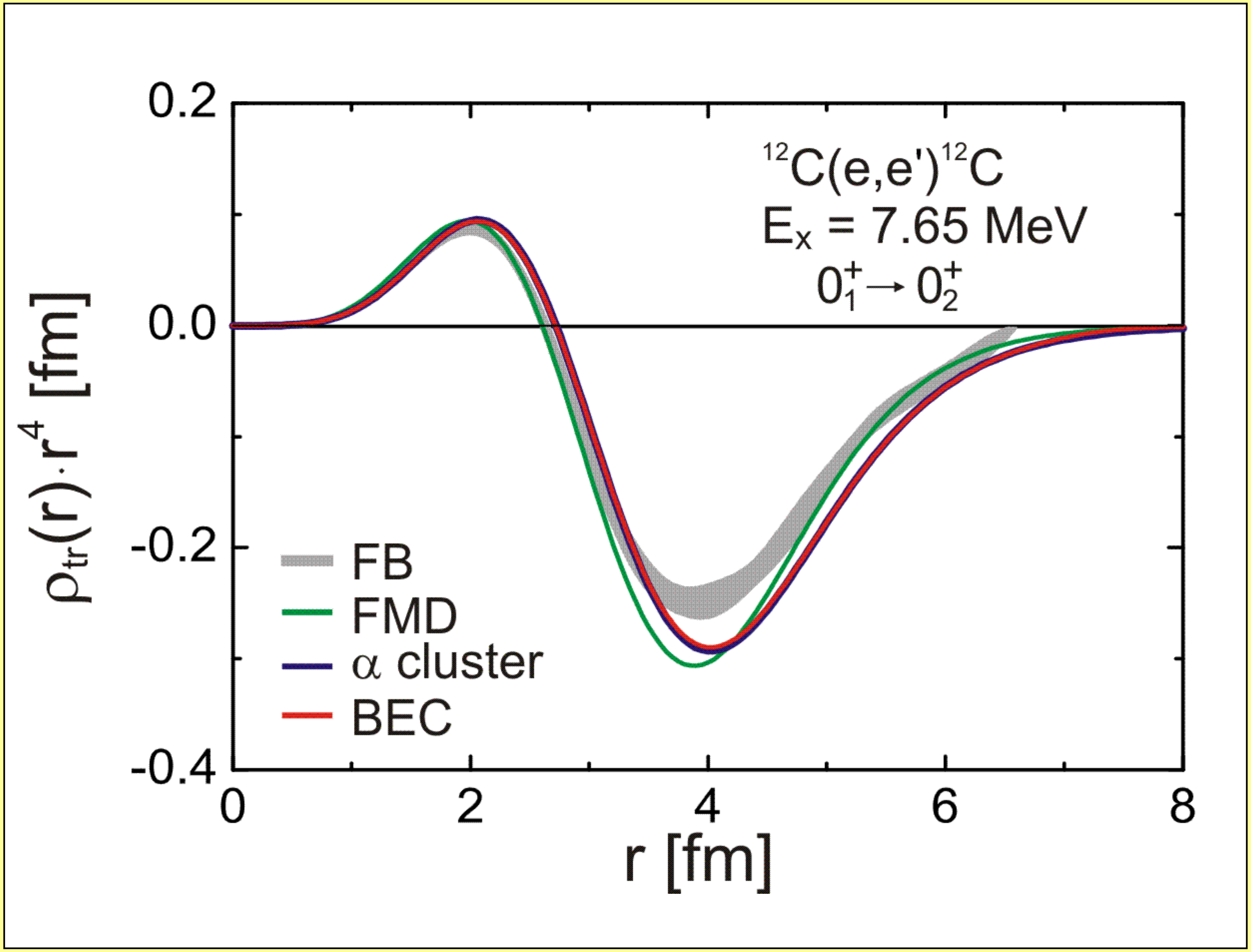


$|\langle 1|0_1^+\rangle| = 0.30$ $|\langle 2|0_1^+\rangle| = 0.25$ $|\langle 3|0_1^+\rangle| = 0.15$ $|\langle 4|0_1^+\rangle| = 0.08$ $|\langle 5|0_1^+\rangle| = 0.94$

