Nature of Mixed-Symmetry 2^+ States in ^{94}Mo from High-Resolution Electron and Proton Scattering and Line Shape of the First Excited $1/2^+$ State in ^{9}Be

Oleksiy Burda, 19.11.2007

- Motivation
- Experiments
- Results and microscopic interpretations
- Summary

Interacting Boson Model - 2

- Pairing of nucleons to s- / d- bosons

- F-spin: π boson: $F_z = 1/2$
  ν boson: $F_z = -1/2$

$$N_\pi , N_\nu : F_{max} = \frac{N_\pi + N_\nu}{2} \geq F \geq \frac{|N_\pi - N_\nu|}{2}$$

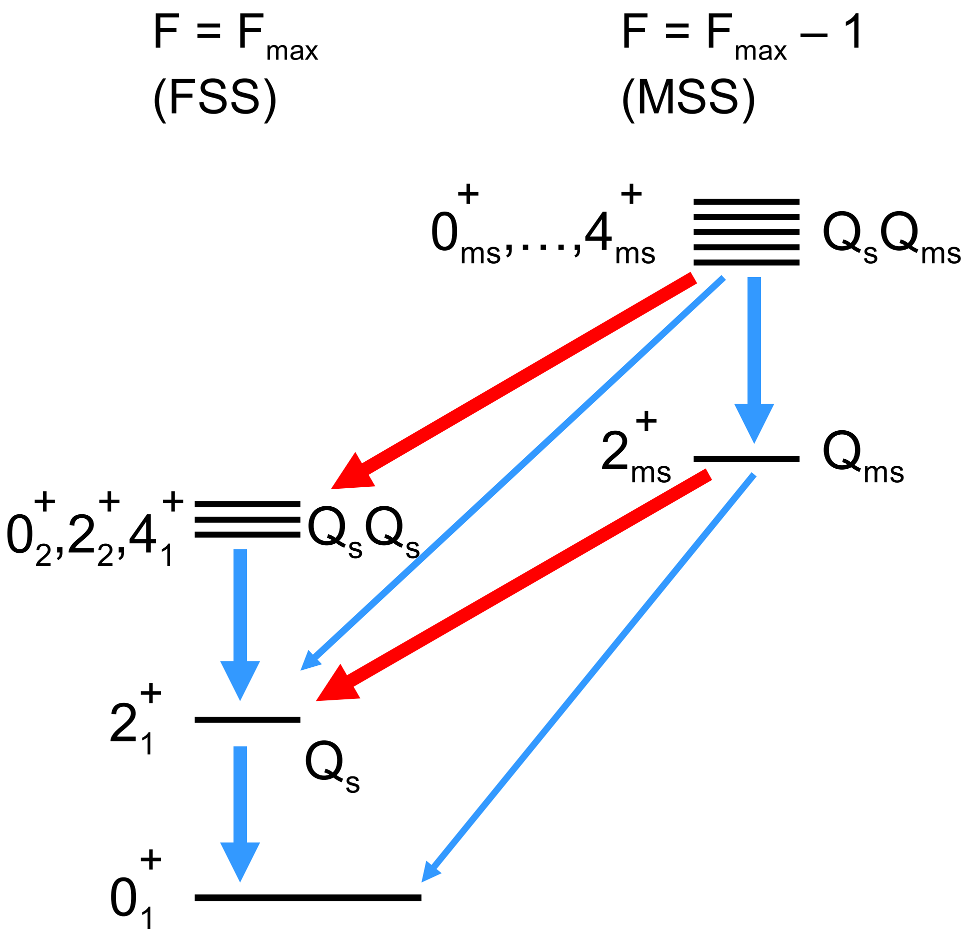
$\rightarrow$ $F = F_{max}$: fully symmetric states (FSS) $\rightarrow$ isoscalar

$\rightarrow$ $F < F_{max}$: mixed-symmetry states (MSS) $\rightarrow$ isovector

- Q-phonon scheme: $Q_s = Q_\pi + Q_\nu$ $\quad |2_1^+\rangle \propto Q_s \,|\, 0_1^+\rangle$

$$Q_{ms} = \frac{N}{2\,N_\pi} Q_\pi - \frac{N}{2\,N_\nu} Q_\nu \qquad |2_{ms}^+\rangle \propto Q_{ms} |\, 0_1^+\rangle$$

Signatures of MSS



- Strong **E2** transitions for decay of symmetric Q-phonon
- Weak E2 transitions for decay of ms Q-phonon
- Strong **M1** transitions for decay of ms states to symmetric states

- Test case ^{94}Mo

N. Pietralla et al., Phys. Rev. Lett. 83, 1303 (1999); Phys. Rev. Lett. 84, 3775 (2000)
C. Fransen et al., Phys. Lett. B 508, 219 (2001); Phys. Rev. C 67, 024307 (2003)

Why (e,e´) and (p,p´)?

- Study of one- and two-phonon 2^+ FSS and MSS with (e,e´) and (p,p´)

→ sensitive to one-phonon components of the wave functions

→ test of fundamental phonon character

→ isoscalar / isovector decomposition

→ purity of two-phonon states

Experiments

- High resolution required to resolve all 2^+ states below 4 MeV

- Lateral dispersion matching technique

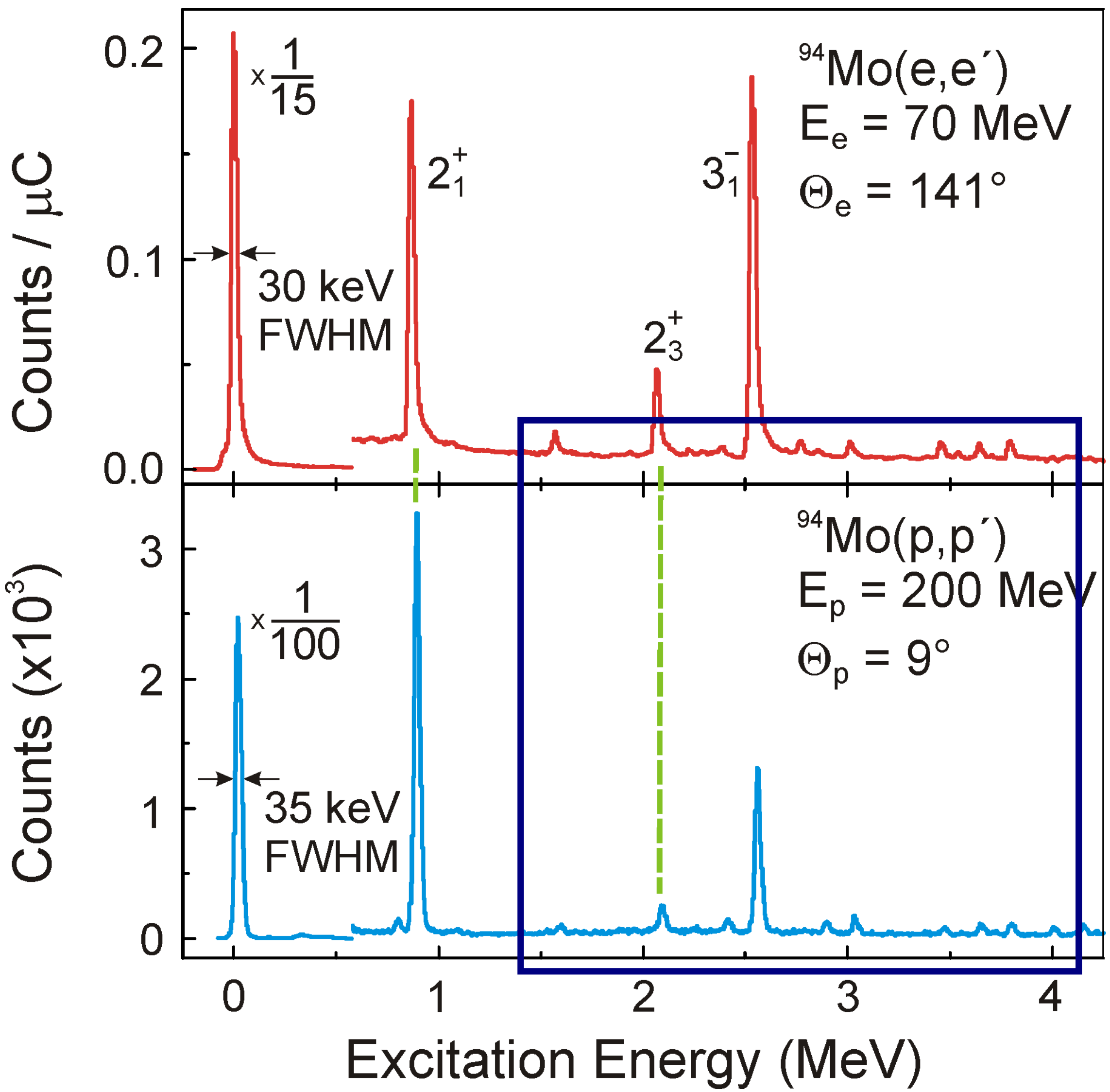
- (e,e´):
  S-DALINAC, TU Darmstadt

  E_e = 70 MeV
  Θ_e = 93° – 165°
  ΔE = 30 keV (FWHM)

