Electron Scattering as a Tool to Study Excited States with Unusual Features

- $J^{\pi} = 1/2^{+}$ resonance at neutron threshold in ^{9}Be

- Structure of the Hoyle state in ^{12}C

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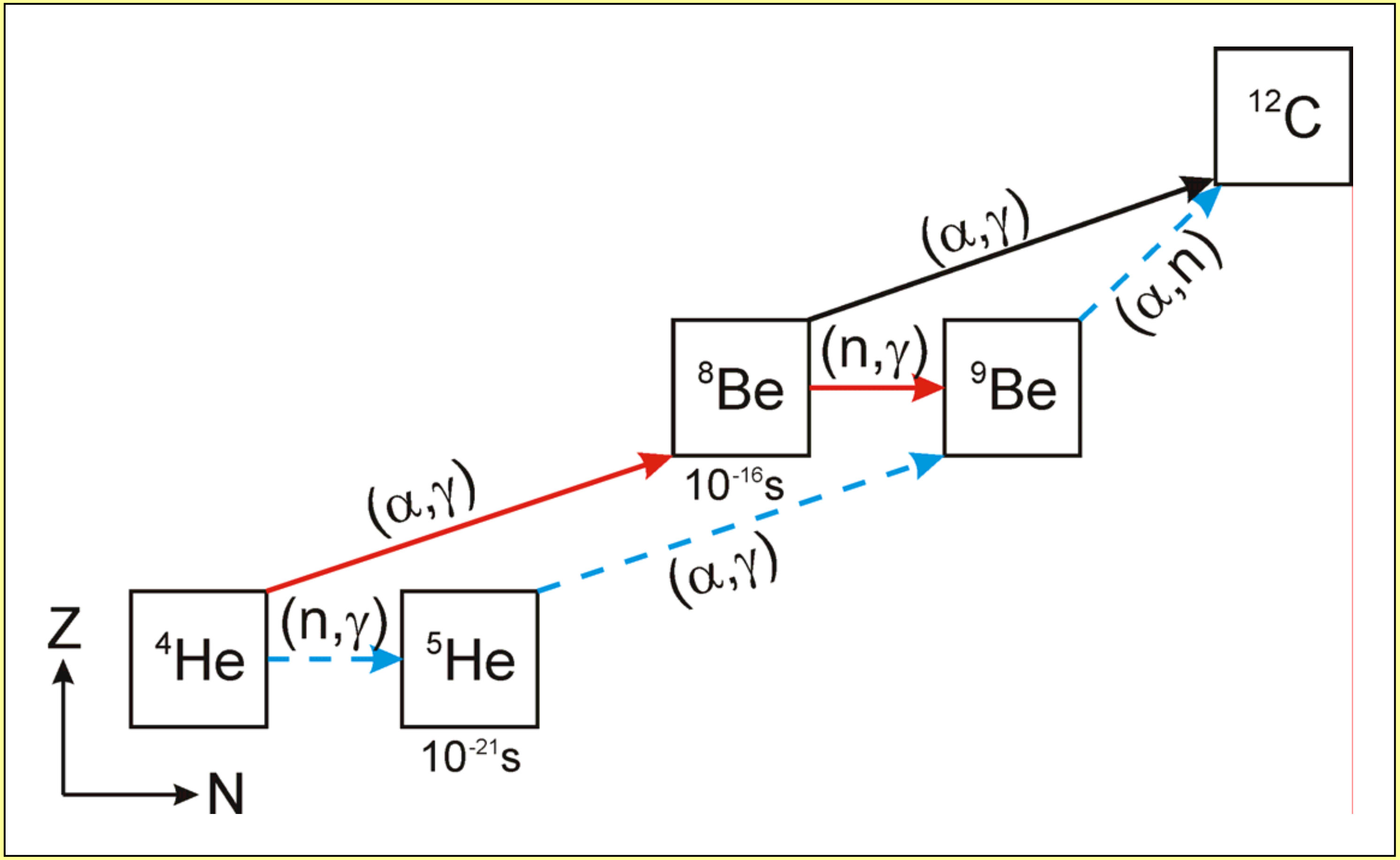
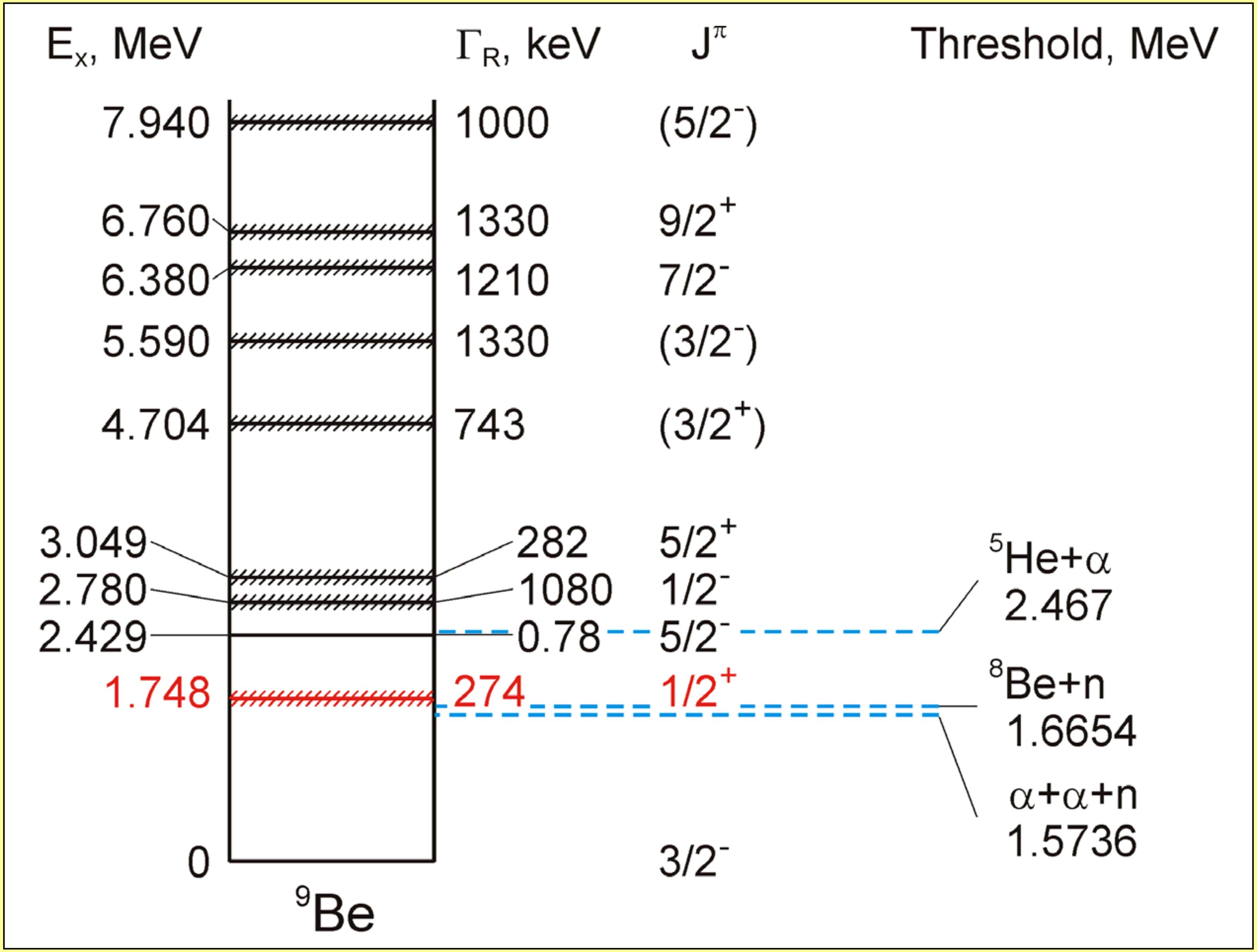
Possible role of ^{9}Be in the production of ^{12}C



- In *n*-rich environment (core-collapse supernovae) this reaction path may provide an alternative route for building up the heavy elements and triggering the *r* process

