Scuola Raimondo Anni

Electro-weak probes in Nuclear Physics

Electron scattering

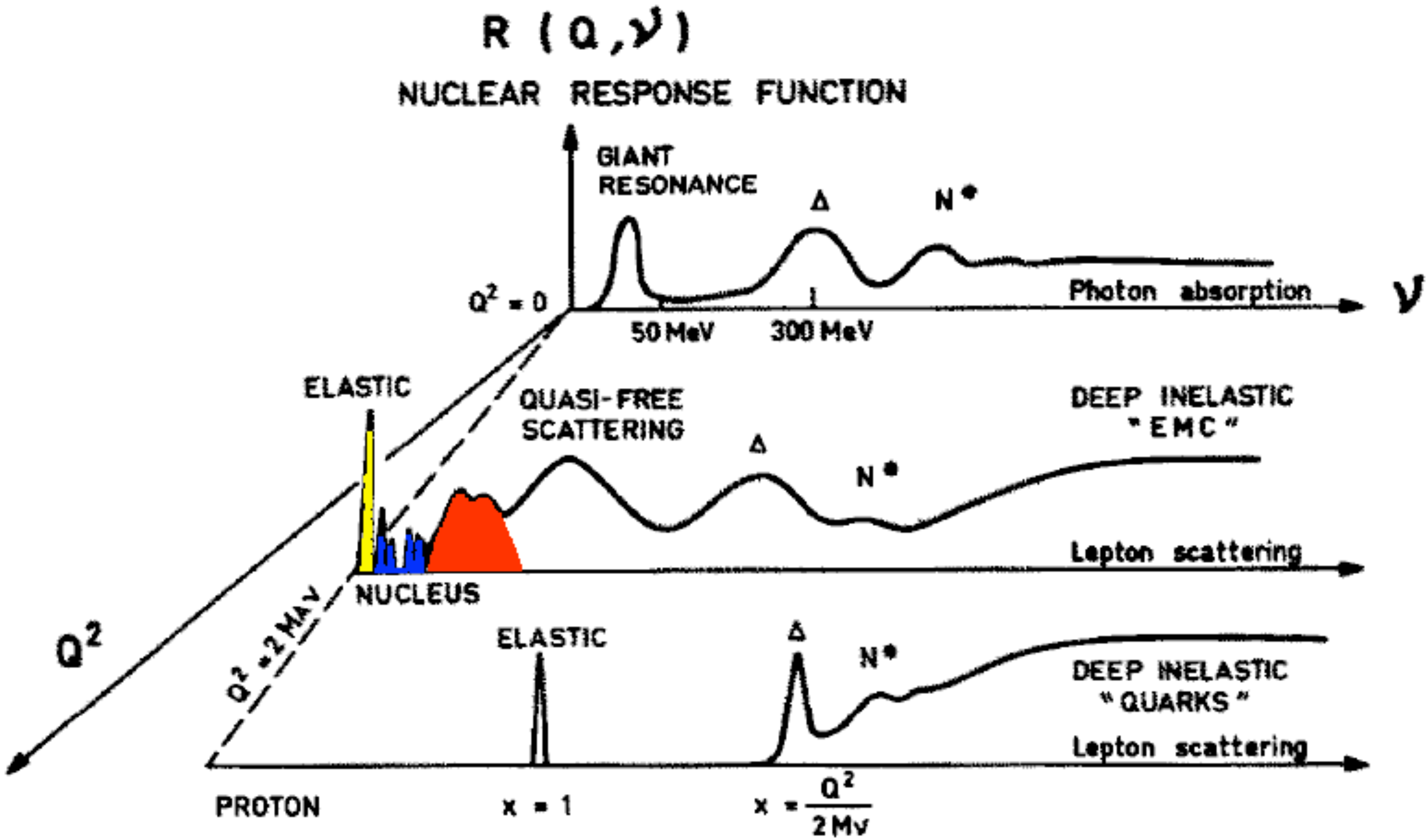
(from ground state to giant resonances)

Antonio M. Lallena

Universidad de Granada

Otranto, 2013

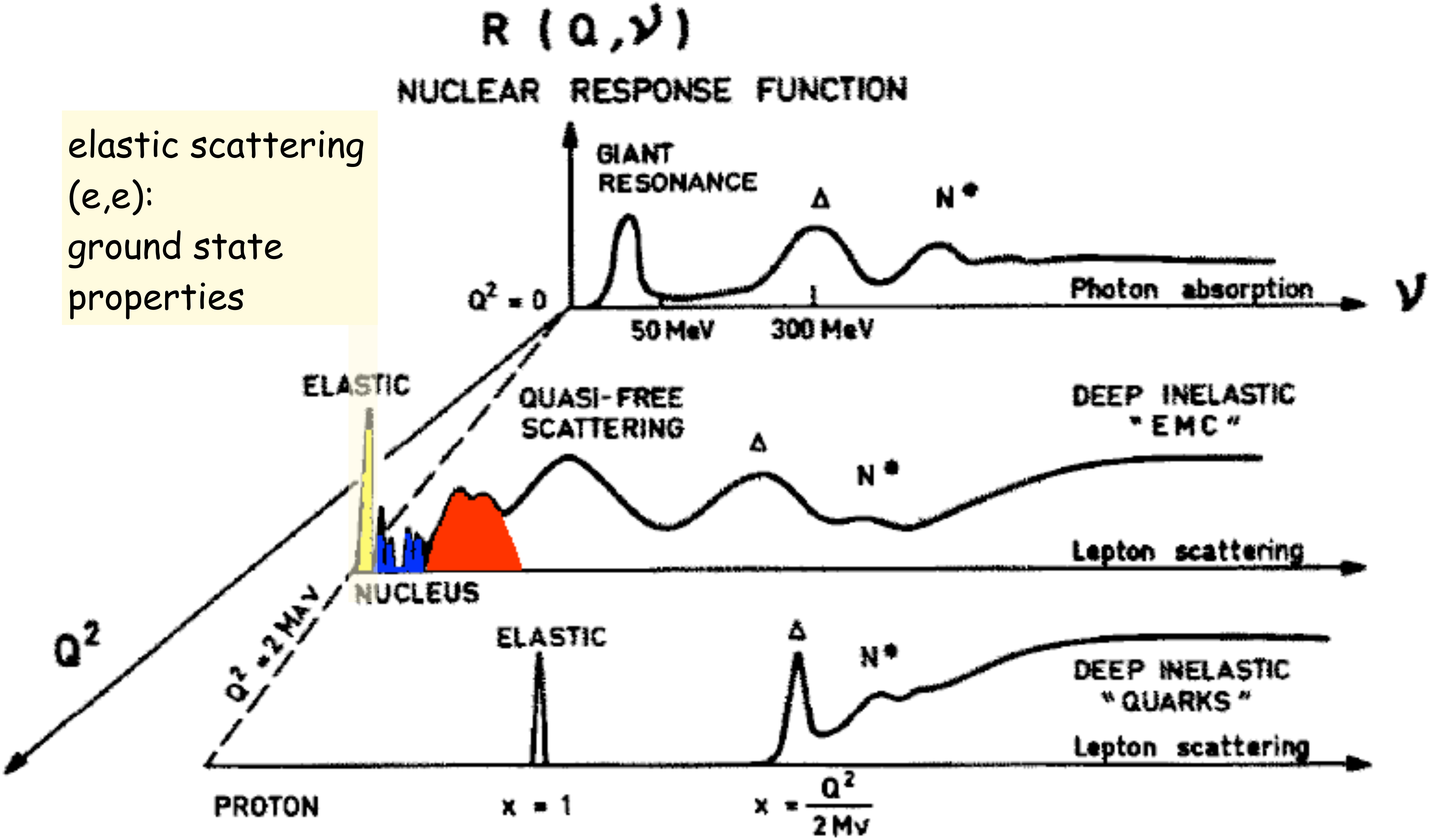
Outline



R (Q, ν)
NUCLEAR RESPONSE FUNCTION
GIANT RESONANCE
Δ
N*
Q² = 0
50 MeV
300 MeV
Photon absorption
ν
ELASTIC
QUASI-FREE SCATTERING
DEEP INELASTIC "EMC"
Δ
N*
Lepton scattering
NUCLEUS
Q²
Q² = 2 MAν
ELASTIC
Δ
N*
DEEP INELASTIC "QUARKS"
Lepton scattering
PROTON
x = 1
x = Q²/2Mν

Outline

elastic scattering
(e,e):
ground state
properties



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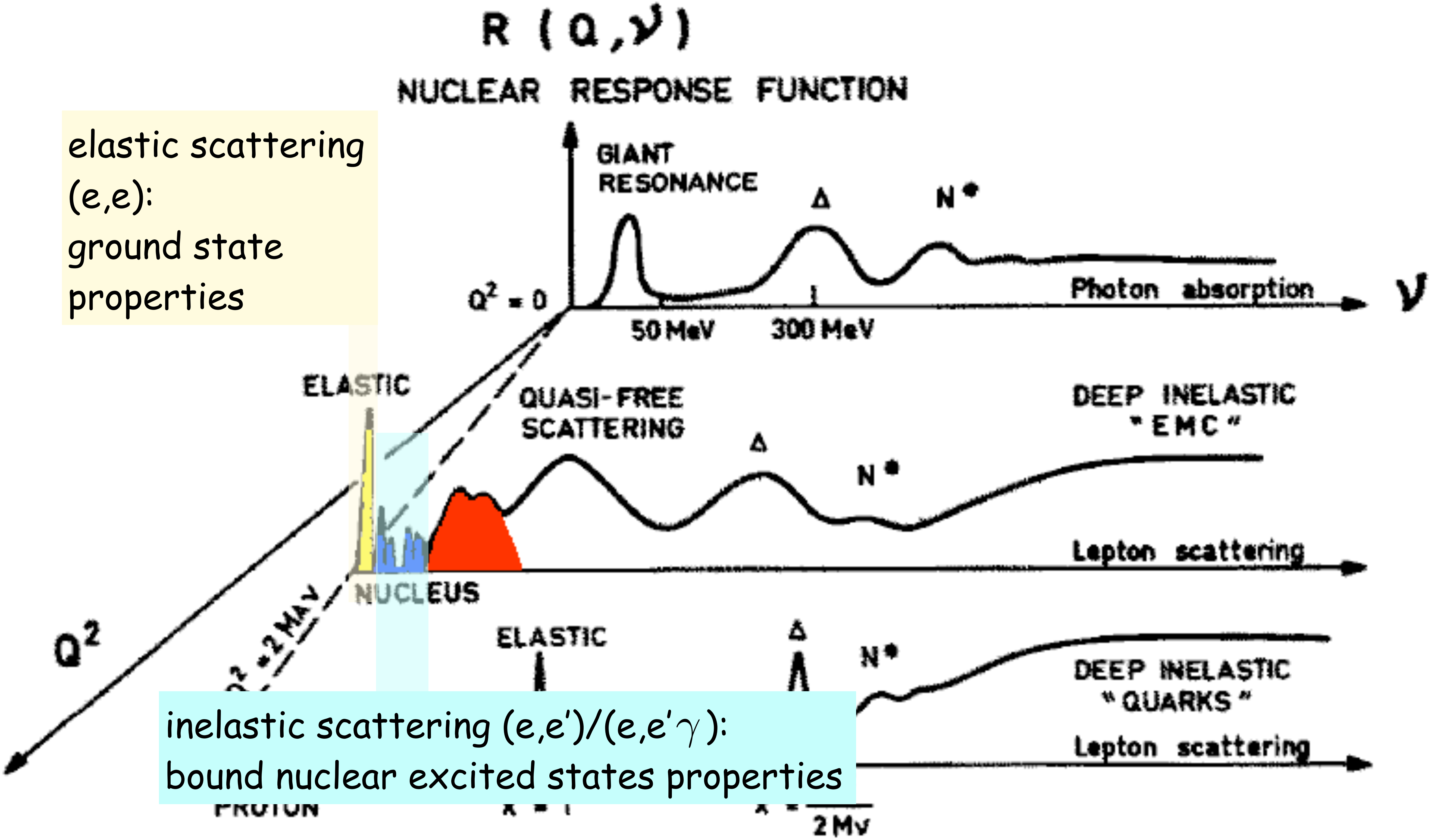

elastic scattering (e,e): ground state properties

inelastic scattering (e,e')/(e,e'γ): bound nuclear excited states properties

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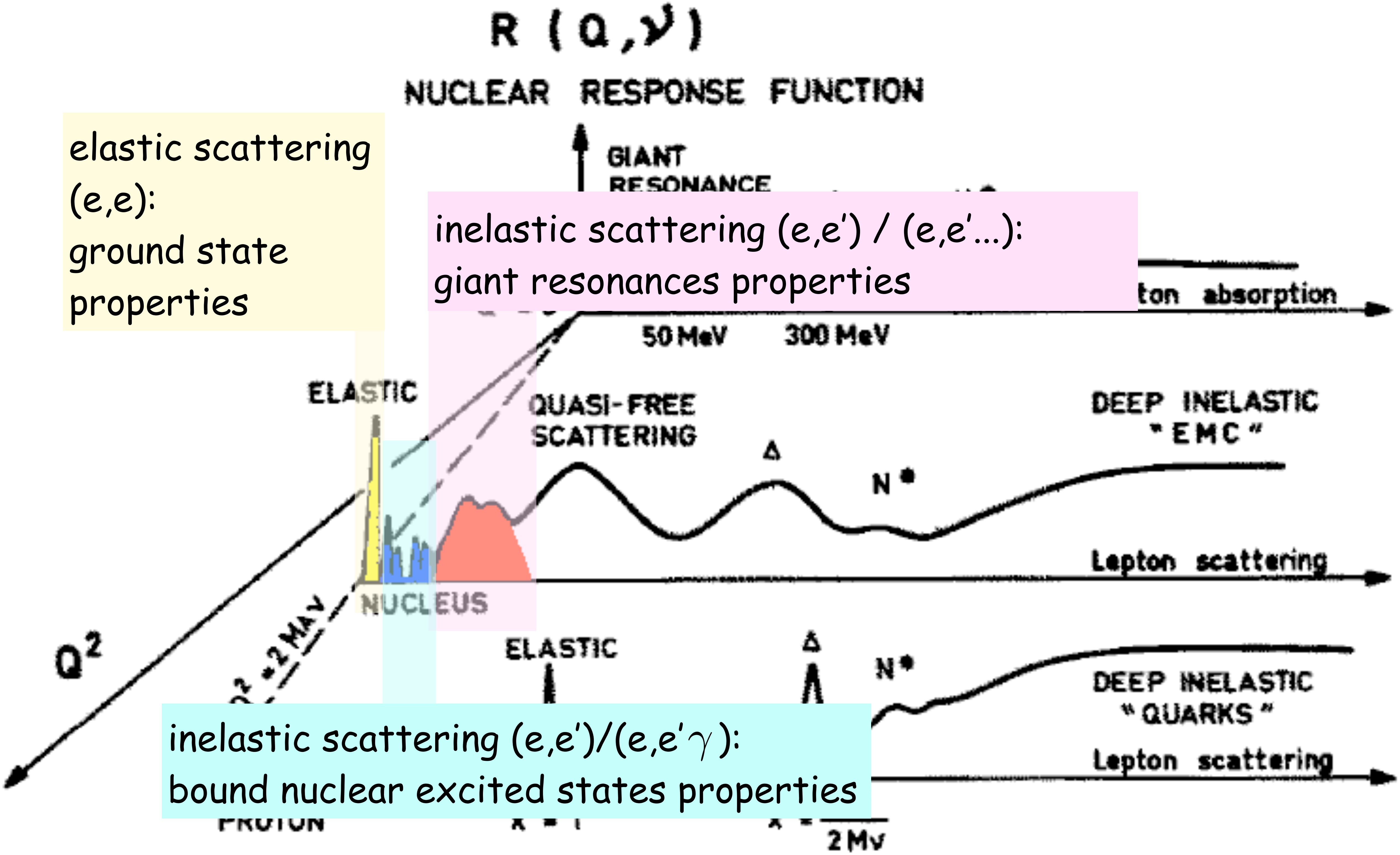

elastic scattering (e,e): ground state properties

inelastic scattering (e,e') / (e,e'...): giant resonances properties

inelastic scattering (e,e')/(e,e'γ): bound nuclear excited states properties

Outline

elastic scattering
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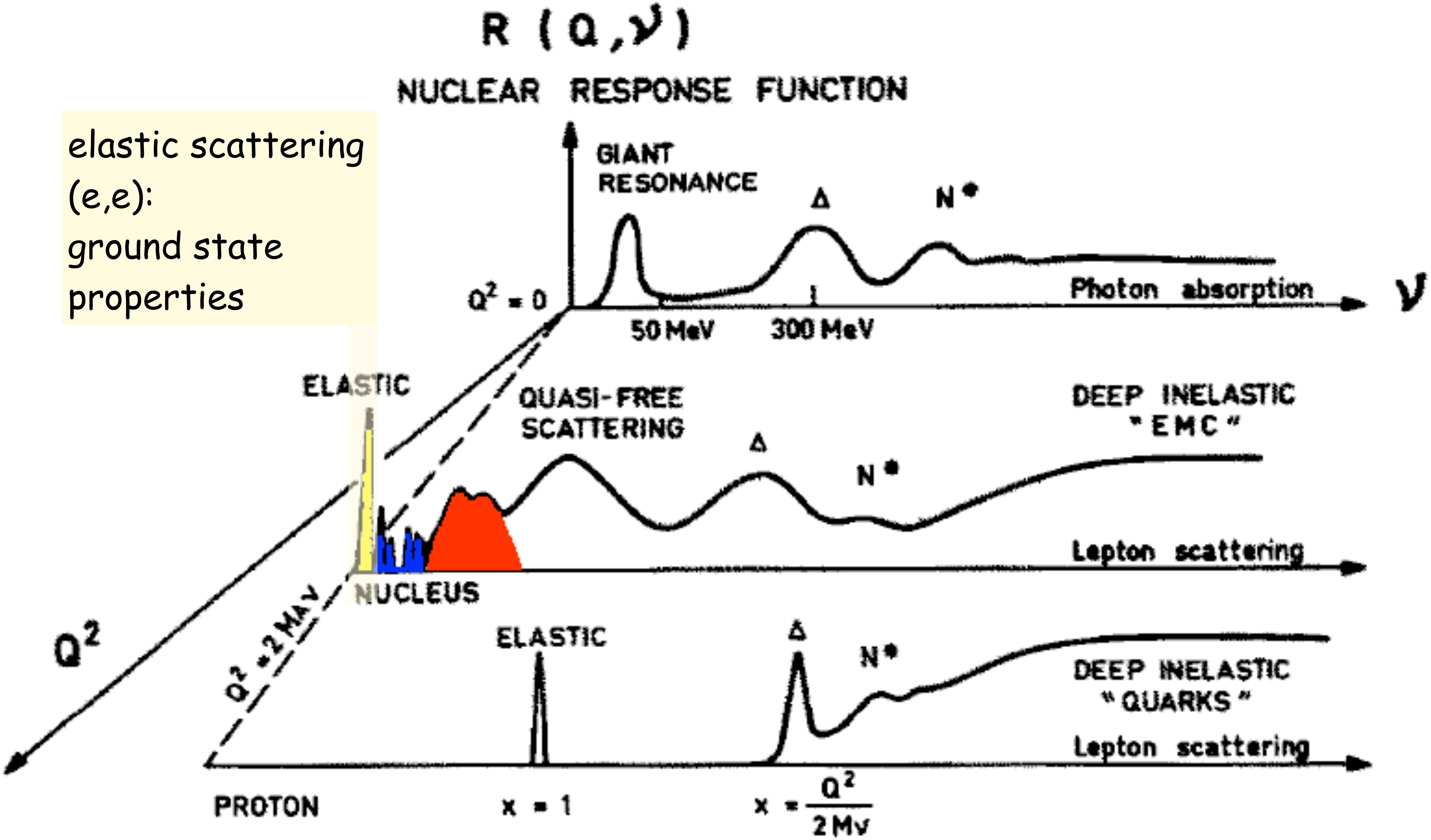

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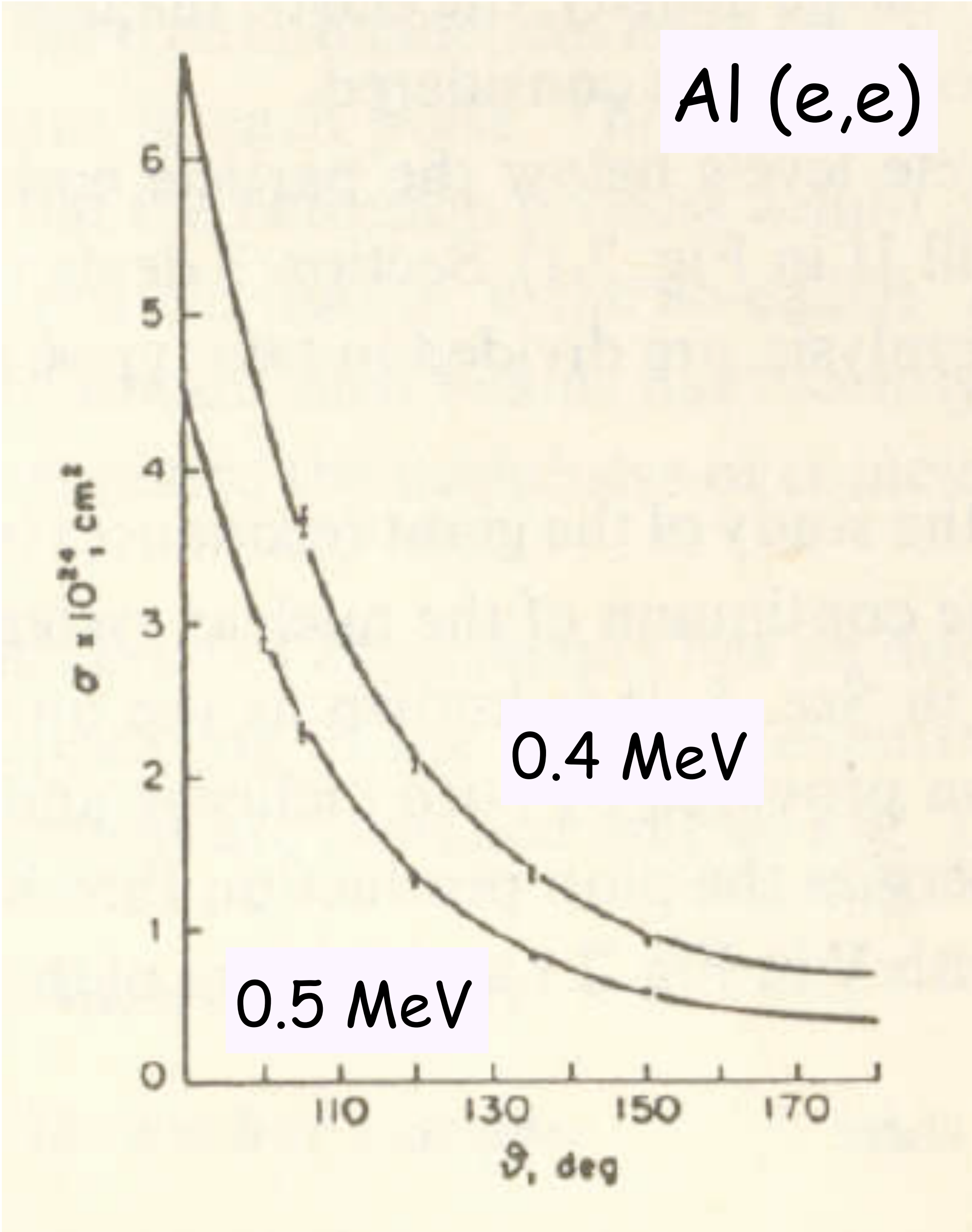

Elastic scattering: ground state

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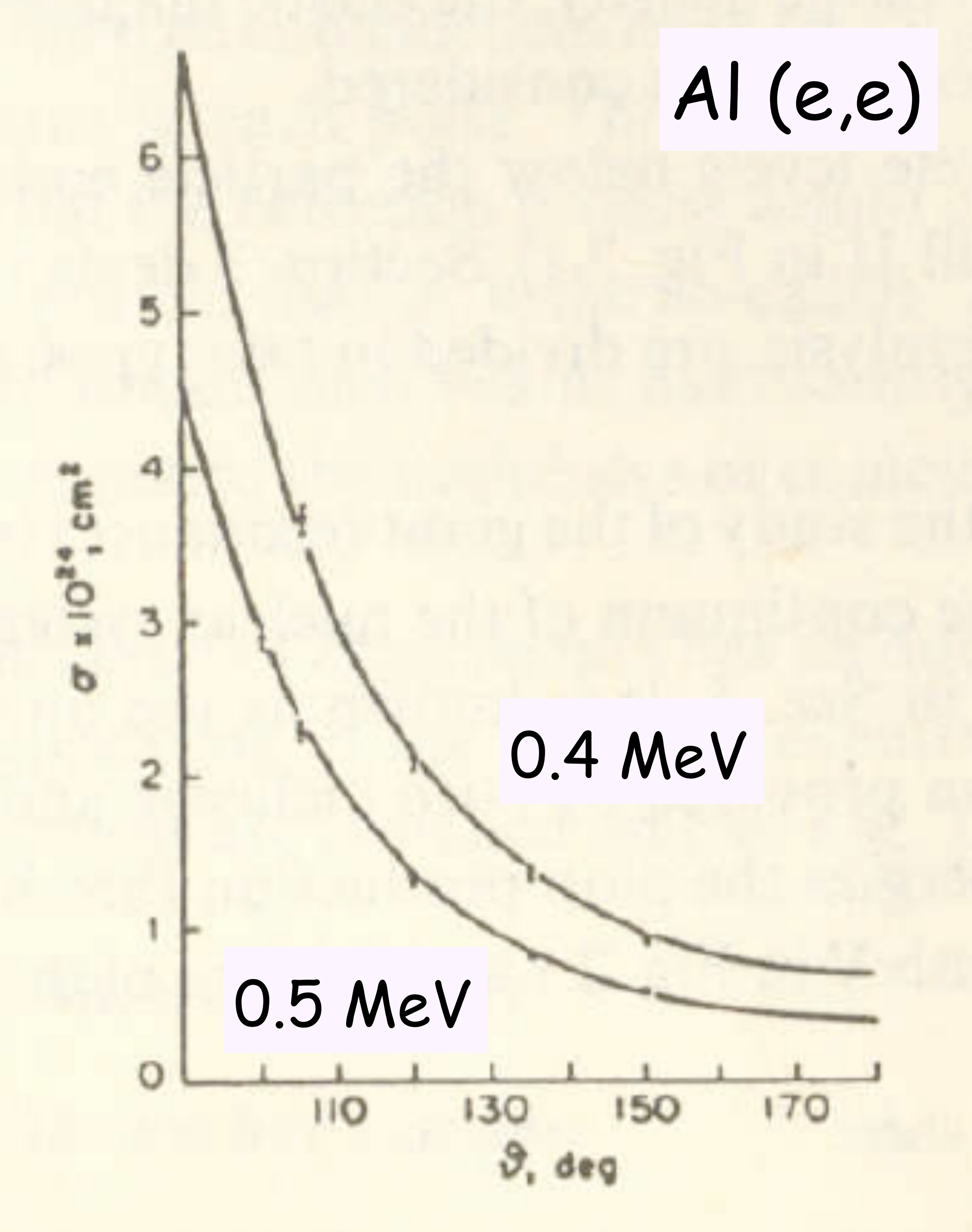
-only inclusive experiments: no excitation nor particle emission

very low energies: < 5 MeV

-low momentum transferred to the nucleus: poor resolution

-the target appears as point charge: Mott cross section

-no information about nuclear structure



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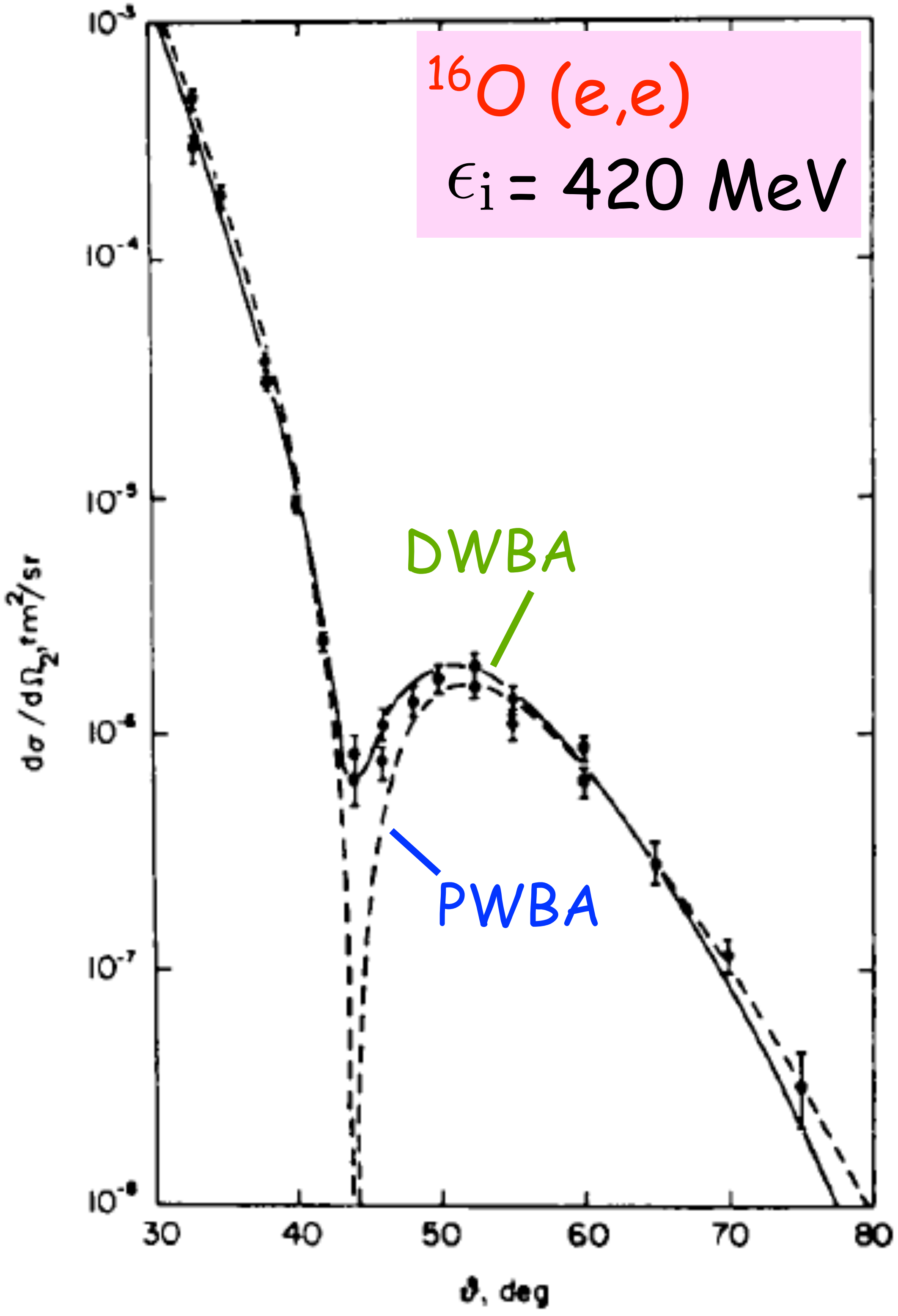

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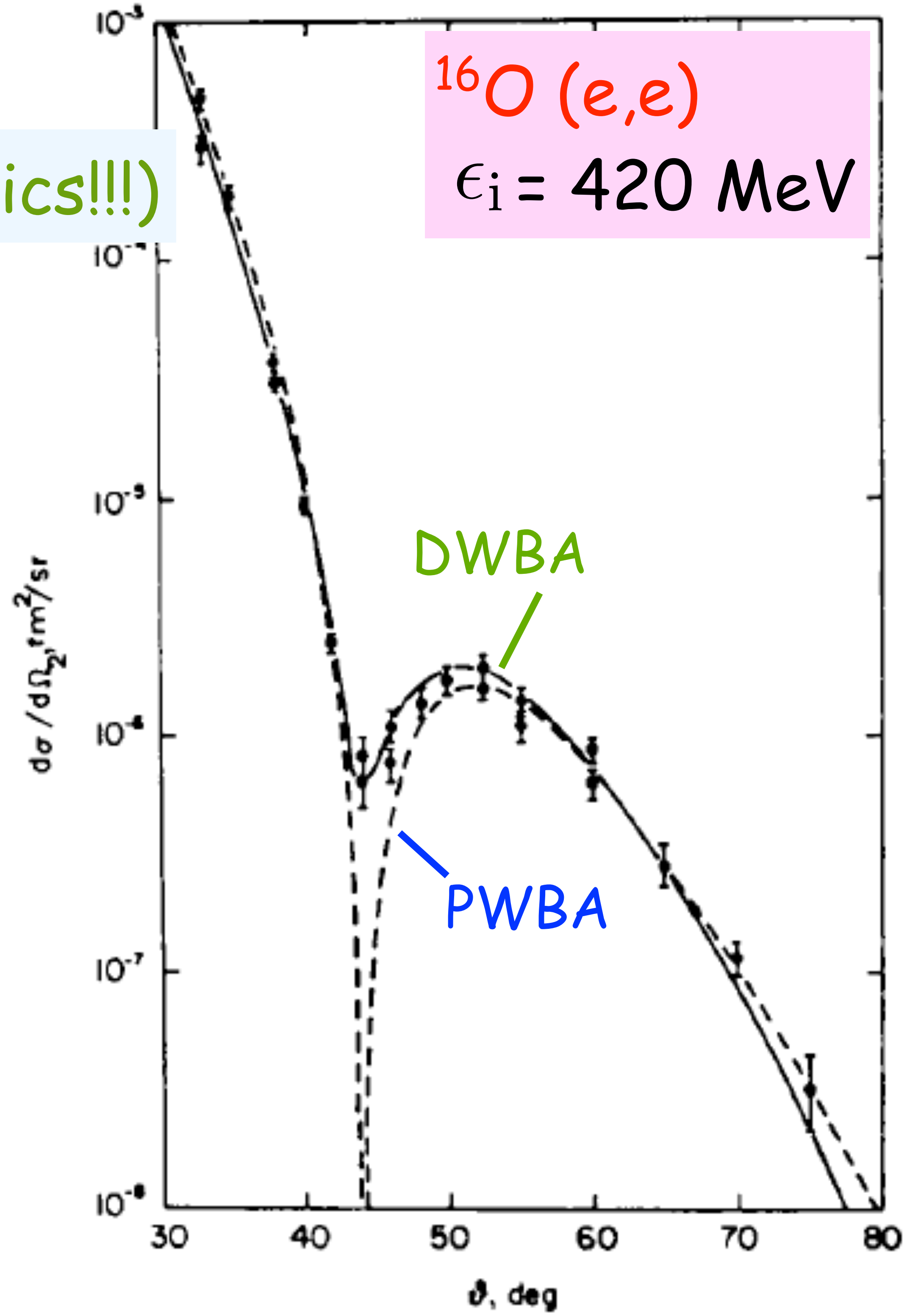
-diffraction pattern: nuclear size (as in optics!!!)