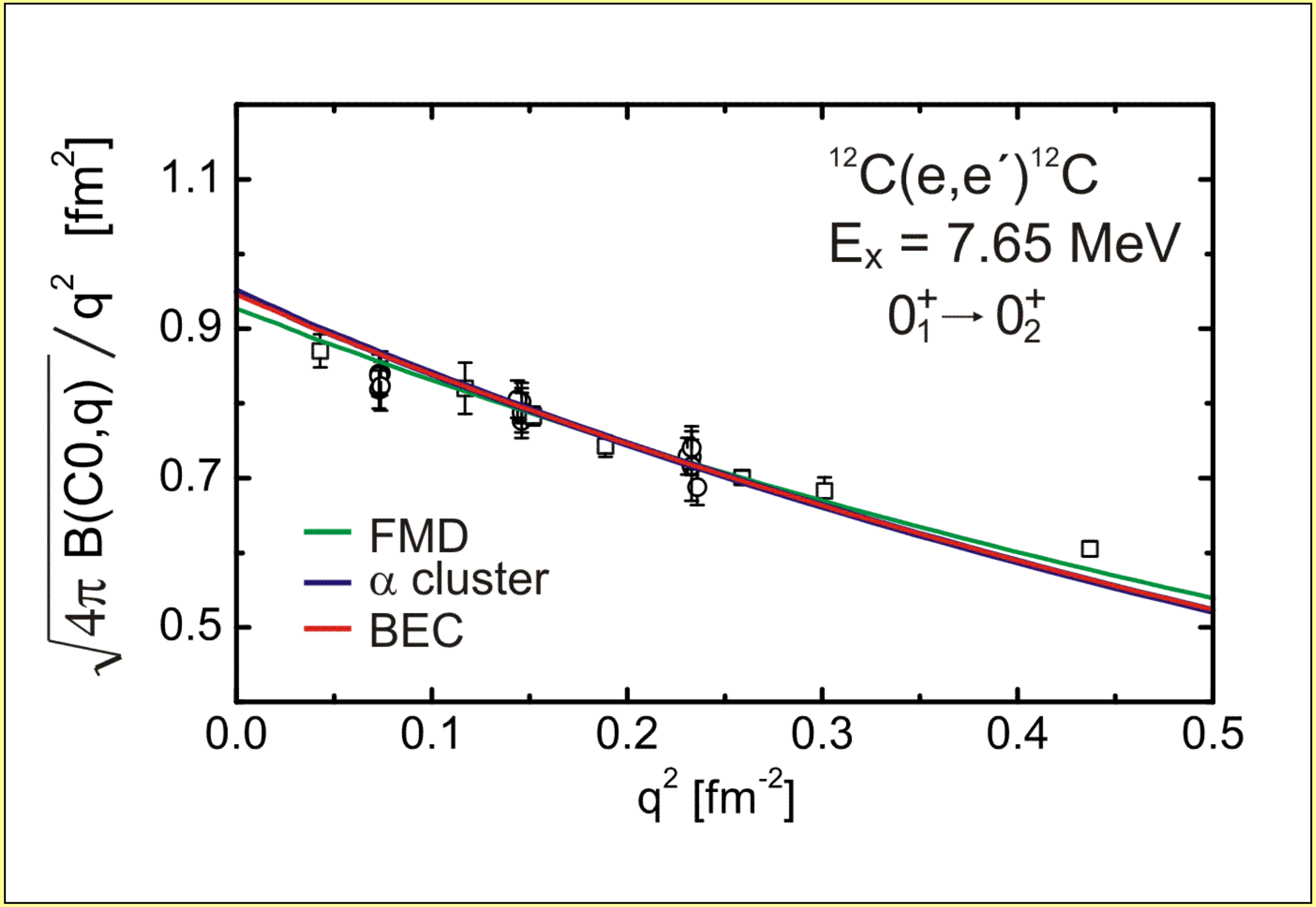
$|\langle 1|0_2^+\rangle| = 0.72$ $|\langle 2|0_2^+\rangle| = 0.71$ $|\langle 3|0_2^+\rangle| = 0.61$ $|\langle 4|0_2^+\rangle| = 0.61$ $|\langle 5|0_2^+\rangle| = 0.04$

- In the FMD and α-cluster model the leading components of the Hoyle state are cluster-like and resemble ^{8}Be + ^{4}He configurations
- But in the “BEC” model the relative positions of α clusters should be uncorrelated

Transition Densities



Normalized Model Predictions at low q



- q dependence differs from data