$J^{\pi} = ½^{+}$ state at threshold



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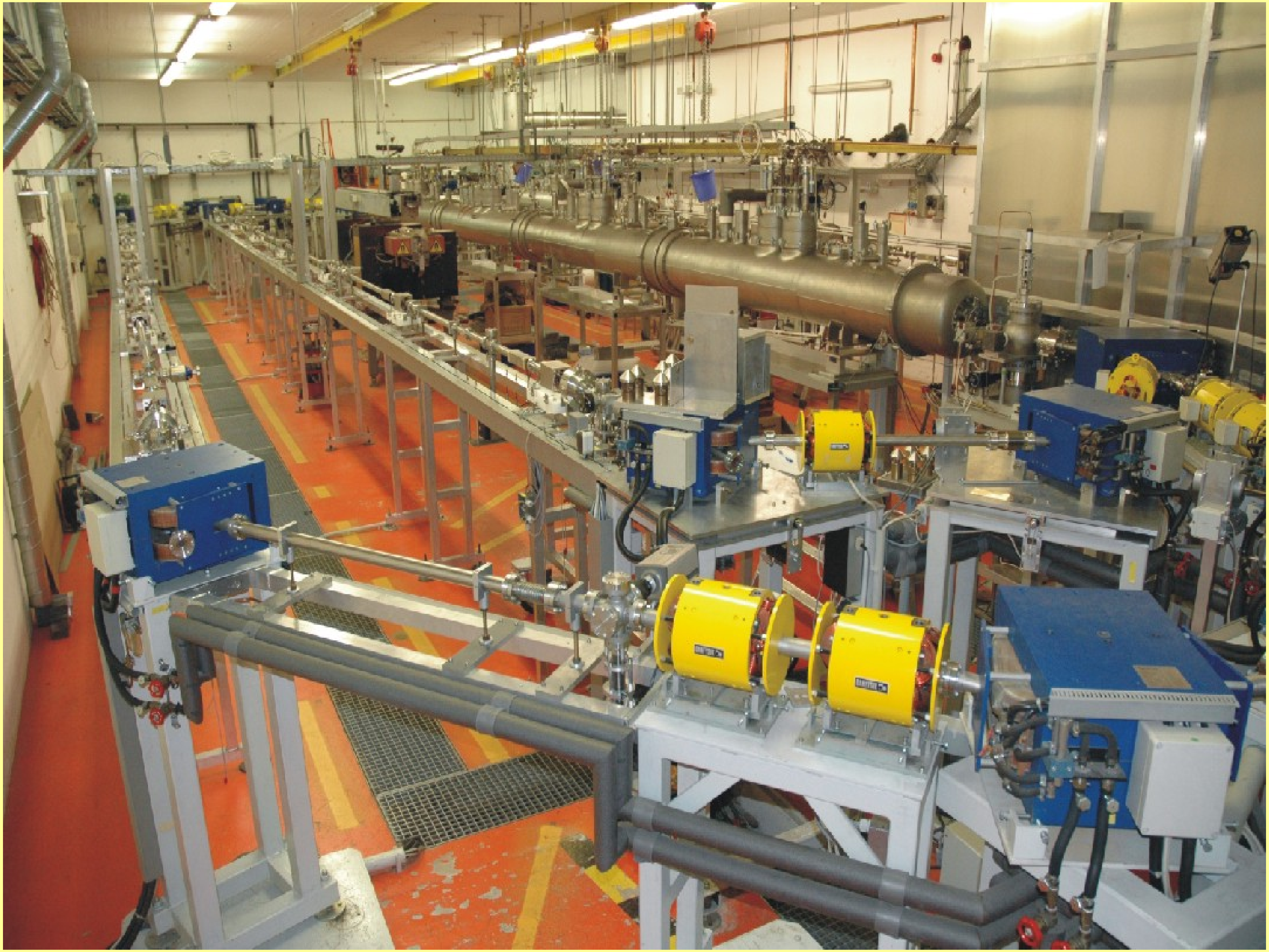
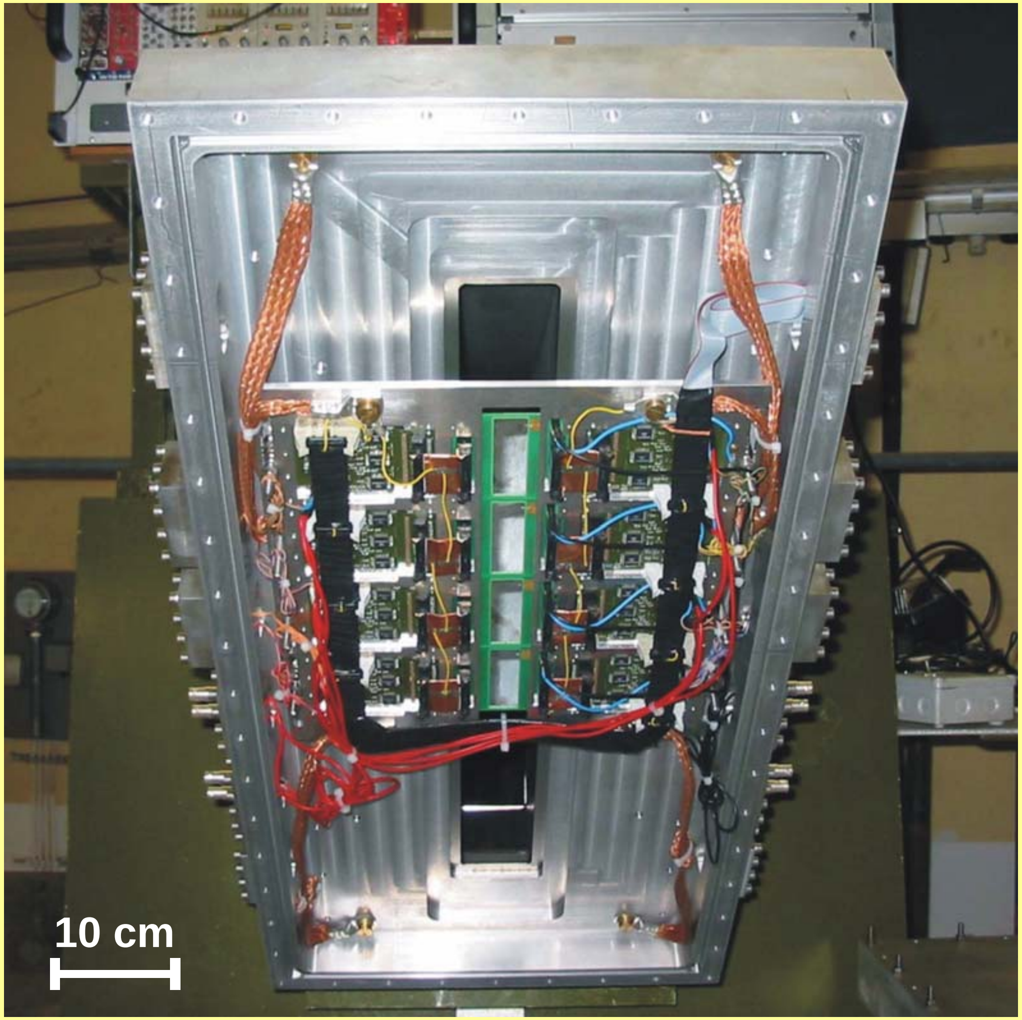