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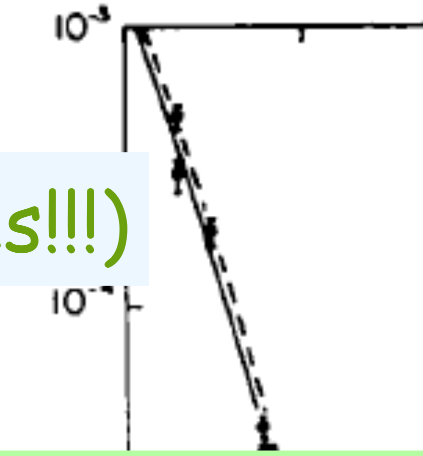

^{16}O (e,e)

ϵ_i = 420 MeV

$$\frac{d\sigma}{d\Omega} = Z^2\,\sigma_{\rm Mott}\,f_{\rm rec}^{-1}\left[\frac{q_\mu^4}{\mathbf{q}^4}|F_{\rm L}(q)|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2} + \tan^2\frac{\theta}{2}\right)|F_{\rm T}(q)|^2\right]$$

$$\sigma_{\rm Mott} = \left(\frac{\alpha\cos\frac{\theta}{2}}{2\,\epsilon_{\rm i}\sin^2\frac{\theta}{2}}\right)^2 \qquad f_{\rm rec} = 1 + \frac{2\,\epsilon_{\rm i}\sin^2\frac{\theta}{2}}{M_{\rm T}} \qquad q_\mu = (\omega, -\mathbf{q}) \qquad J_\mu(\mathbf{r}) = [\rho(\mathbf{r}), -\mathbf{J}(\mathbf{r})]$$

$$|F_{\rm L}(q)|^2 = \frac{4\pi}{Z^2}\frac{1}{2J_i+1}\sum_{\lambda=0}^{\infty}\left|\langle J_f\|M_\lambda^{\rm Coul}(q)\|J_i\rangle\right|^2 ; \qquad M_{\lambda\mu}^{\rm Coul}(q) = \int d\mathbf{r}\, j_\lambda(qr)\, Y_{\lambda\mu}(\hat{\mathbf{r}})\,\rho(\mathbf{r})$$

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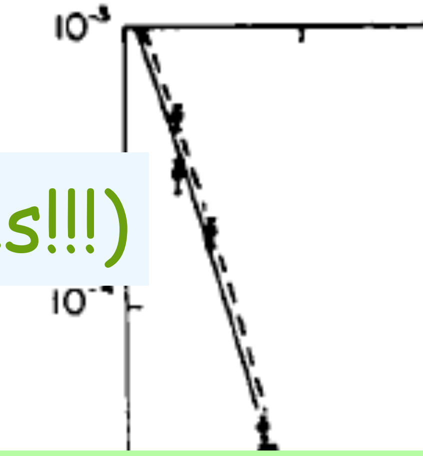

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$$\frac{d\sigma}{d\Omega} = Z^2\, \sigma_{\rm Mott}\, f_{\rm rec}^{-1}\, \frac{4\pi}{Z^2}\, \left|\langle 0 \| M_0^{\rm Coul}(q) \| 0\rangle\right|^2$$

$$= 4\pi\, \sigma_{\rm Mott}\, f_{\rm rec}^{-1}\, \left|\int dr\, r^2\, j_0(qr)\, \rho(r)\right|^2$$

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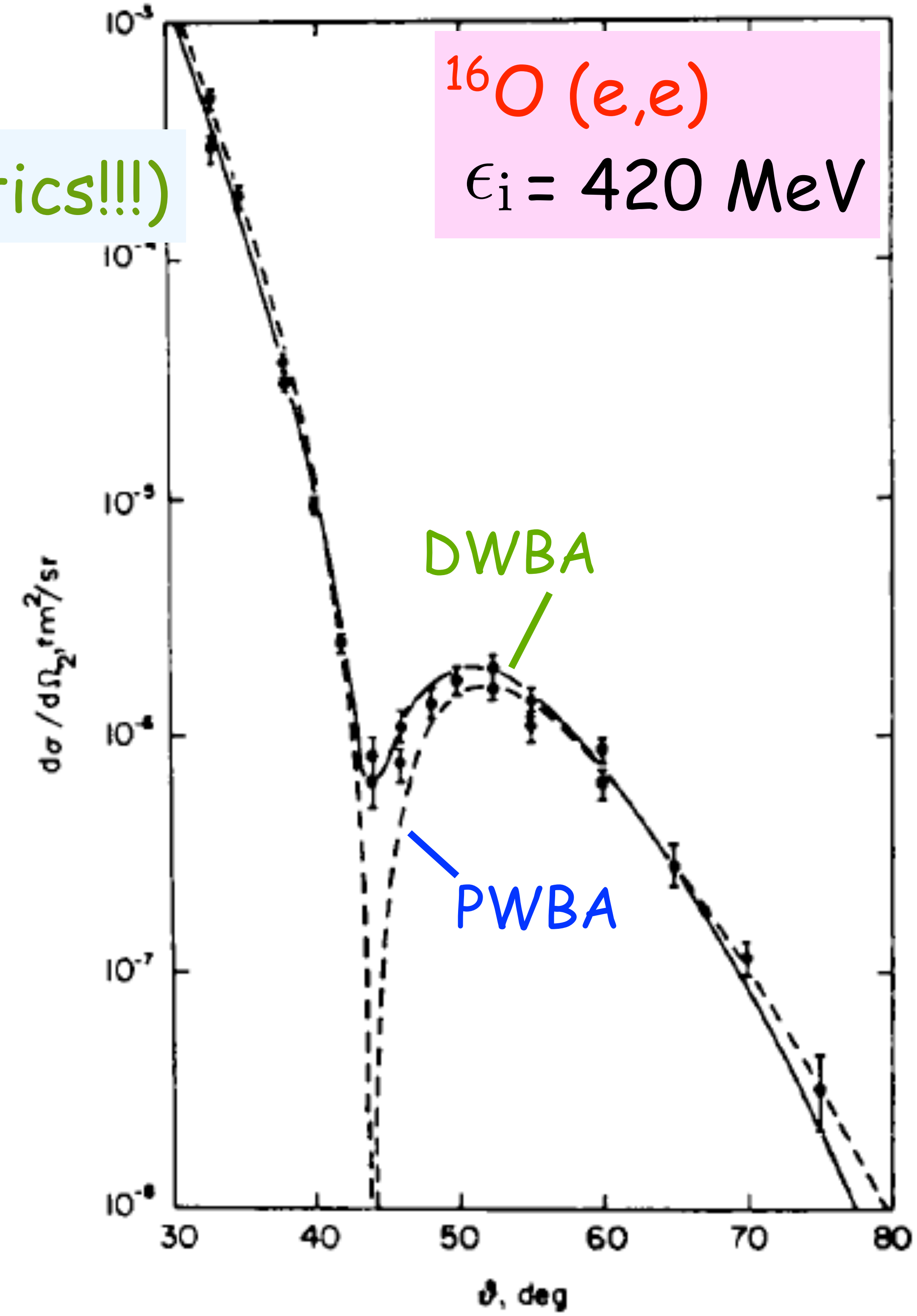
zeroes of $j_1(x)$: x = 4.49, 7.73, ...

nuclear radius: $R = r_0\, A^{1/3}$



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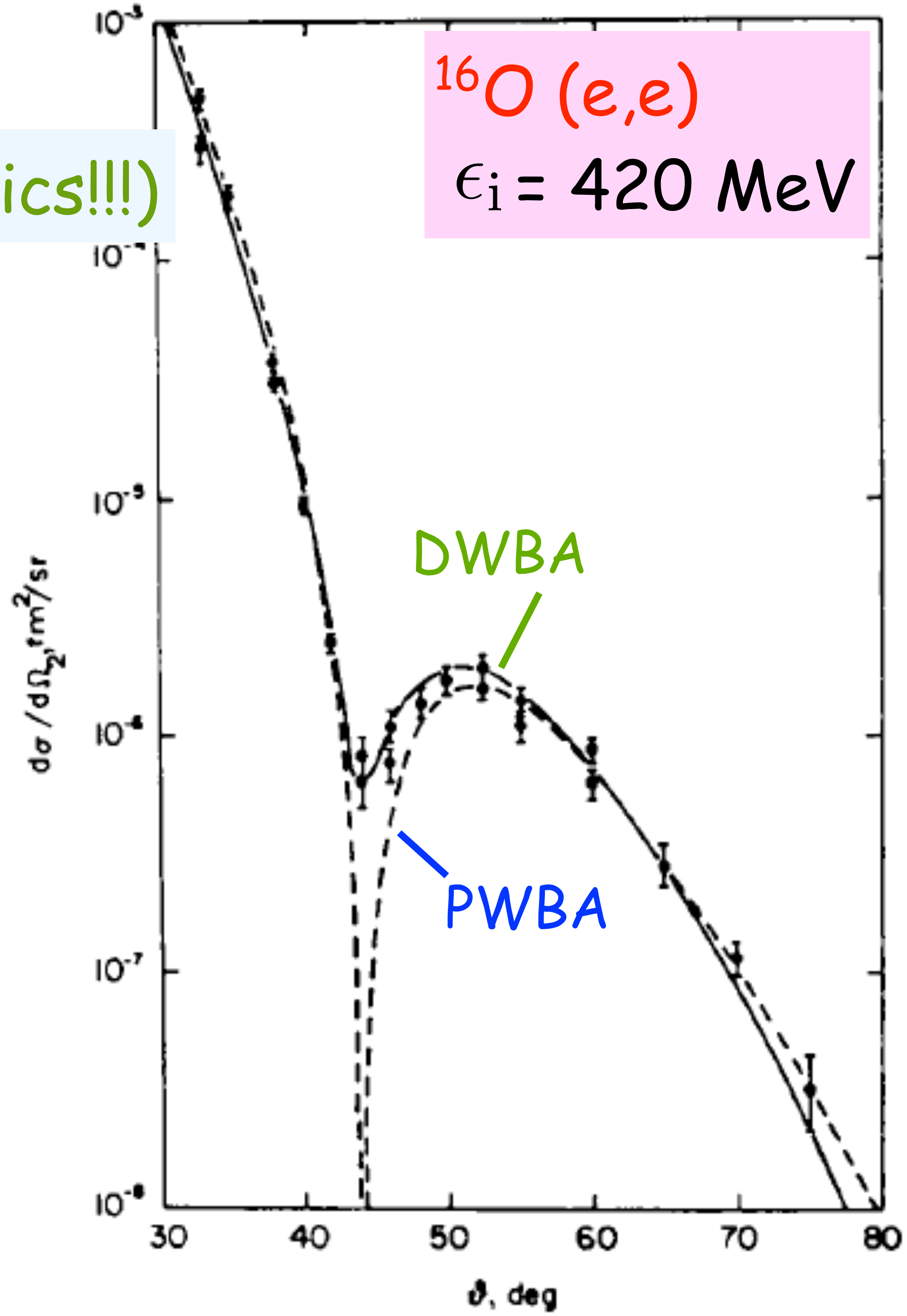

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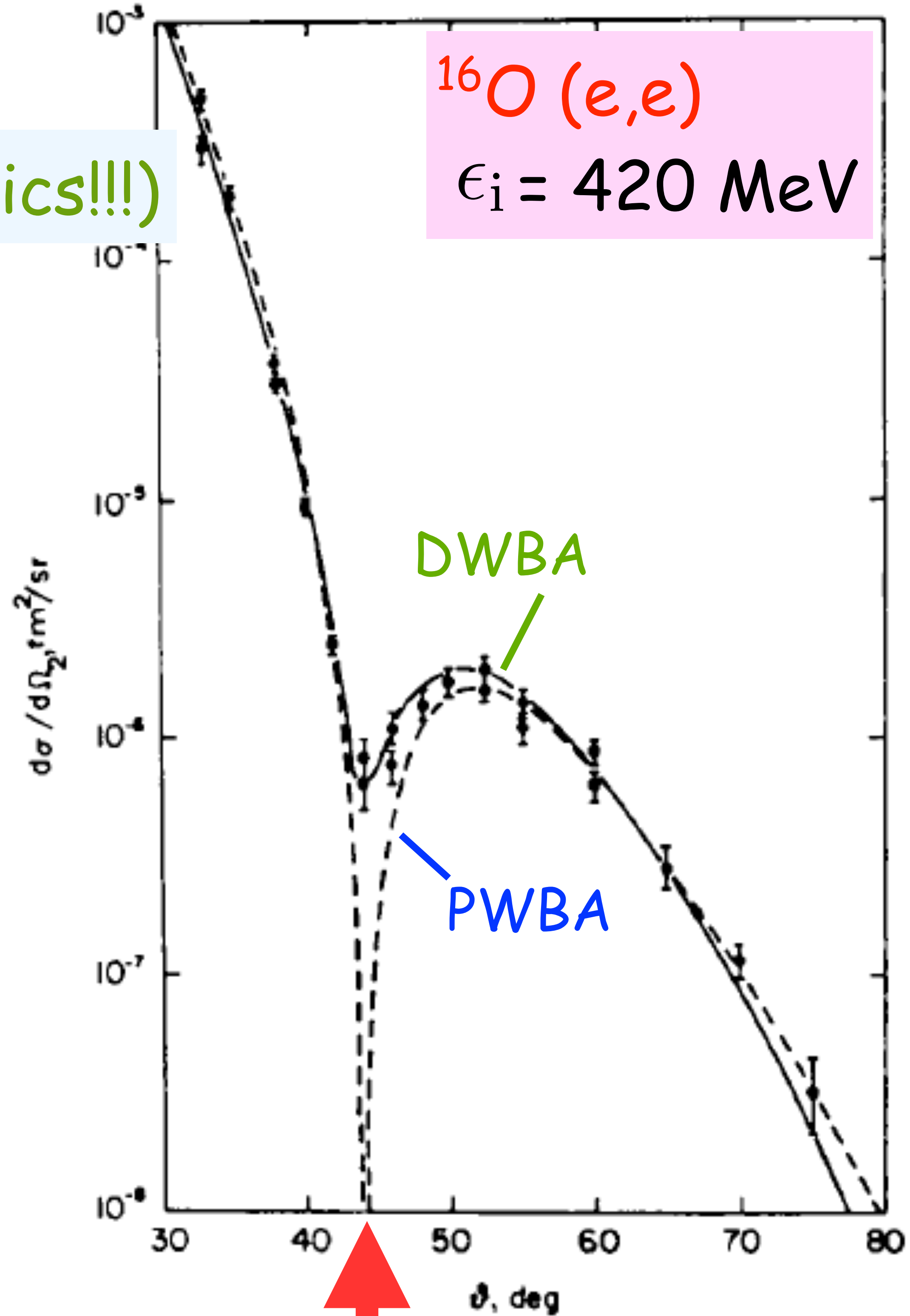

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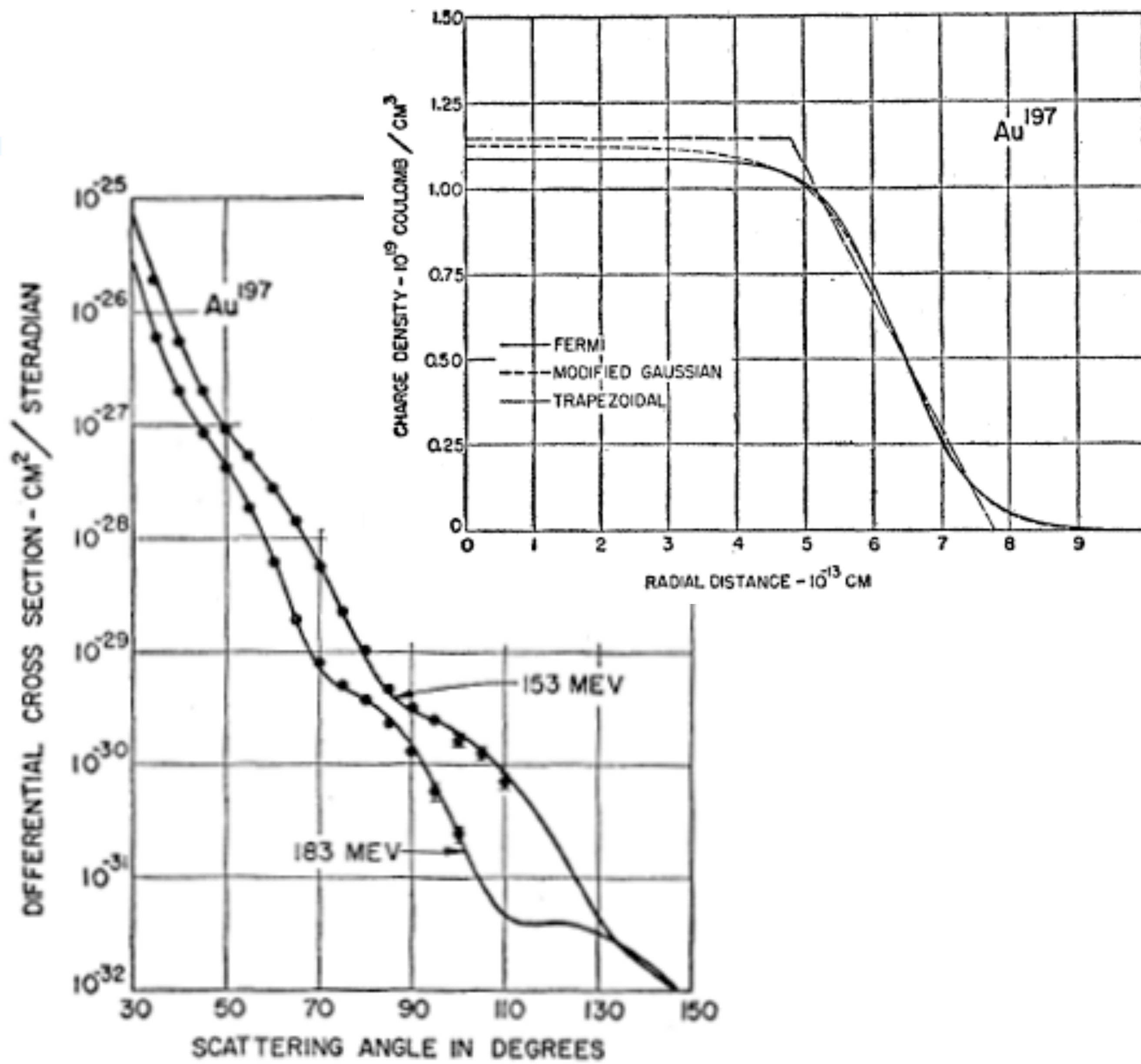
modified Gaussian:

$$\rho(r) = \frac{\rho_2}{1+\exp[(r^2-c^2)/z_2^2]}$$

trapezoidal:

$$\rho(r) = \begin{cases} \rho_3\,, & 0 \leq r < c - z_3\,, \\ \rho_3 \frac{c+z_3-r}{2z_3}\,, & c - z_3 \leq r < c + z_3\,, \\ 0\,, & r \geq x + z_3\,. \end{cases}$$



Hahn, Ravenhall, Hofstadter

Phys. Rev. 101 (1956) 1131

Elastic scattering: ground state

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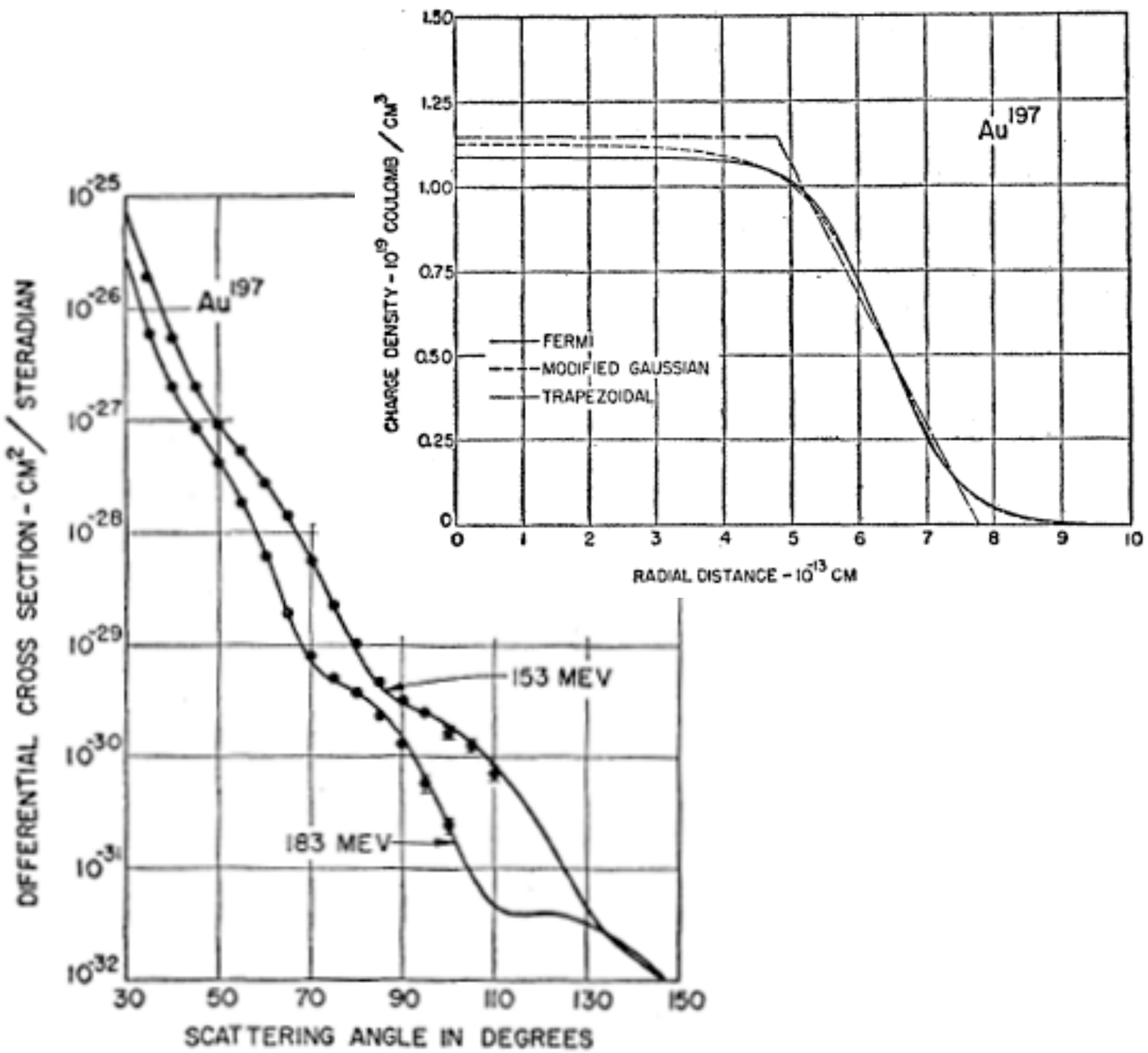

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Elastic scattering: ground state

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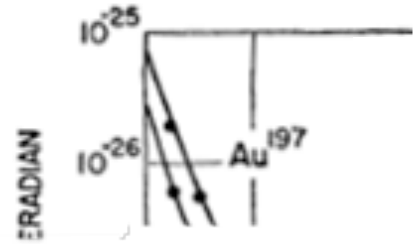

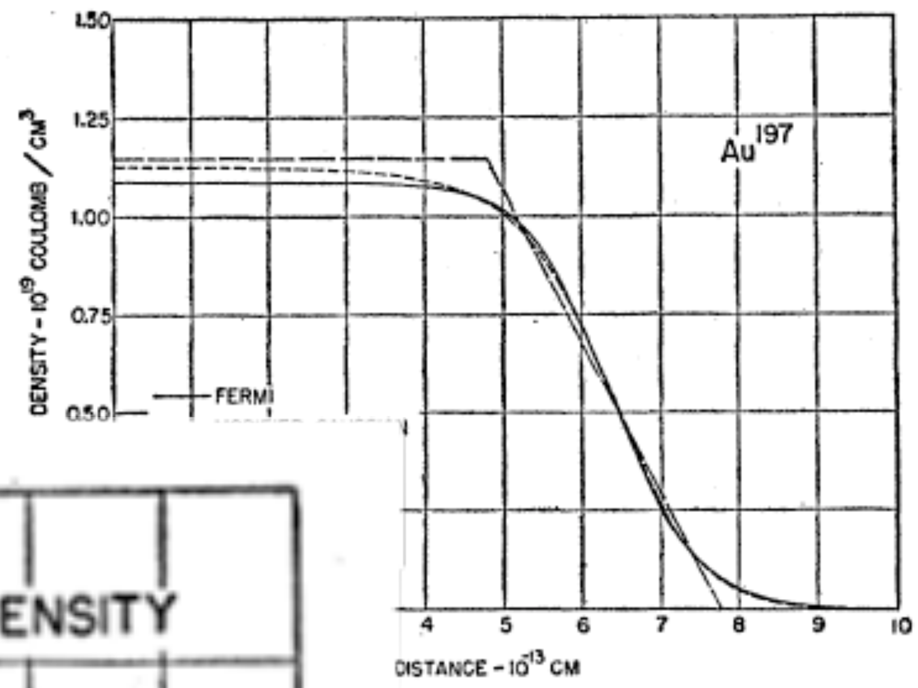

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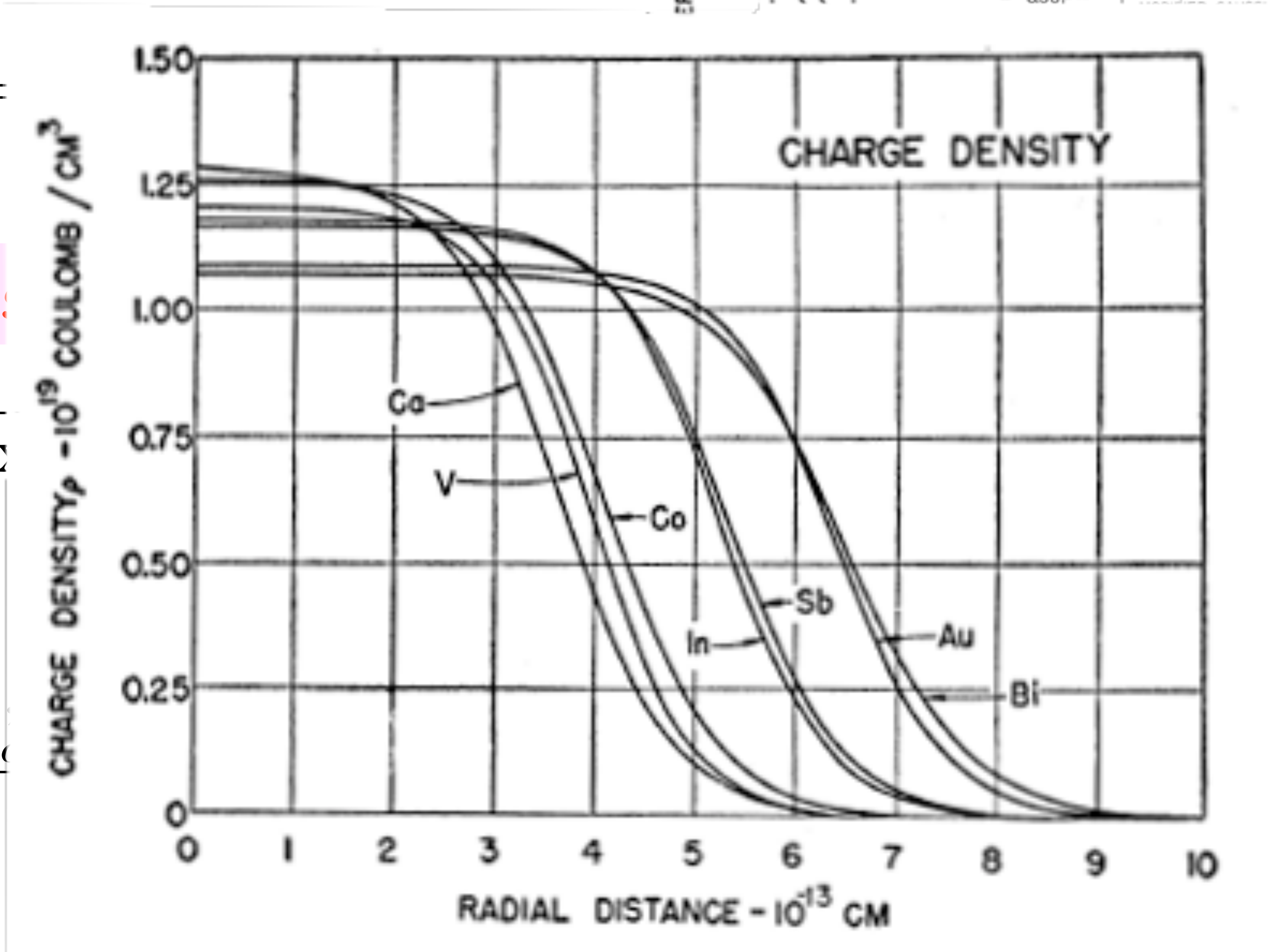

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lack of knowledge for large q:
uncertainty in the density

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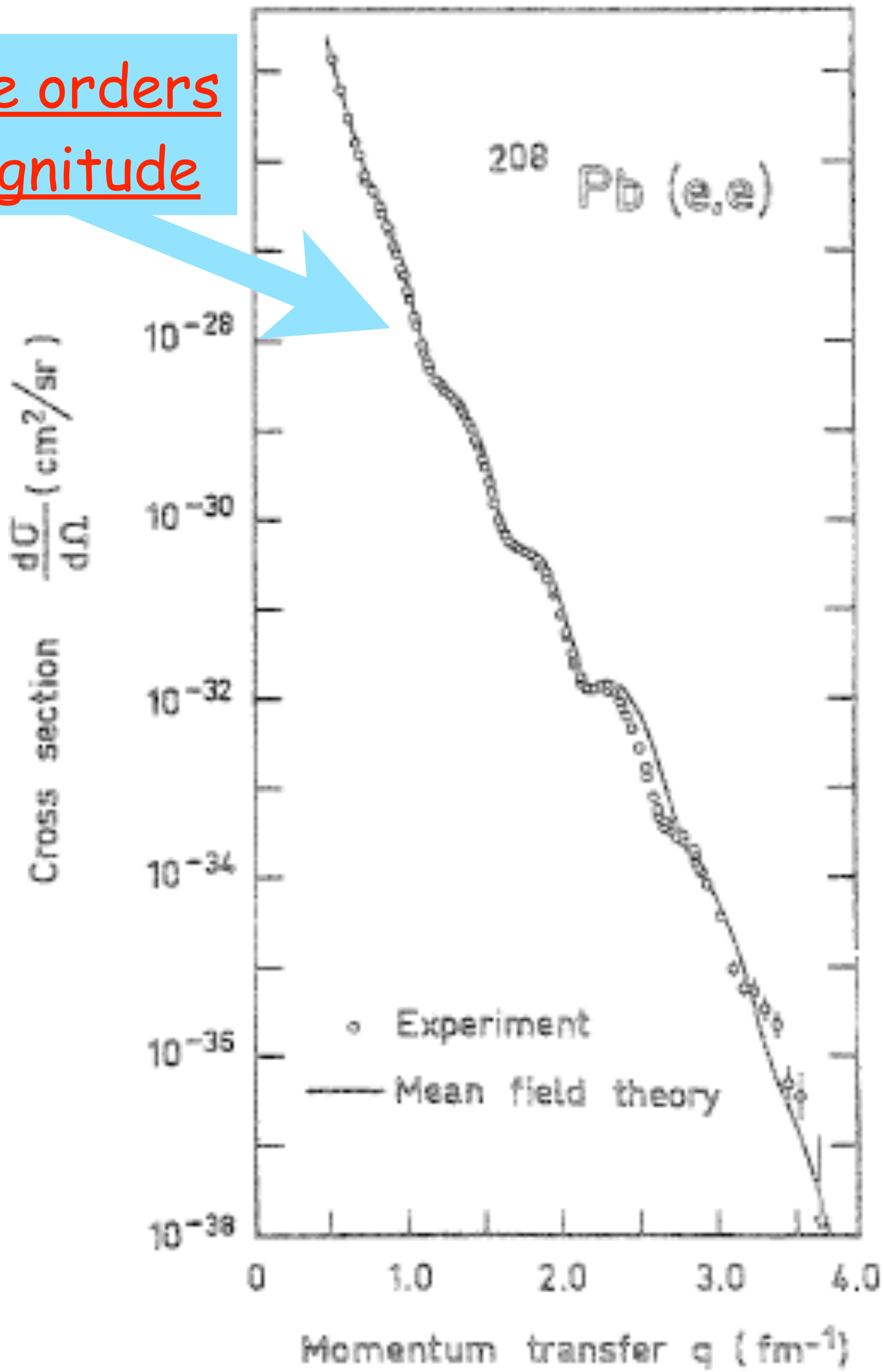
twelve orders of magnitude



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$$\rho(r) = \sum_{n=1}^{\infty} A_n\, P_n(r)$$

orthonormal basis: sum of Gaussians, Fourier-Bessel, Hermite, Laguerre, ...