  (p,p´):
  iThemba LABS

  E_p = 200 MeV
  Θ_p = 4.5° – 26°
  ΔE = 35 keV (FWHM)

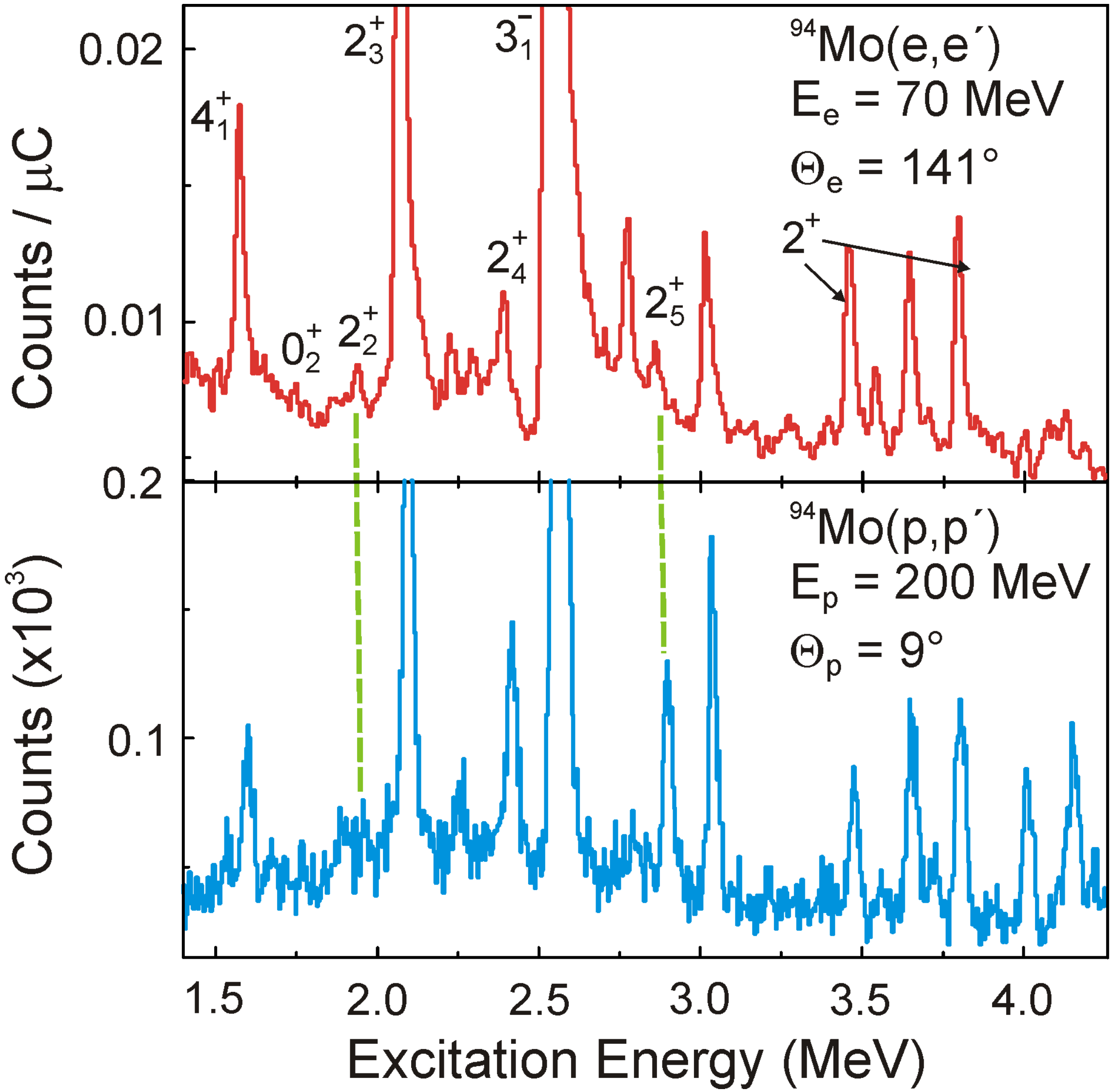
Data: Strong Transitions



S-DALINAC

iThemba LABS

Data: Weak Transitions



S-DALINAC

iThemba LABS

Theoretical Calculation

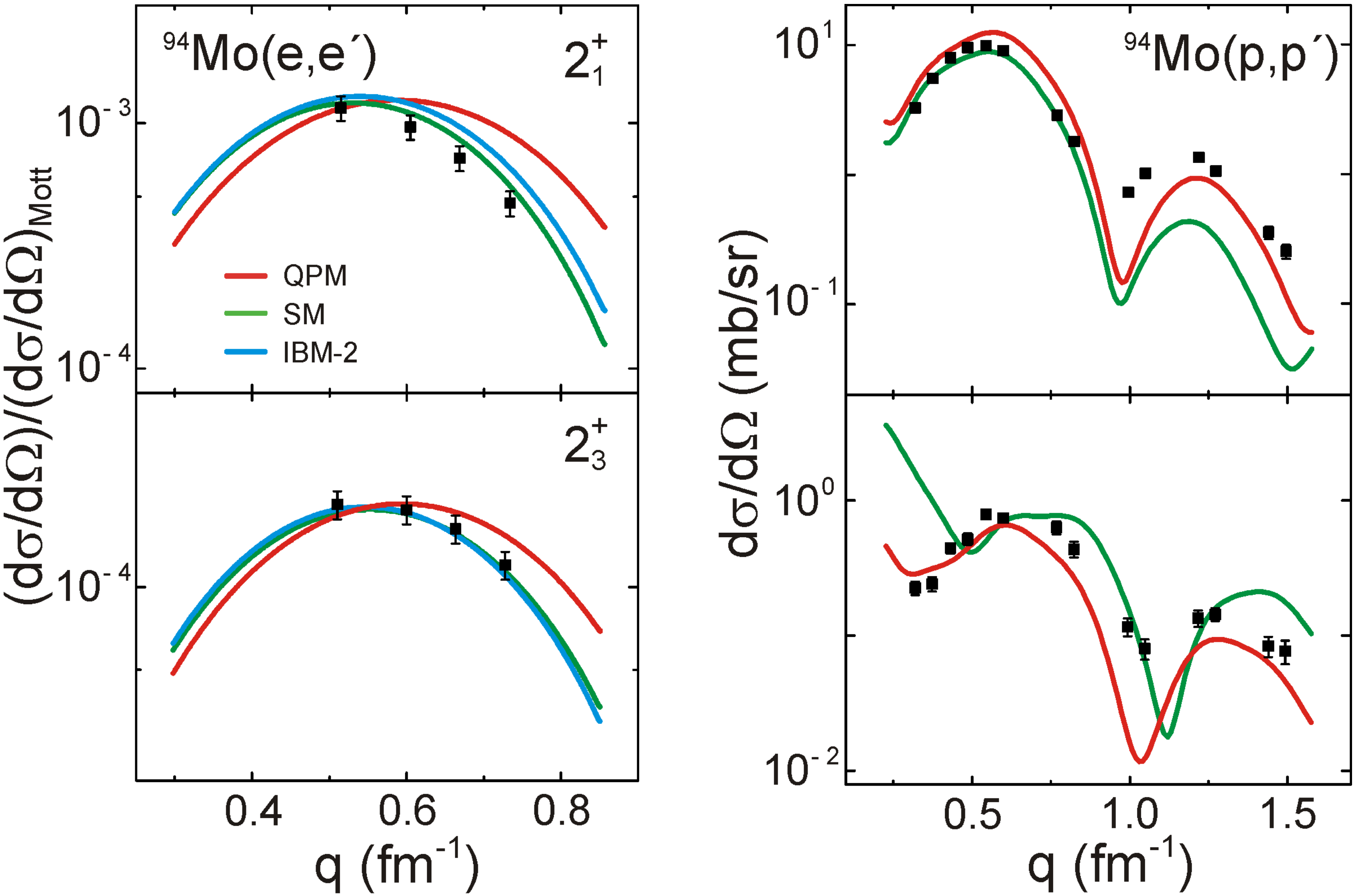
- Quasiparticle Phonon Model (QPM)
  → full (up to 3 phonons)
  → pure one- or two-phonon states

- Shell Model (SM)
  → ^{88}Sr core / $V_{low\text{-}k}$

- IBM-2
  → transition densities from SM
  → U(5) limit to describe dominant transitions

- Cross Section
  → DWBA / Love-Franey effective
  projectile-target interaction for (p,p´)