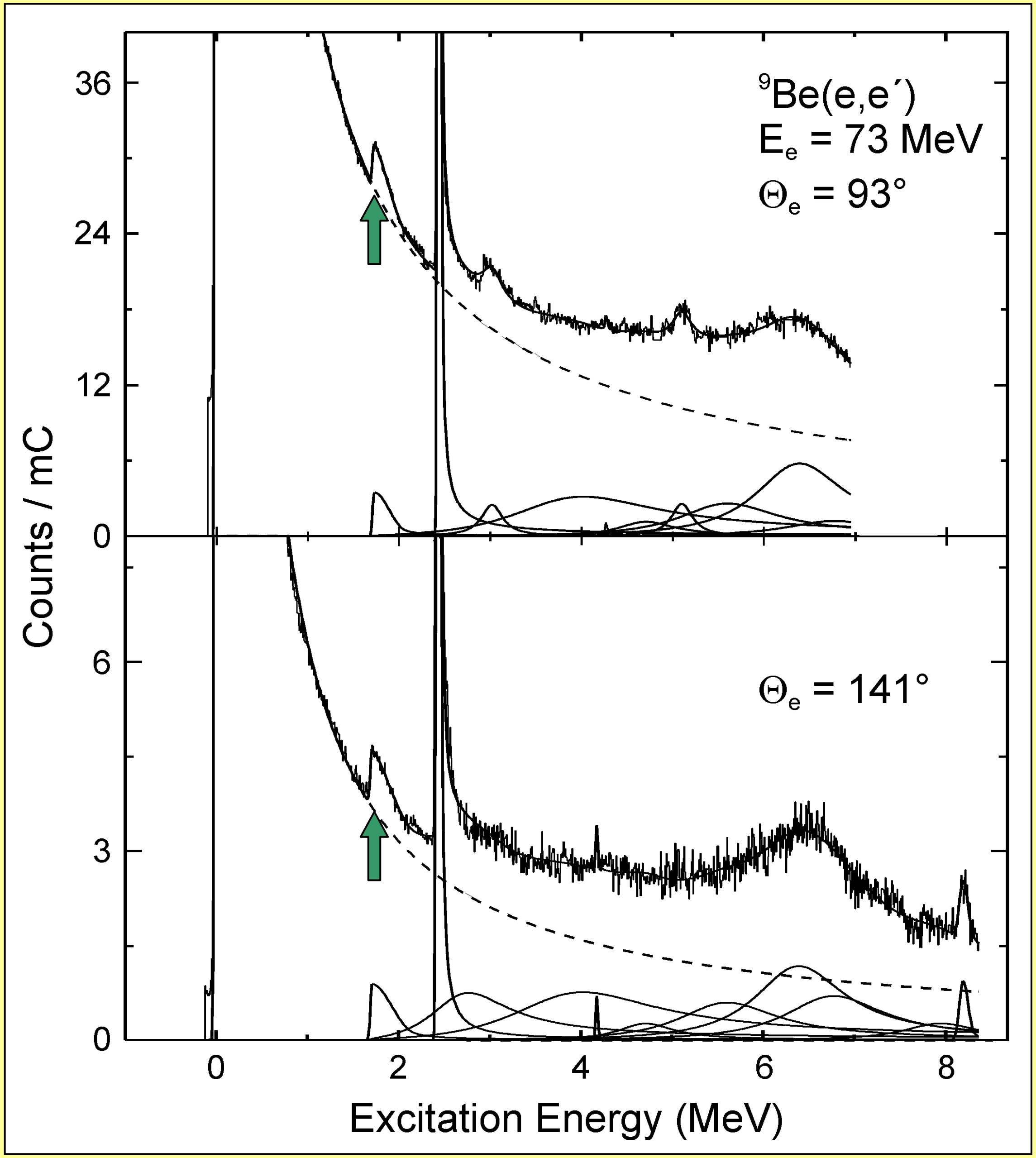
Lintott spectrometer

Detector system

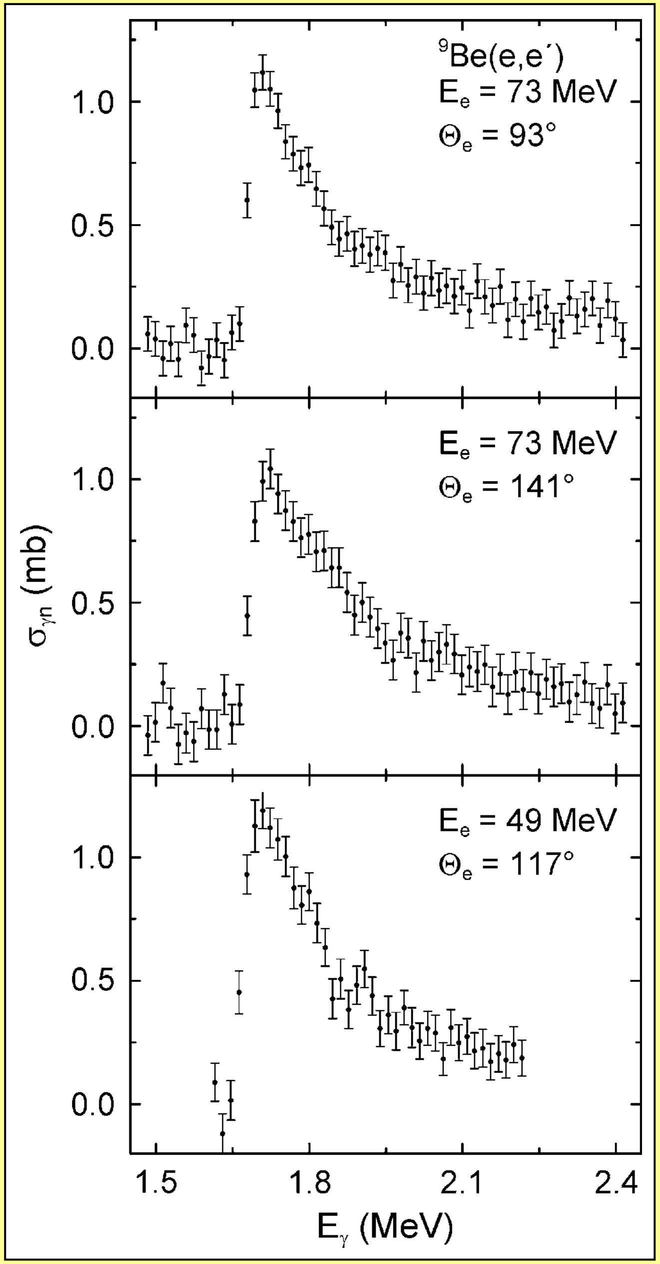


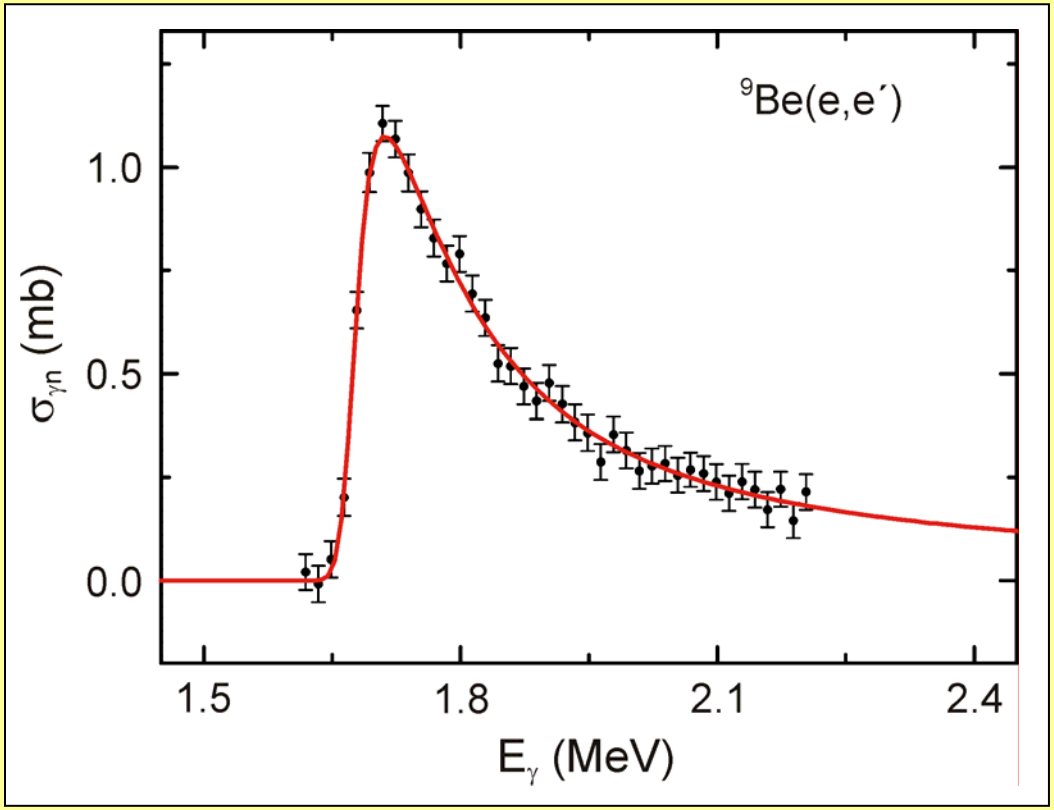
- Si microstrip detector system: 4 modules, each 96 strips with pitch of 650 μm
- Count rate up to 100 kHz
- Energy resolution $1.5\text{x}10^{-4}$