-cut of the series: uncertainty in the density

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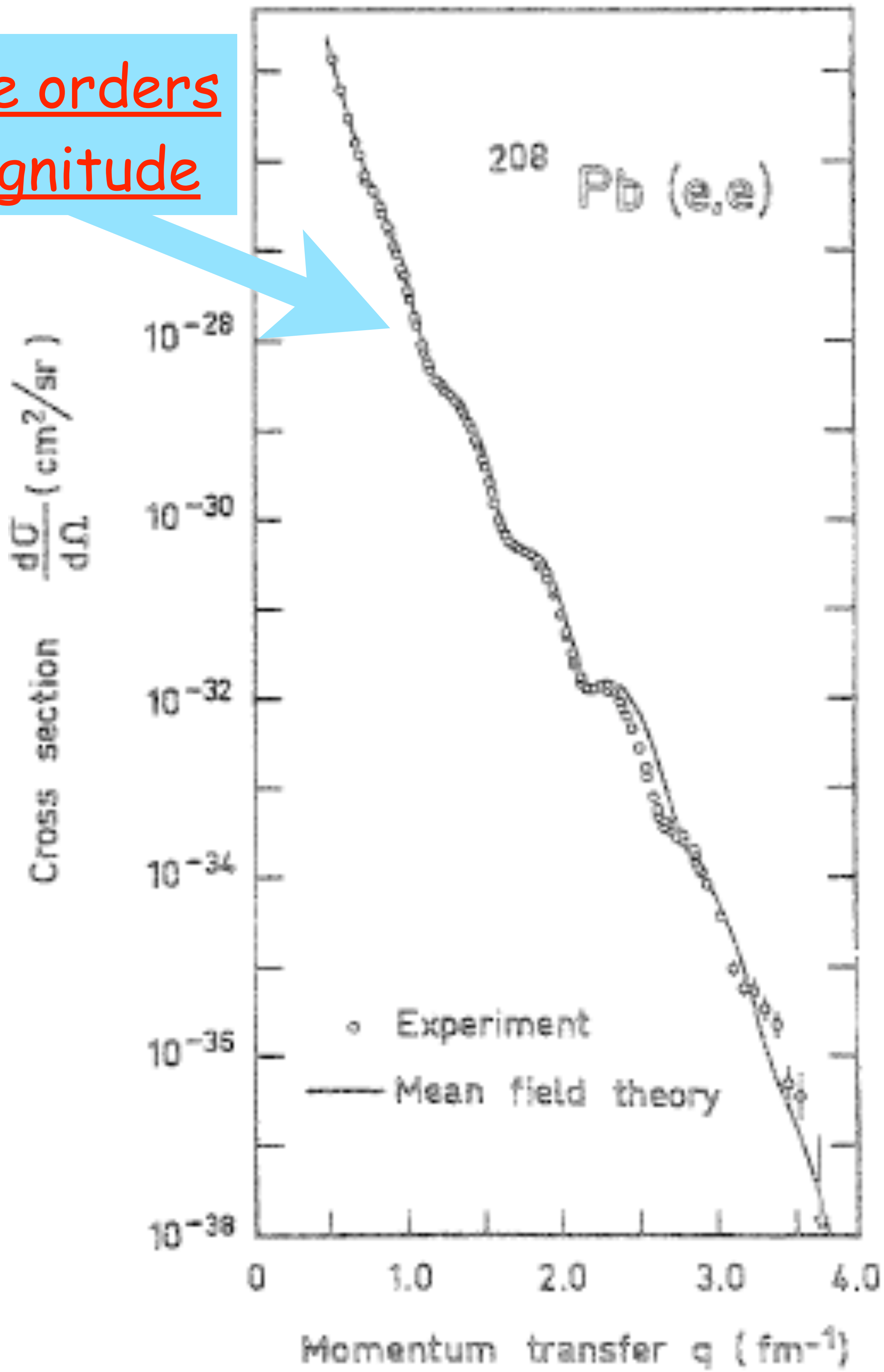

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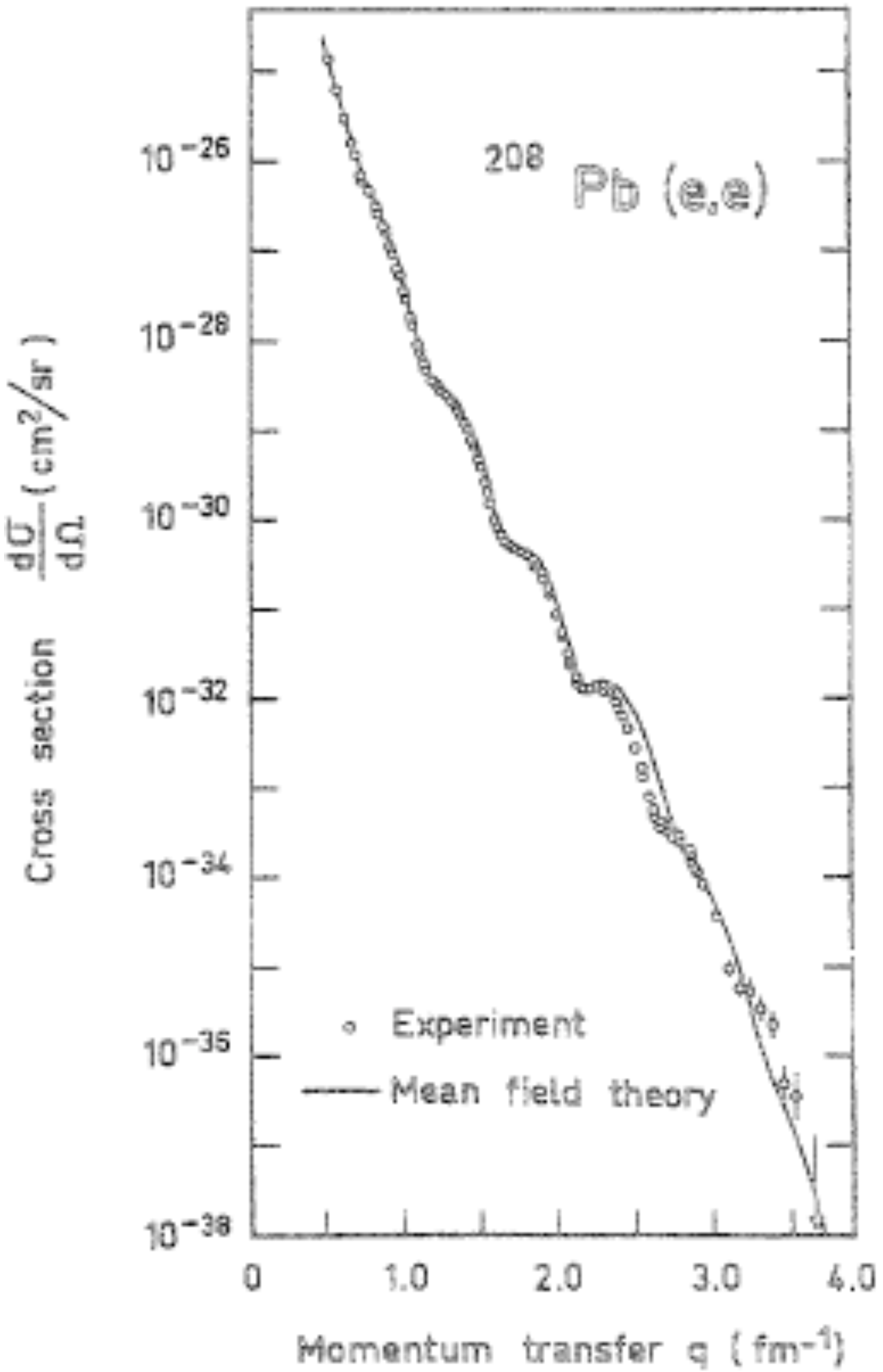
number of terms: cannot be increased above certain value!!! [Anni, Co', Pellegrino, Nucl. Phys. A 584 (1995) 35]



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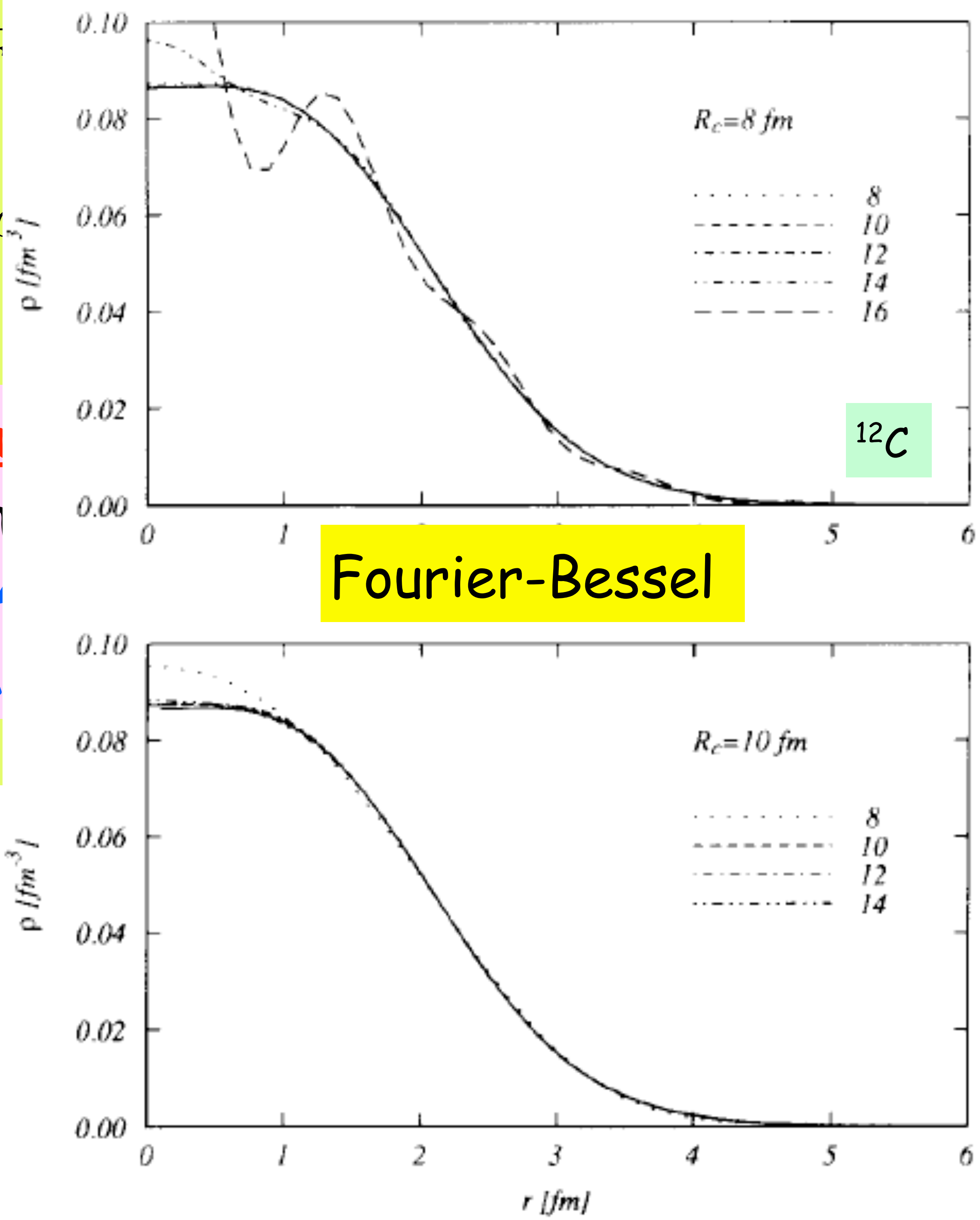
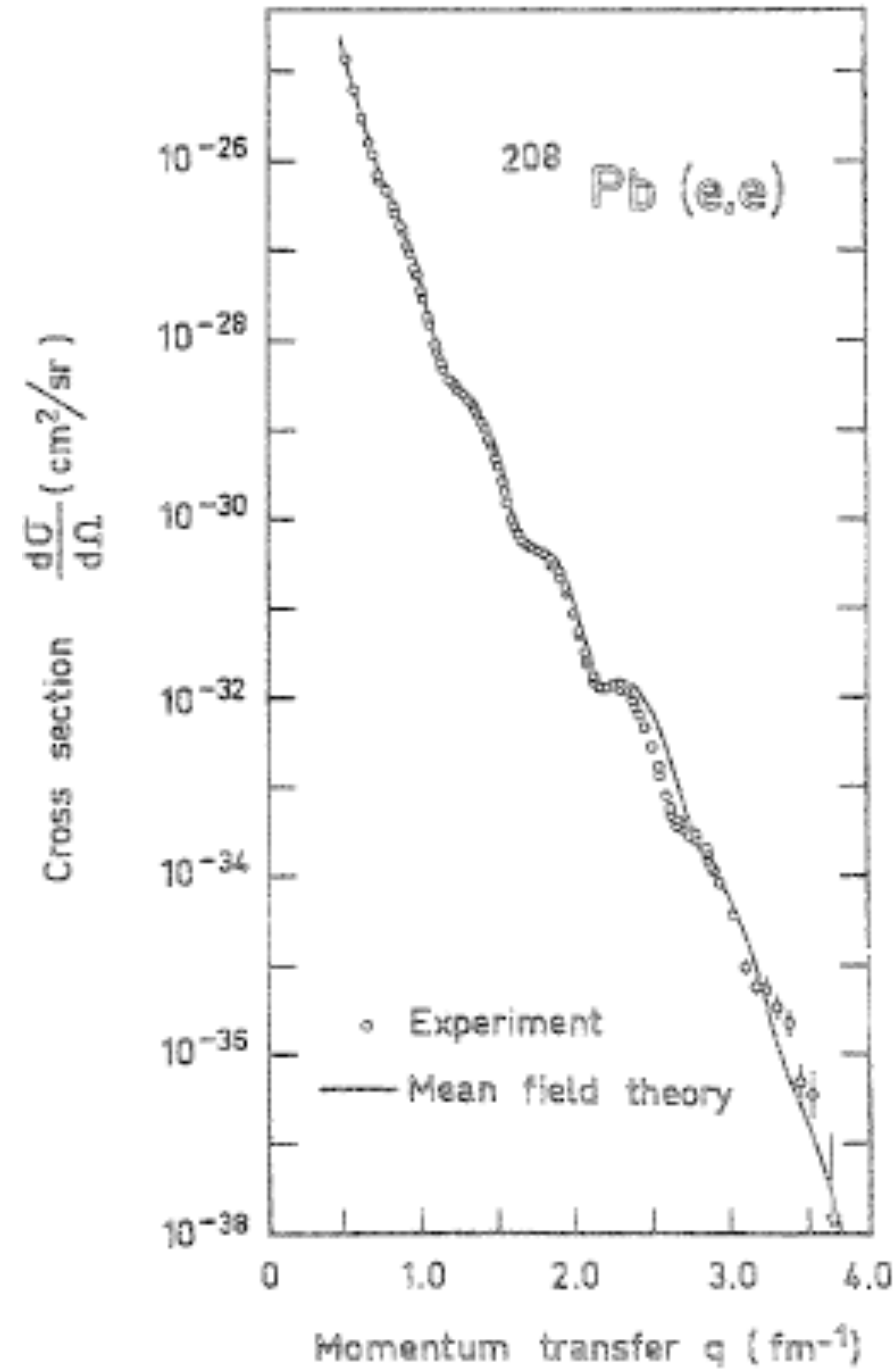


Fourier-Bessel



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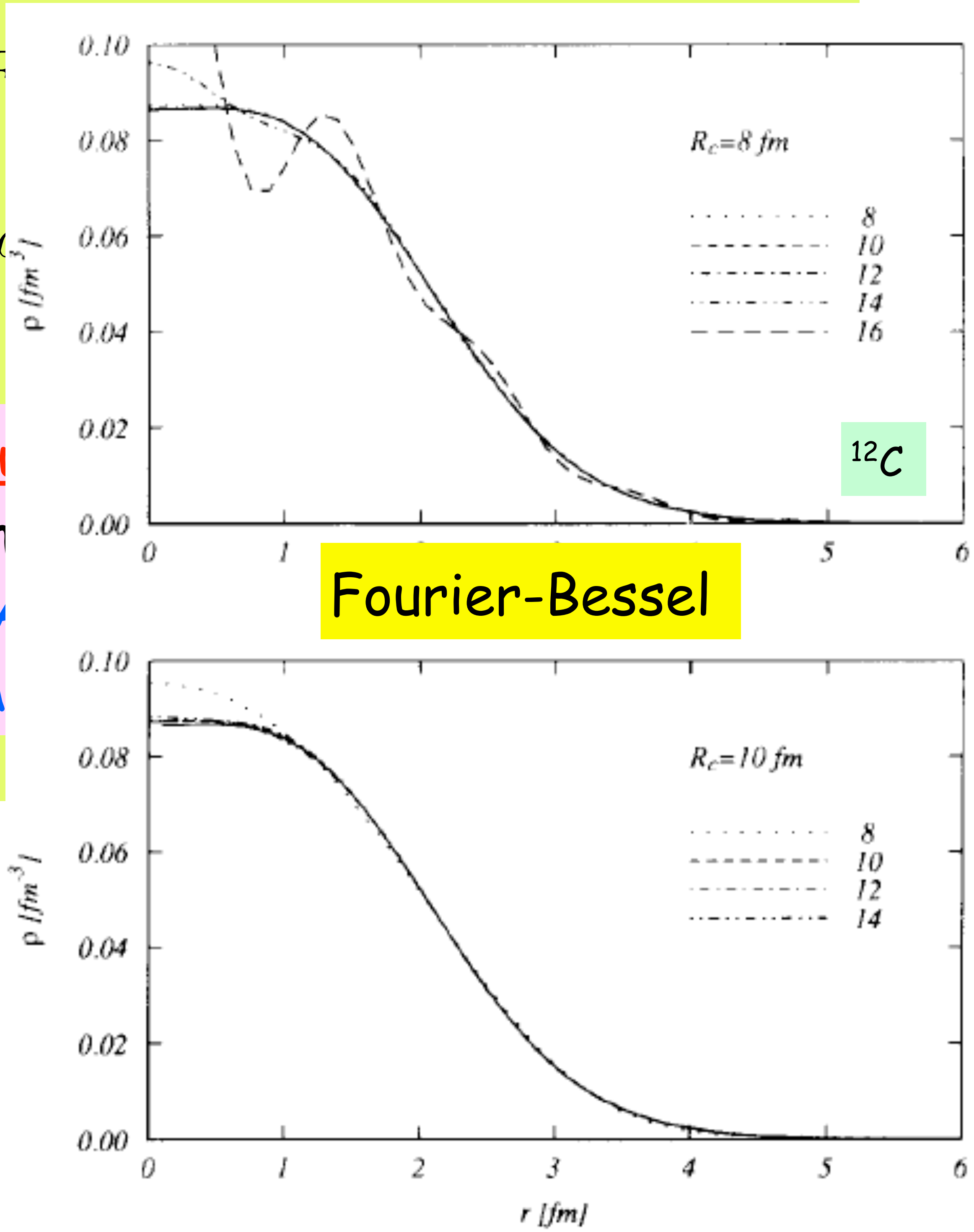

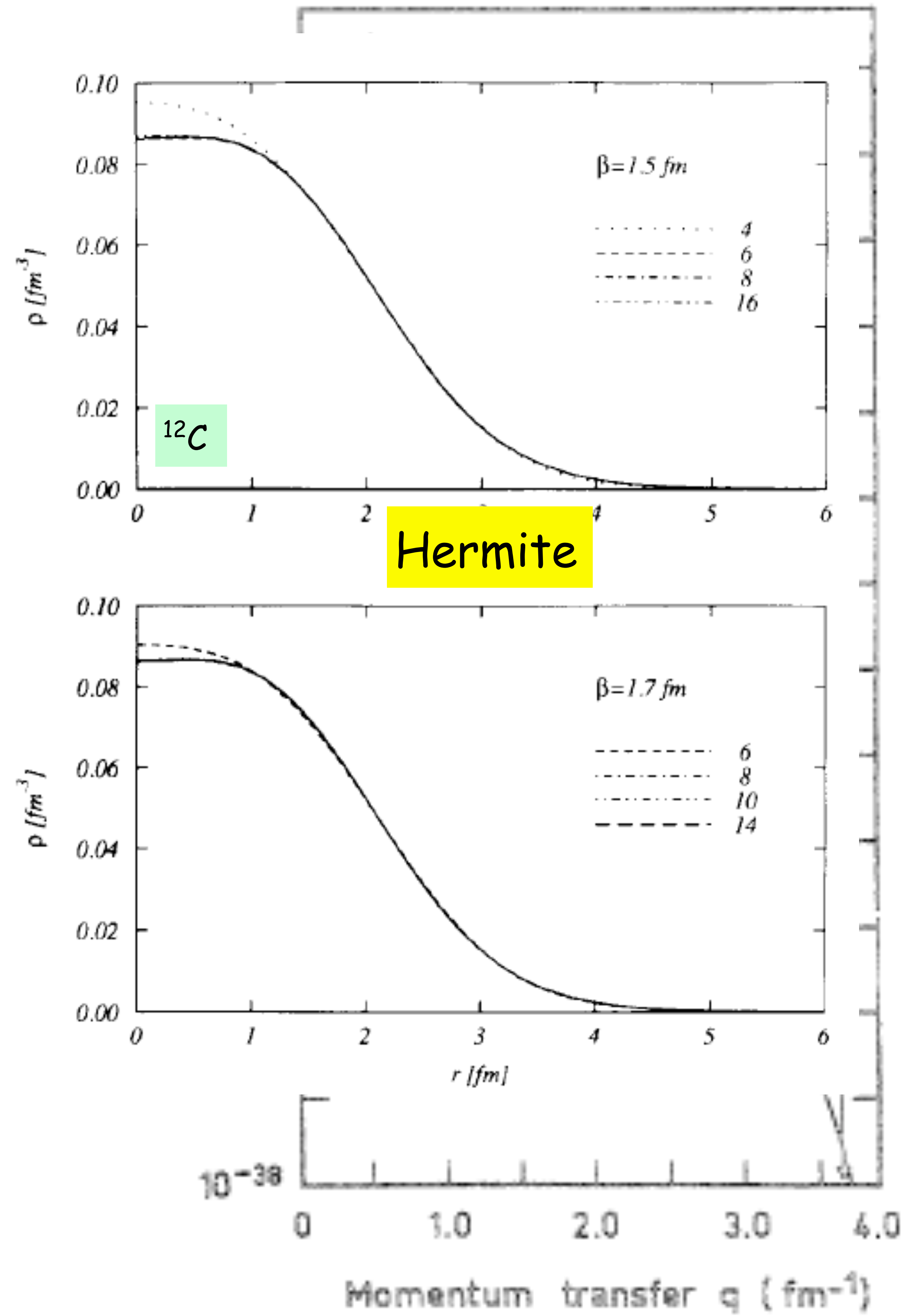

Elastic scattering: ground state

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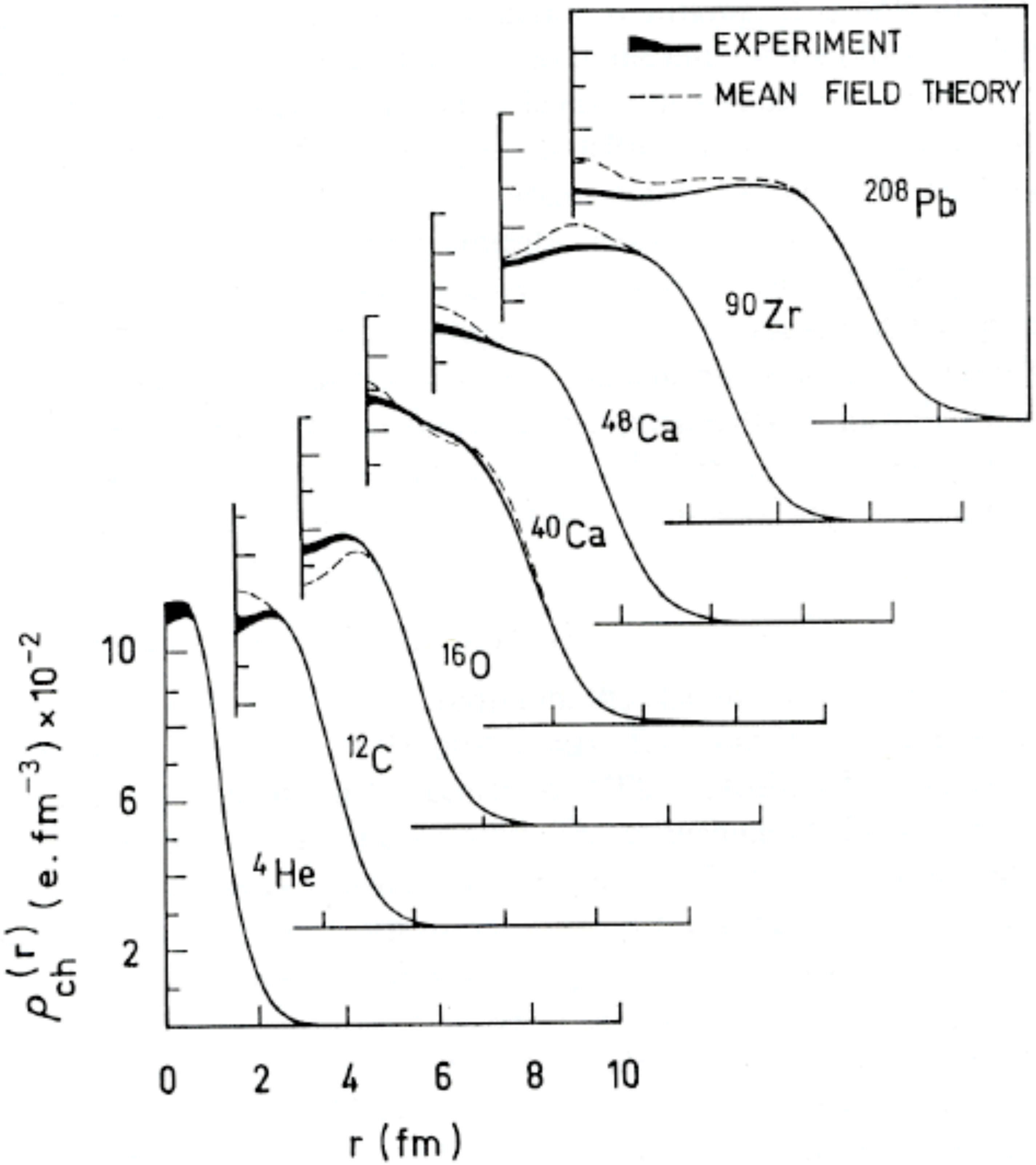

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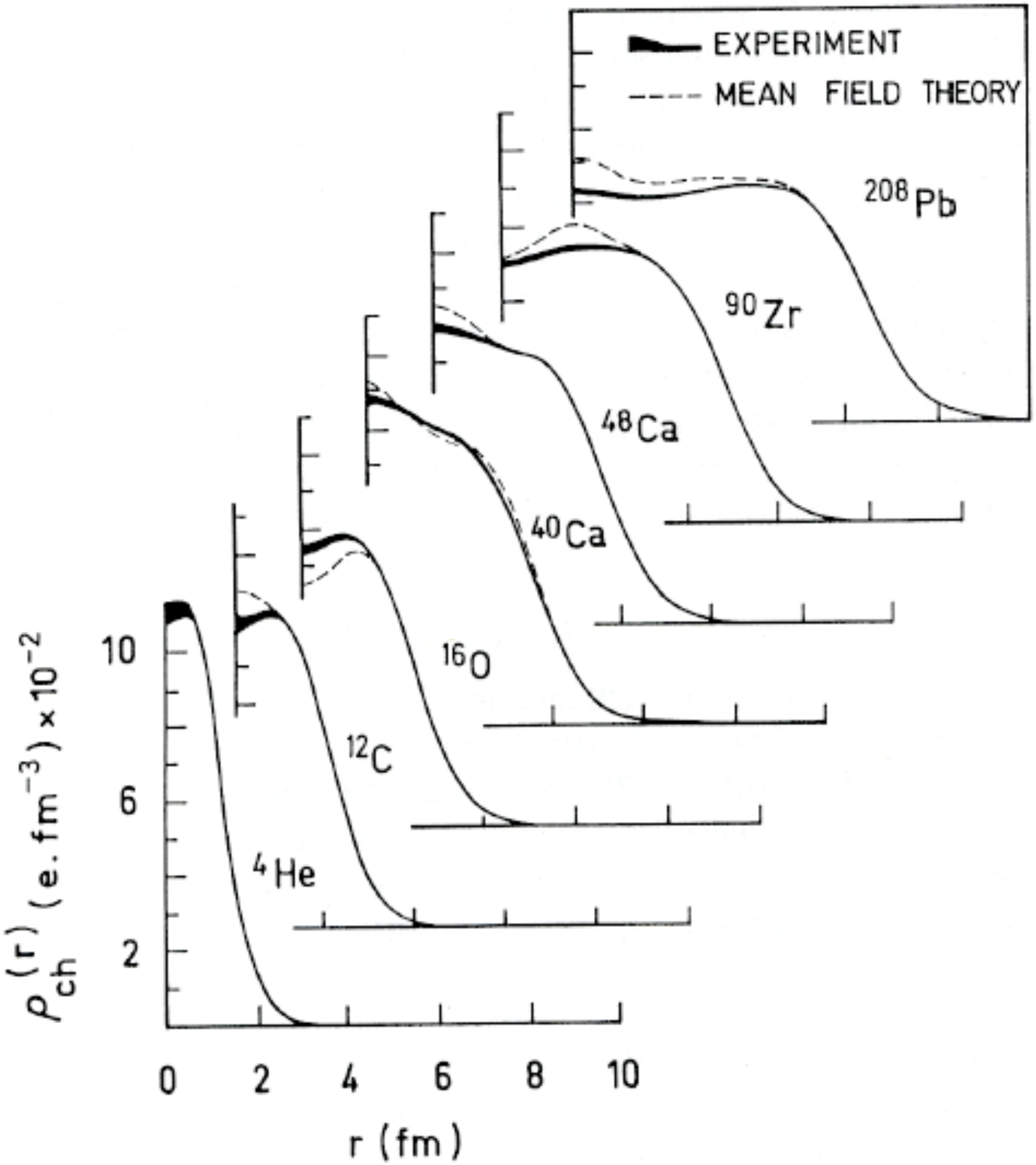
largest discrepancies: ^{208}Pb where "mean field approach" is supposed to work very well !!!