One-Phonon FSS and MSS



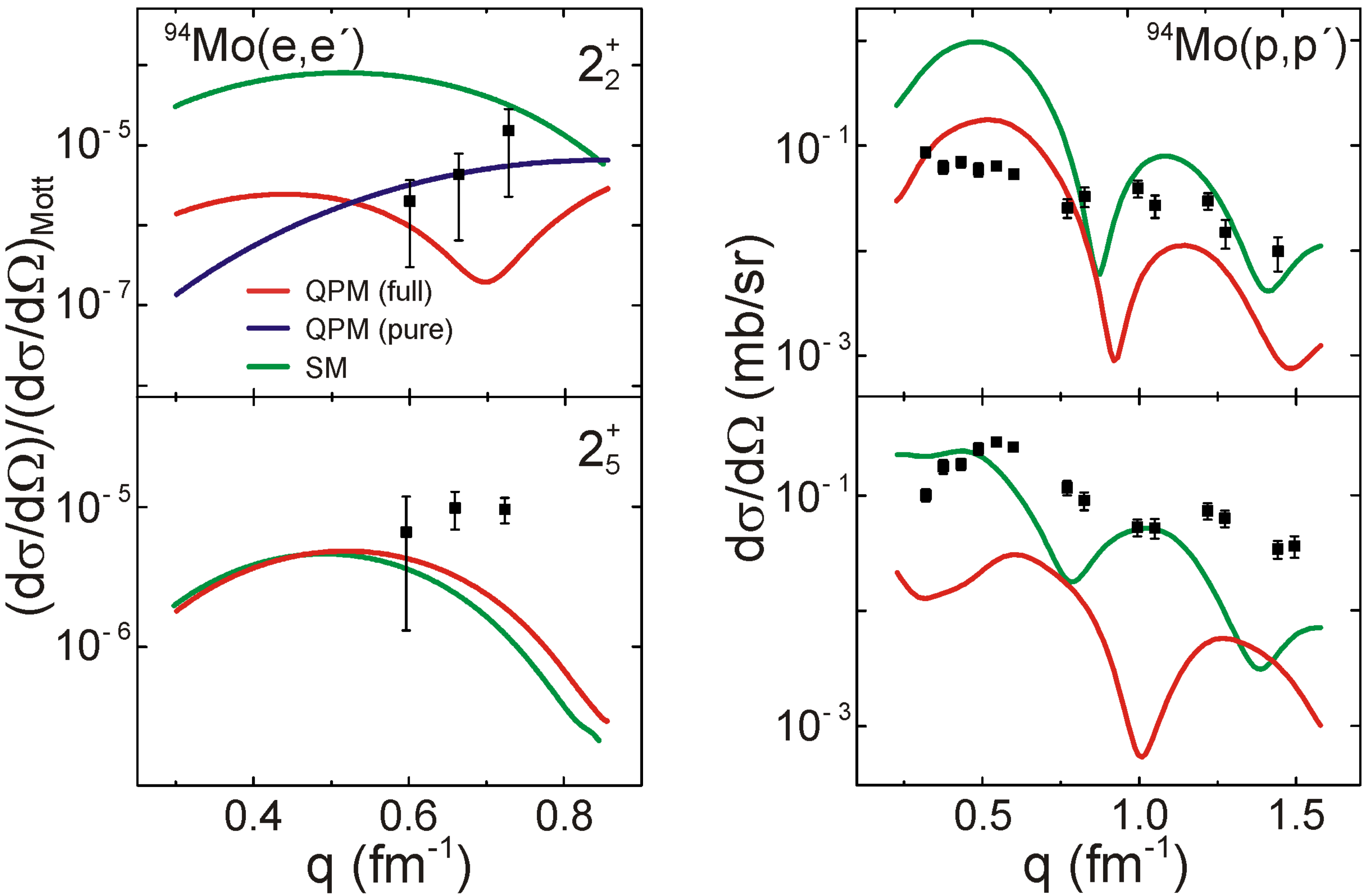
- one-phonon character confirmed

Wave Functions of One-Phonon FSS and MSS

Main configuration	$2^+_{1,\mathrm{FSS}}$		$2^+_{3,\mathrm{MSS}}$	
	QPM	SM	QPM	SM
$\pi\,(1g_{9/2}\,1g_{9/2})$	0.60	0.39	0.64	0.51
$\nu\,(2d_{5/2}\,2d_{5/2})$	0.70	0.55	-0.71	-0.33

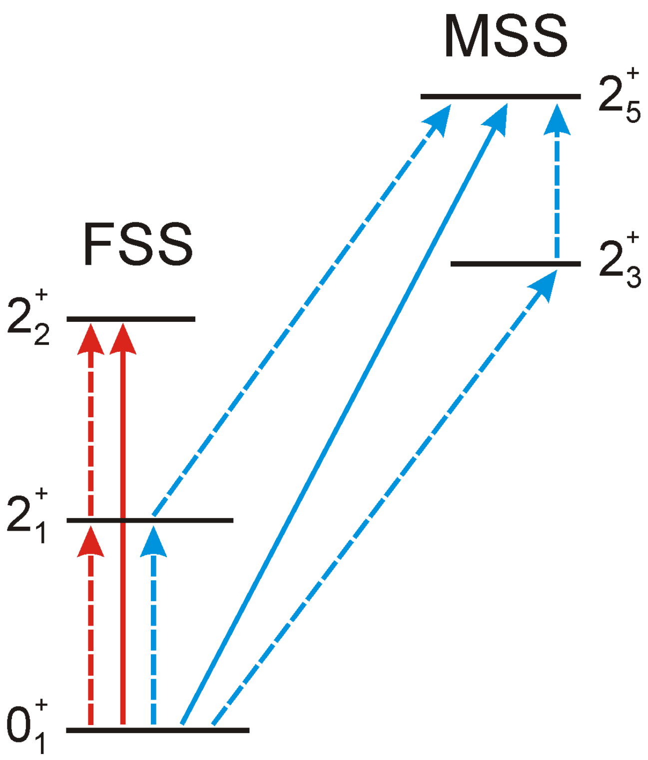
- FSS $\rightarrow$ isoscalar
- MSS $\rightarrow$ isovector

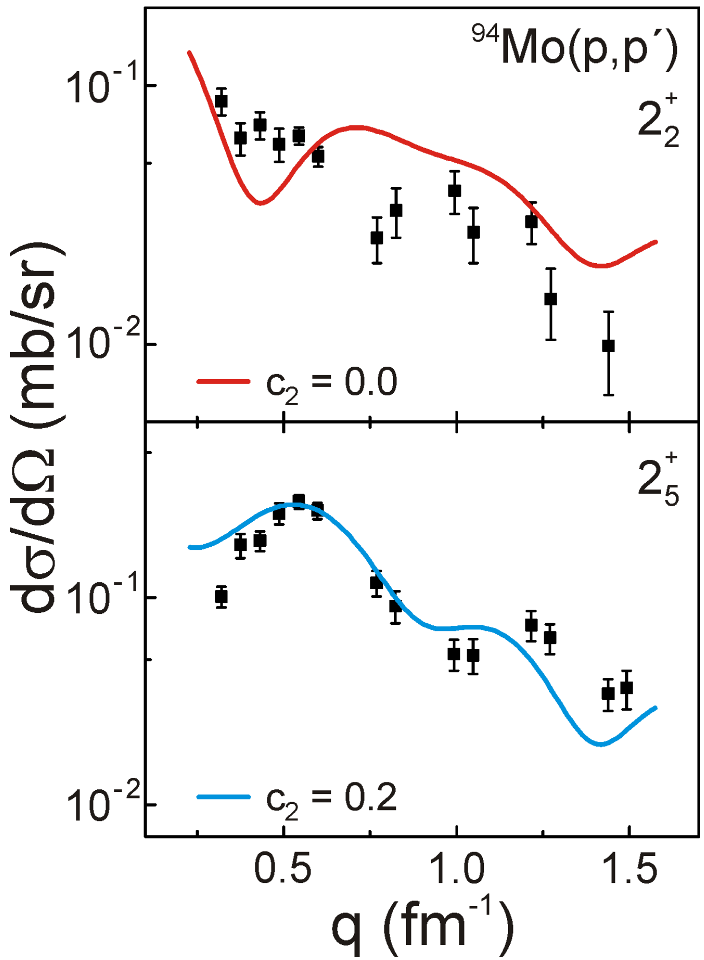
Two-Phonon FSS and MSS



- pure two-phonon state
- ~10% one-phonon admixtures in MSS
- two-step contributions ?

Coupled-Channel Analysis





- pure two-phonon FSS confirmed
- admixture to two-phonon MSS confirmed

Summary

- Study of one- and two-phonon FSS and MSS 2^+ states in ^{94}Mo with high-resolution (e,e´) and (p,p´) experiments

- Combined analysis with microscopic models reveals:

  → dominant one-phonon character of 2_1^+ and 2_3^+ states

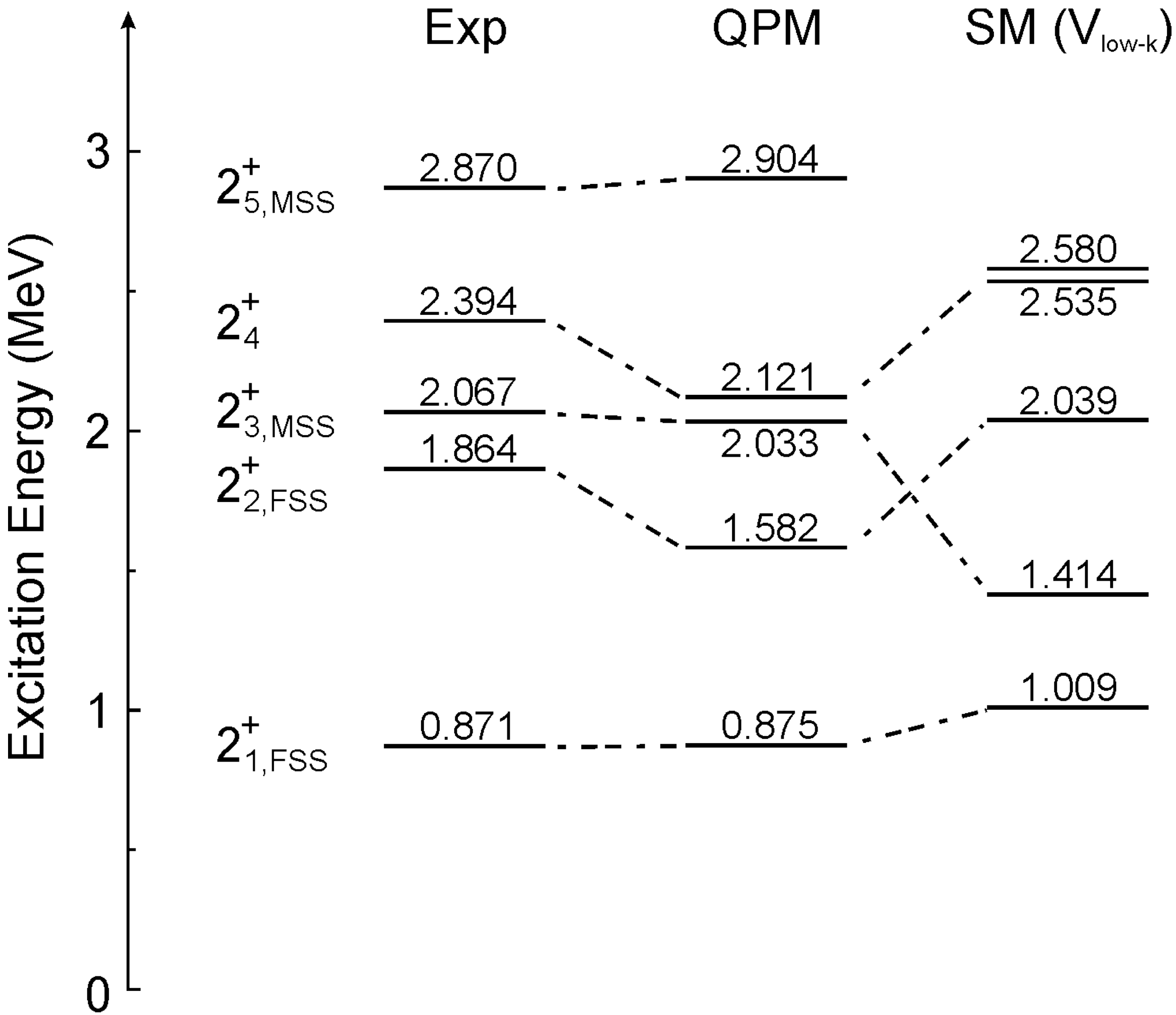
  → isovector character of one-phonon MSS within the valence shell

  → quantitatively consistent conclusions after inclusion of two-step processes in (p,p´) cross sections