Spectrum of the ^{9}Be(e,e´) reaction and deconvolution



$^9Be(\gamma,n)$ extracted from $^9Be(e,e')$

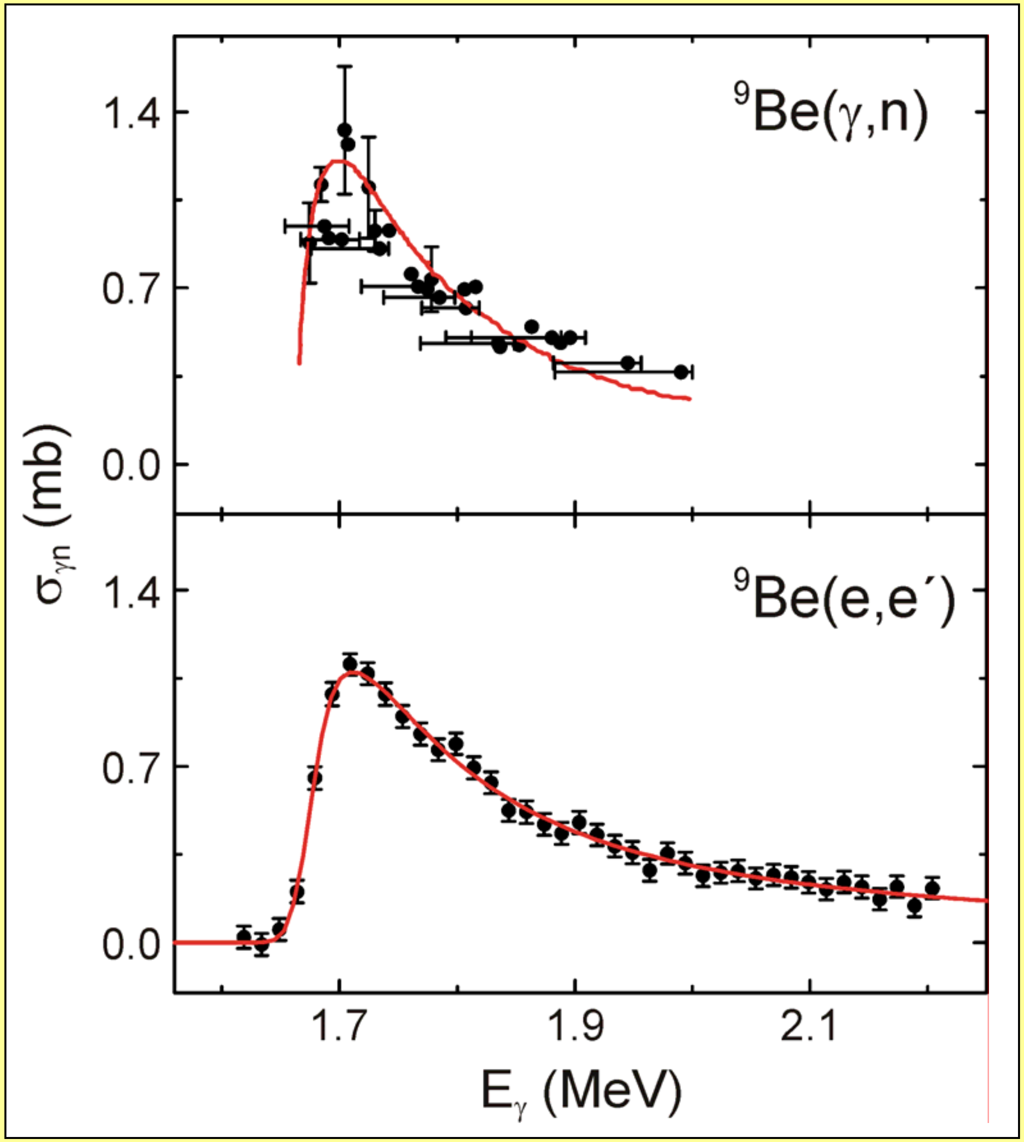




$E_R = 1.748(6)$ MeV

$\Gamma_R = 274(8)$ keV

Comparison: ^{9}Be(γ,n) and ^{9}Be(e,e´)



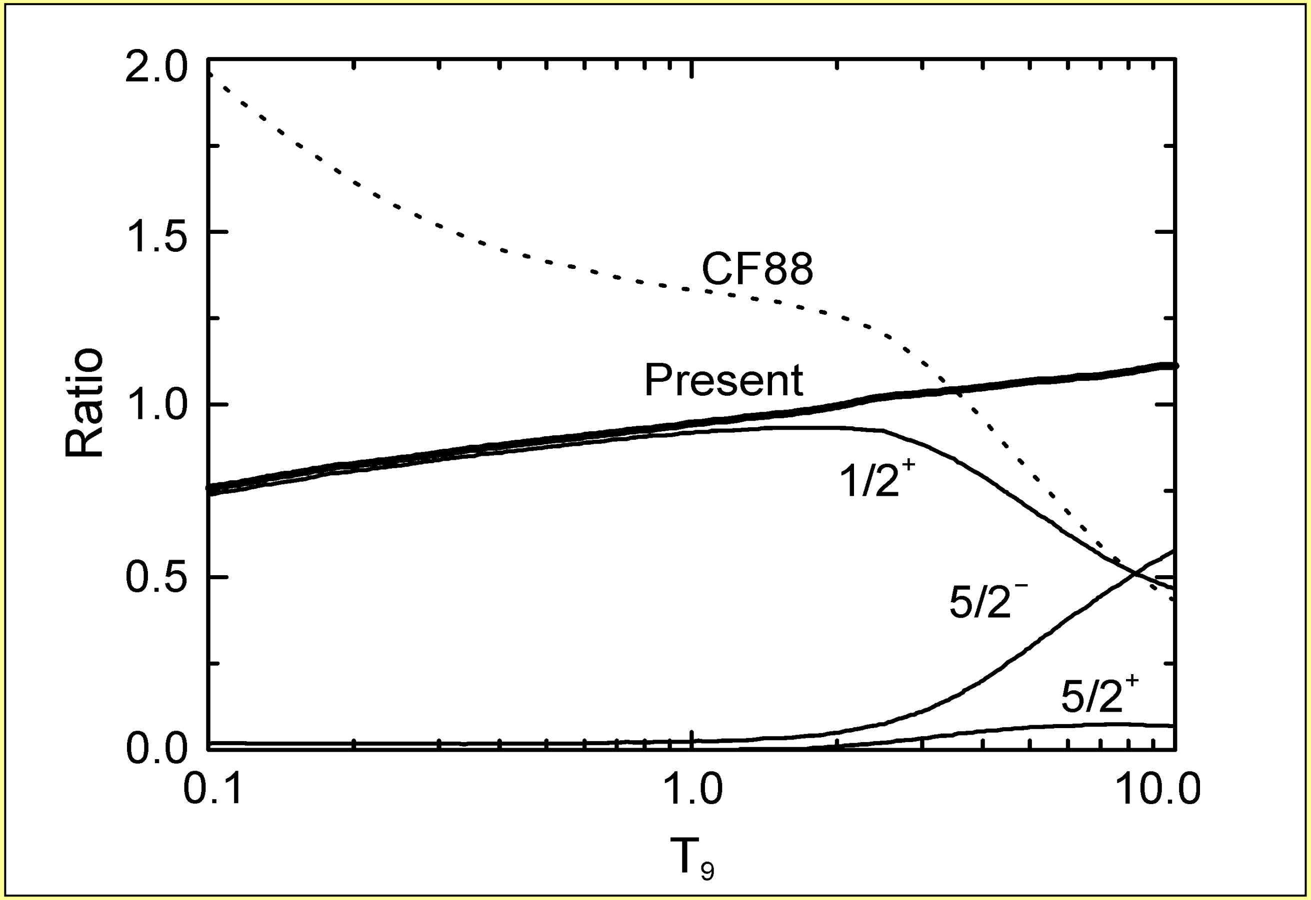
H. Utsonomiya et al.,
PRC 63, 018801 (2000)