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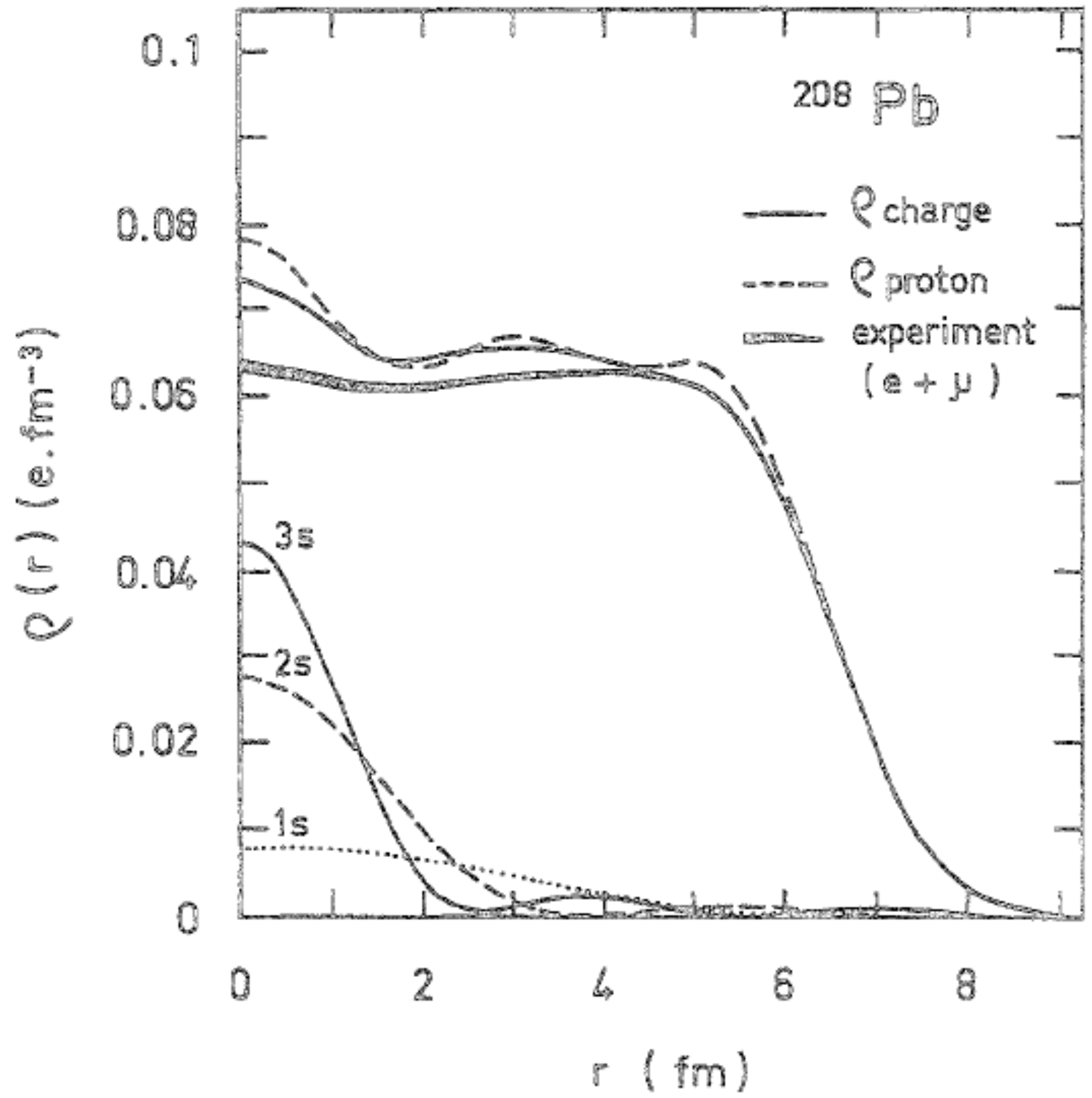

Elastic scattering: ground state

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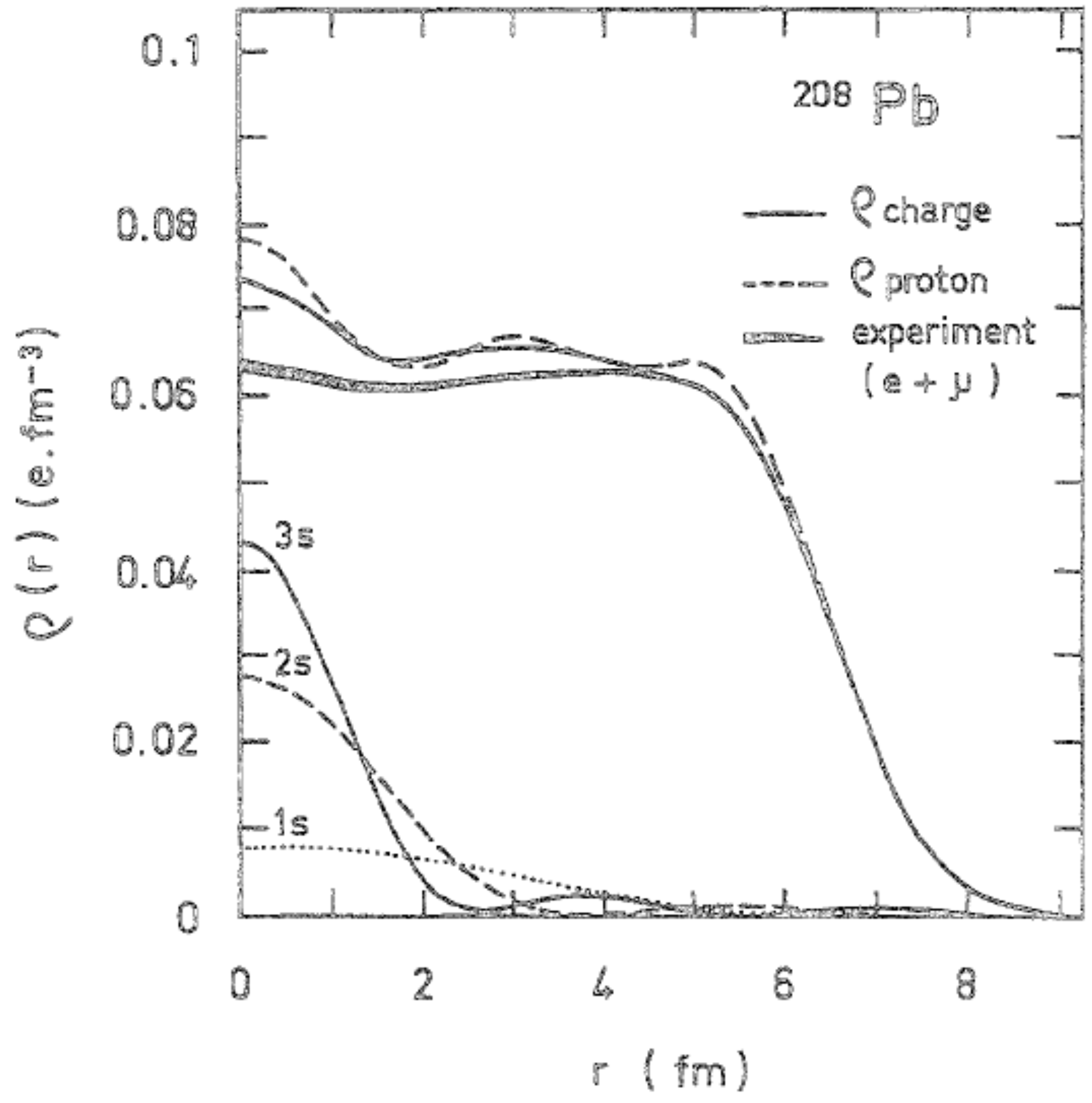
-single-particles are zero at r=0, except "**s**" waves

-3s proton state: first candidate being responsible of the "bump" at r=0



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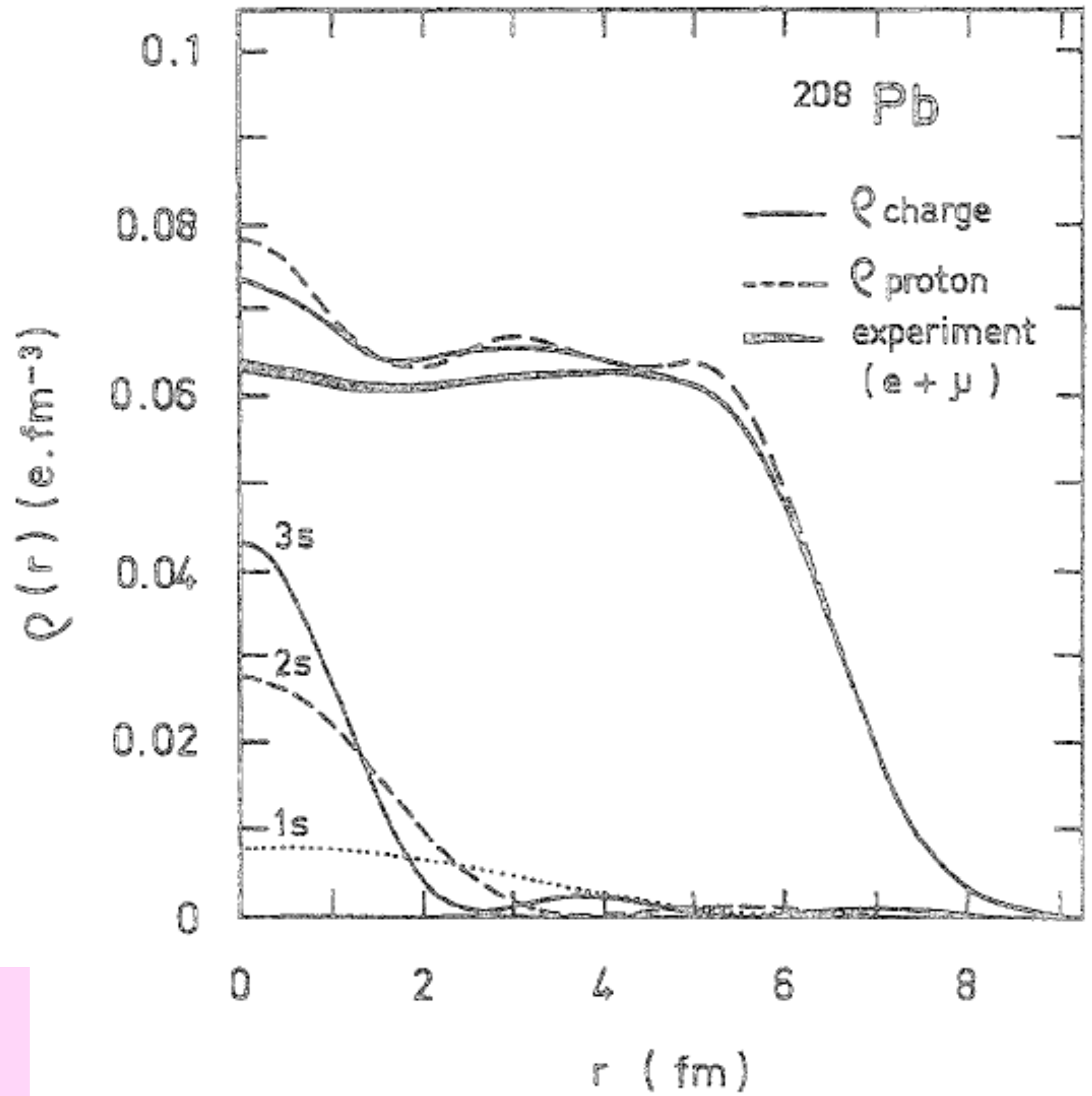

is it possible to isolate experimentally this proton single-particle state?

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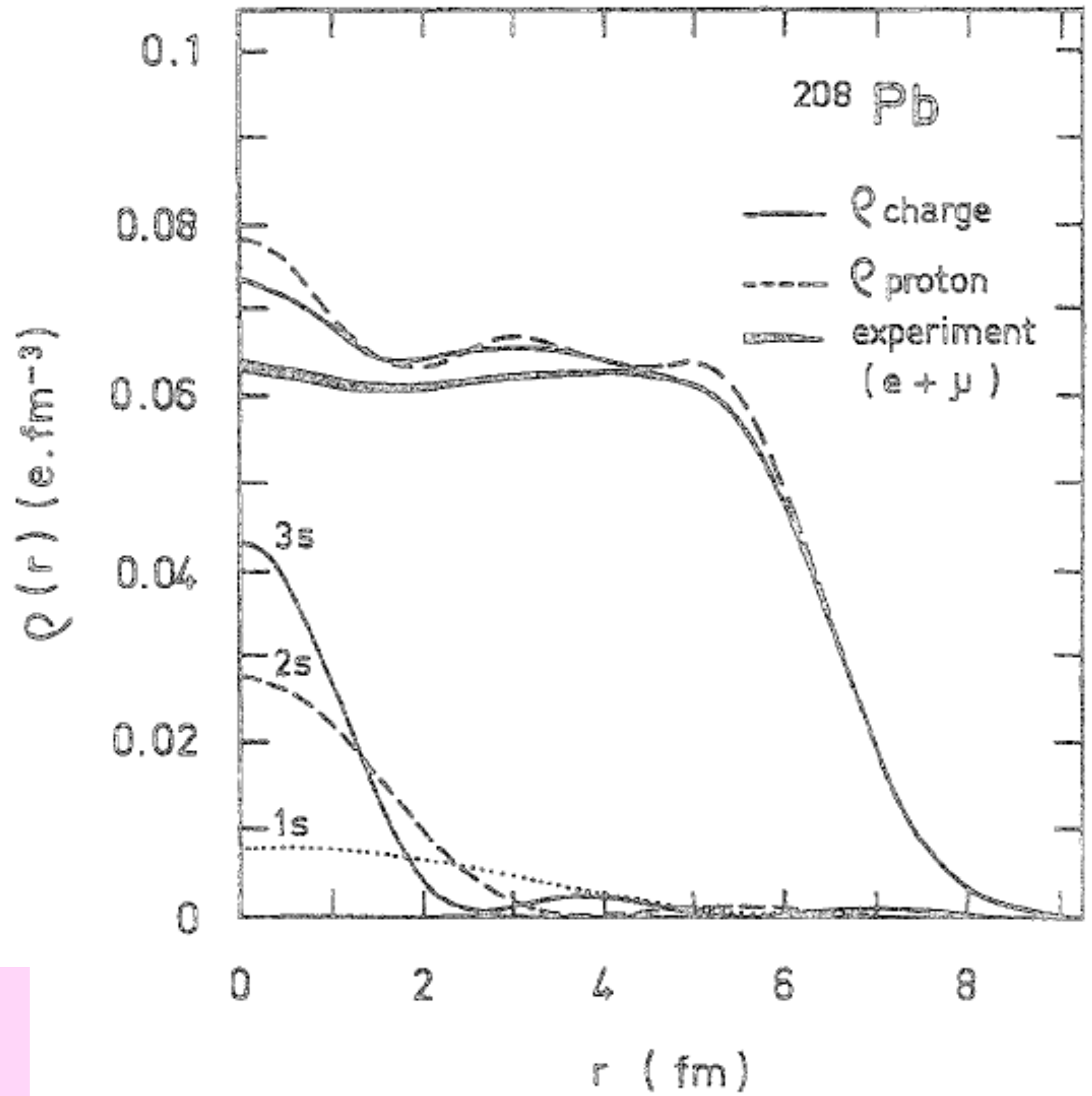

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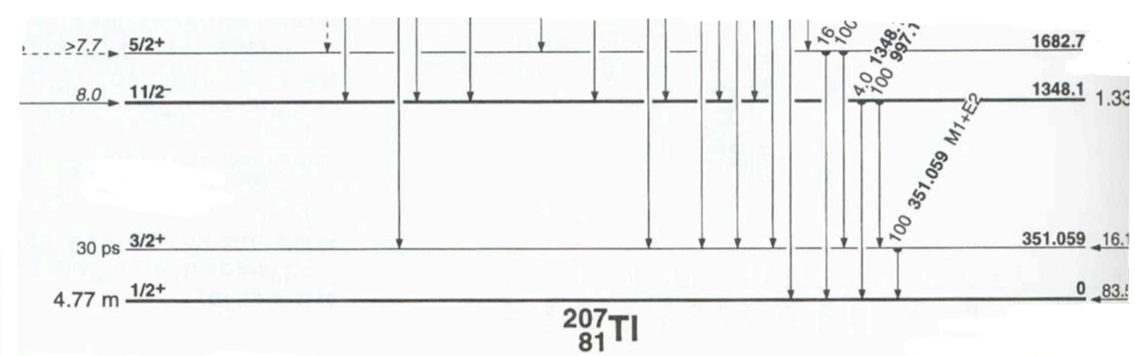

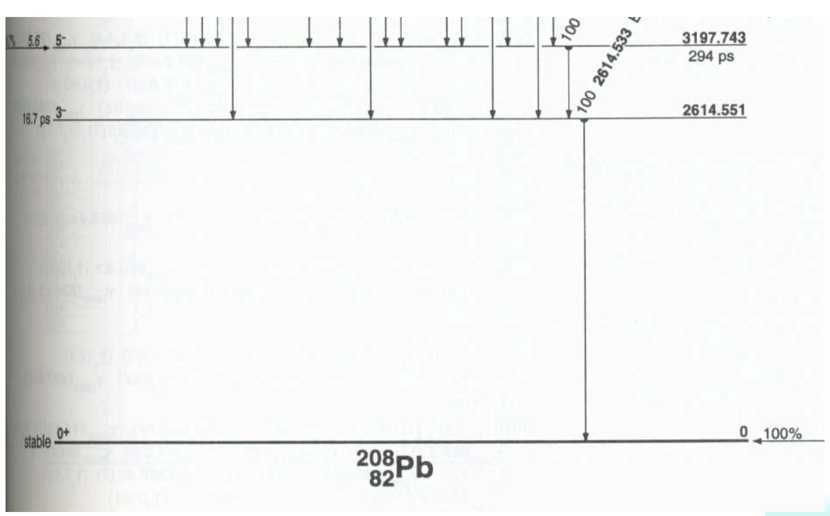

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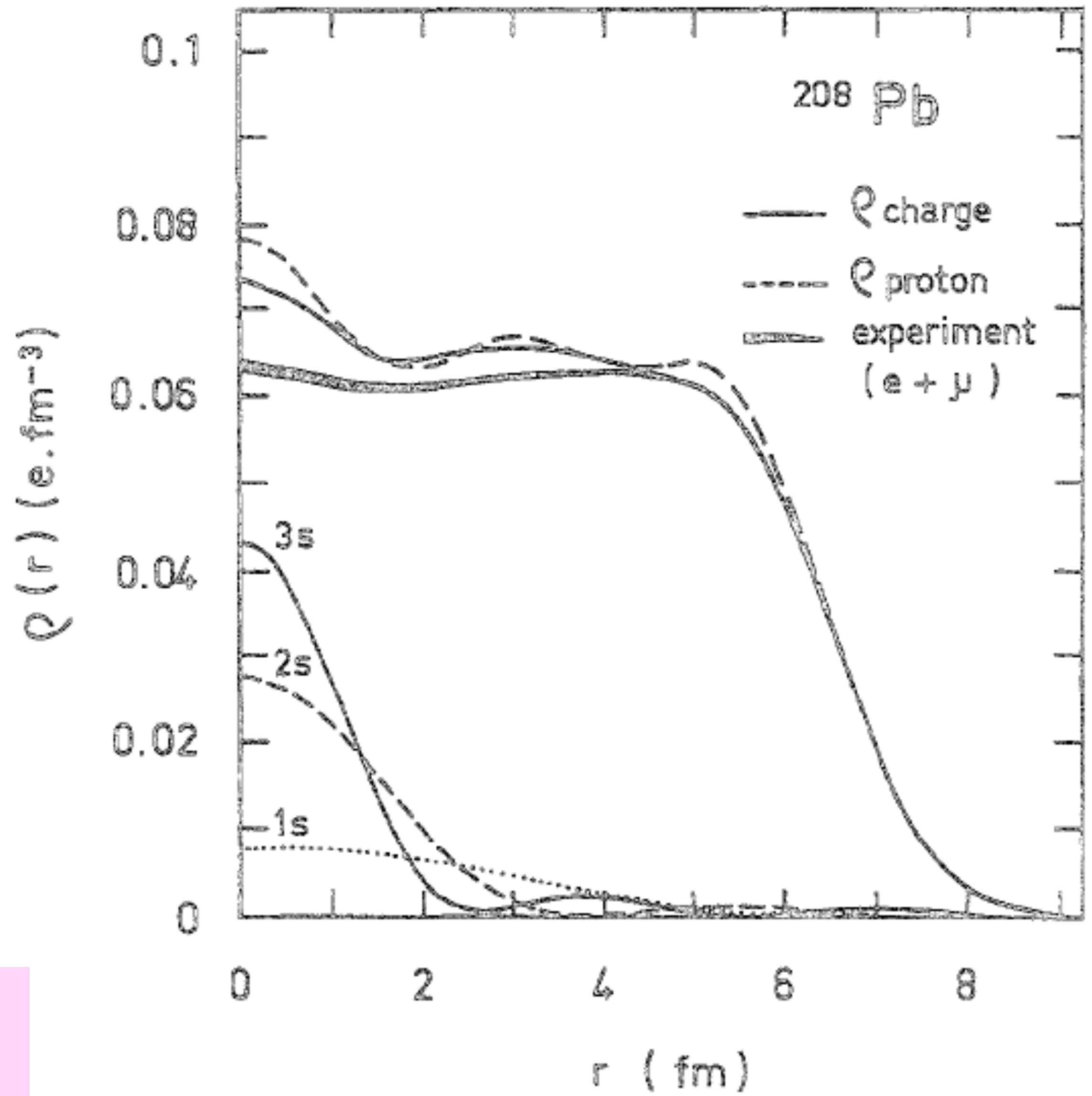
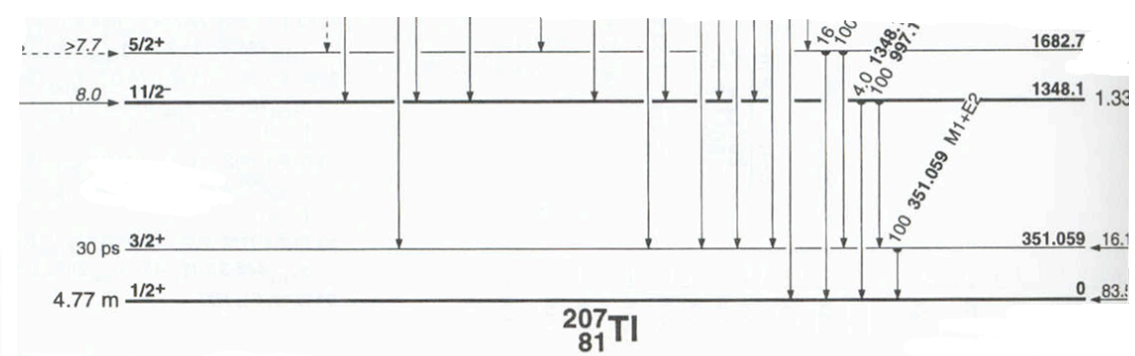
-single-particles are zero at r=0, except "s" waves

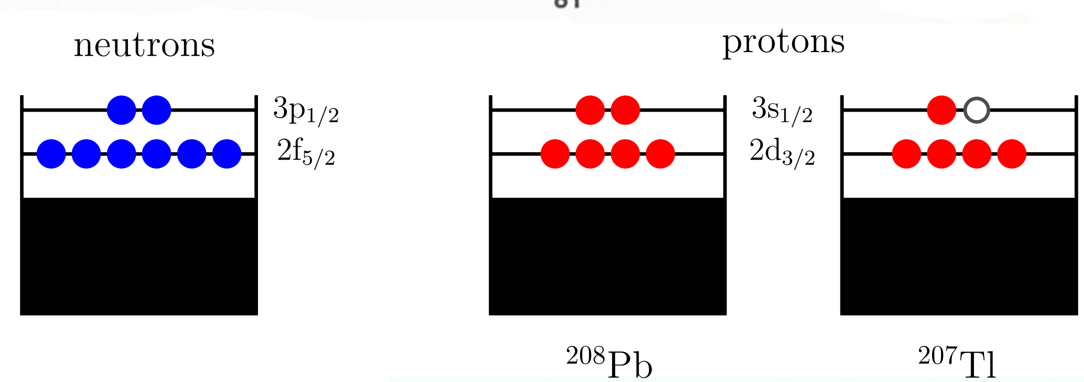
-3s proton state: first candidate being responsible of the "bump" at r=0

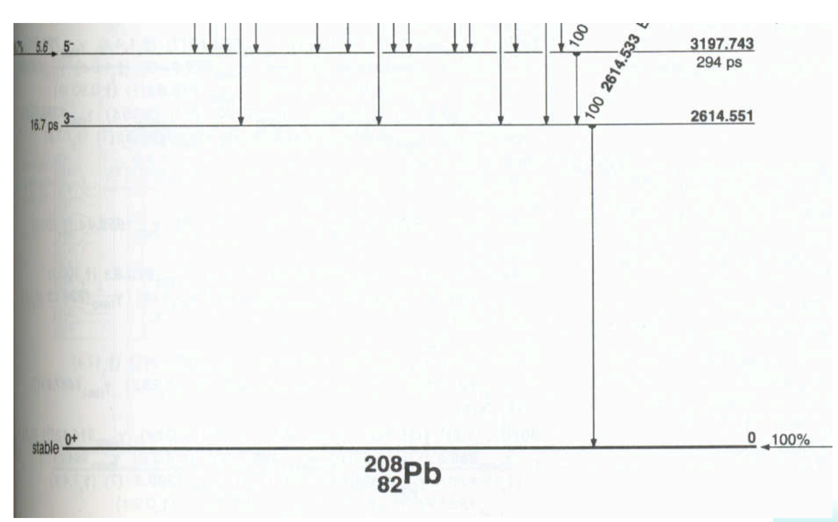


is it possible to isolate experimentally this proton single-particle state?