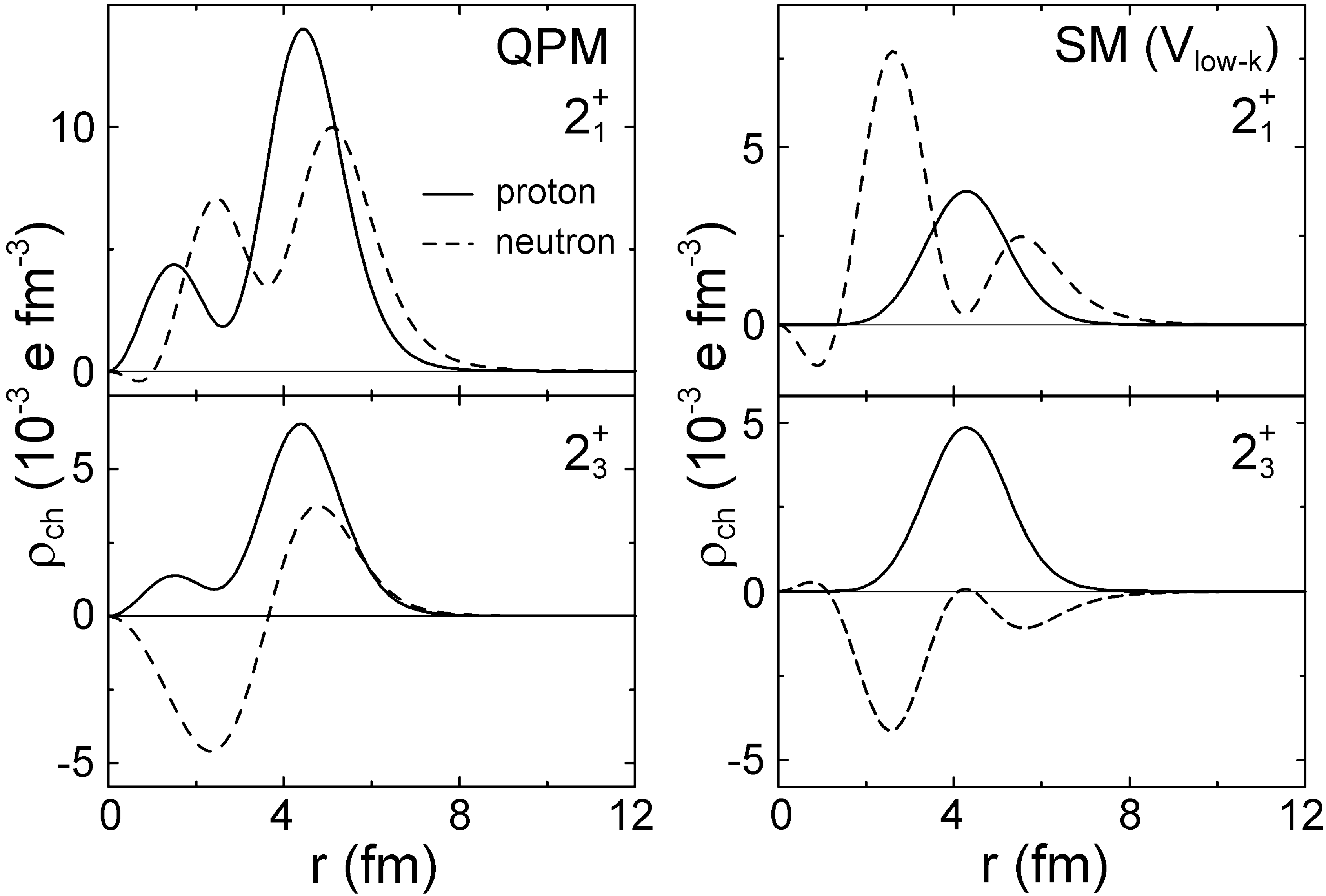
  → two-phonon FSS quite pure

  → dominant two-phonon character of two-phonon MSS

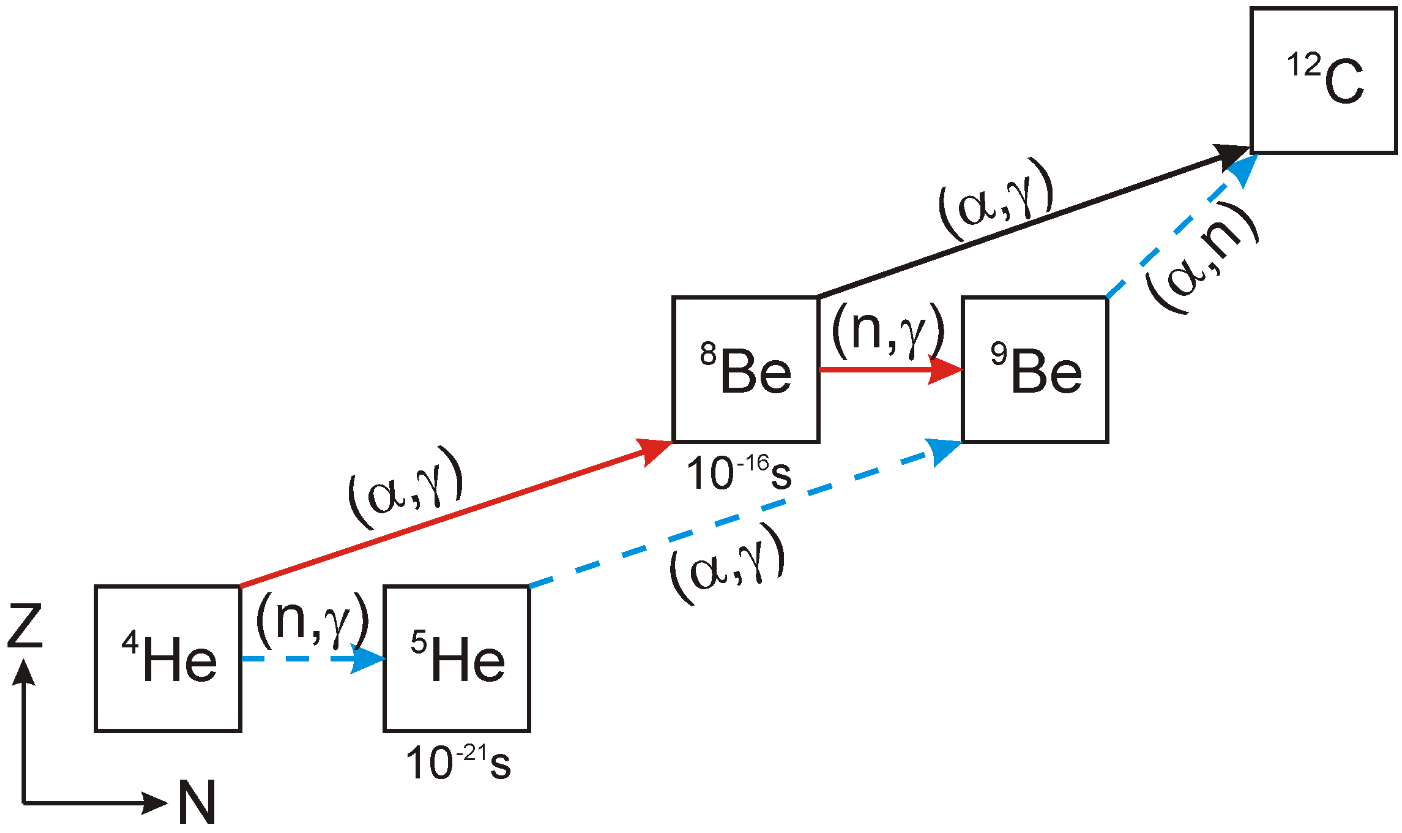
Mo94: Theoretical Predictions



Mo94: Radial Transition Charge Densities

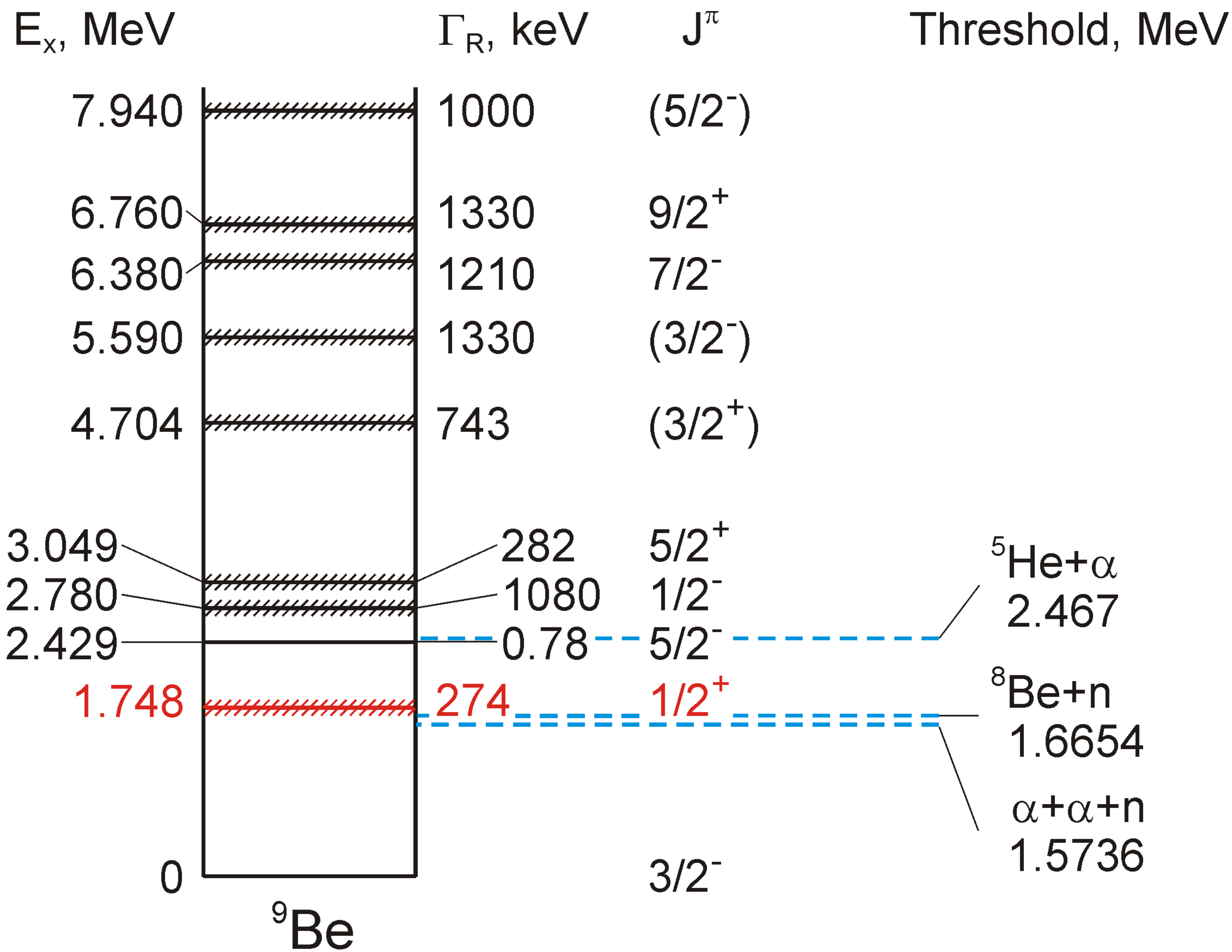


Possible Role of ^{9}Be in the Production of ^{12}C



- 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

$J^{\pi} = 1/2^{+}$ State at Threshold

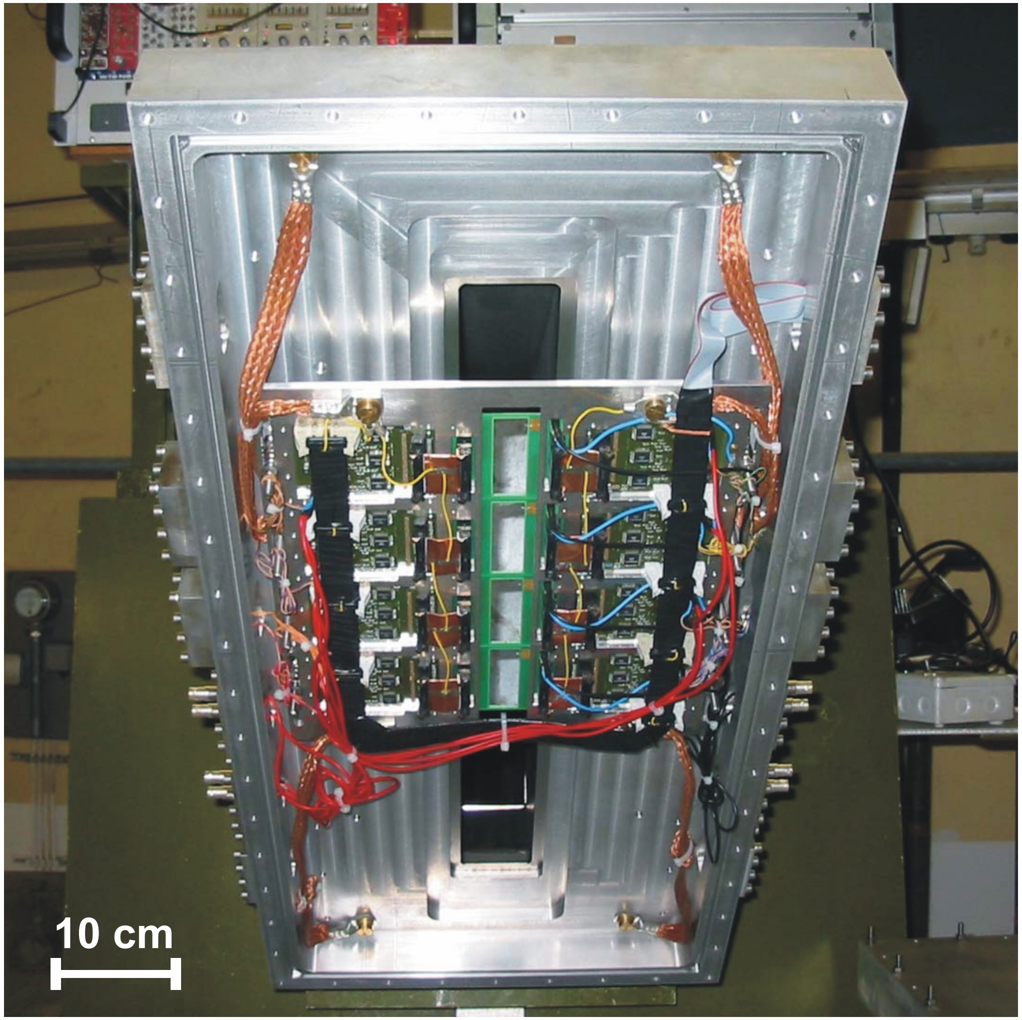


	Real photons exp.	(e,e′)		Reanalysis of [78]
	Ref. [77]	Ref. [78]	Ref. [79]	by Barker [81]
E_R, MeV	1.75(1)	1.684(7)	1.68(15)	1.7316
Γ_R, keV	283(42)	217(10)	200(20)	280
$B(E1)\uparrow$, e^2fm^2	0.0535(35)	0.027(2)	0.034(3)	0.0685