E_R = 1.75(1) MeV
Γ_R = 283(42) keV

O. Burda et al.,
to be published

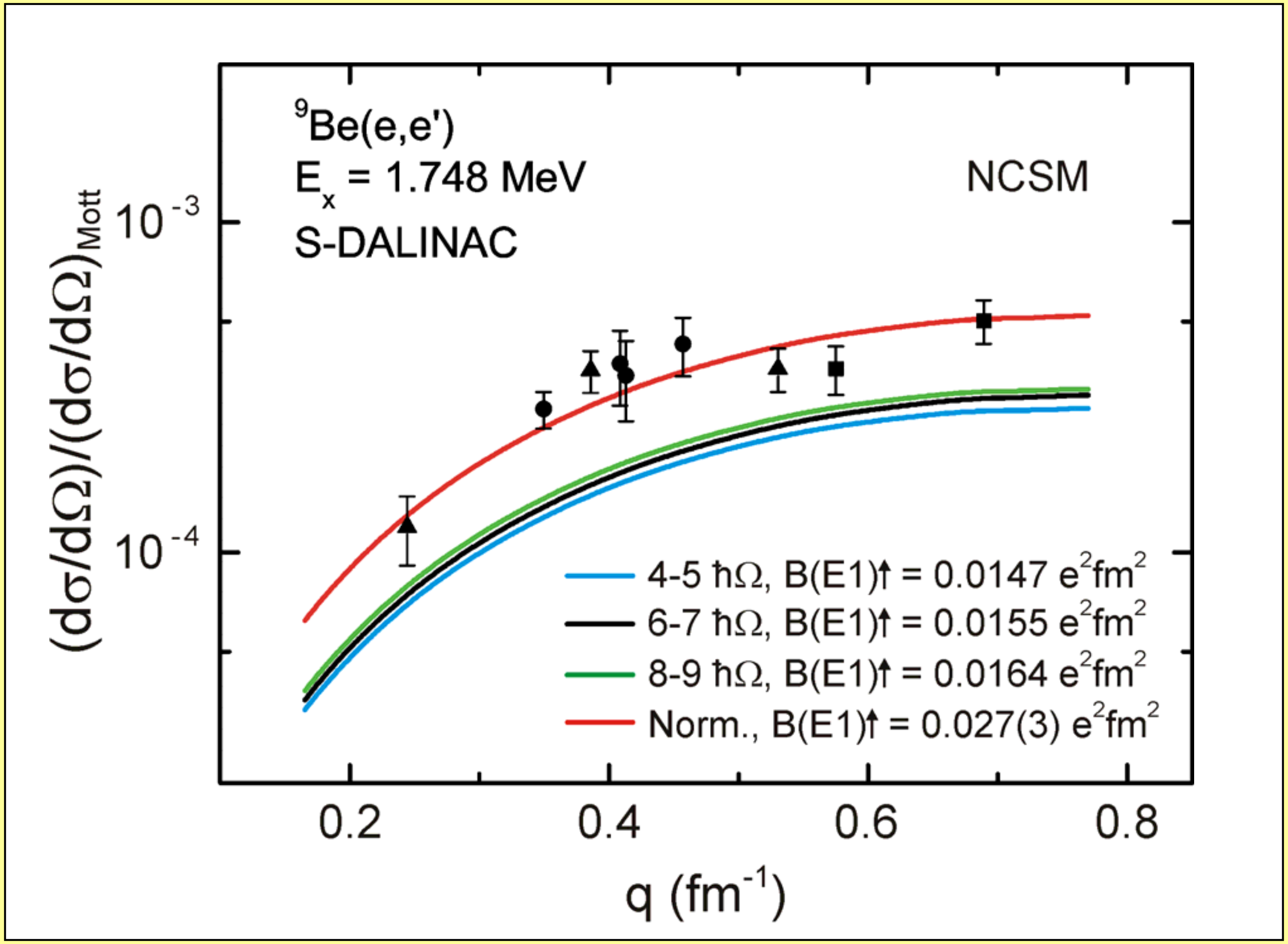
E_R = 1.748(6) MeV
Γ_R = 274(8) keV

Reaction rate of $\alpha\alpha n \to {}^9Be$



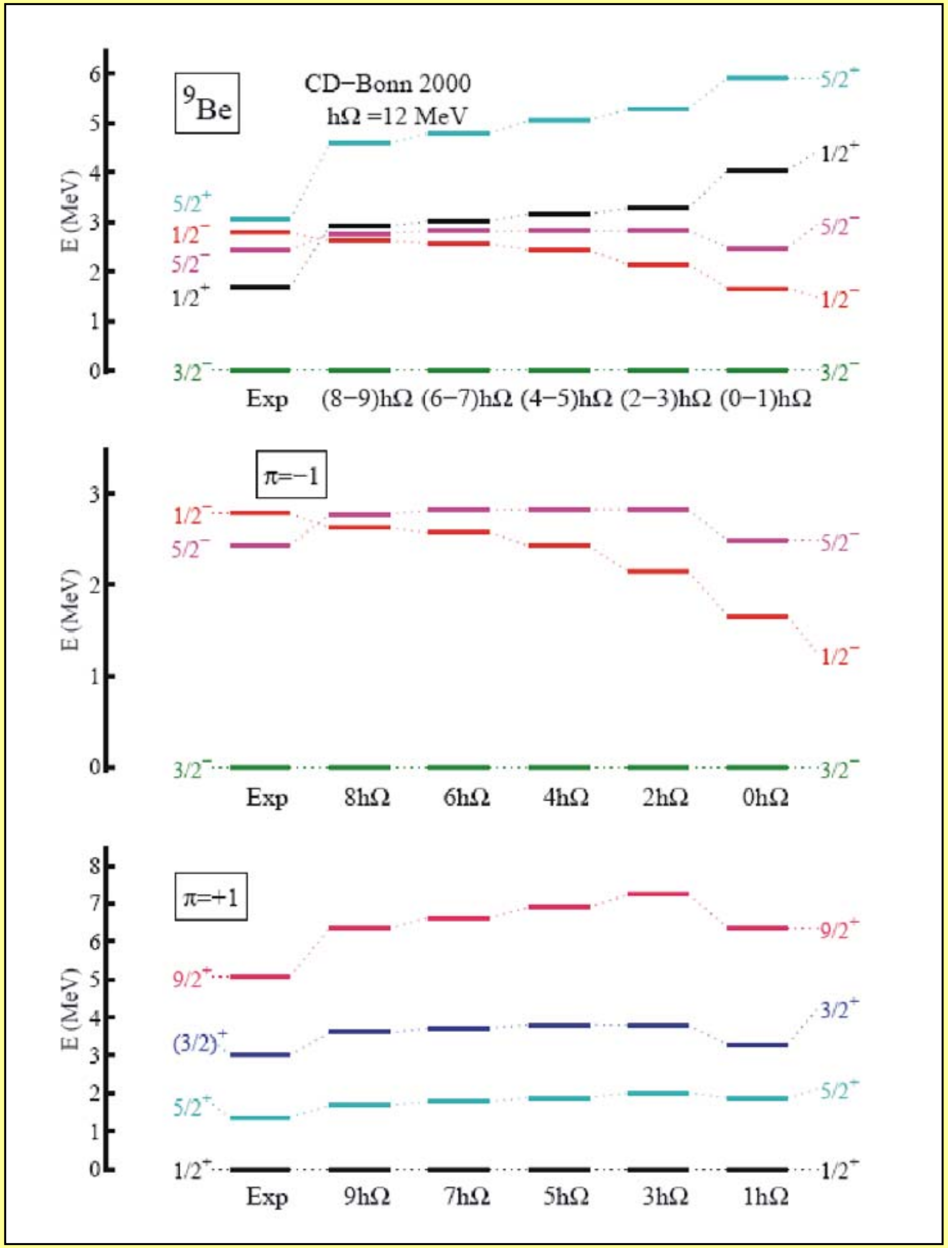
- Rate is shown as ratio to the compilation of C. Angulo et al., NPA 656, 3 (1999)
- For T_9 = 0.1 – 3 this resonance determines exclusively $^4He(\alpha,\gamma)^8Be(n,\gamma)^9Be$ chain
- Determined reaction rate differs up to 20% from adopted values

Form factor of the $J^\pi = ½^+$ state

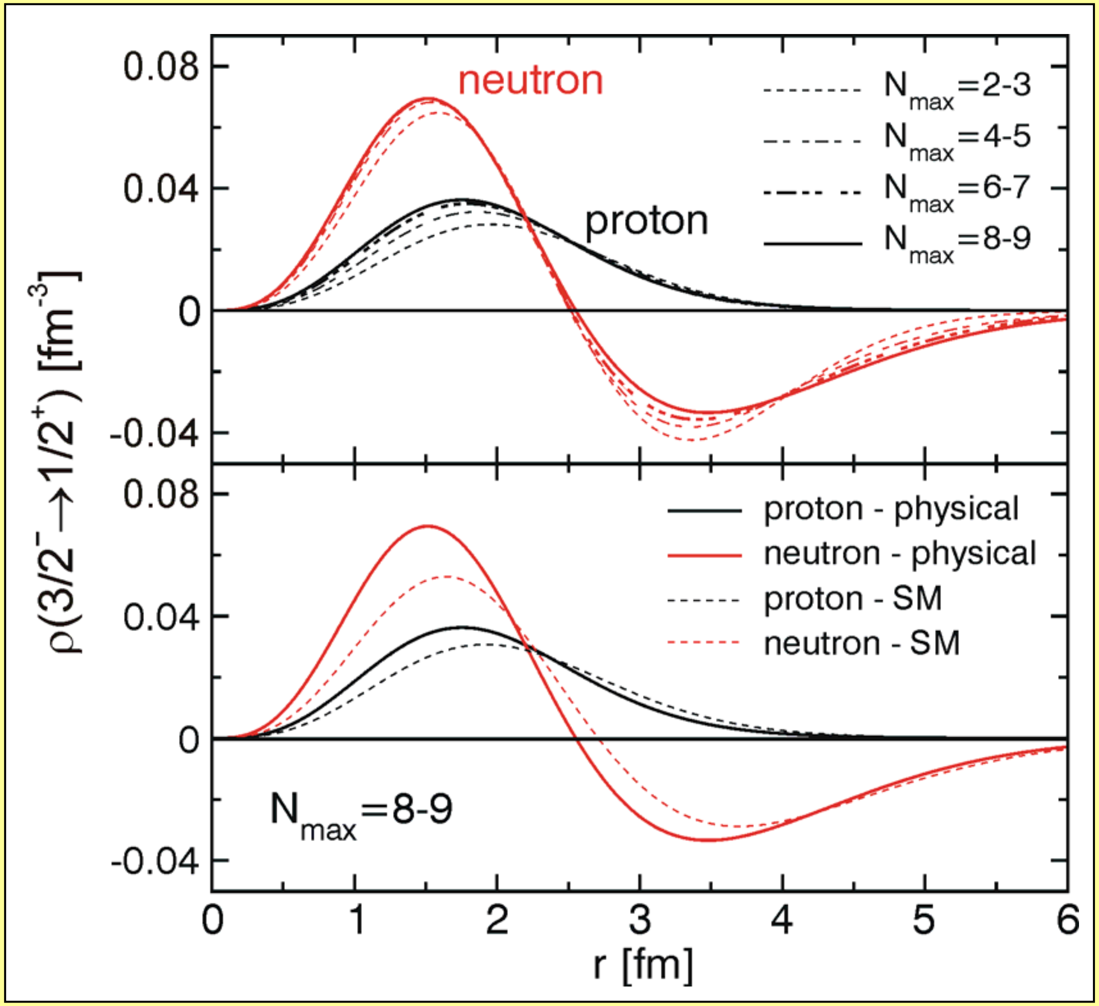


- NCSM (C. Forssén): correct *q* dependence but difference in magnitude compared to the data
- B(*C*1) ≠ B(*E*1) at photon point *k* = *q* → violation of Siegert theorem ?