charge density difference $\rho(^{208}\mathrm{Pb}) - \rho(^{207}\mathrm{Tl})$

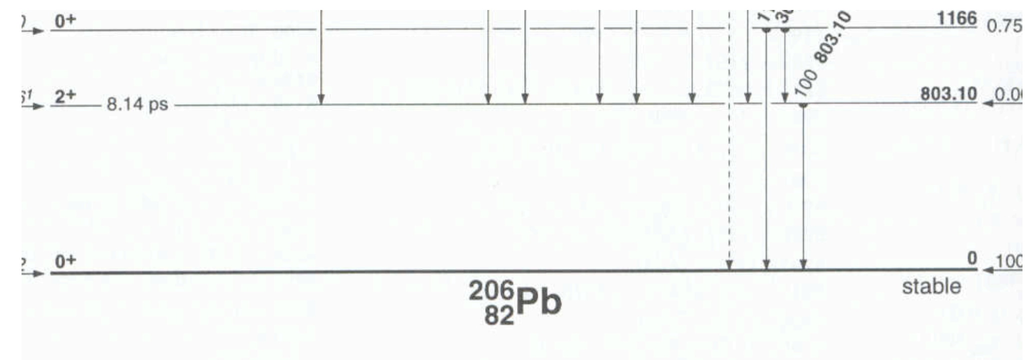


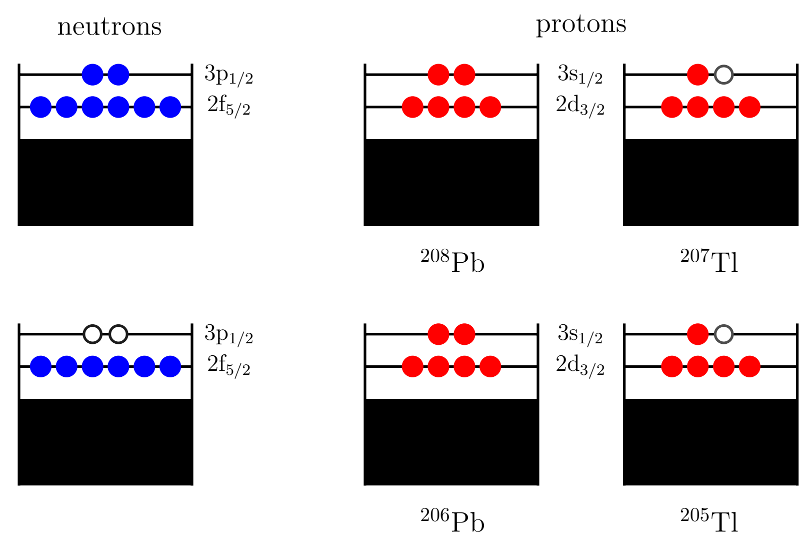


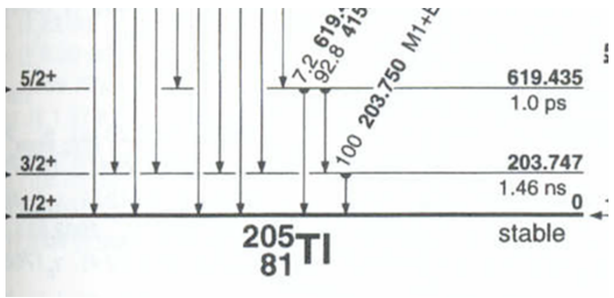


Elastic scattering: ground state

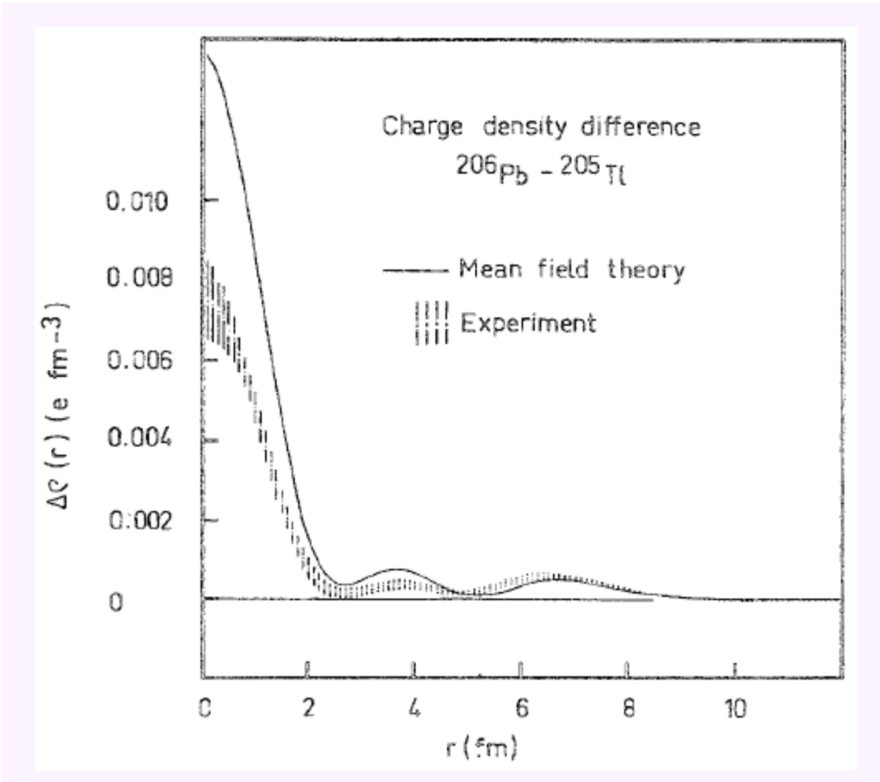
Elastic scattering: ground state

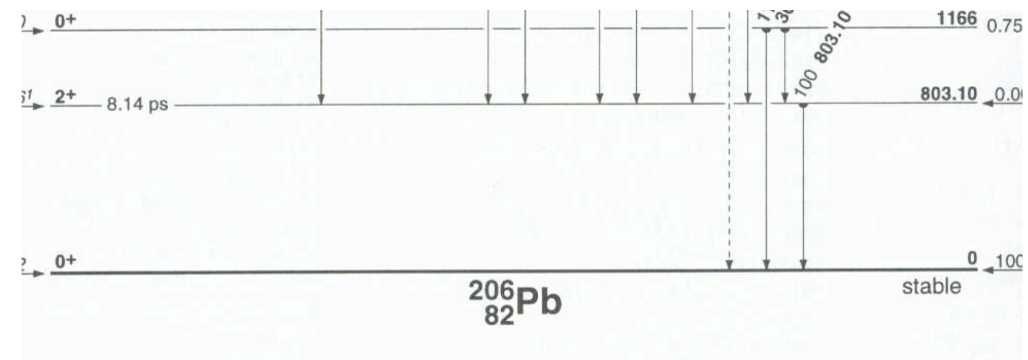


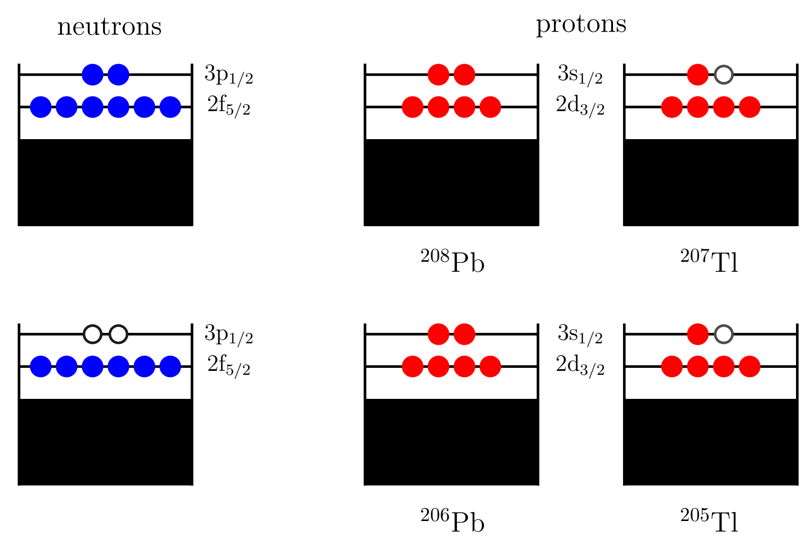


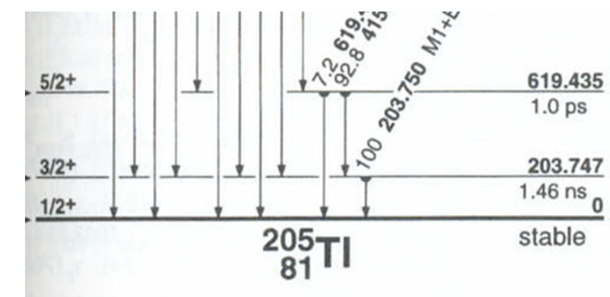


Elastic scattering: ground state

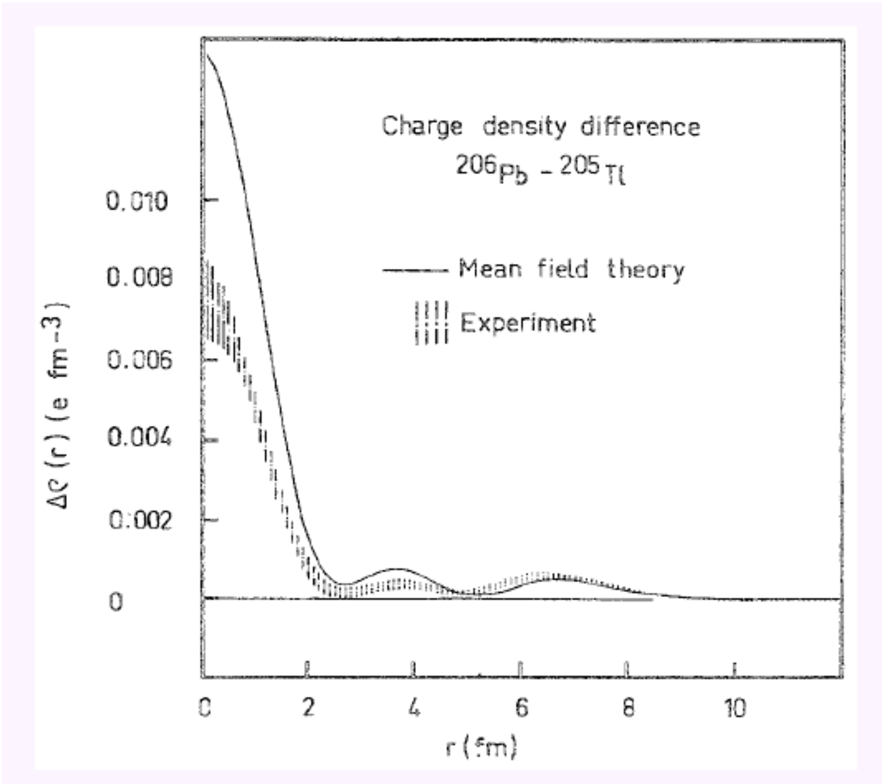


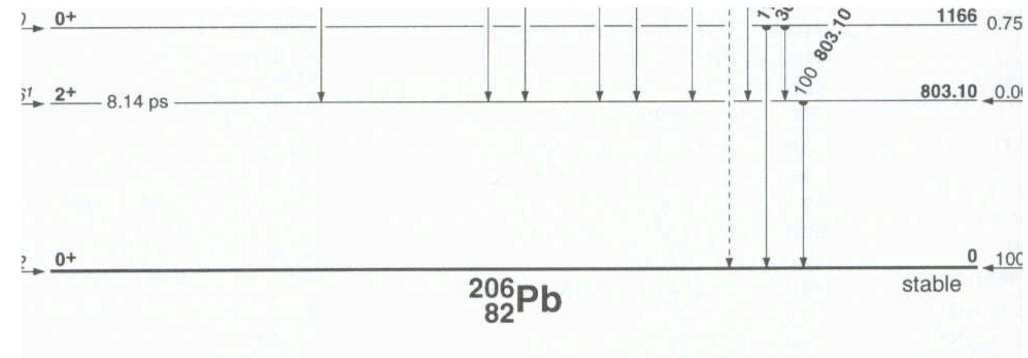


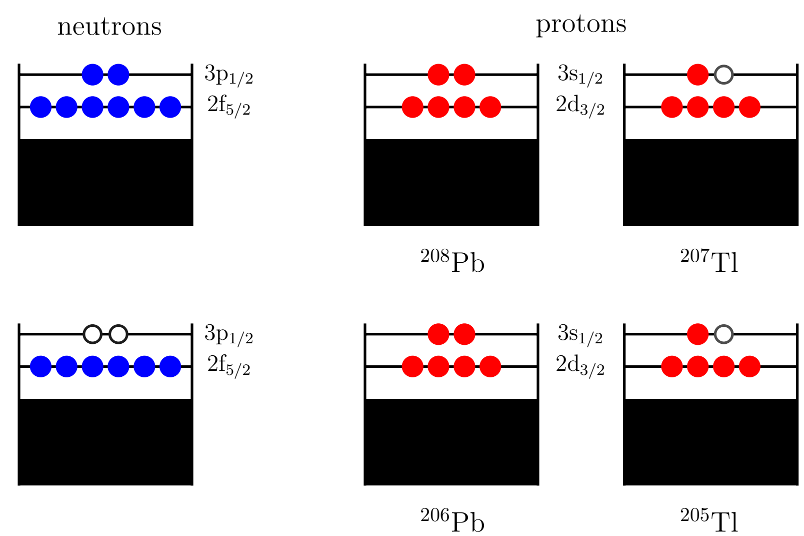


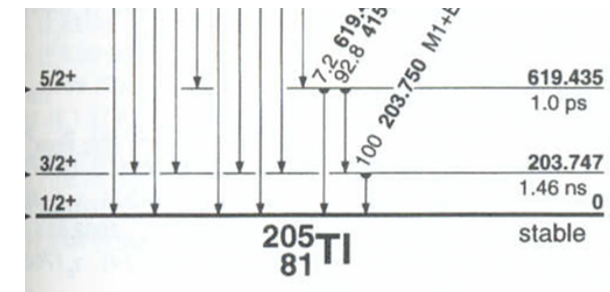


Elastic scattering: ground state



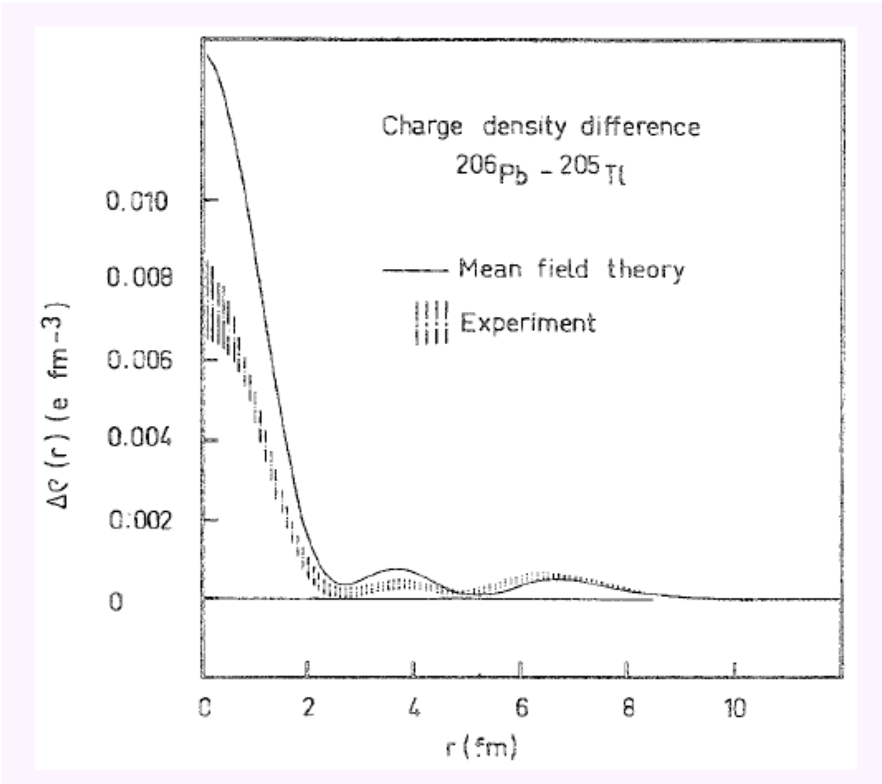


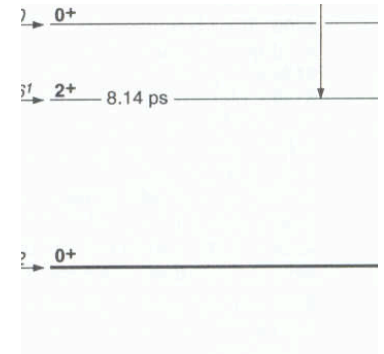


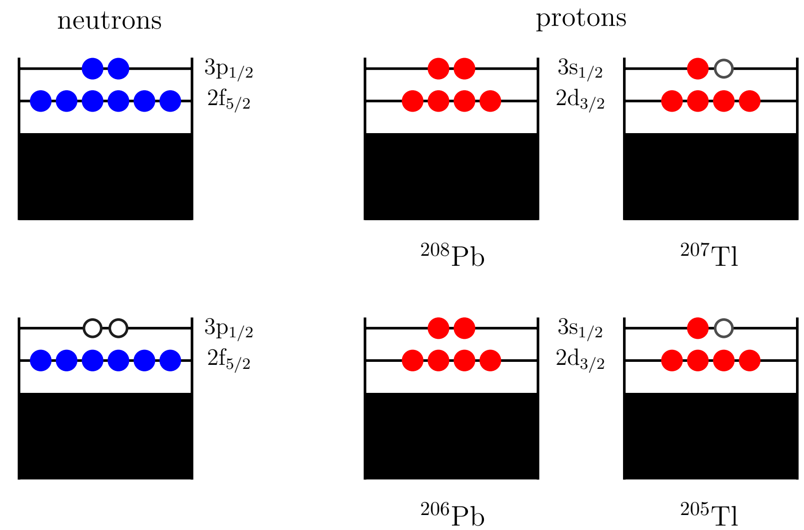


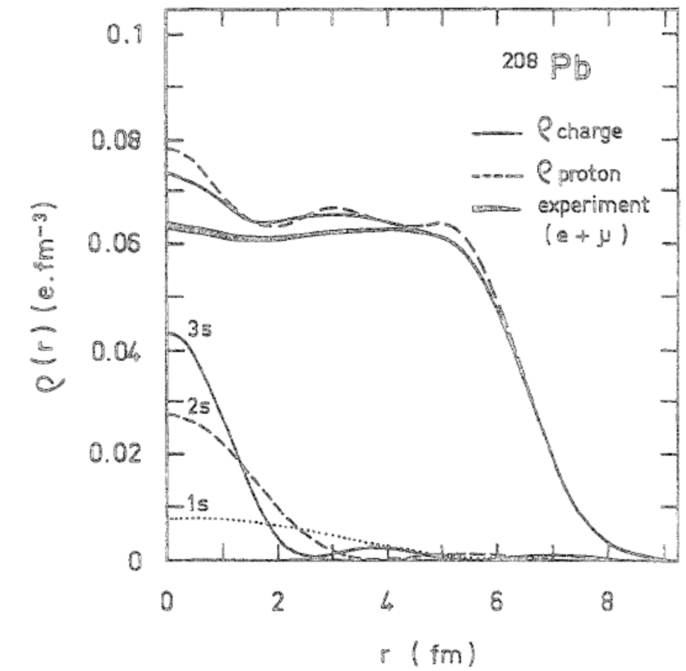
polarization effects: coupling of low-lying excited states of ^{206}Pb to 3s proton hole

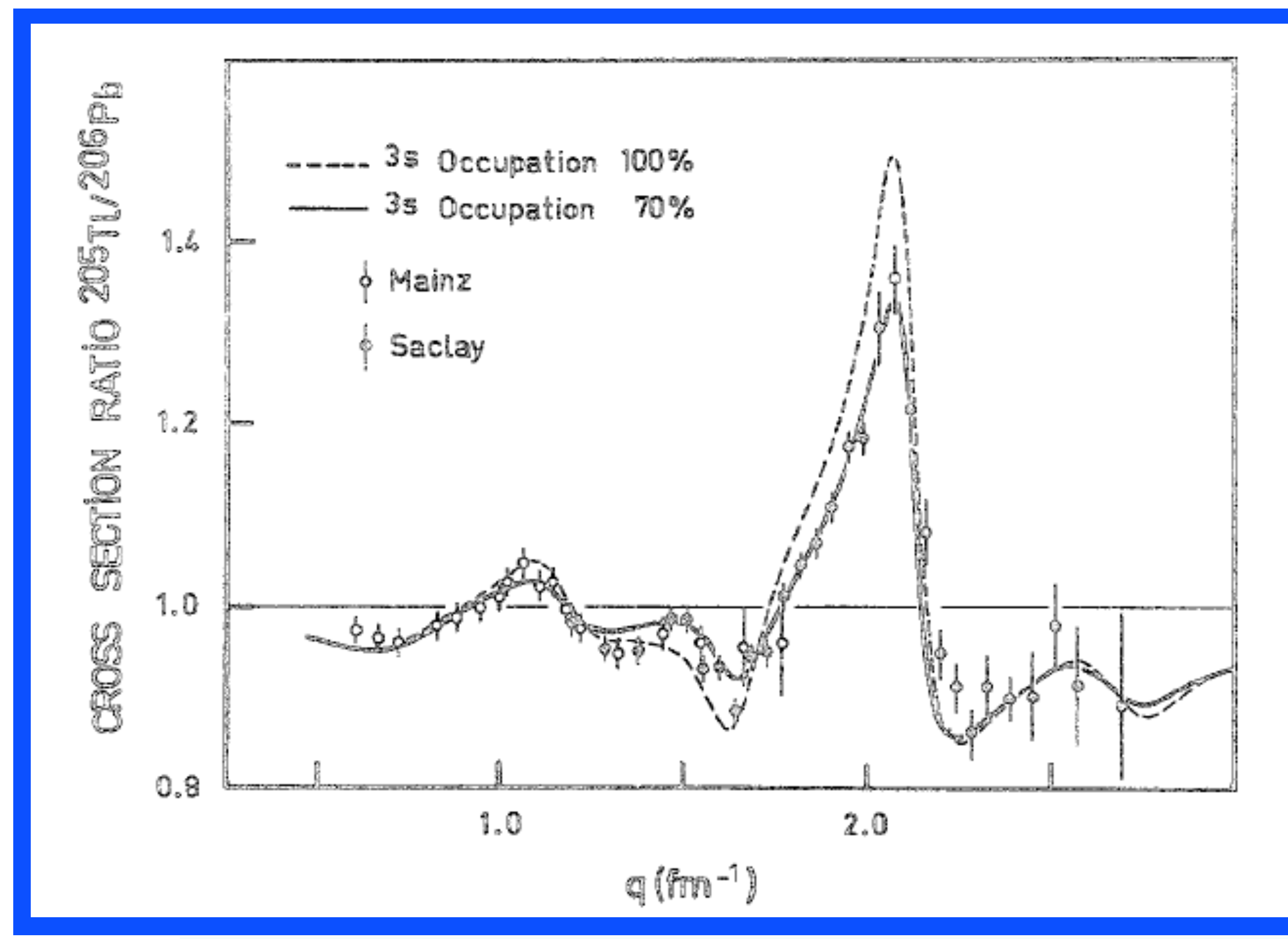
Elastic scattering: ground state





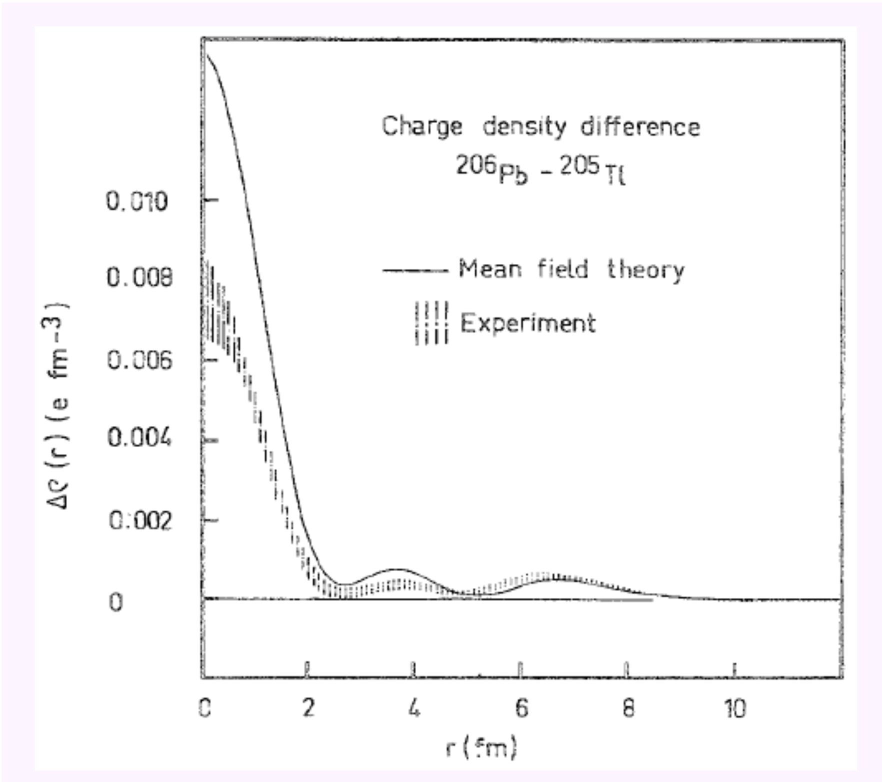


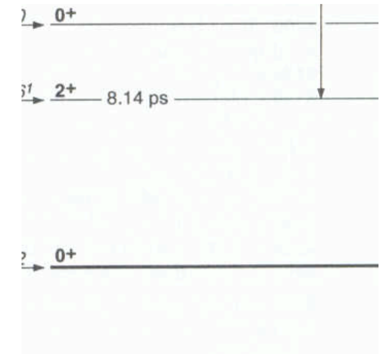


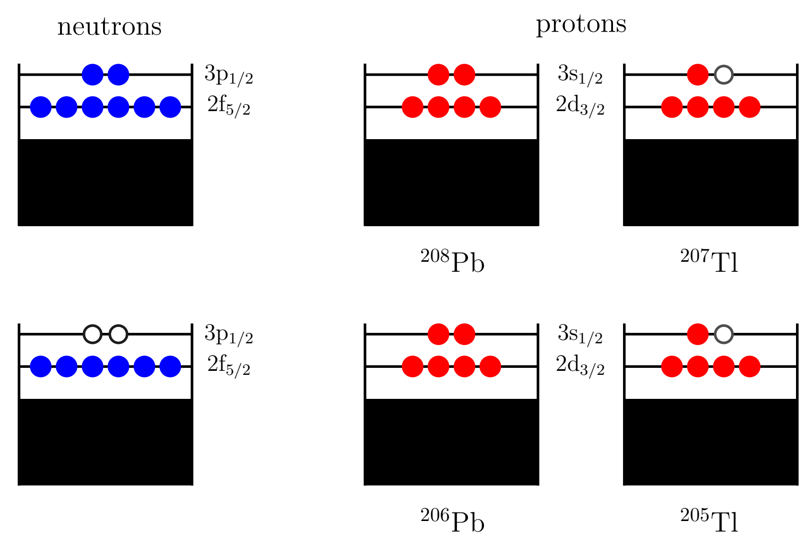


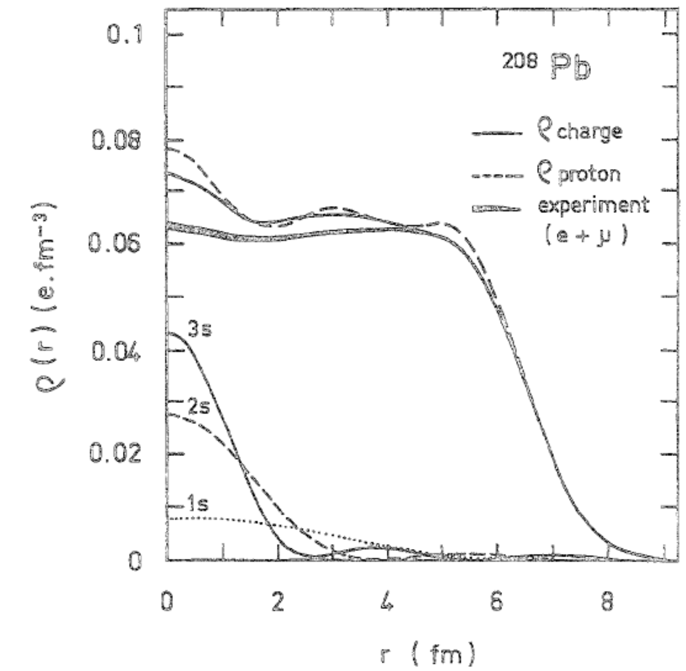
<u>polarization effects</u>: coupling of low-lying excited states of ^{206}Pb to 3s proton hole

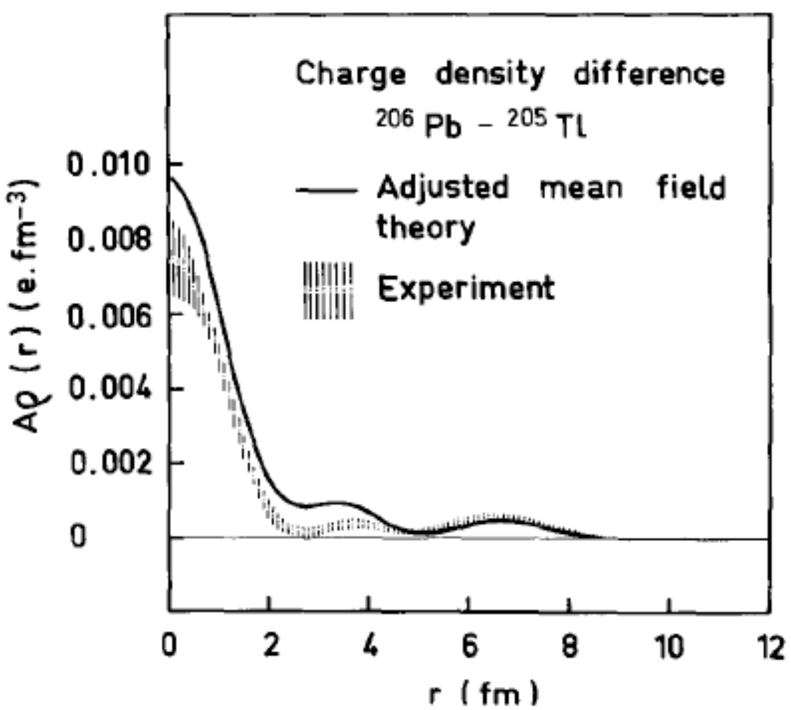
Elastic scattering: ground state

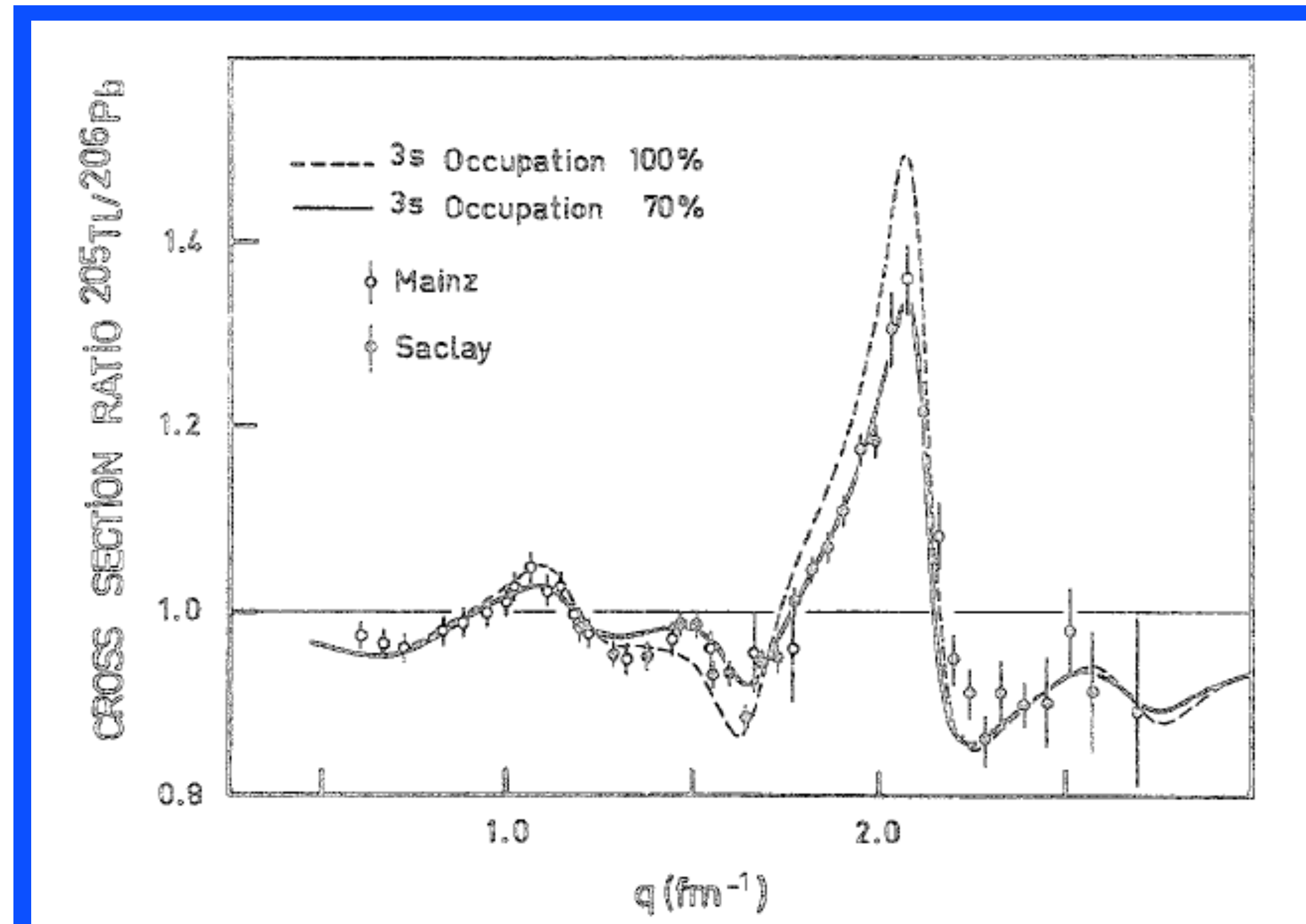






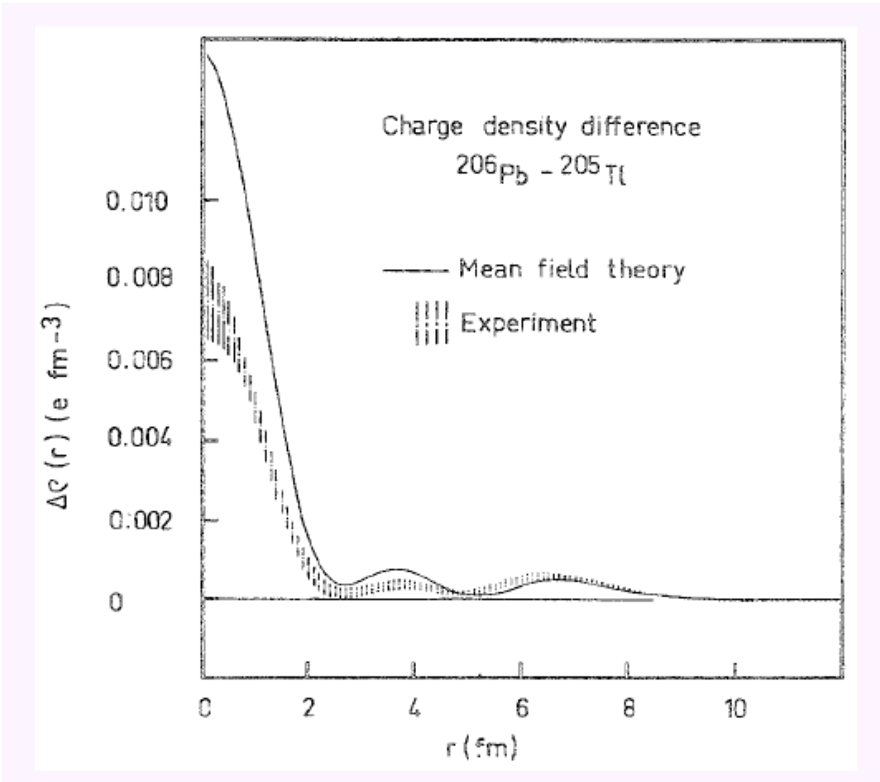


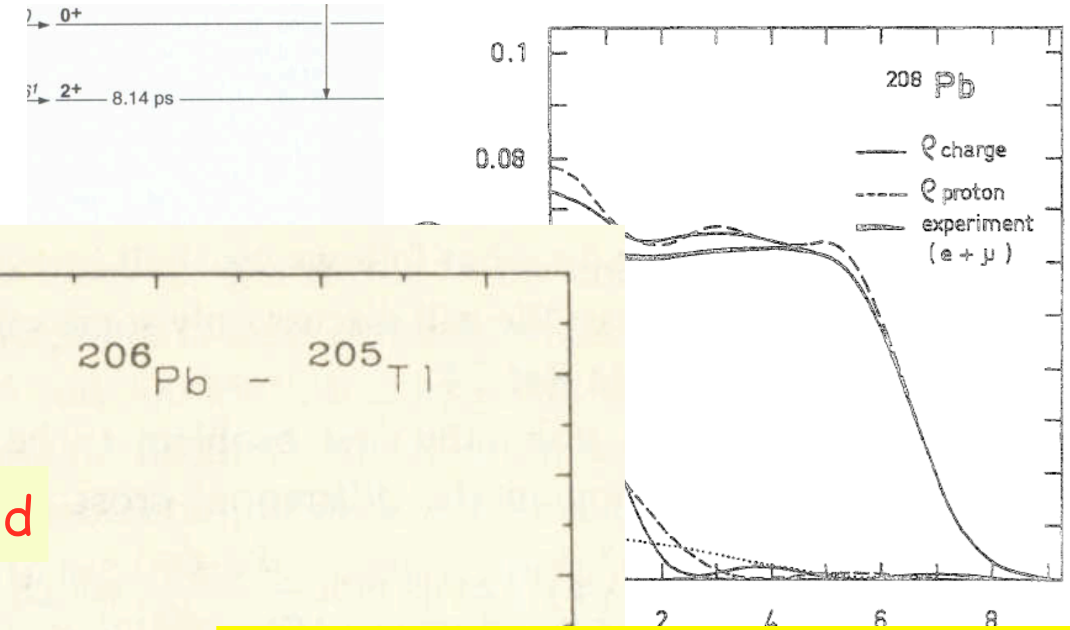


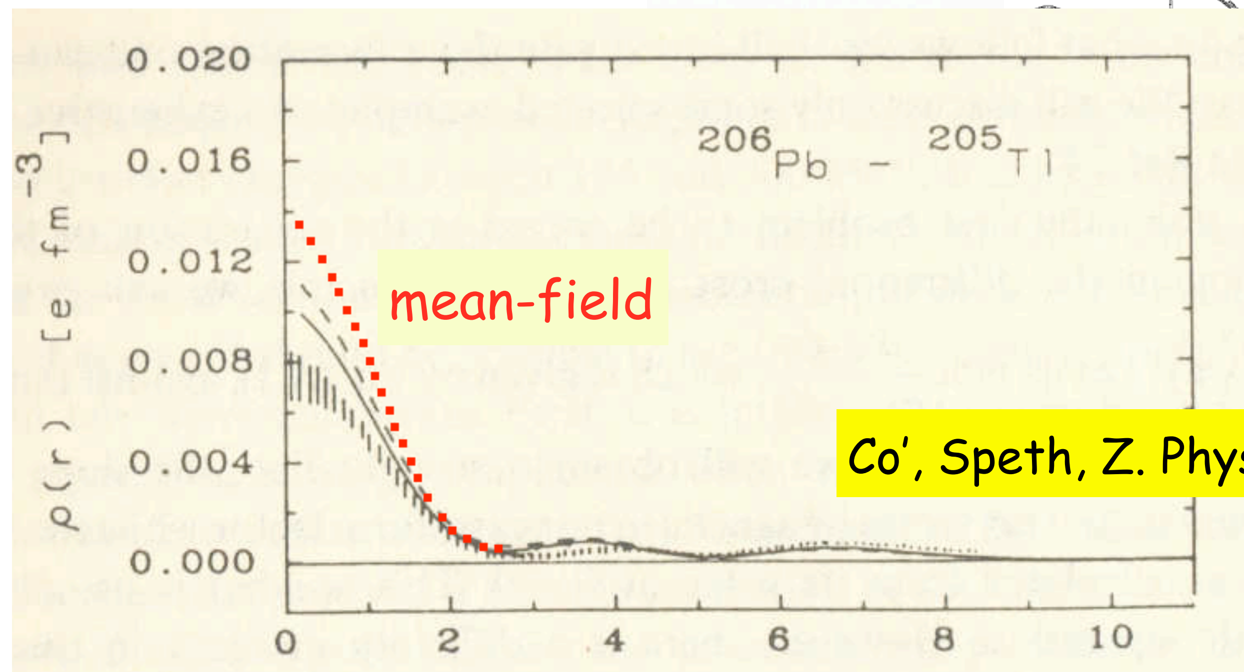


polarization effects: coupling of low-lying excited states of ^{206}Pb to 3s proton hole