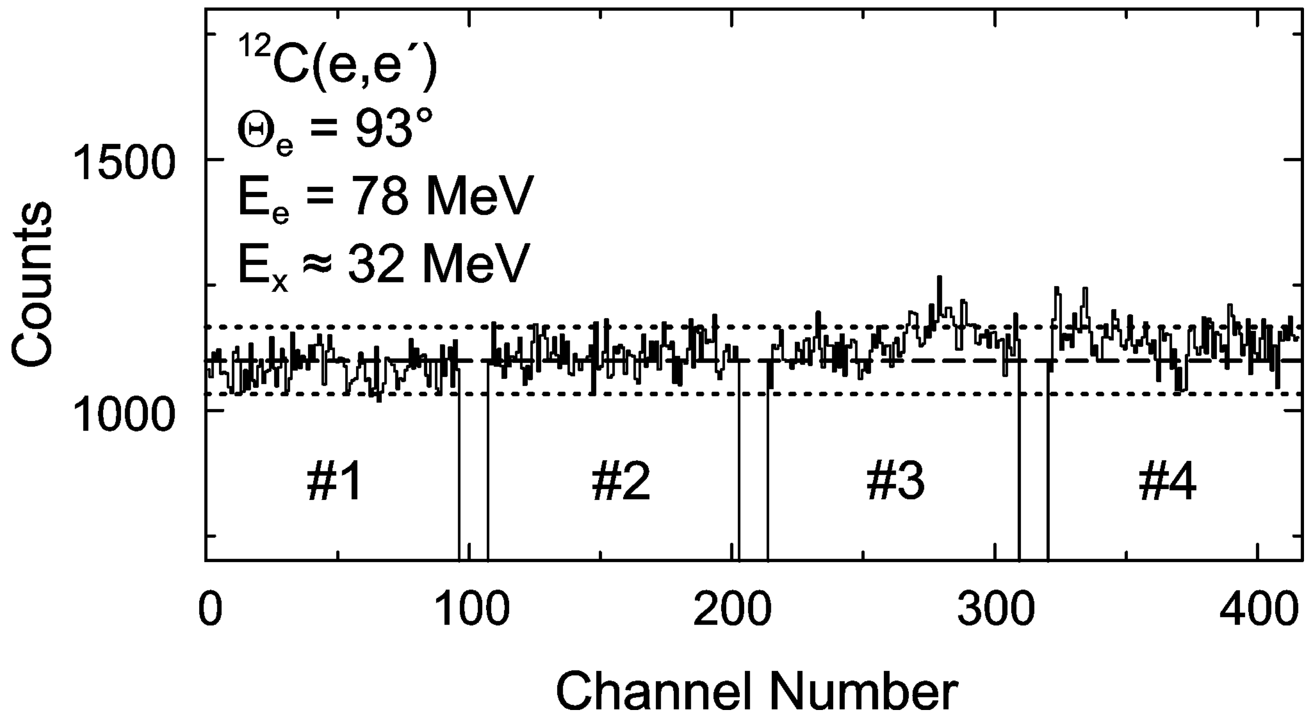
	present data		old data [78]
	73 MeV, 93°	73 MeV, 141°	49 MeV, 117°
E_R, MeV	1.746(8)	1.768(12)	1.737(10)
Γ_R, keV	265(10)	308(20)	275(14)

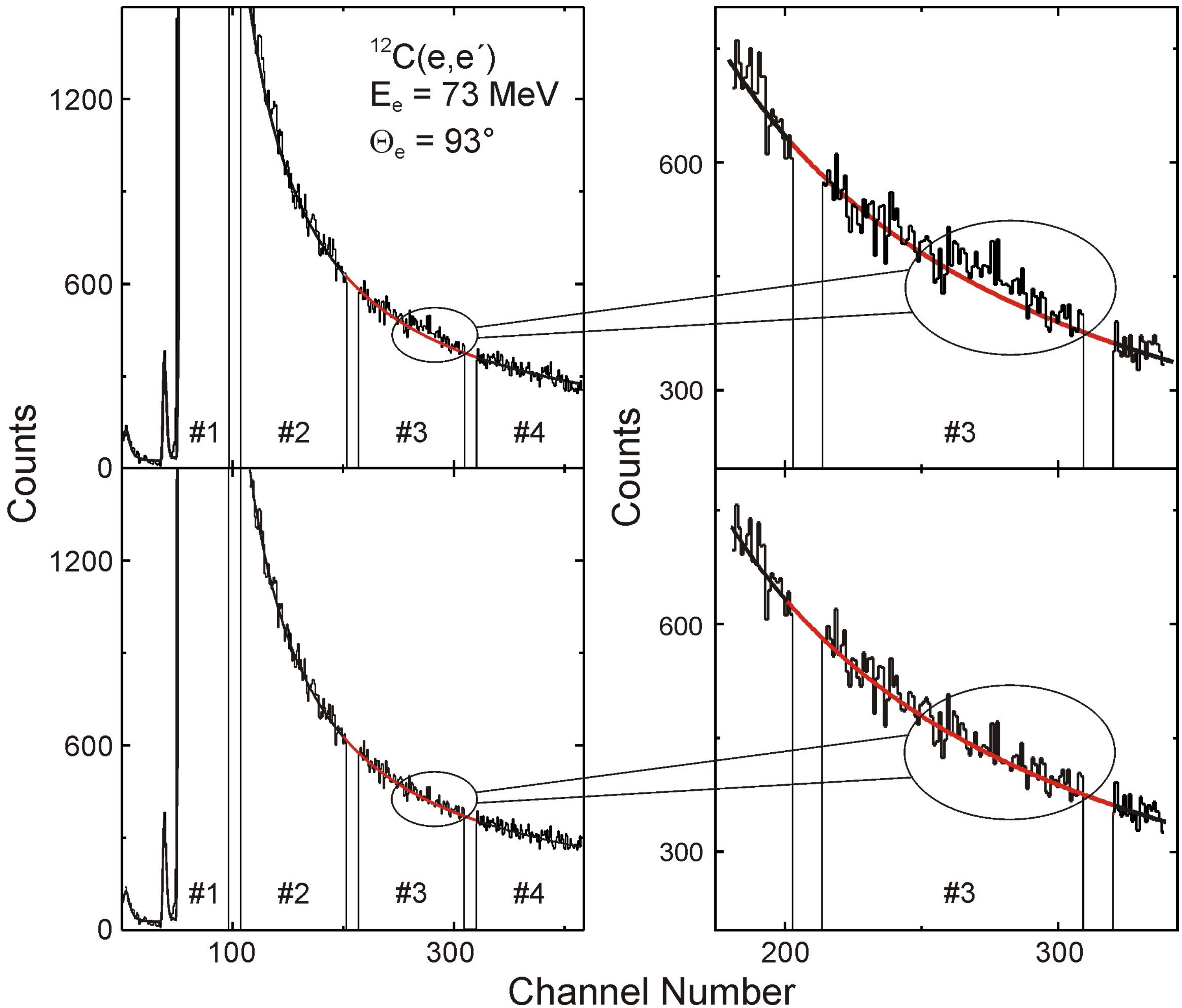
Lintott Spectrometer

Focal Plane Detector System



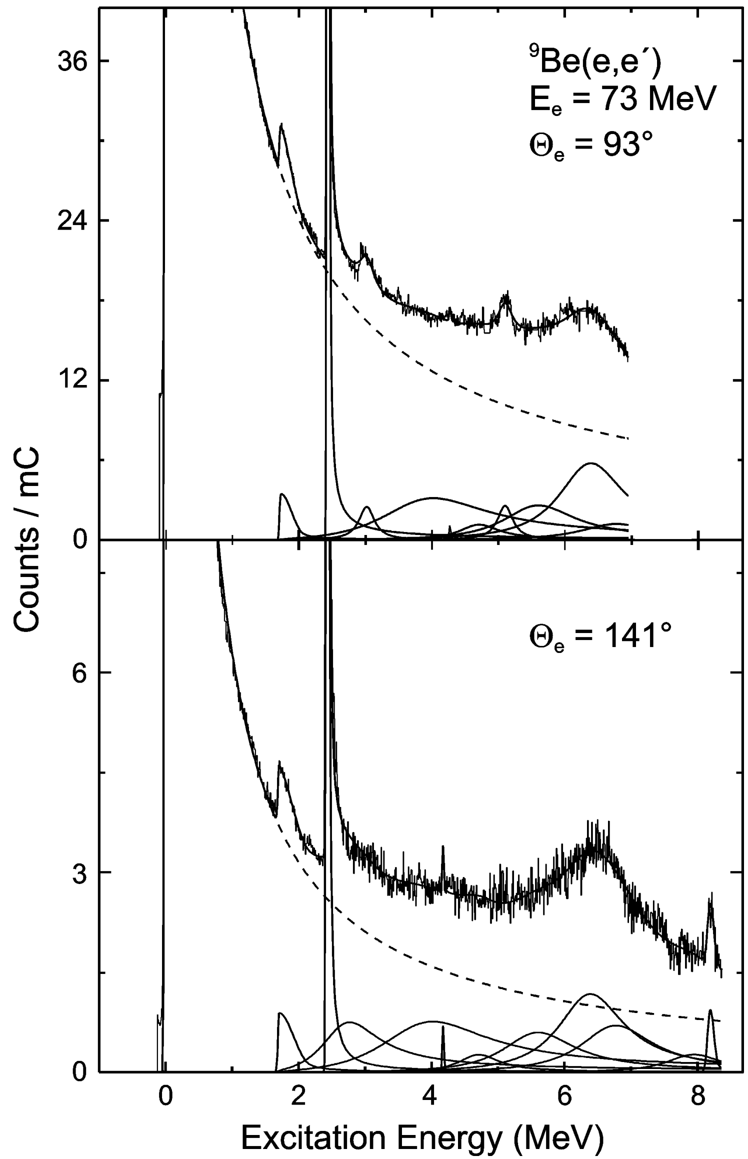
- Si microstrip detector system: 4 modules, each 96 strips with pitch of 650 μ m
- Count rate up to 100 kHz
- Energy resolution 1.5×10^{-4}