Convergence behavior of NCSM results



Radial transition densities from NCSM



Problems and possible improvements

- E1 operator needs to be renormalized → effective charges

  but: convergence even slower than for the binding energies

- State is unbound → put a tail onto the insufficient HO wave functions

  ↔ projection onto a (core + particle) subspace

  successful for strong s.p. component and well defined core configuration, but both are questionable here

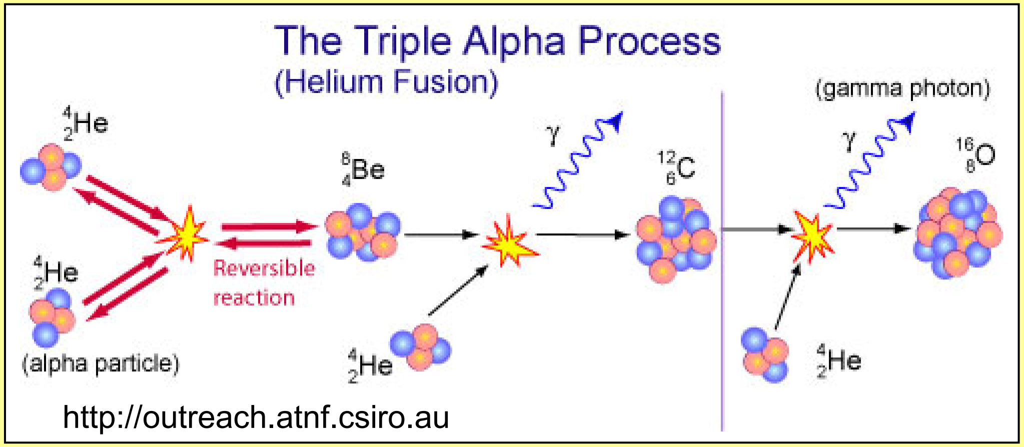
- Calculate also the transverse E1 response to investigate possible sources of the violation of Siegert's theorem

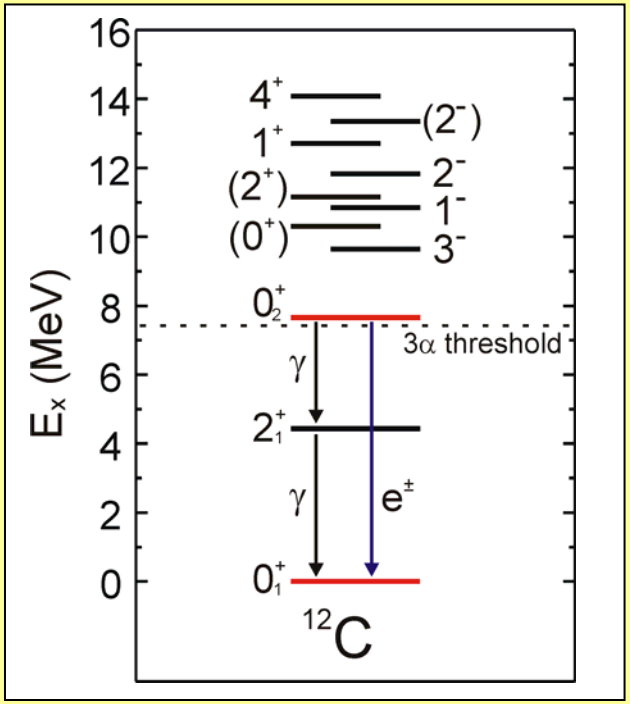
Hoyle state in ^{12}C

- Astrophysical motivation
- High-resolution electron scattering experiments
- Structure of the Hoyle state: a “BEC” ?
- Comparison with FMD and a-cluster model predictions

M. Chernykh, H. Feldmeier, T. Neff, PvNC and A. Richter, PRL 98, 032501 (2007)

Motivation: triple alpha process





- Reaction rate:

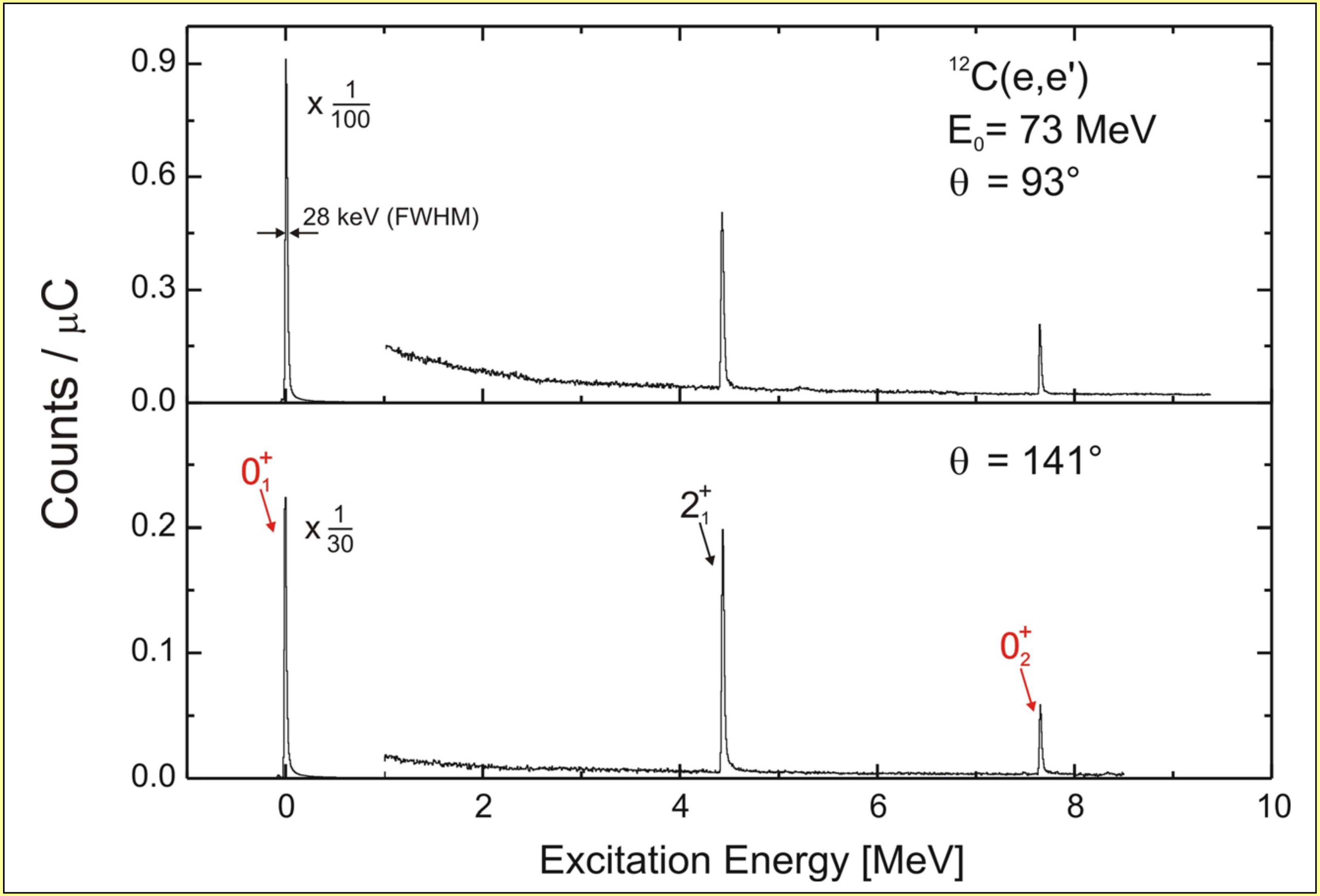
$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

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

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

- Electron scattering → M(E0) → extraction of Γ_π
- 0_1^+ and 0_2^+ (7.654 MeV) states in ^{12}C
  – density distributions
  – model predictions