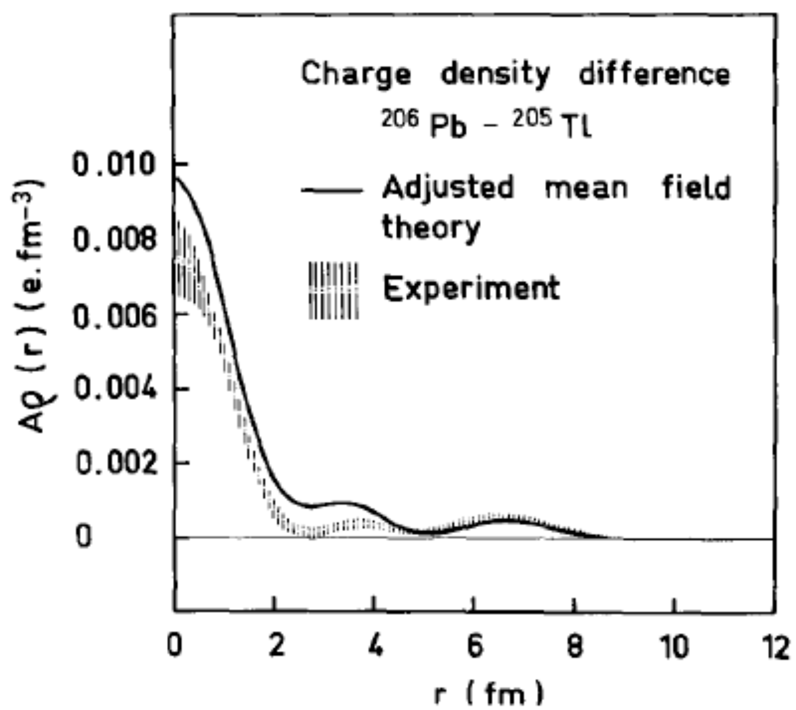
Elastic scattering: ground state

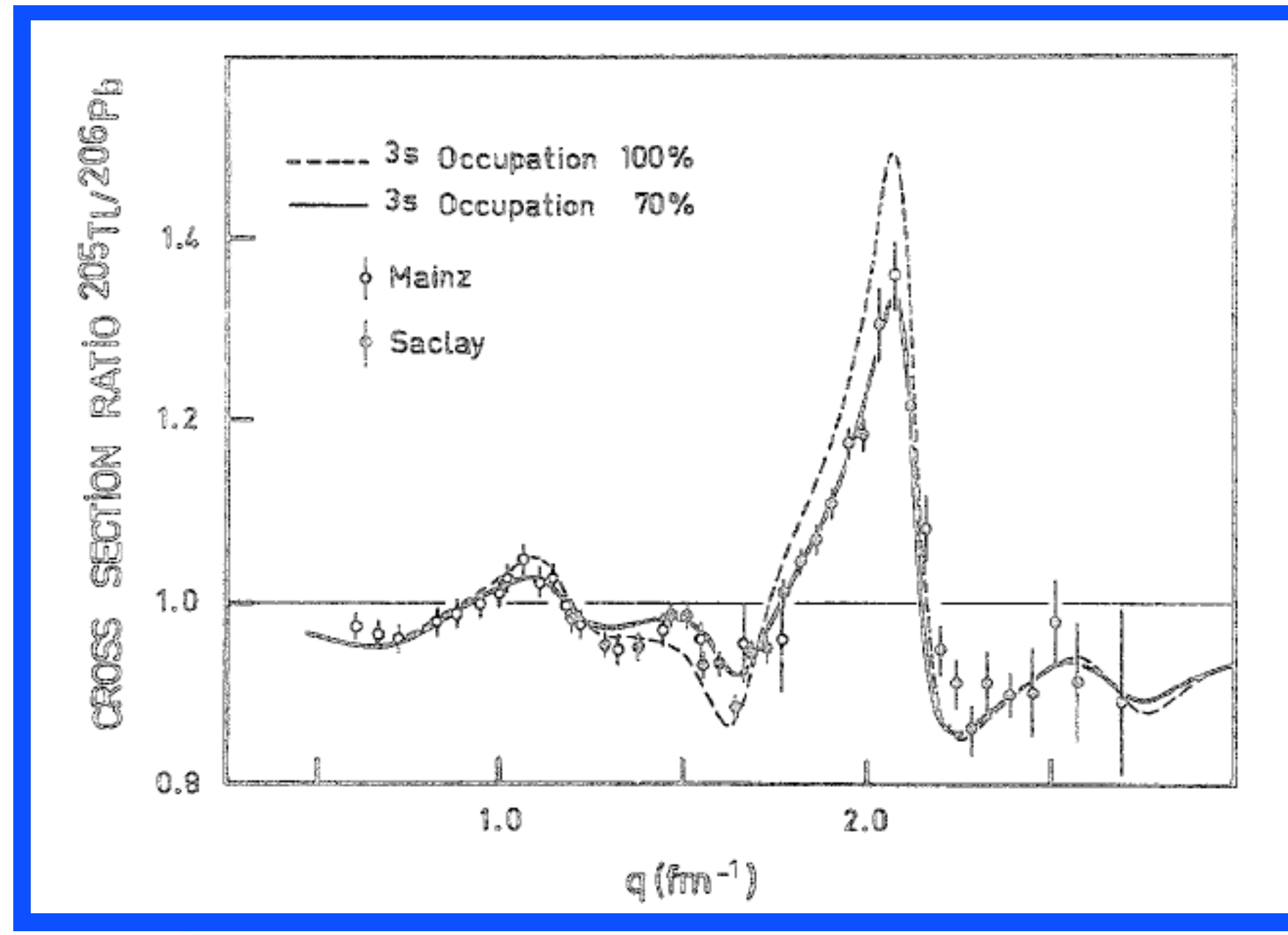






Co', Speth, Z. Phys. A 326 (1987) 392





polarization effects: coupling of low-lying excited states of ^{206}Pb to 3s proton hole

Elastic scattering: ground state

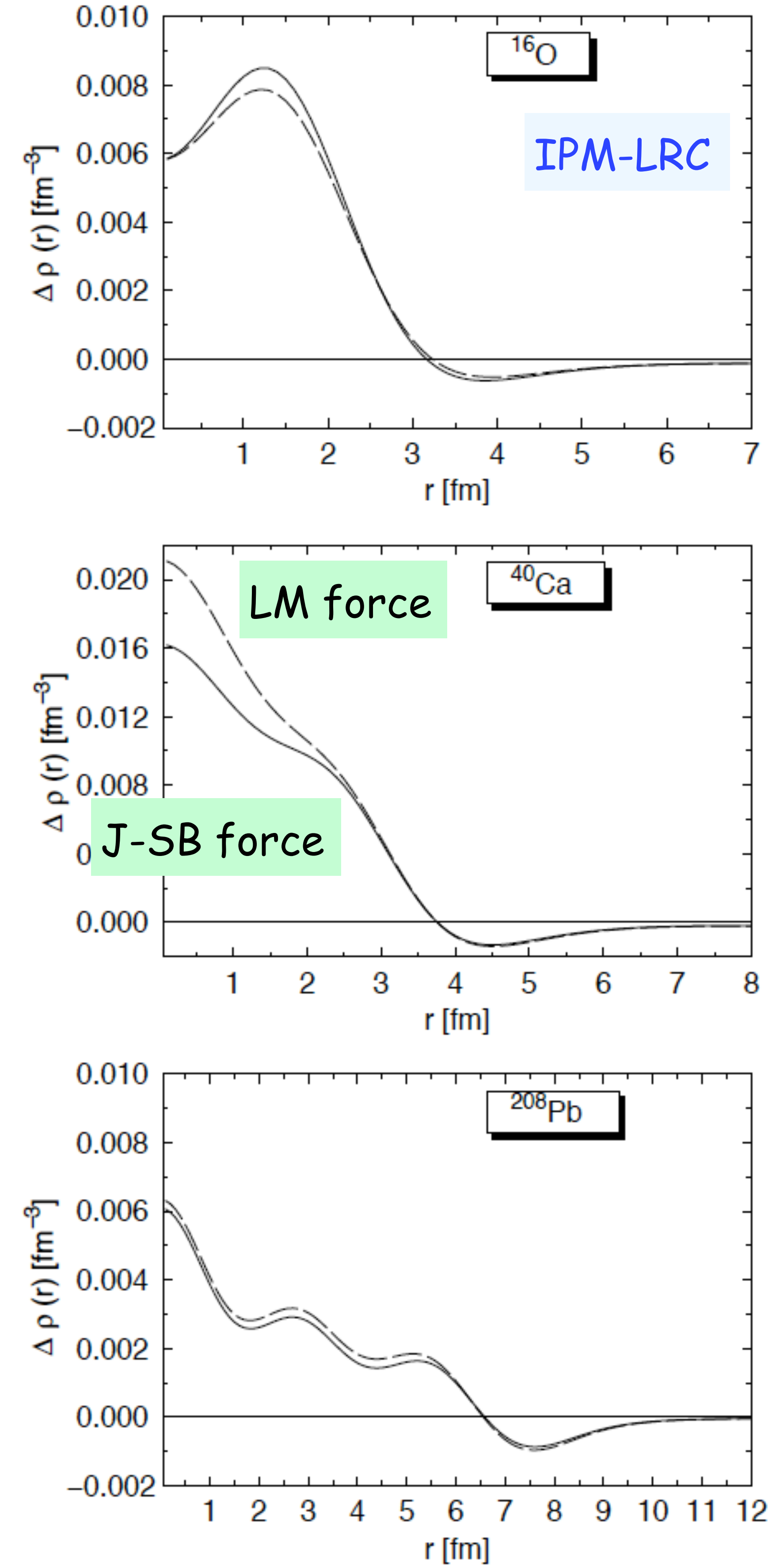
Anguiano, Co', J. Phys. G 27 (2001) 2109

short- and long-range correlations

long-range correlations: RPA

$$4\pi\rho_{LRC}(r) = \sum_{(nlj)h}(2j_h+1)(R_{(nlj)h}(r))^2\left[1-\frac{1}{2}\frac{1}{2j_h+1}\sum_p\sum_{J,N}(2J+1)|Y_{ph}(J,N)|^2\right]$$
$$+\sum_{(nlj)p}(2j_p+1)(R_{(nlj)p}(r))^2\left[\frac{1}{2}\frac{1}{2j_p+1}\sum_h\sum_{J,N}(2J+1)|Y_{ph}(J,N)|^2\right]$$

$$< A|\mathcal{O}_J|A > - < A-1;i|\mathcal{O}_J|k;A-1 > = < i||\mathcal{O}_J||k >$$
$$+\sum_N\sum_{p_1p_2h_1h_2} < ip_1||V||kh_1 > \frac{X_{p_1h_1}(J,N)X^*_{p_2h_2}(J,N)}{\epsilon_{p_1}-\epsilon_{h_1}-\omega_N} < p_2||\mathcal{O}_J||h_2 >$$
$$-\sum_N\sum_{p_1p_2h_1h_2} < ip_1||V||kh_1 > \frac{Y_{p_1h_1}(J,N)Y^*_{p_2h_2}(J,N)}{\epsilon_{p_1}+\epsilon_{h_1}-\omega_N} < h_2||\mathcal{O}_J||p_2 >$$



Elastic scattering: ground state

Anguiano, Co', J. Phys. G 27 (2001) 2109

short- and long-range correla[...]

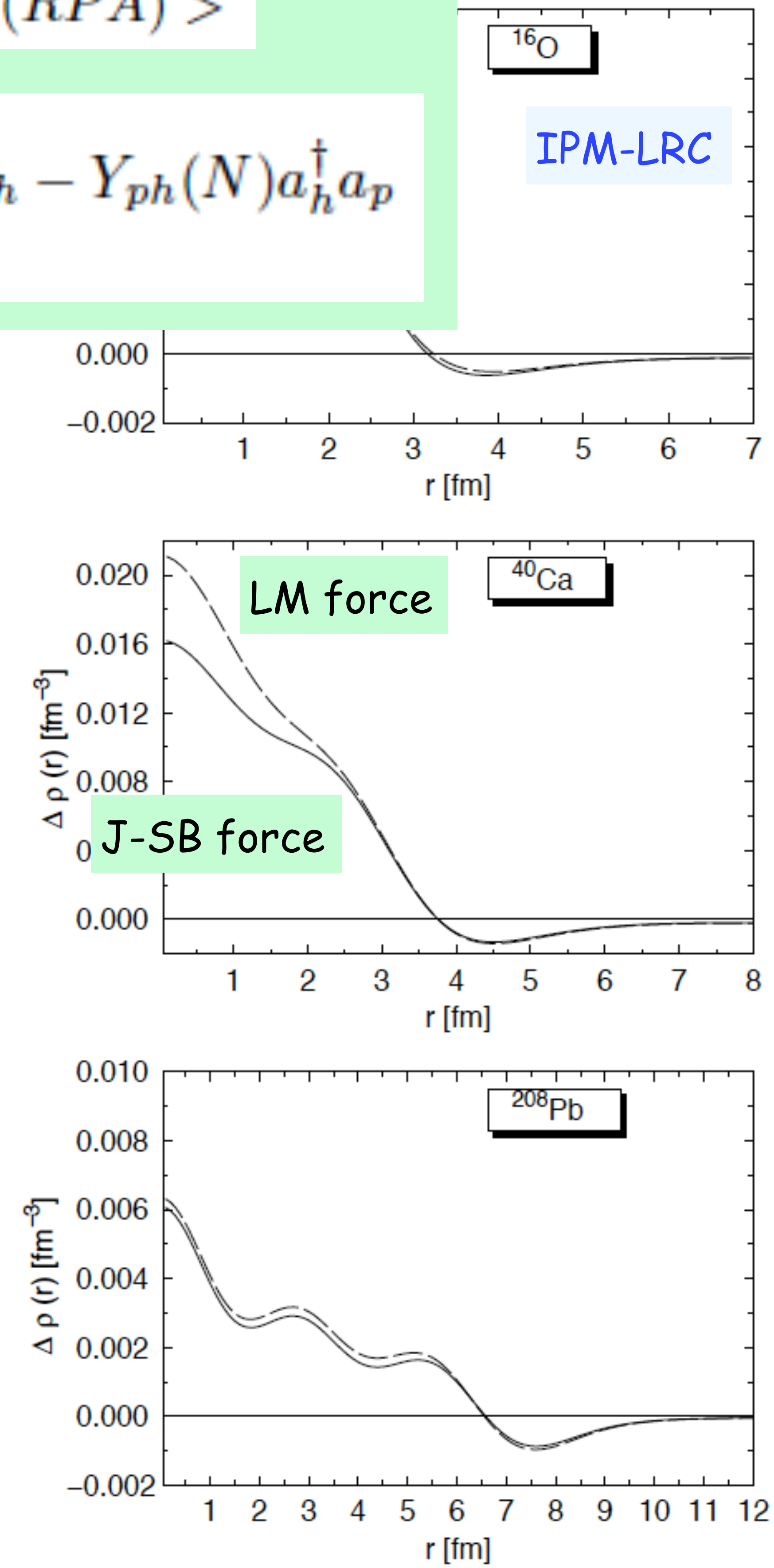
long-range correlations: RPA

$$|\Psi_N(RPA)>= Q_N^\dagger |\Psi_0(RPA)>$$

$$Q_N^\dagger = \sum_{ph} X_{ph}(N) a_p^\dagger a_h - Y_{ph}(N) a_h^\dagger a_p$$

$$\begin{aligned} 4\pi\rho_{LRC}(r) &= \sum_{(nlj)h} (2j_h+1)(R_{(nlj)h}(r))^2 \left[1 - \frac{1}{2}\frac{1}{2j_h+1}\sum_p \sum_{J,N} (2J+1)|Y_{ph}(J,N)|^2 \right. \\ &+ \sum_{(nlj)p} (2j_p+1)(R_{(nlj)p}(r))^2 \left[\frac{1}{2}\frac{1}{2j_p+1}\sum_h \sum_{J,N} (2J+1)|Y_{ph}(J,N)|^2 \right] \end{aligned}$$

$$\begin{aligned} &< A|\mathcal{O}_J|A > - < A-1; i|\mathcal{O}_J|k; A-1 > = < i||\mathcal{O}_J||k > \\ &+ \sum_N \sum_{p_1 p_2 h_1 h_2} < ip_1||V||kh_1 > \frac{X_{p_1h_1}(J,N) X^*_{p_2h_2}(J,N)}{\epsilon_{p_1} - \epsilon_{h_1} - \omega_N} < p_2||\mathcal{O}_J||h_2 > \\ &- \sum_N \sum_{p_1 p_2 h_1 h_2} < ip_1||V||kh_1 > \frac{Y_{p_1h_1}(J,N) Y^*_{p_2h_2}(J,N)}{\epsilon_{p_1} + \epsilon_{h_1} - \omega_N} < h_2||\mathcal{O}_J||p_2 > \end{aligned}$$



Elastic scattering: ground state

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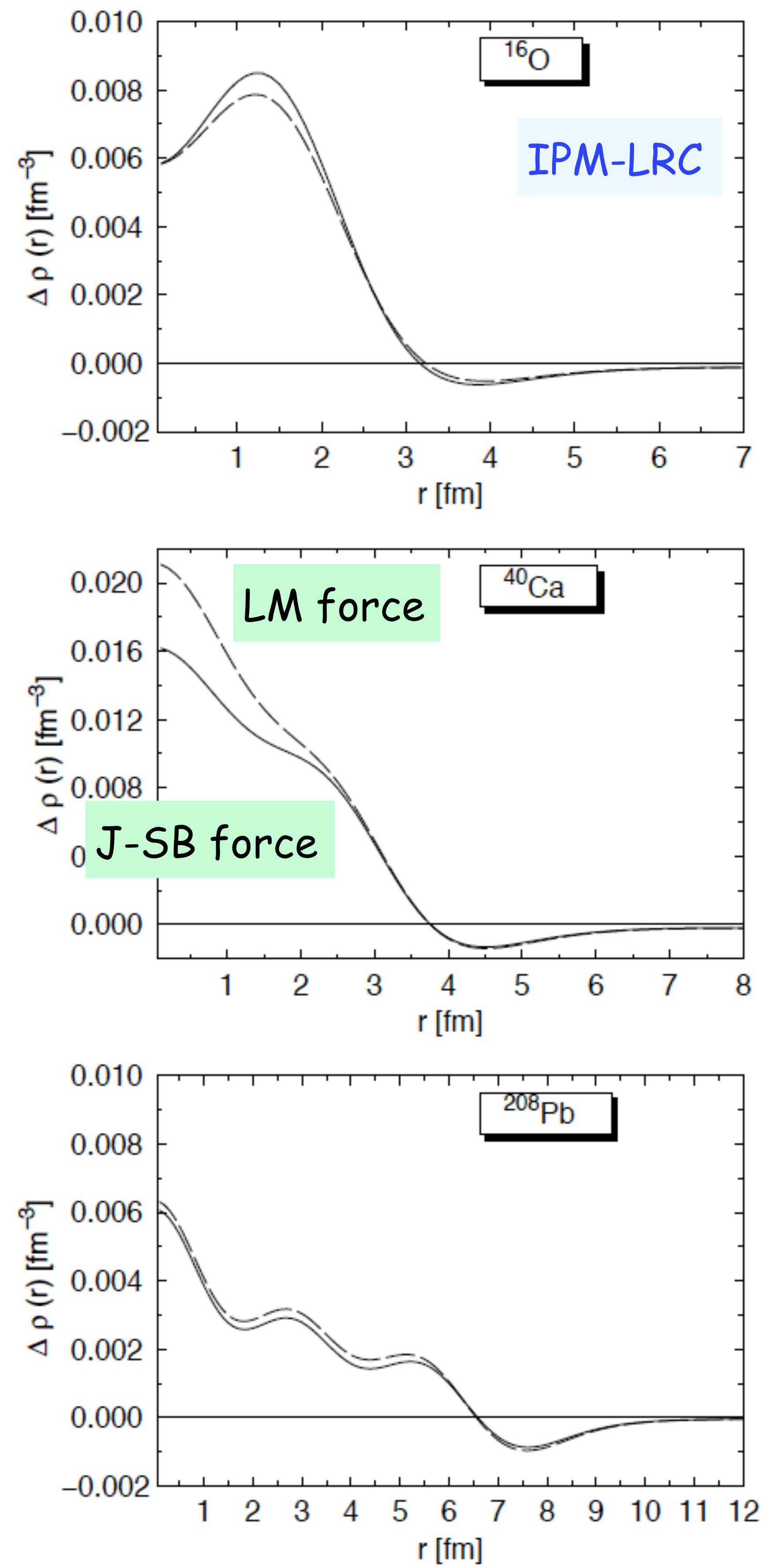
short- and long-range correlations

long-range correlations: RPA

$$4\pi\rho_{LRC}(r) = \sum_{(nlj)h}(2j_h+1)(R_{(nlj)h}(r))^2\left[1-\frac{1}{2}\frac{1}{2j_h+1}\sum_p\sum_{J,N}(2J+1)|Y_{ph}(J,N)|^2\right]$$
$$+\sum_{(nlj)p}(2j_p+1)(R_{(nlj)p}(r))^2\left[\frac{1}{2}\frac{1}{2j_p+1}\sum_h\sum_{J,N}(2J+1)|Y_{ph}(J,N)|^2\right]$$

$$< A|\mathcal{O}_J|A > - < A-1; i|\mathcal{O}_J|k; A-1 > = < i||\mathcal{O}_J||k >$$
$$+\sum_N\sum_{p_1p_2h_1h_2} < ip_1||V||kh_1 > \frac{X_{p_1h_1}(J,N)X^*_{p_2h_2}(J,N)}{\epsilon_{p_1}-\epsilon_{h_1}-\omega_N} < p_2||\mathcal{O}_J||h_2 >$$
$$-\sum_N\sum_{p_1p_2h_1h_2} < ip_1||V||kh_1 > \frac{Y_{p_1h_1}(J,N)Y^*_{p_2h_2}(J,N)}{\epsilon_{p_1}+\epsilon_{h_1}-\omega_N} < h_2||\mathcal{O}_J||p_2 >$$



Elastic scattering: ground state

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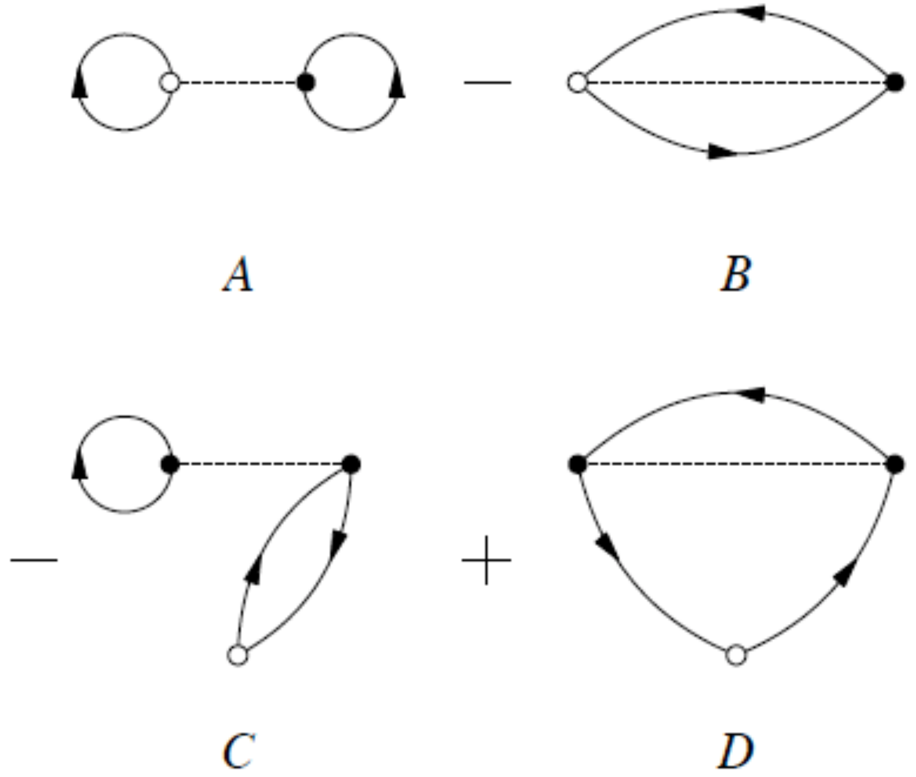
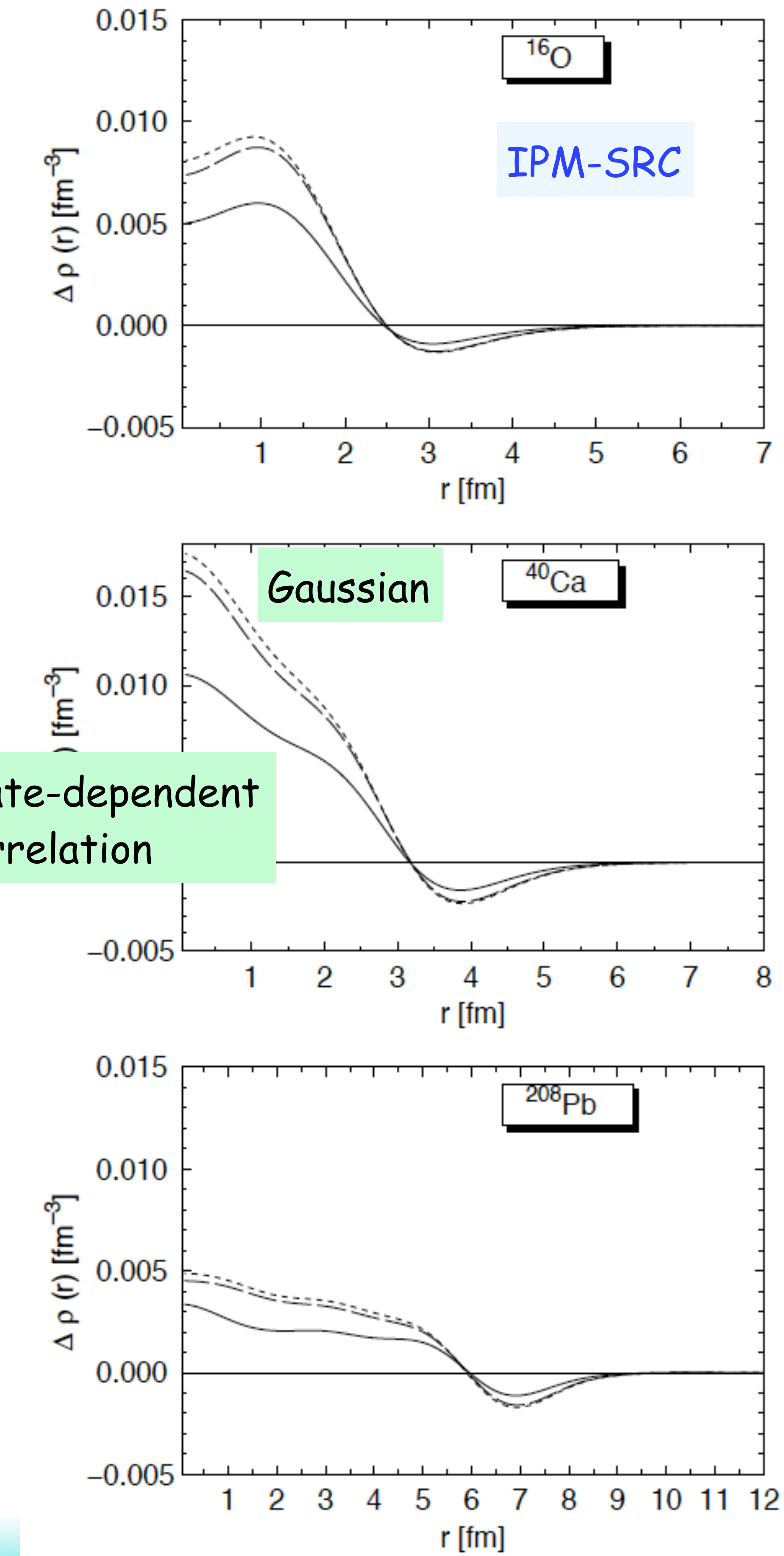
short- and long-range correlations

short-range correlations

$$< \mathcal{O} >= \frac{< \Psi_0|\mathcal{O}|\Psi_0 >}{< \Psi_0|\Psi_0 >} \qquad Q(\mathbf{r}) = \sum_i \delta(\mathbf{r}-\mathbf{r}_i)\frac{1}{2}\left[1+\tau_3(i)\right]$$