$^{12}C(e,e')$
$\Theta_e = 93°$
$E_e = 78$ MeV
$E_x \approx 32$ MeV
1500
1000
Counts
#1
#2
#3
#4
0
100
200
300
400
Channel Number

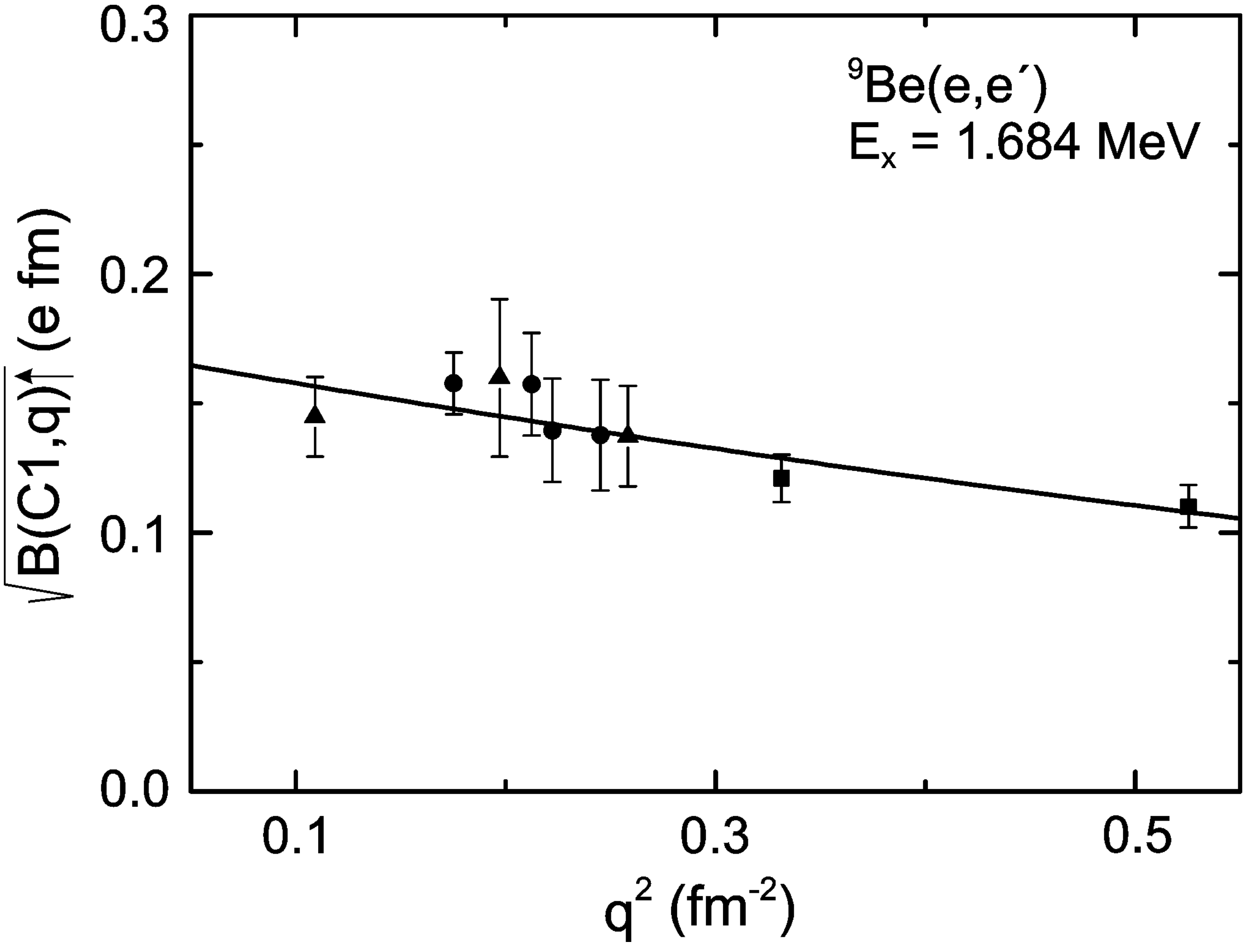


$^{12}C(e,e')$
E_e = 73 MeV
Θ_e = 93°
1200
600
0
300
#1
#2
#3
#4
100
200
300
Counts
Channel Number

Data



^{9}Be(e,e´)
E_e = 73 MeV
Θ_e = 93°
Θ_e = 141°
36
24
12
0
6
3
0
0
2
4
6
8
Counts / mC
Excitation Energy (MeV)



^{9}Be(e,e´)
E_x = 1.684 MeV
$\sqrt{B(C1,q)\uparrow}$ (e fm)
q^2 (fm^{-2})
0.0
0.1
0.2
0.3
0.1
0.3
0.5

$$A + a \longrightarrow B^* \longrightarrow \begin{cases} C + c \\ D + d \\ \ldots \end{cases}$$

$$\sigma(E_B) = const \cdot \left| \left\langle C + c \,\middle|\, \hat{O} \,\middle|\, A + a \right\rangle \right|^2 \cdot \rho(E_B)$$

$$\sigma_{a,c}(E) = \frac{\pi}{2\,k_a^2}\, g_J \,\frac{\Gamma_a\,\Gamma_c}{\left(E - E_\lambda - \Delta(E)\right)^2 + \frac{\Gamma^2}{4}}$$

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

$$g_J = \frac{2J+1}{2I+1}$$

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

$$\Gamma_\gamma = \frac{16\,\pi}{9}\, e^2\, k_\gamma^3\, B(E1,k)\!\downarrow$$

$$\Gamma_n = 2\,\sqrt{\epsilon\,(E_\gamma - S_n)}$$

$$\Delta = 0$$

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

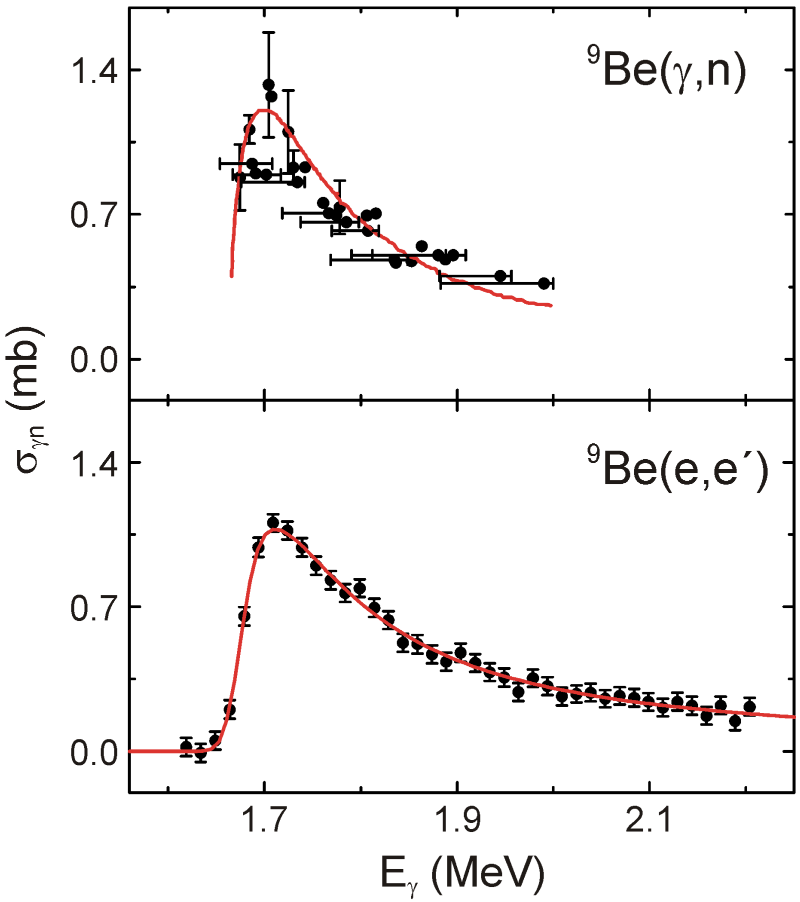
$$E_R = E_\lambda + \Delta(E_R)$$

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

$$\sigma_{e,e'}(E_x) = \frac{16\,\pi^2}{9}\,\frac{e^2}{\hbar c}\,B(E1,q)\!\uparrow\;\frac{E_x\,\sqrt{\epsilon\,(E_x - S_n)}}{(E_x - E_R)^2 + \epsilon\,(E_x - S_n)}$$