Measured spectra



Theoretical approaches: 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

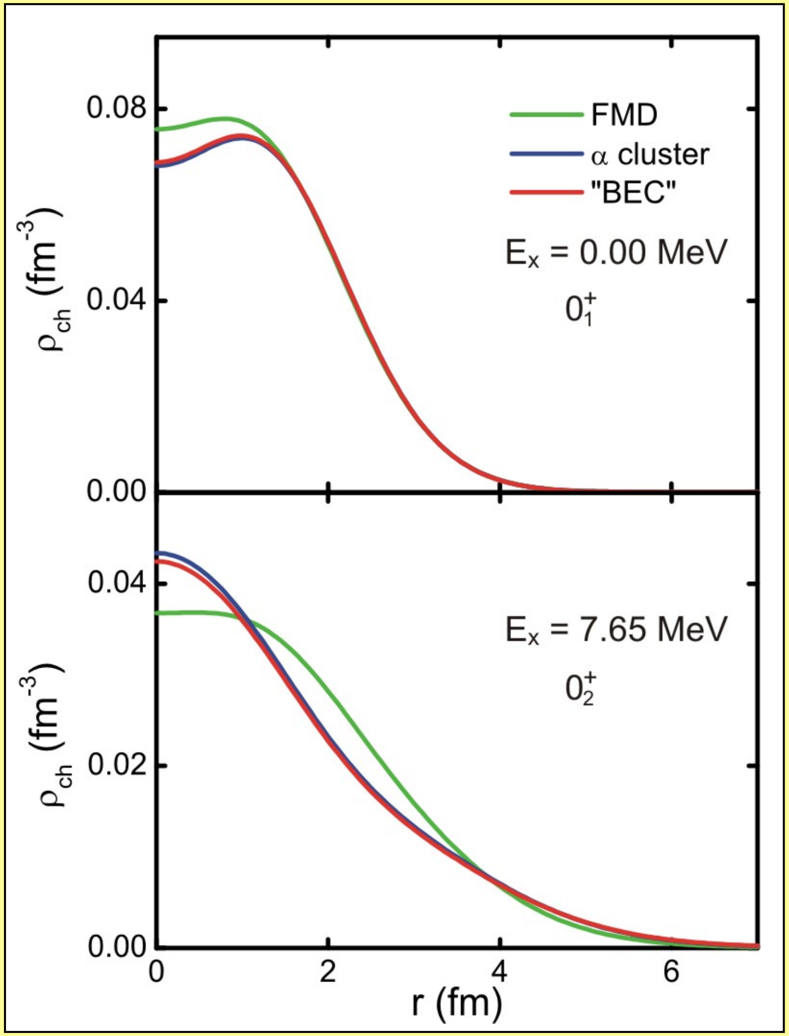
Theoretical approaches: α-cluster and "BEC" models

- α-cluster model
  - FMD wave function restricted to α-cluster triangle configurations only

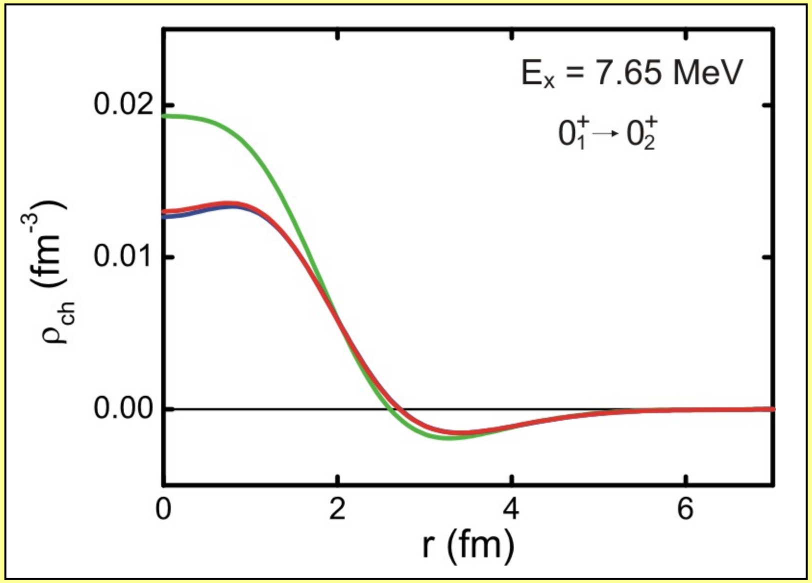
- "BEC" model
  - System of 3 ^{4}He nuclei in 0s state (like α condensate)
  - Hoyle state is a "dilute gas" of α particles

- Volkov interaction
  - Simple central interaction
  - Parameters adjusted to reproduce α binding energy, radius, $\alpha-\alpha$ scattering data and ground state energy of ^{12}C
  - Only reasonable for ^{4}He, ^{8}Be and ^{12}C nuclei