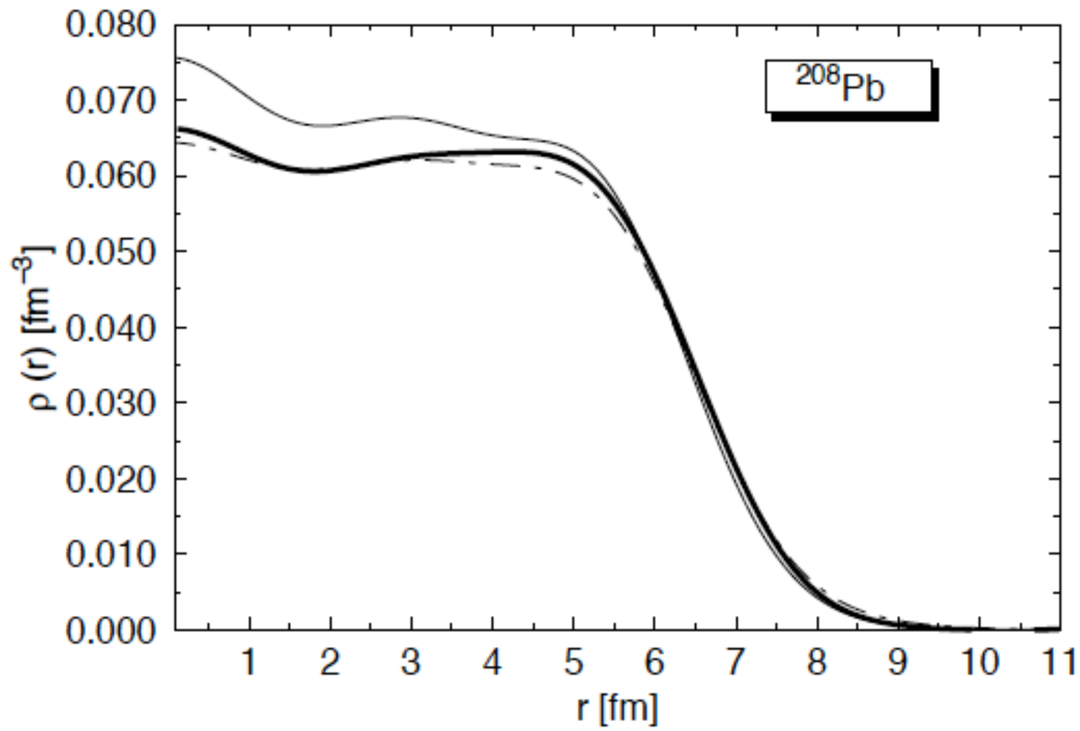
$$\Psi_0(1,2...A) = G(1,2...A)\Phi_0(1,2...A)$$

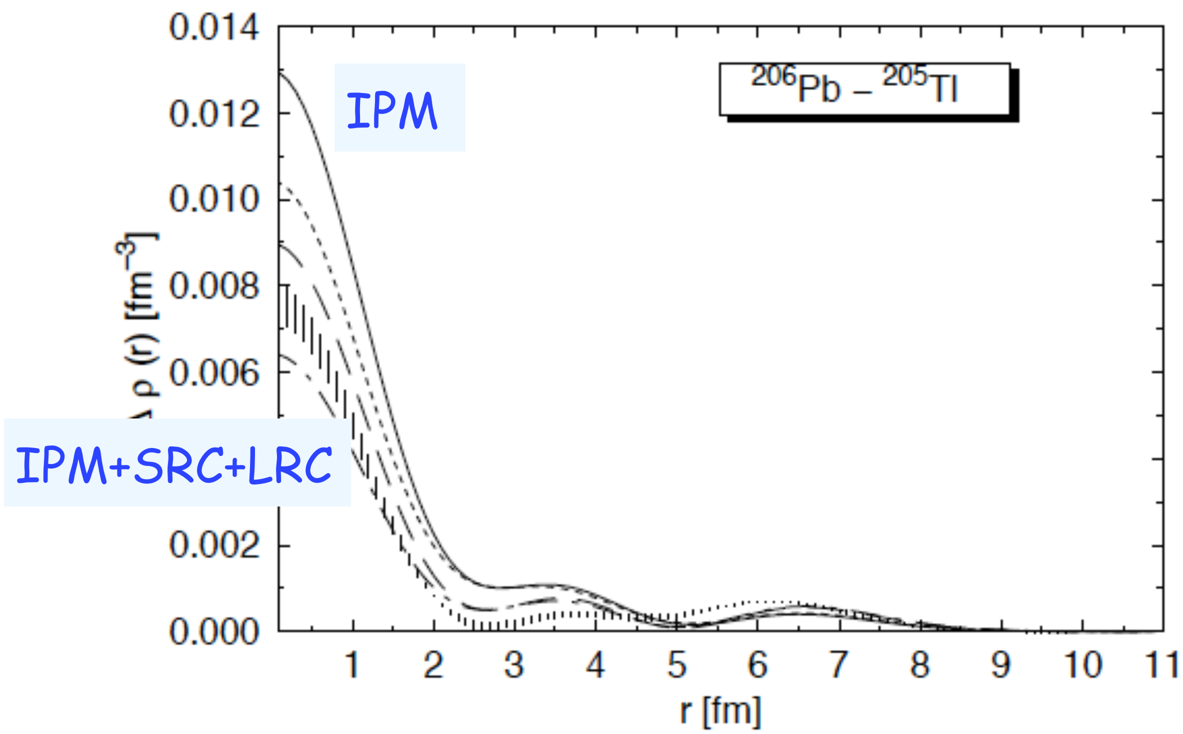


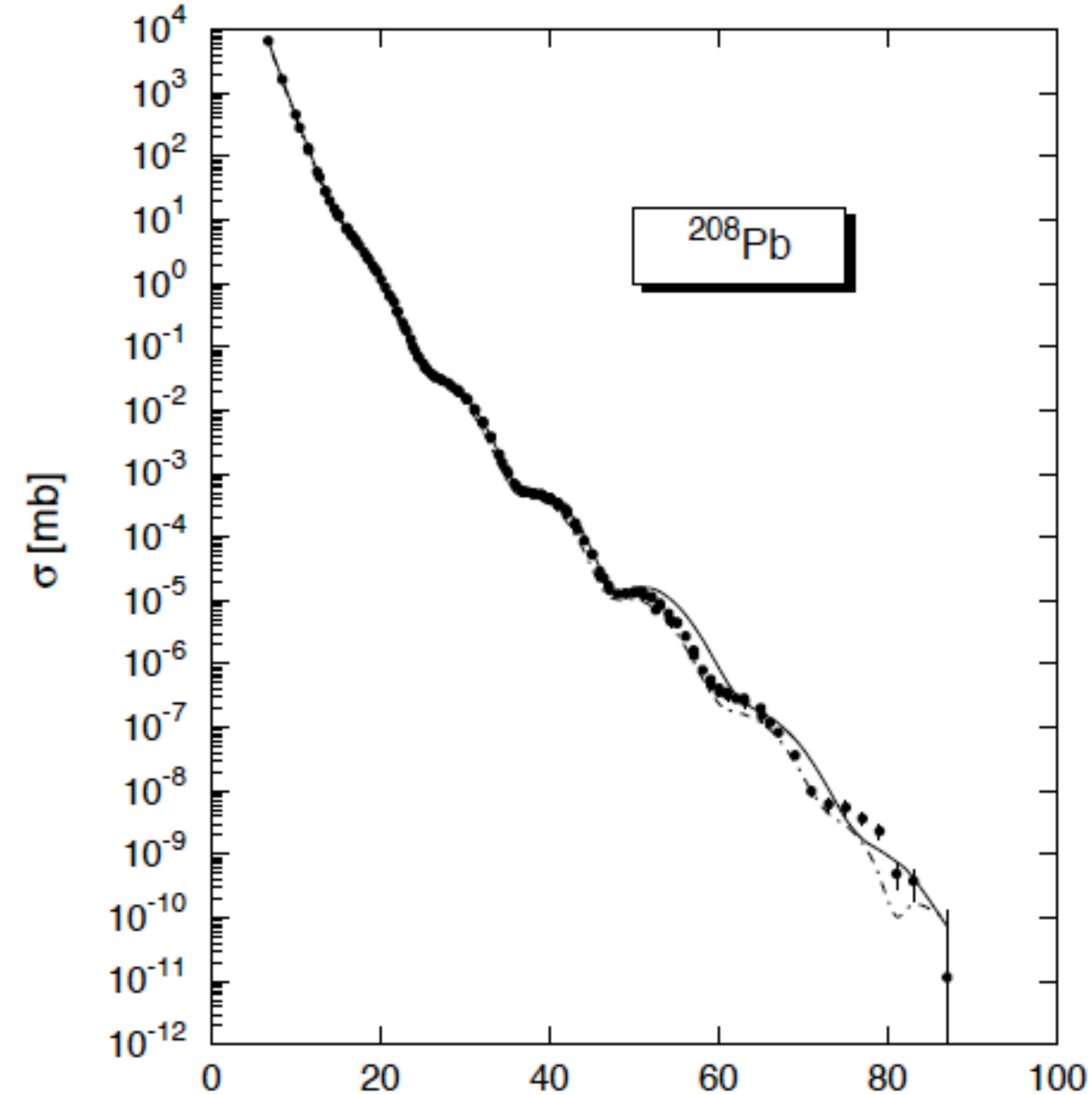


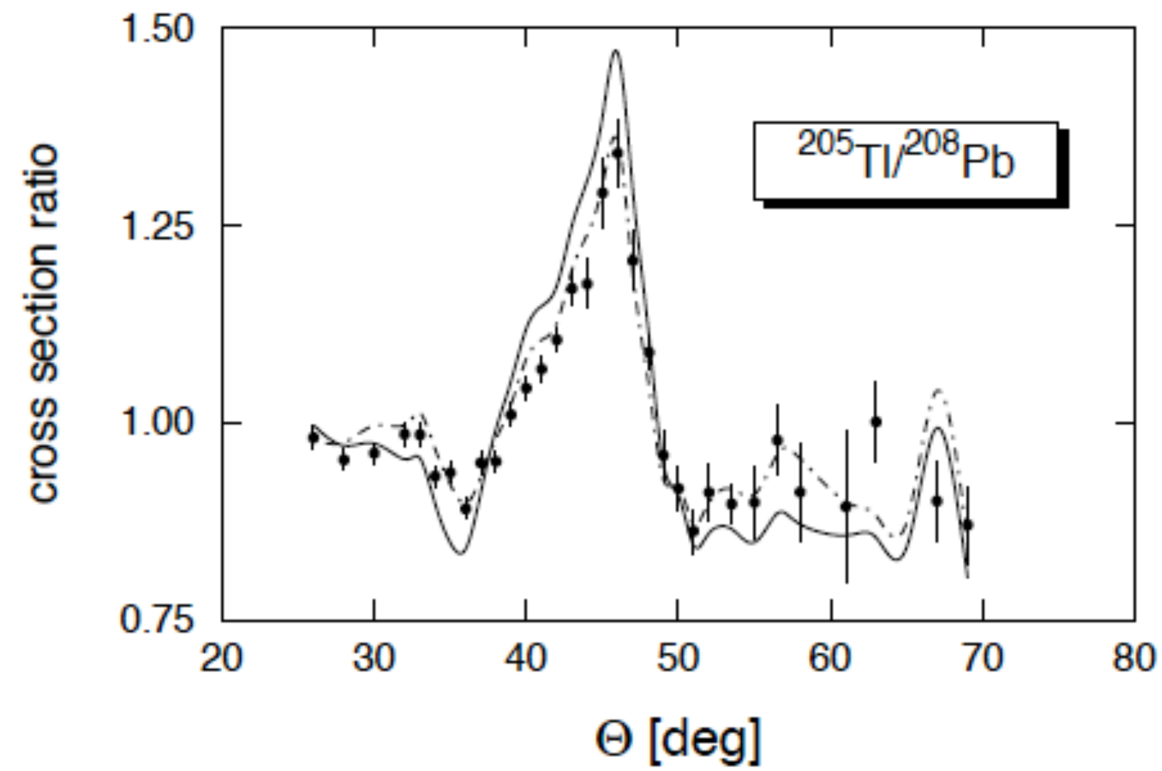
Elastic scattering: ground state

$$
\begin{aligned}
|1/2^+, {}^{205}\mathrm{Tl}> \; &= \; \alpha_1(|3s_{1/2}>^{-1} \otimes |0^+, {}^{206}\mathrm{Pb}> \\
&+ \; \alpha_2(|2d_{3/2}>^{-1} \otimes |2^+, {}^{206}\mathrm{Pb}> \\
&+ \; \alpha_3(|2d_{5/2}>^{-1} \otimes |2^+, {}^{206}\mathrm{Pb}>
\end{aligned}
$$









Elastic scattering: ground state

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$J_i = 0$ "even-even" nuclei: nothing else

Elastic scattering: ground state

$J_i = 0$ "even-even" nuclei: nothing else

what about nuclei with $J_i \neq 0$?

Elastic scattering: ground state

$J_i = 0$ "even-even" nuclei: nothing else

what about nuclei with $J_i \neq 0$?

	$M_{\lambda\mu}^{\mathrm{Coul}}$	$T_{\lambda\mu}^{\mathrm{el}}$	$T_{\lambda\mu}^{\mathrm{mag}}$
T	even	odd	odd
P	even	even	odd

Elastic scattering: ground state

$J_i = 0$ "even-even" nuclei: nothing else

what about nuclei with $J_i \neq 0$?

	$M^{\rm Coul}_{\lambda\mu}$	$T^{\rm el}_{\lambda\mu}$	$T^{\rm mag}_{\lambda\mu}$
T	even	odd	odd
P	even	even	odd

$$\frac{d\sigma}{d\Omega} = Z^2\, \sigma_{\rm Mott}\, f_{\rm rec}^{-1} \left[\frac{q_\mu^4}{\mathbf{q}^4} |F_{\rm L}(q)|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2} + \tan^2\frac{\theta}{2} \right) |F_{\rm T}(q)|^2 \right]$$

$$\sigma_{\rm Mott} = \left(\frac{\alpha \cos\frac{\theta}{2}}{2\,\epsilon_{\rm i} \sin^2\frac{\theta}{2}} \right)^2 \qquad f_{\rm rec} = 1 + \frac{2\,\epsilon_{\rm i}\sin^2\frac{\theta}{2}}{M_{\rm T}} \qquad q_\mu = (\omega, -\mathbf{q}) \qquad J_\mu(\mathbf{r}) = [\rho(\mathbf{r}), -\mathbf{J}(\mathbf{r})]$$

$$|F_{\rm L}(q)|^2 = \frac{4\pi}{Z^2}\frac{1}{2J_i+1}\sum_{\lambda=0}^{\infty} \left| \langle J_f \| M^{\rm Coul}_{\lambda}(q) \| J_i \rangle \right|^2 \; ; \qquad M^{\rm Coul}_{\lambda\mu}(q) = \int d\mathbf{r}\, j_\lambda(qr)\, Y_{\lambda\mu}(\hat{\mathbf{r}})\, \rho(\mathbf{r})$$

$$|F_{\rm T}(q)|^2 = \frac{4\pi}{Z^2}\frac{1}{2J_i+1}\sum_{\lambda=1}^{\infty} \left[\left| \langle J_f \| T^{\rm el}_{\lambda}(q) \| J_i \rangle \right|^2 + |\langle J_f \| T^{\rm mag}_{\lambda}(q) \| J_i \rangle|^2 \right] \; ;$$

$$T^{\rm el}_{\lambda\mu}(q) = \frac{1}{q}\int d\mathbf{r}\, \nabla \times [j_\lambda(qr)\, \mathbf{Y}_{\lambda\lambda\mu}(\hat{\mathbf{r}})] \cdot \mathbf{J}(\mathbf{r})\,, \qquad T^{\rm mag}_{\lambda\mu}(q) = \int d\mathbf{r}\, j_\lambda(qr)\, \mathbf{Y}_{\lambda\lambda\mu}(\hat{\mathbf{r}}) \cdot \mathbf{J}(\mathbf{r})$$

Elastic scattering: ground state

$J_i = 0$ "even-even" nuclei: nothing else

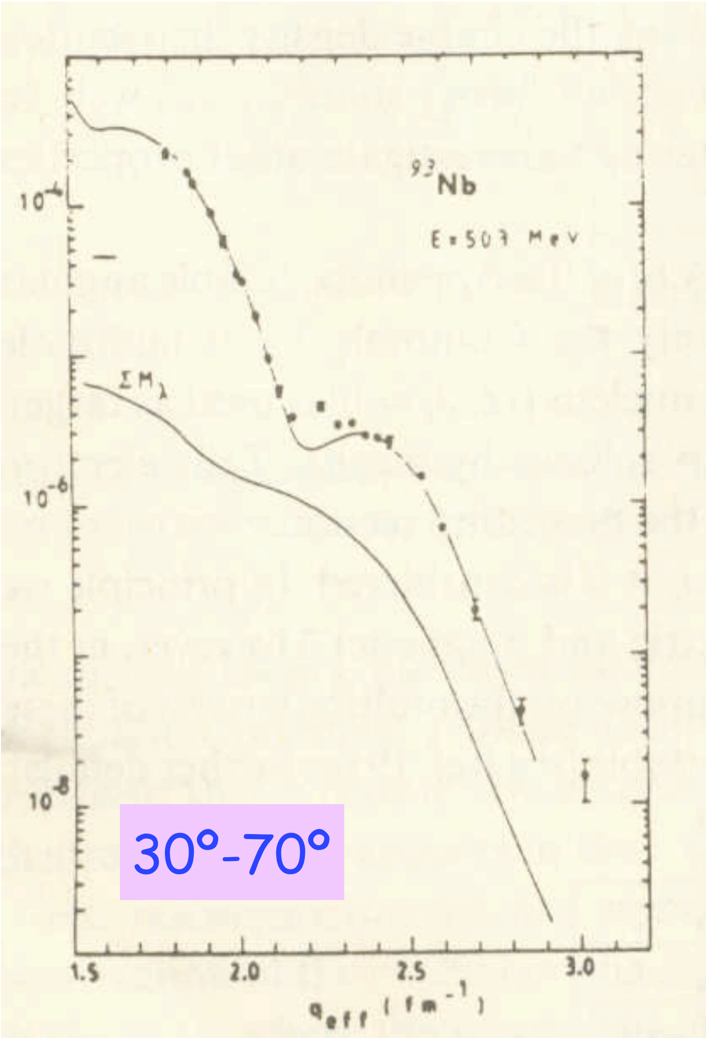
what about nuclei with $J_i \neq 0$?

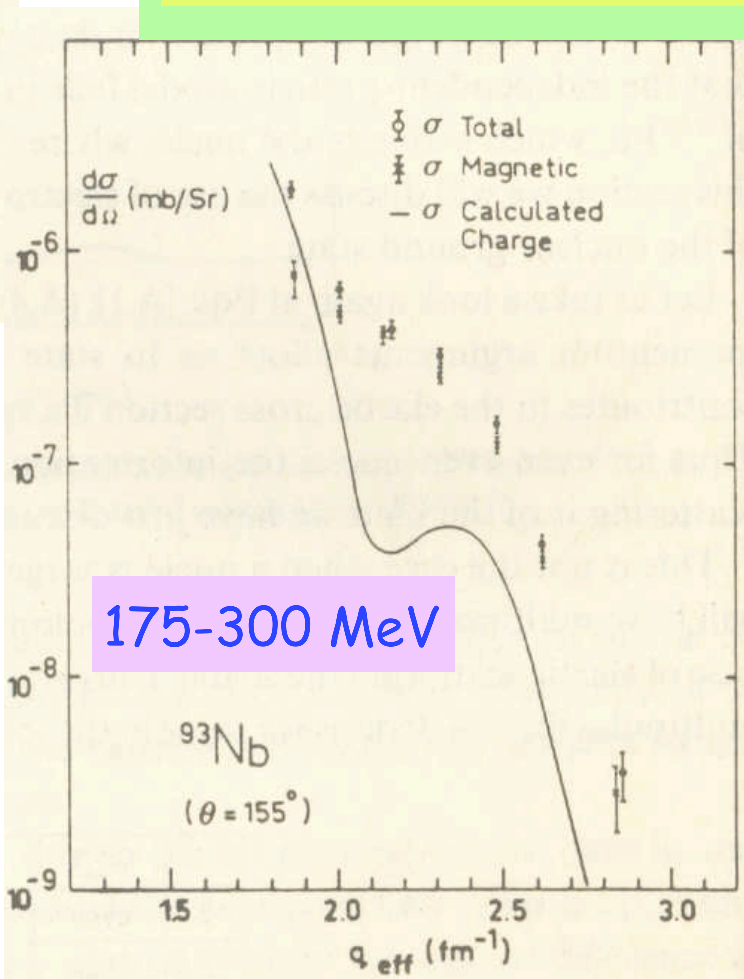
	$M^{\rm Coul}_{\lambda\mu}$	$T^{\rm el}_{\lambda\mu}$	$T^{\rm mag}_{\lambda\mu}$
T	even	odd	odd
P	even	even	odd

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 4\pi\,\sigma_{\rm Mott}\, f_{\rm rec}^{-1}\,\frac{1}{2J_i+1}\left[\frac{q_\mu^4}{\mathbf{q}^4}\sum_{\lambda\equiv{\rm even}} |\langle J_i \| M^{\rm Coul}_\lambda(q) \| J_i\rangle|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2} + \tan^2\frac{\theta}{2}\right)\sum_{\lambda\equiv{\rm odd}} |\langle J_i \| T^{\rm mag}_\lambda(q) \| J_i\rangle|^2\right]$$

Elastic scattering: ground state

$J_i = 0$ "even-even" nuclei: nothing else





what about nuclei with $J_i \neq 0$?

	$M^{\mathrm{Coul}}_{\lambda\mu}$	$T^{\mathrm{el}}_{\lambda\mu}$	$T^{\mathrm{mag}}_{\lambda\mu}$
T	even	odd	odd
P	even	even	odd

$$\frac{d\sigma}{d\Omega} = 4\pi\,\sigma_{\mathrm{Mott}}\,f^{-1}_{\mathrm{rec}}\,\frac{1}{2J_i+1}\left[\frac{q^4_\mu}{\mathbf{q}^4}\sum_{\lambda\equiv\mathrm{even}}|\langle J_i\|M^{\mathrm{Coul}}_\lambda(q)\|J_i\rangle|^2 + \left(-\frac{1}{2}\frac{q^2_\mu}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right)\sum_{\lambda\equiv\mathrm{odd}}|\langle J_i\|T^{\mathrm{mag}}_\lambda(q)\|J_i\rangle|^2\right]$$

-at forward angles: negligible contribution of the magnetic part

-at backward angles: the magnetic contribution dominates the cross section

Elastic scattering: ground state

$J_i = 0$ "even-even" nuclei: nothing else

what about nuclei with $J_i \neq 0$?

	$M^{\rm Coul}_{\lambda\mu}$	$T^{\rm el}_{\lambda\mu}$	$T^{\rm mag}_{\lambda\mu}$
T	even	odd	odd
P	even	even	odd

$$\frac{d\sigma}{d\Omega} = 4\pi\,\sigma_{\rm Mott}\, f^{-1}_{\rm rec}\, \frac{1}{2J_i+1}\left[\frac{q^4_\mu}{\mathbf{q}^4}\sum_{\lambda\equiv \rm even}|\langle J_i\|M^{\rm Coul}_\lambda(q)\|J_i\rangle|^2 + \left(-\frac{1}{2}\frac{q^2_\mu}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right)\sum_{\lambda\equiv \rm odd}|\langle J_i\|T^{\rm mag}_\lambda(q)\|J_i\rangle|^2\right]$$

-Coulomb/magnetic separation: combination of forward/backward measurements, or

-Rosenbluth separation: $\frac{d\sigma}{d\Omega}$ vs. $\tan^2\frac{\theta}{2}$ for fixed ω and q (straight line)

-slope: proportional to the (full) transverse magnetic contribution

-ordinate at origin: gives the (full) longitudinal Coulomb part

-but valid only if distortion effects are negligible: otherwise DWBA cross section required

Elastic scattering: ground state

Elastic scattering: ground state

simplest situation: $J_i = \frac{1}{2}$

-only C0 and M1 multipoles survive

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 4\pi\,\sigma_{\mathrm{Mott}}\,f_{\mathrm{rec}}^{-1}\,\frac{1}{2J_i+1}\left[\frac{q_\mu^4}{\mathbf{q}^4}\sum_{\lambda\equiv\mathrm{even}}|\langle J_i\|M_\lambda^{\mathrm{Coul}}(q)\|J_i\rangle|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right)\sum_{\lambda\equiv\mathrm{odd}}|\langle J_i\|T_\lambda^{\mathrm{mag}}(q)\|J_i\rangle|^2\right]$$

Elastic scattering: ground state

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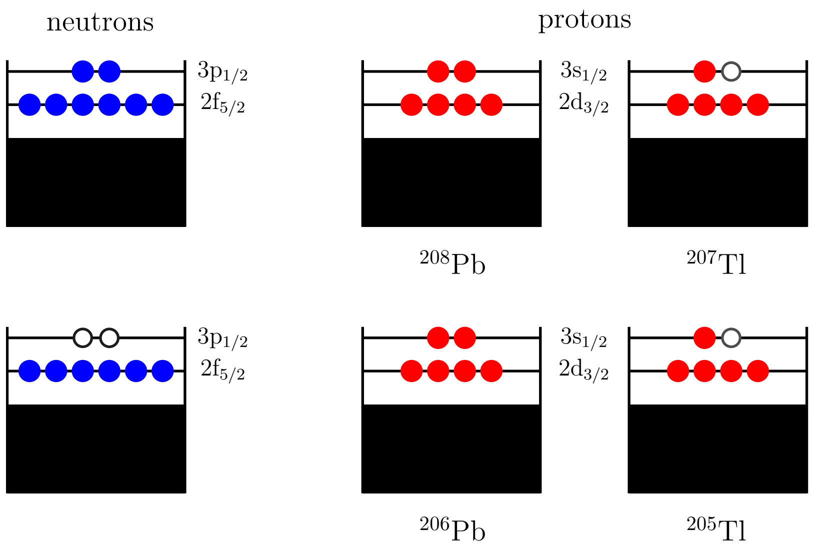
^{207}Pb (1/2$^-$) and ^{205}Tl (1/2$^+$)



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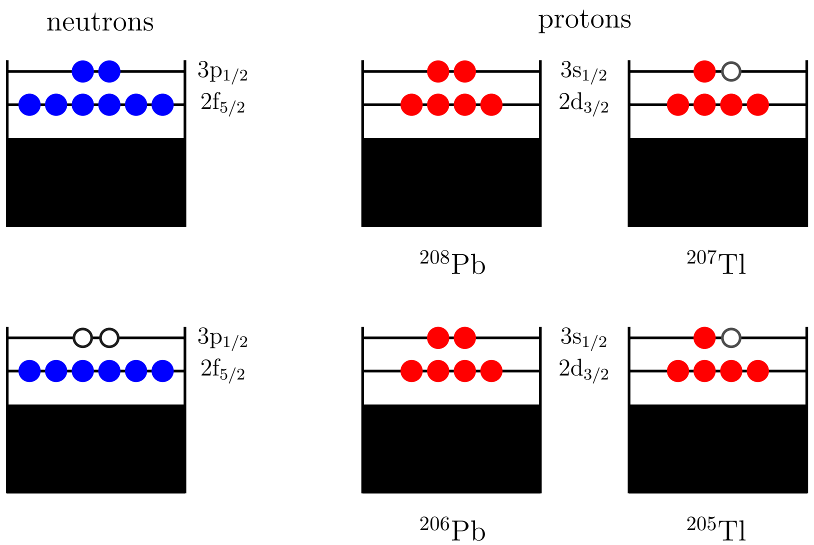
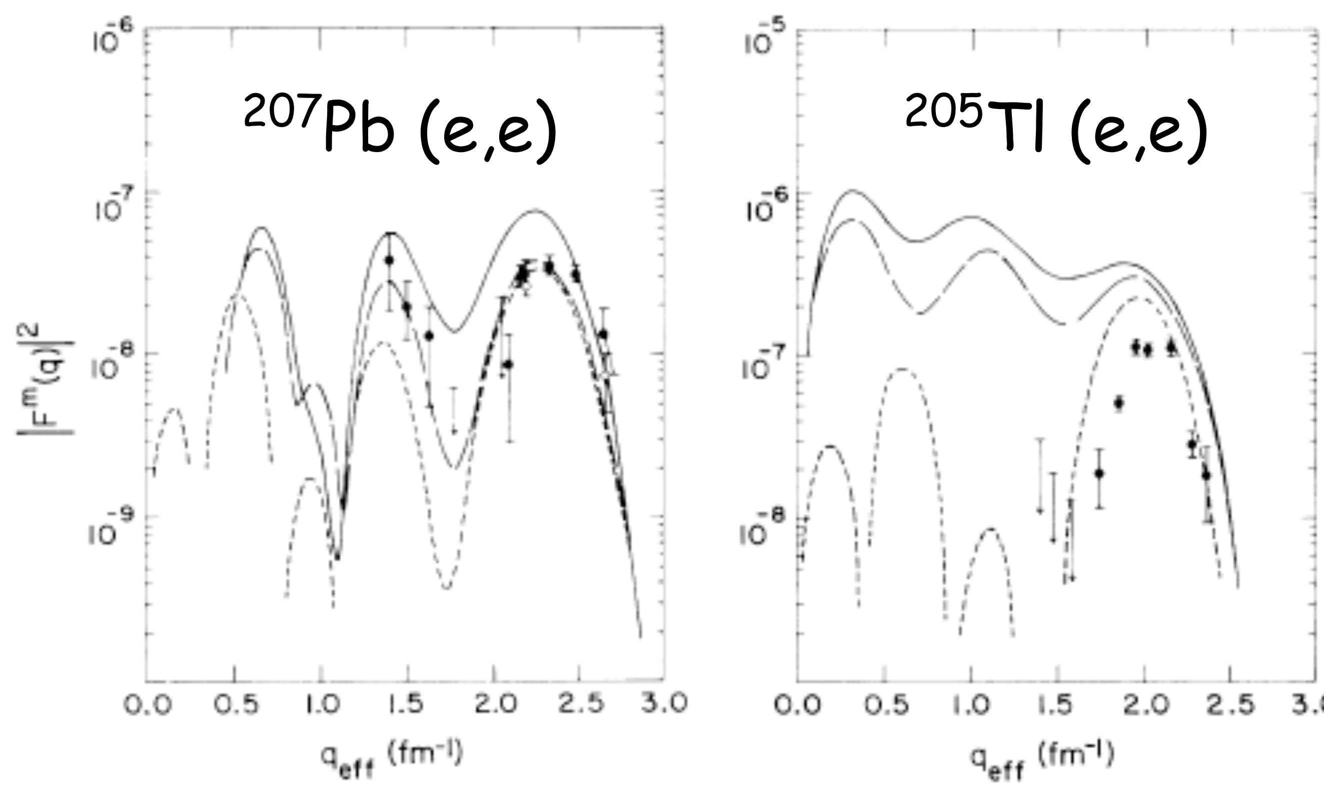


<u>difficult experiment</u>: no data below 1 fm^{-1}

-Coulomb form factor > transverse form factor even at 180°: imposible separation

-precise measurement of ^{208}Pb cross section and charge scattering ratios ^{207}Pb/^{208}Pb and ^{205}Tl/^{208}Pb

-this permitted to correct from distortion effects and to separate Coulomb/magnetic responses



Papanicolas et al., Phys. Rev. Lett. 58 (1987) 2296

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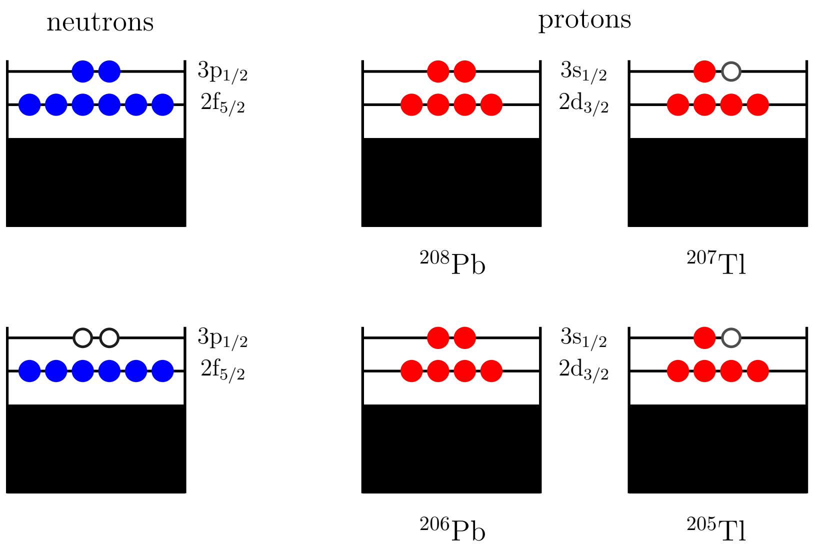