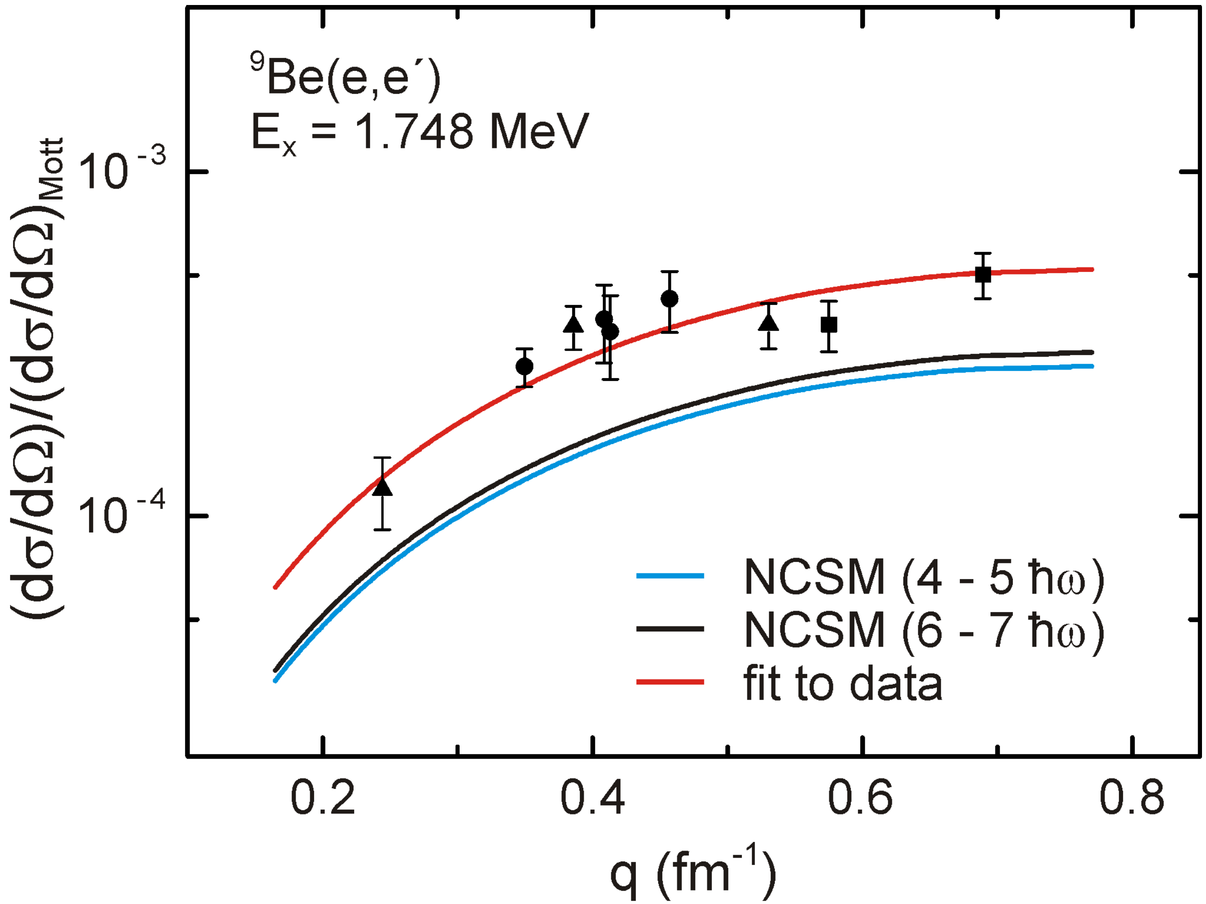
$$\sqrt{B(C1,q)} = \sqrt{B(C1,k)}\,\left(1 - q^2\,\frac{R_{tr}^2}{10} + q^4\,\frac{R_{tr}^4}{280} - \ldots\right)$$

Comparison: $^{9}Be(\gamma,n)$ and $^{9}Be(e,e')$

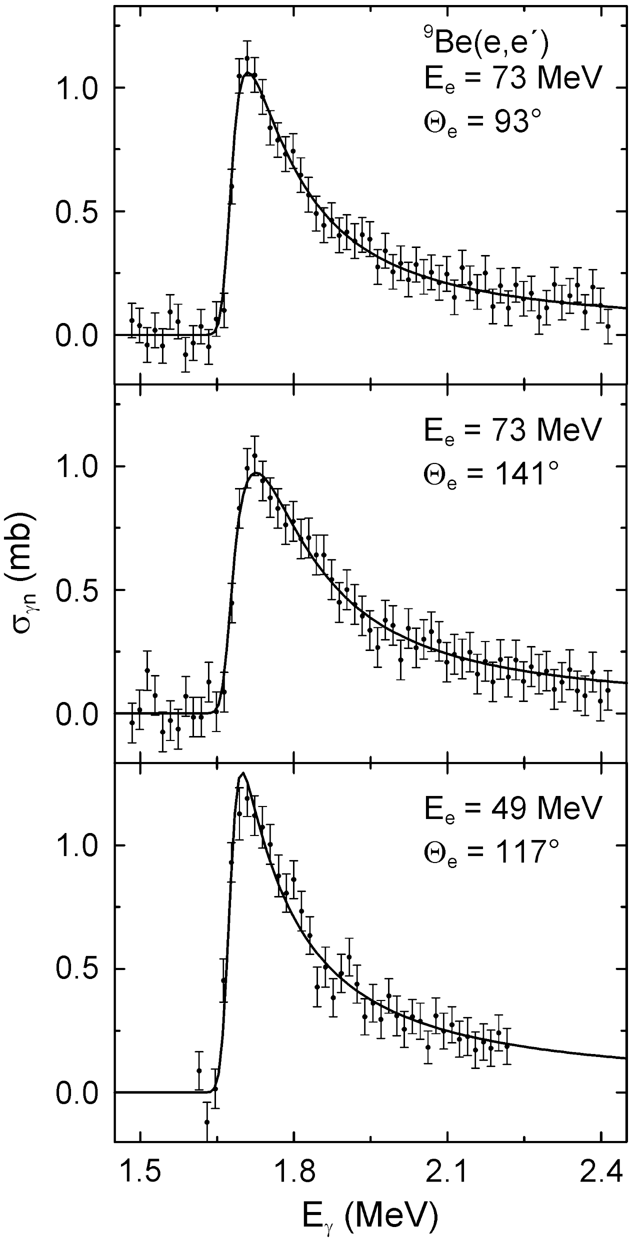


- Final values: E_x = 1.748(6) MeV and Γ = 274(8) keV of $J^\pi = 1/2^+$ resonance
  - For T_9 = 0.1 – 3 K this resonance determines exclusively $^{4}He(\alpha,\gamma)^{8}Be(n,\gamma)^{9}Be$ chain
  - Determined reaction rate differs up to 20% from adopted values

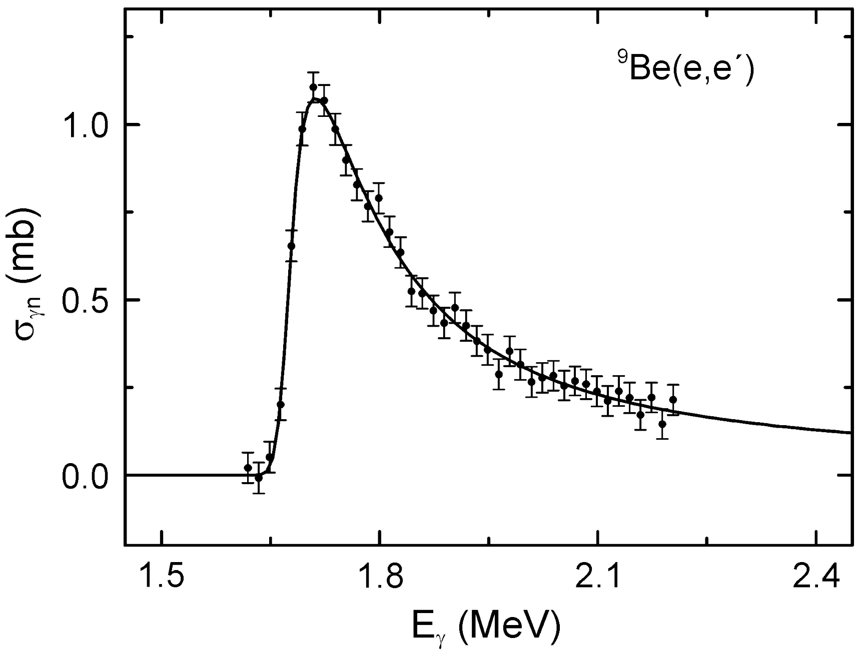
Form Factor of the $J^{\pi} = 1/2^{+}$ State



- NCSM: correct q dependence but difference in magnitude compared to the data (C. Forssén)
- B(C1) ≠ B(E1) at photon point $k = q$
  → violation of Siegert theorem ?



^{9}Be(e,e´)
E_e = 73 MeV
Θ_e = 93°
E_e = 73 MeV
Θ_e = 141°
E_e = 49 MeV
Θ_e = 117°
$\sigma_{\gamma n}$ (mb)
0.0
0.5
1.0
1.5
1.8
2.1
2.4
E_γ (MeV)



^{9}Be(e,e´)
$\sigma_{\gamma n}$ (mb)
0.0
0.5
1.0
1.5
1.8
2.1
2.4
E_γ (MeV)