^{12}C densities

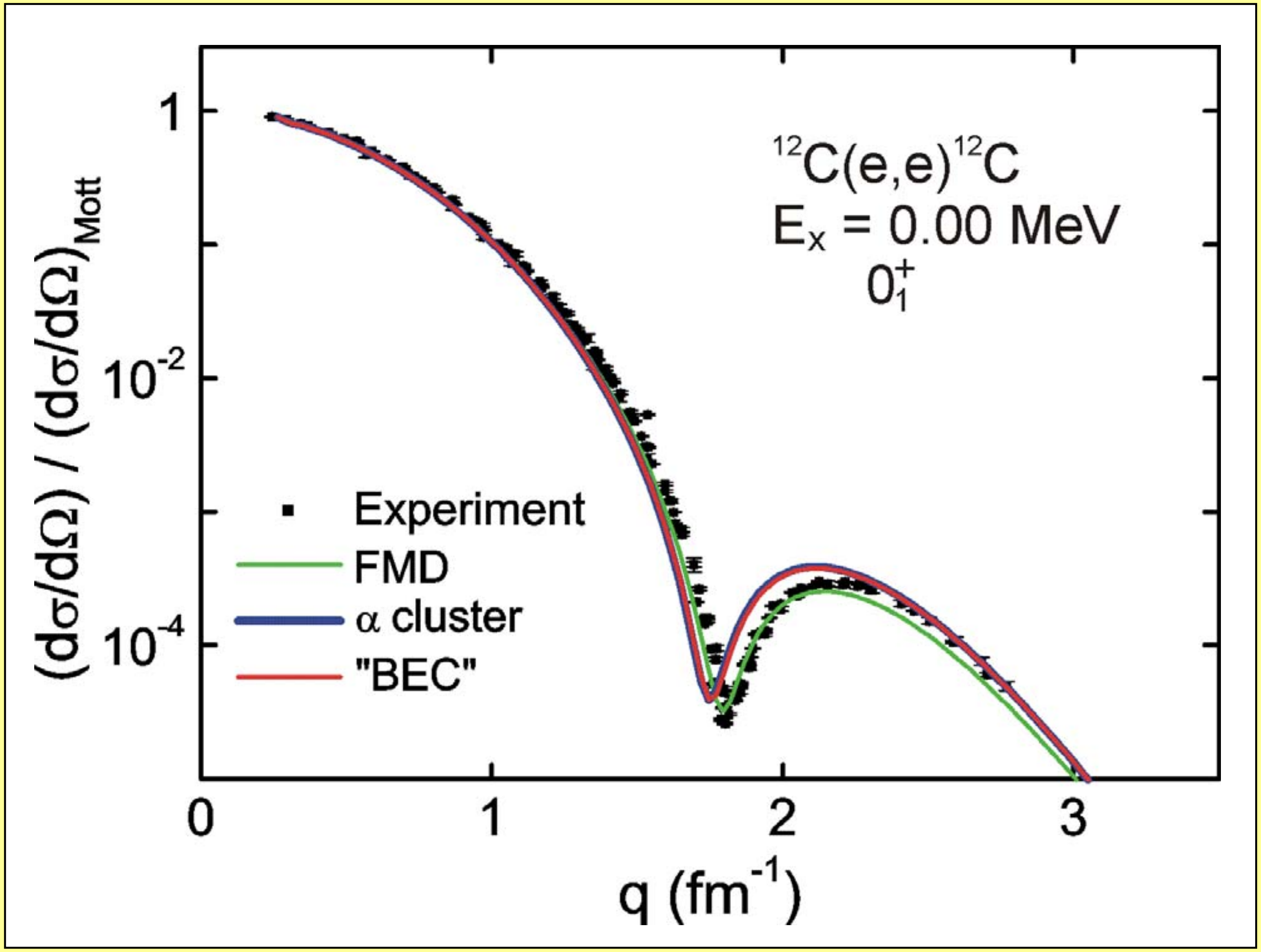


- Ground state density can be tested via elastic form factor



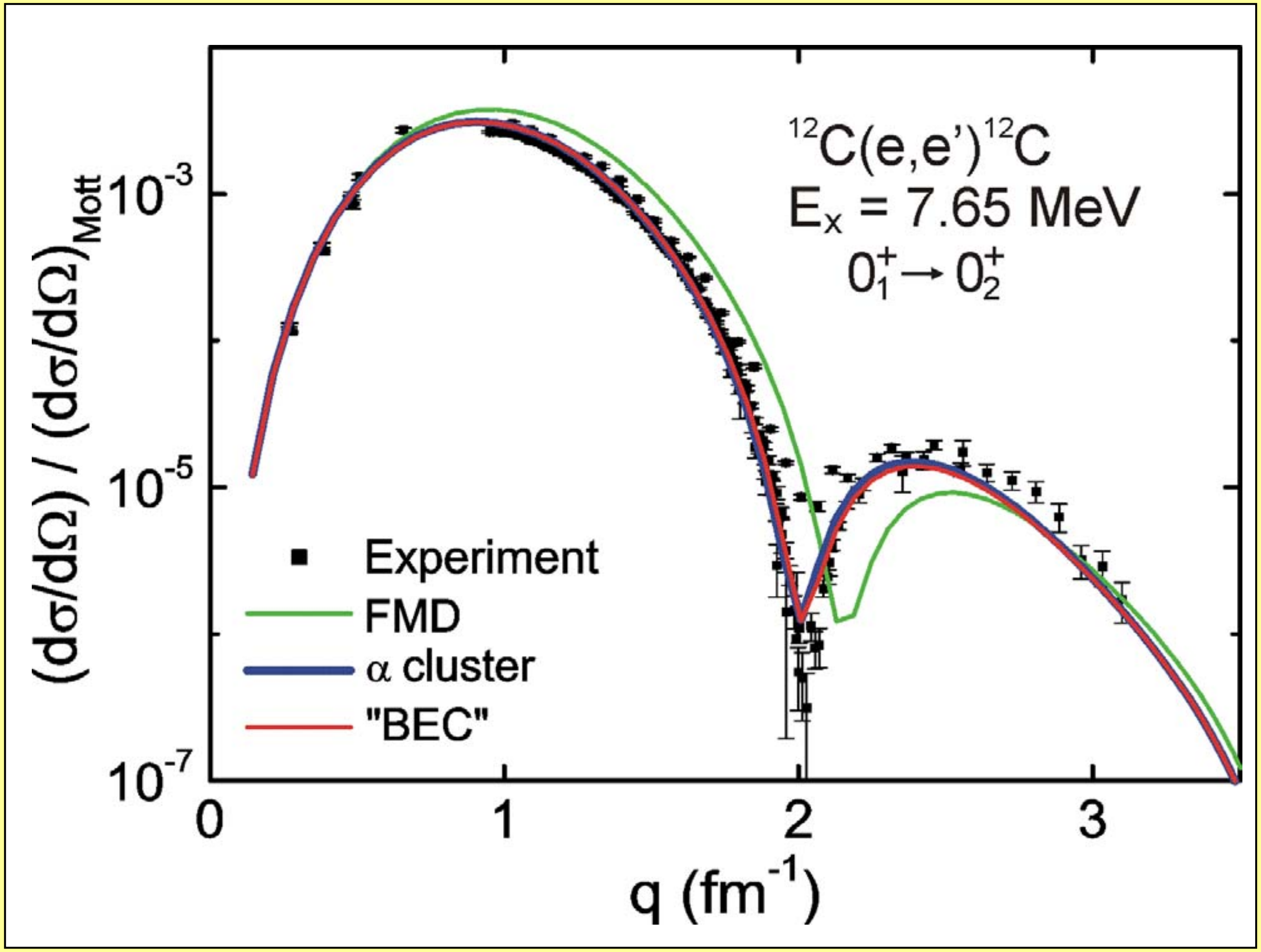
- Transition density can be tested via transition form factor

Elastic form factor



- H. Crannell, data compilation
- Described well by FMD

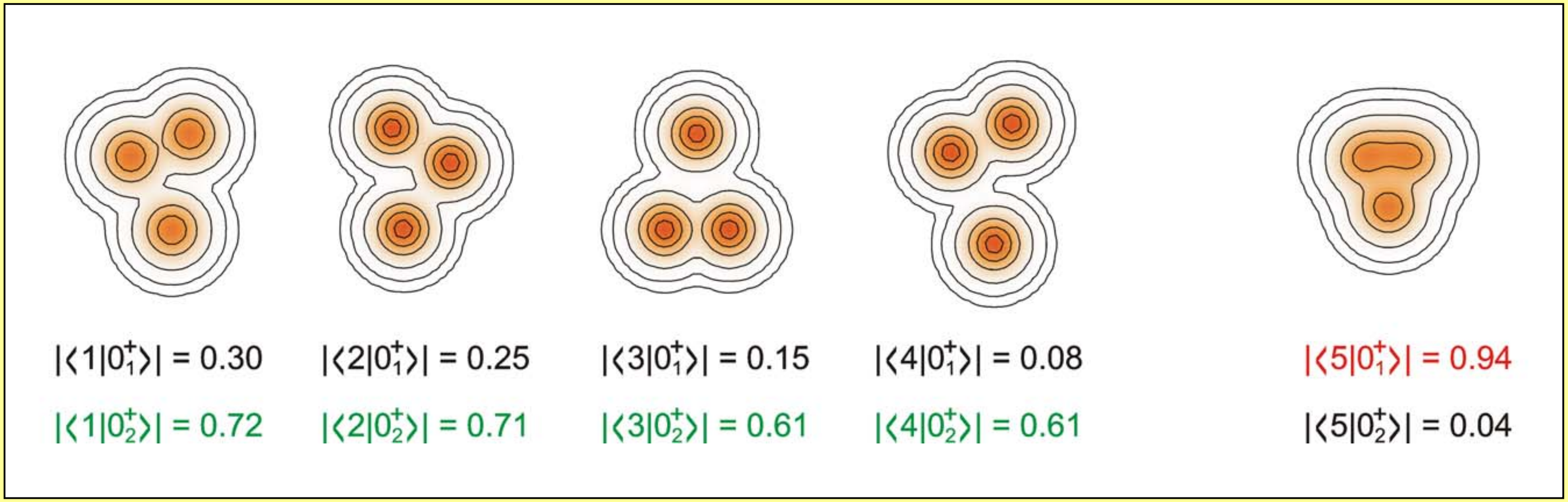
Transition form factor to the Hoyle state



- H. Crannell, data compilation, plus measurements at low q from Darmstadt
- Described better by α-cluster models
- FMD might be improved by taking α-α scattering data into account

What is actual structure of the Hoyle state ?

- Overlap with FMD basis states



- 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

Summary and outlook

- Summary
  - Hoyle state is not a true Bose-Einstein condensate
  - $^{8}Be + \alpha$ structure
- Outlook
  - ^{12}C: 0_3^+ and 2_2^+ states
  - ^{16}O: 0^+ states at 13 - 15 MeV
  - Improved E0 matrix element: Γ_π for decay of the Hoyle state

One-Level Approximation of *R*-Matrix Theory

$$\sigma_{\gamma,n}(E_\gamma) = \frac{\pi}{2\,k_\gamma^2}\,\frac{2J+1}{2I+1}\,\frac{\Gamma_\gamma\,\Gamma_n}{(E_\gamma - E_\lambda - \Delta(E_\gamma))^2 + \frac{\Gamma^2}{4}}$$

$$\Gamma_\gamma = \frac{16\,\pi}{9}\,e^2\,k_\gamma^3\,B(E1,k)\!\downarrow \qquad \Gamma_n = 2\,\sqrt{\epsilon\,(E_\gamma - S_n)}$$

$$\Delta(E_\gamma) = -\gamma^2\,(S(E_\gamma) - B_n) = 0$$

$$\Gamma_n \gg \Gamma_\gamma \qquad \Gamma \simeq \Gamma_n$$

$$\sigma_{\gamma,n}(E_\gamma) = \frac{16\,\pi^2}{9}\,\frac{e^2}{\hbar c}\,g_J\,B(E1,k)\!\downarrow\,\frac{E_\gamma\,\sqrt{\epsilon\,(E_\gamma - S_n)}}{(E_\gamma - E_R)^2 + \epsilon\,(E_\gamma - S_n)}$$

$$\Gamma_R(E_R) = 2\,\sqrt{\epsilon(E_R - S_n)}$$

One-Level Approximation of *R*-Matrix Theory

$$\sigma_{e,e'}(E_x) = const \times \frac{E_x \sqrt{\epsilon\,(E_x - S_n)}}{(E_x - E_R)^2 + \epsilon\,(E_x - S_n)}$$

$$\Gamma_R = 2\sqrt{\epsilon(E_R - S_n)}$$

Extraction of the B(C1,k) Transition Strength

$$\sqrt{B(C1,q)} = \sqrt{B(C1,0)}\,\left(1 - q^2\,\frac{R_{tr}^2}{10} + q^4\,\frac{R_{tr}^4}{280} - \ldots\right)$$

Siegert´s theorem: $B(E1,q) = (k/q)^2\,B(C1,q)$

at photon point (q = k) $B(E1,k) = B(C1,k)$

Extraction of the B(E1) Transition Strength