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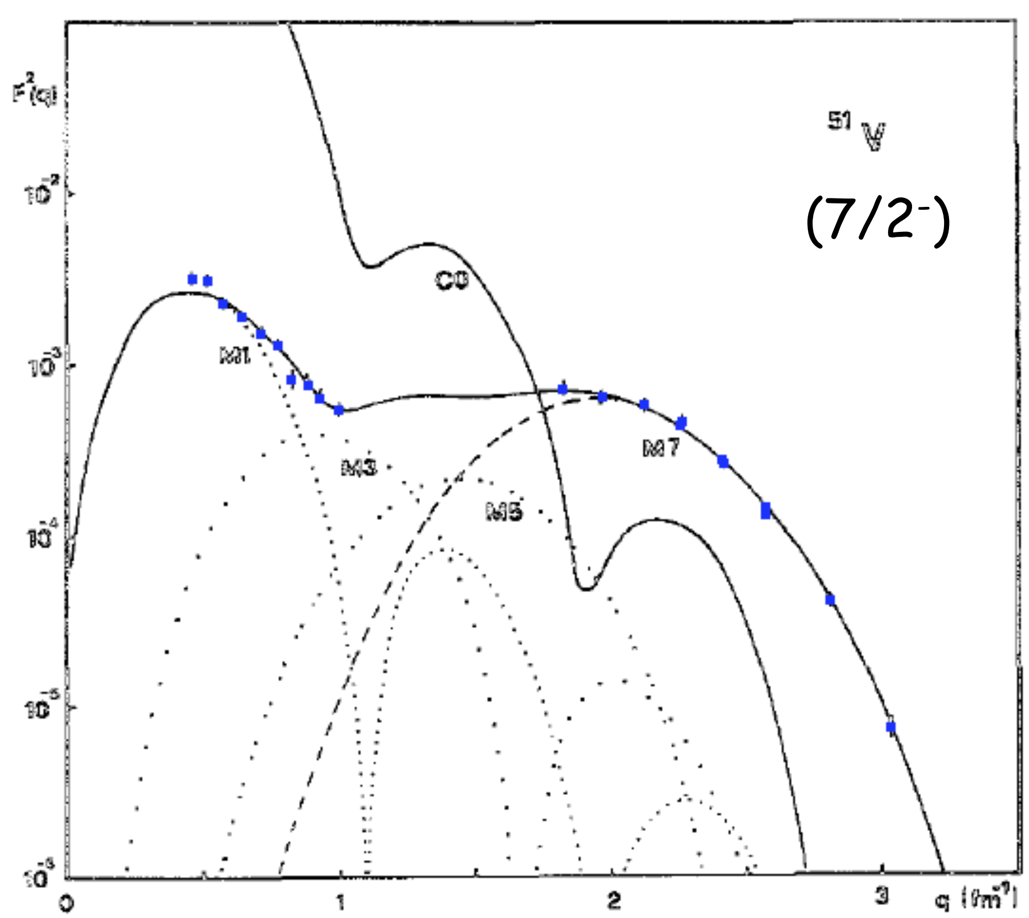

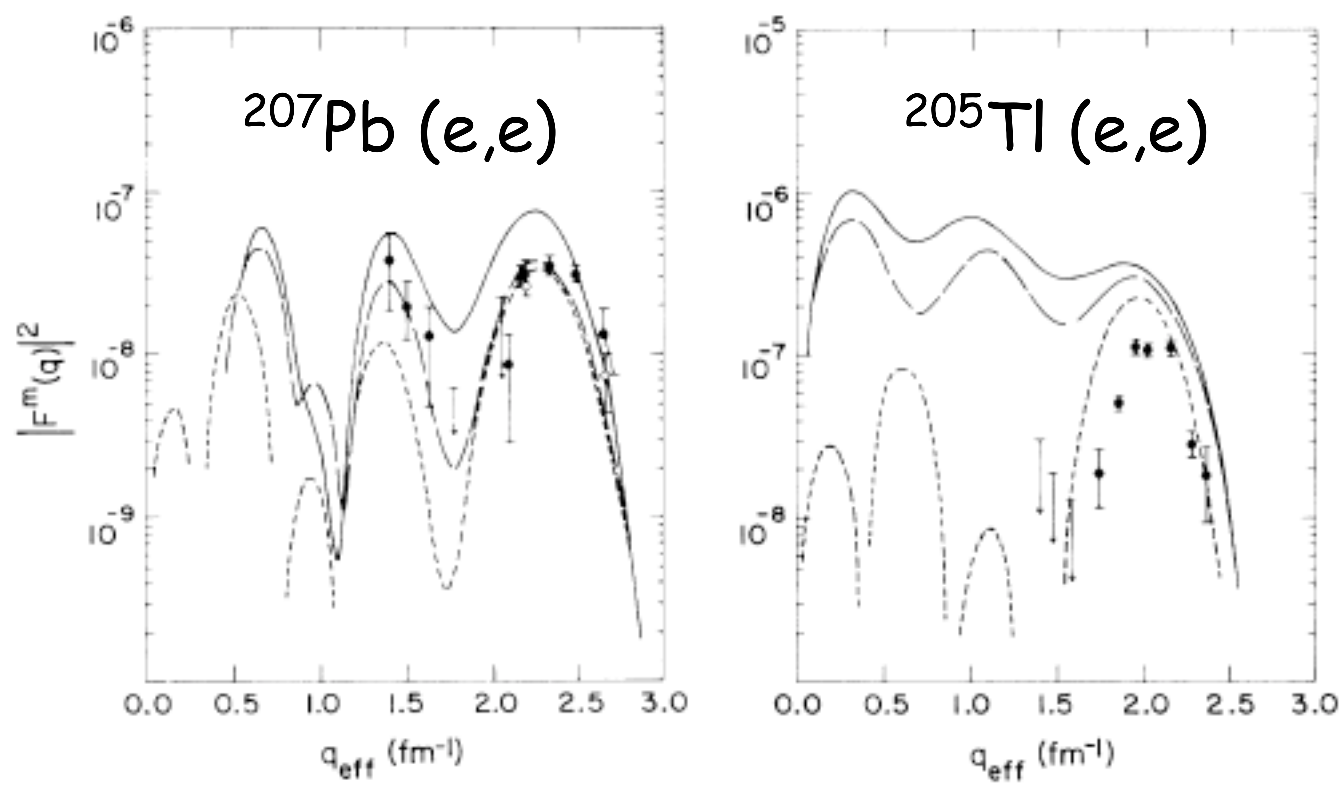

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Elastic scattering: ground state

meson-exchange currents (MEC)

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meson-exchange currents (MEC)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = Z^2\,\sigma_{\mathrm{Mott}}\,f_{\mathrm{rec}}^{-1}\left[\frac{q_\mu^4}{\mathbf{q}^4}|F_{\mathrm{L}}(q)|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2} + \tan^2\frac{\theta}{2}\right)|F_{\mathrm{T}}(q)|^2\right]$$

$$\sigma_{\mathrm{Mott}} = \left(\frac{\alpha\cos\frac{\theta}{2}}{2\,\epsilon_{\mathrm{i}}\sin^2\frac{\theta}{2}}\right)^2 \qquad f_{\mathrm{rec}} = 1 + \frac{2\,\epsilon_{\mathrm{i}}\sin^2\frac{\theta}{2}}{M_{\mathrm{T}}} \qquad q_\mu = (\omega, -\mathbf{q}) \qquad J_\mu(\mathbf{r}) = [\rho(\mathbf{r}), -\mathbf{J}(\mathbf{r})]$$

$$|F_{\mathrm{L}}(q)|^2 = \frac{4\pi}{Z^2}\frac{1}{2J_i+1}\sum_{\lambda=0}^{\infty}\left|\langle J_f\|M_\lambda^{\mathrm{Coul}}(q)\|J_i\rangle\right|^2 \;; \qquad M_{\lambda\mu}^{\mathrm{Coul}}(q) = \int \mathrm{d}\mathbf{r}\, j_\lambda(qr)\,Y_{\lambda\mu}(\hat{\mathbf{r}})\,\rho(\mathbf{r})$$

$$|F_{\mathrm{T}}(q)|^2 = \frac{4\pi}{Z^2}\frac{1}{2J_i+1}\sum_{\lambda=1}^{\infty}\left[\left|\langle J_f\|T_\lambda^{\mathrm{el}}(q)\|J_i\rangle\right|^2 + |\langle J_f\|T_\lambda^{\mathrm{mag}}(q)\|J_i\rangle|^2\right] \;;$$

$$T_{\lambda\mu}^{\mathrm{el}}(q) = \frac{1}{q}\int \mathrm{d}\mathbf{r}\,\nabla\times[j_\lambda(qr)\,\mathbf{Y}_{\lambda\lambda\mu}(\hat{\mathbf{r}})]\cdot\mathbf{J}(\mathbf{r})\,, \qquad T_{\lambda\mu}^{\mathrm{mag}}(q) = \int \mathrm{d}\mathbf{r}\, j_\lambda(qr)\,\mathbf{Y}_{\lambda\lambda\mu}(\hat{\mathbf{r}})\cdot\mathbf{J}(\mathbf{r})$$

Elastic scattering: ground state

meson-exchange currents (MEC)

nuclear current:

one-body nuclear current $\mathbf{J}_{\mathrm{OB}}(\mathbf{r},t)$

-convection: due to proton movement

-spin-magnetization: due to nucleon spin

-but "continuity equation" tells us:

$$\nabla \cdot \mathbf{J}(\mathbf{r},t) = -\frac{\partial \rho(\mathbf{r},t)}{\partial t} = -i[H,\rho(\mathbf{r},t)]_-$$

the hamiltonian: $H = T + V$

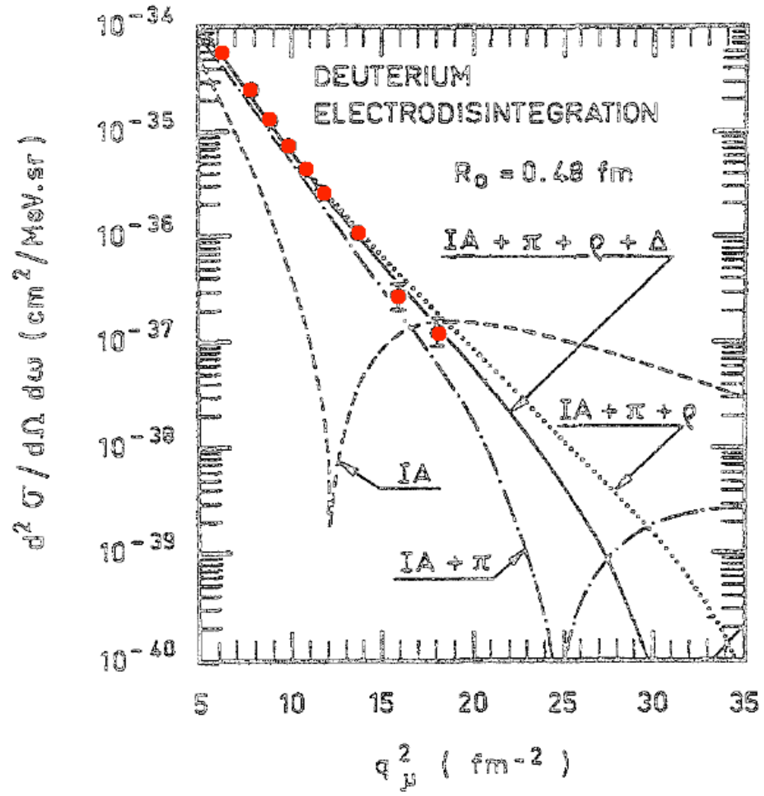
and $\nabla \cdot \mathbf{J}_{\mathrm{OB}}(\mathbf{r},t) = -i[T,\rho(\mathbf{r},t)]_-$ is satisfied

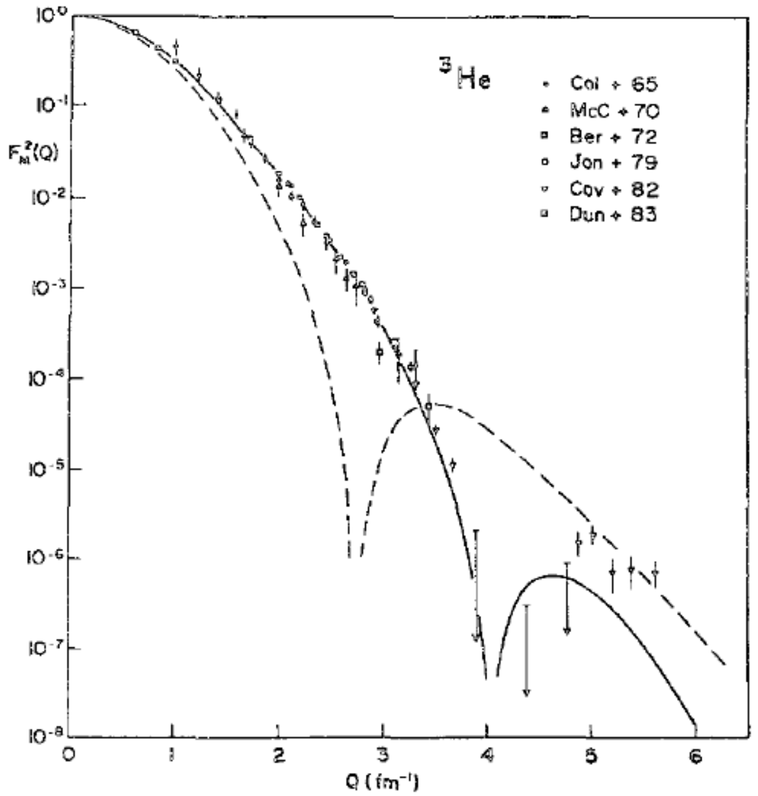
as a consequence: $\nabla \cdot \mathbf{J}_{\mathrm{MEC}}(\mathbf{r},t) = -i[V,\rho(\mathbf{r},t)]_-$

and a two-body nuclear current $\mathbf{J}_{\mathrm{MEC}}(\mathbf{r},t)$ must be considered

Elastic scattering: ground state

meson-exchange currents (MEC)

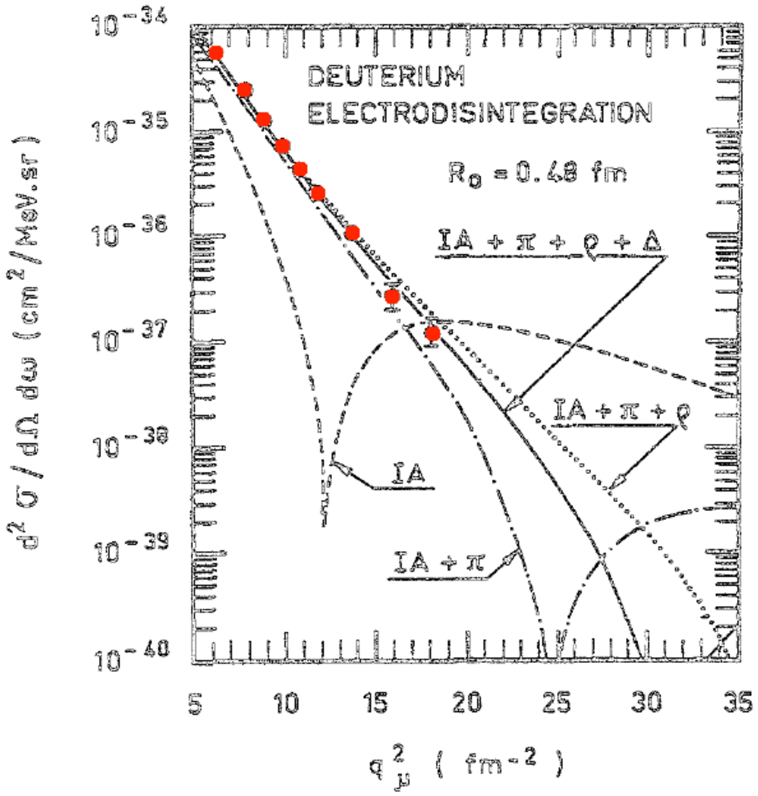


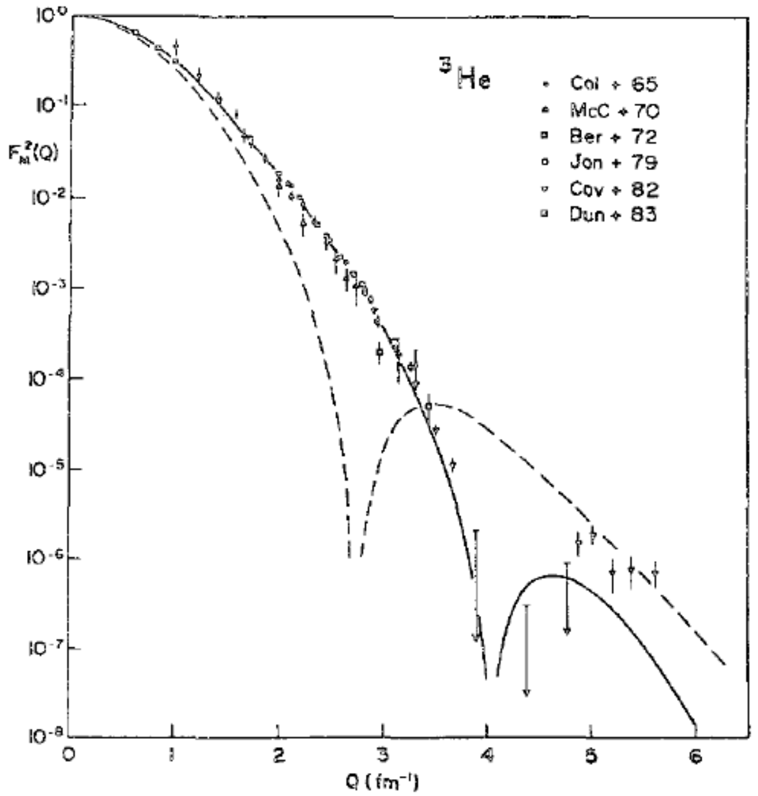


Elastic scattering: ground state

meson-exchange currents (MEC)

-lack of MEC signatures in medium/heavy nuclei:
uncertainties in the nuclear wave function





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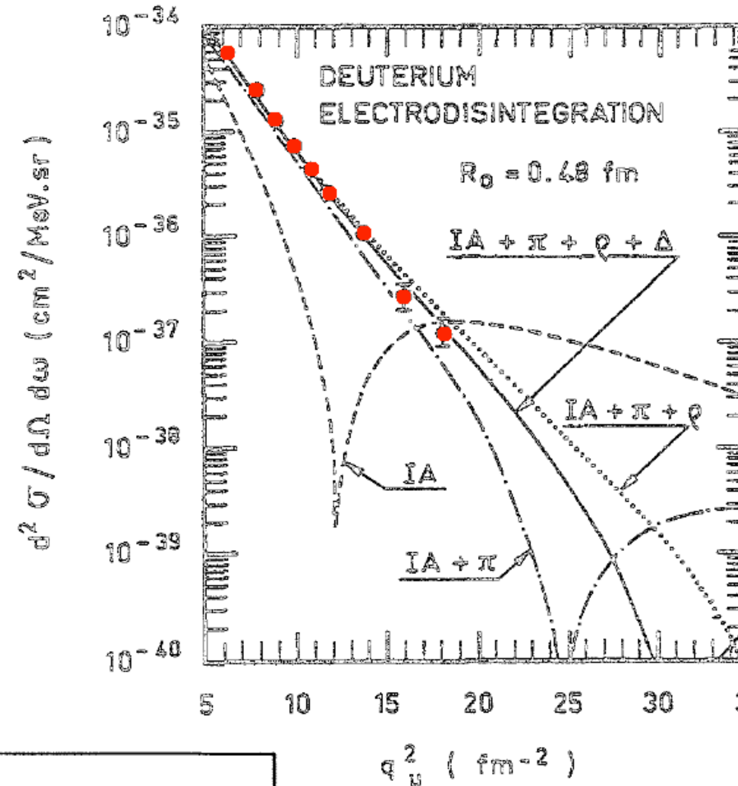

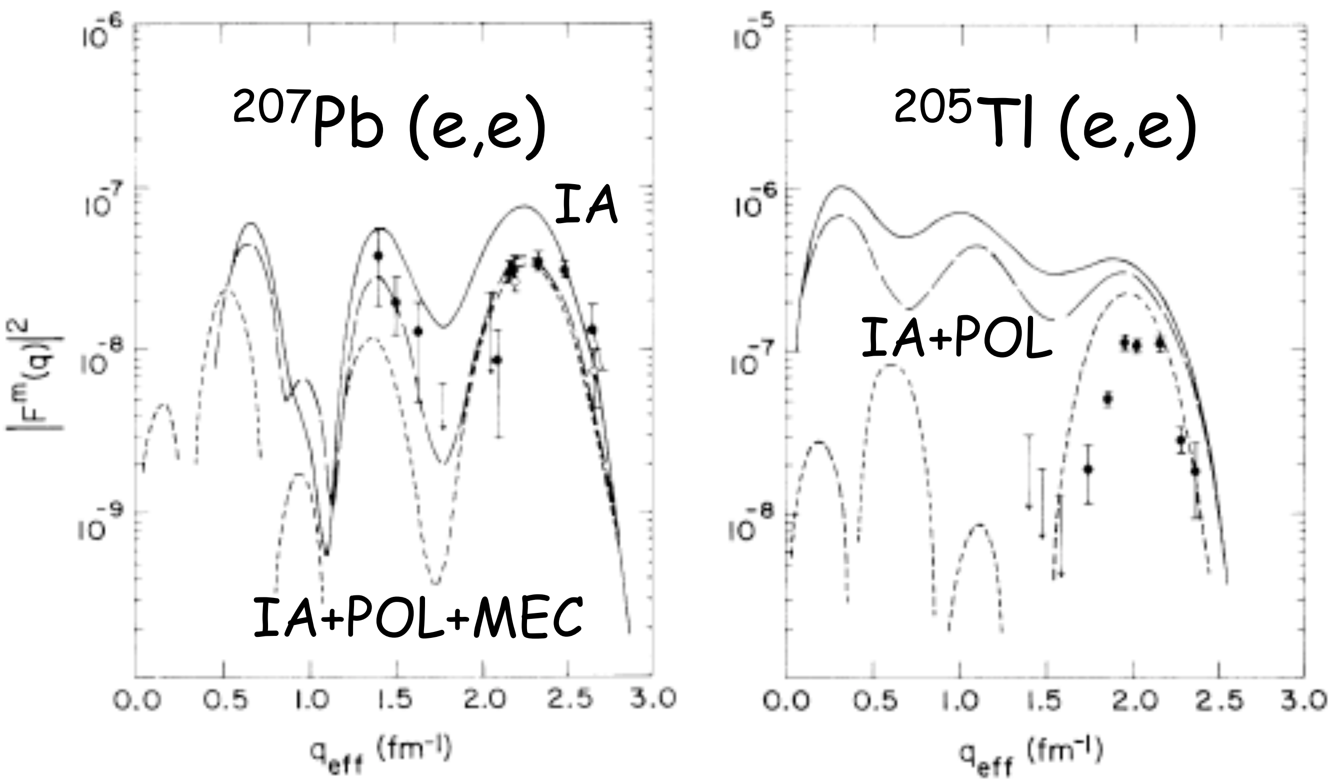

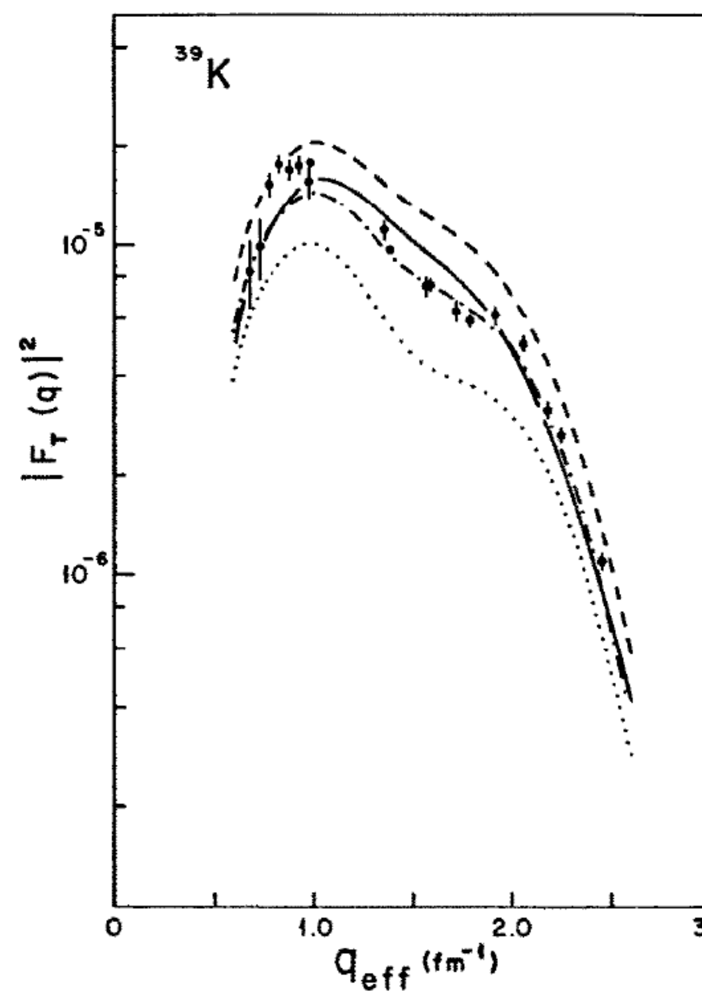

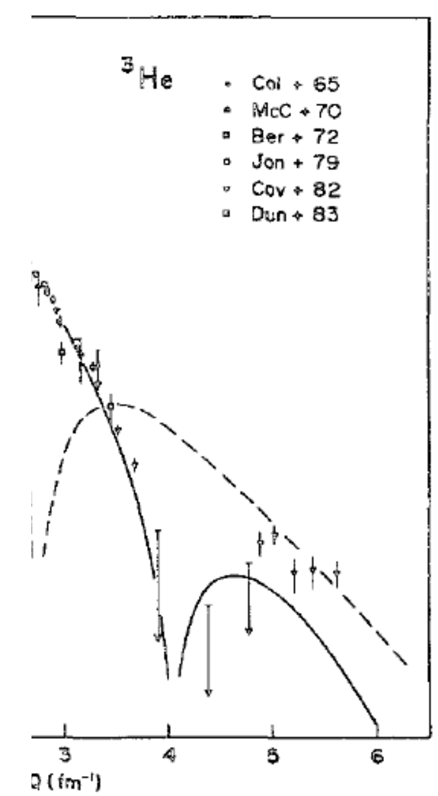

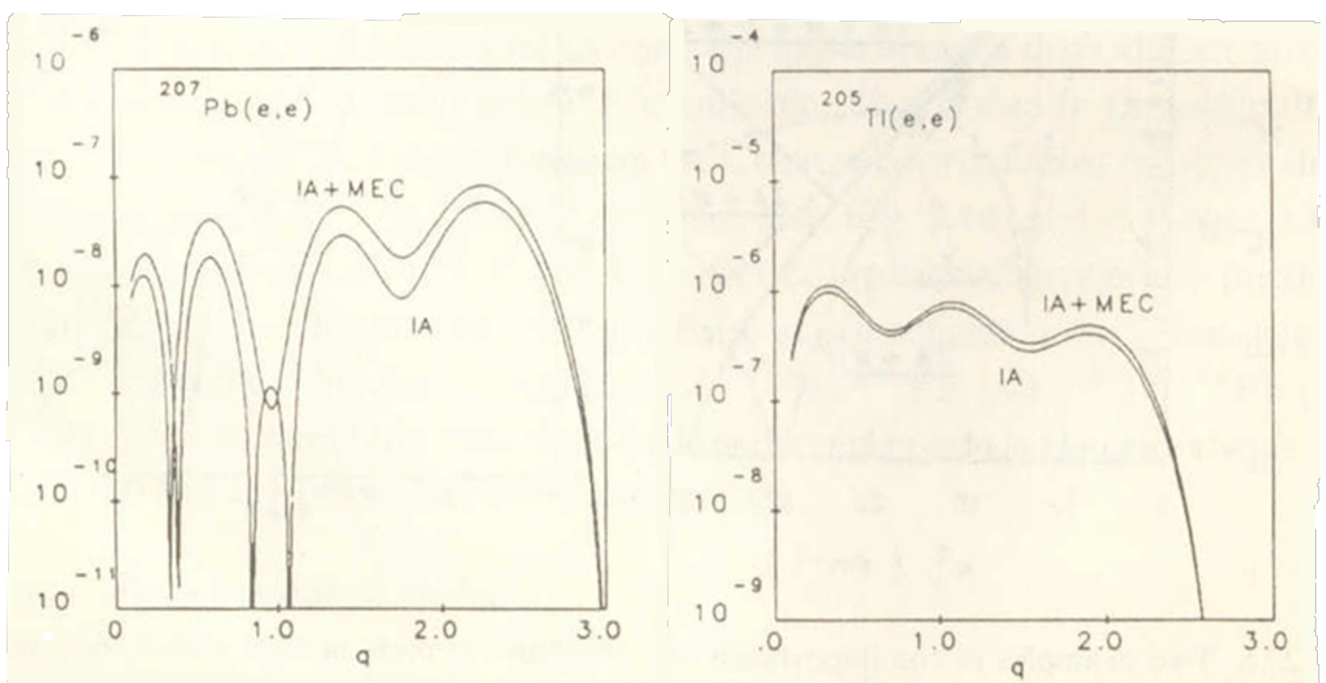

strong interference MEC/POL?

Elastic scattering: ground state

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$J_i \neq 0$ nuclei open a new possibility: <u>polarization</u> $\vec{A}(\vec{e}, e)$

Elastic scattering: ground state

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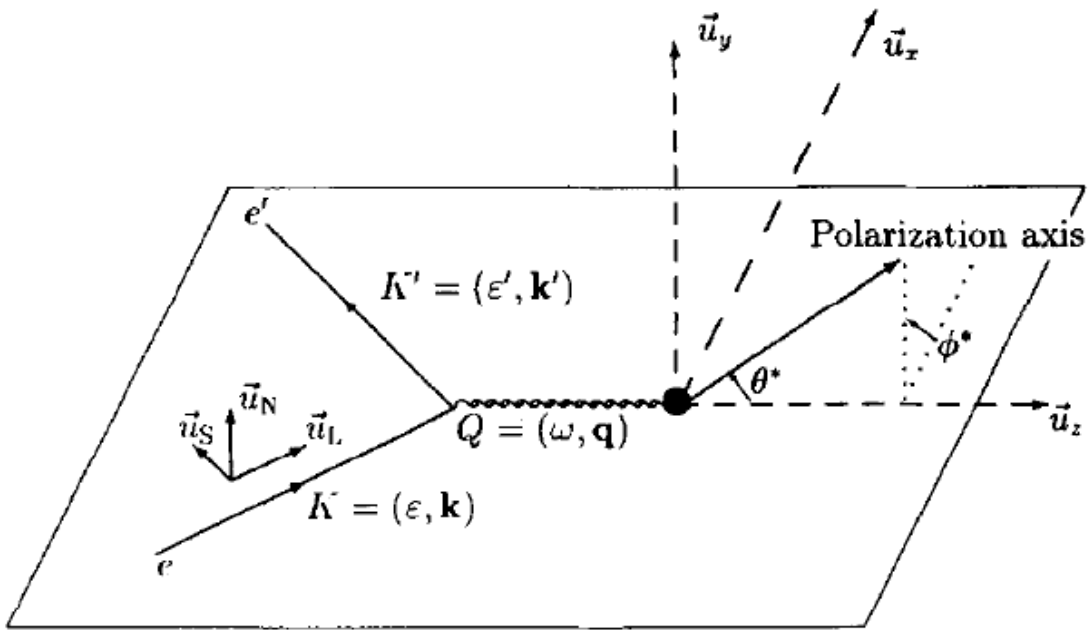

-the nucleus is polarized: (θ^*, ϕ^*)

-the incident electron is polarized: helicity h

(projection of the electron spin over its momentum)

-the polarization of the outgoing electrons is not measured

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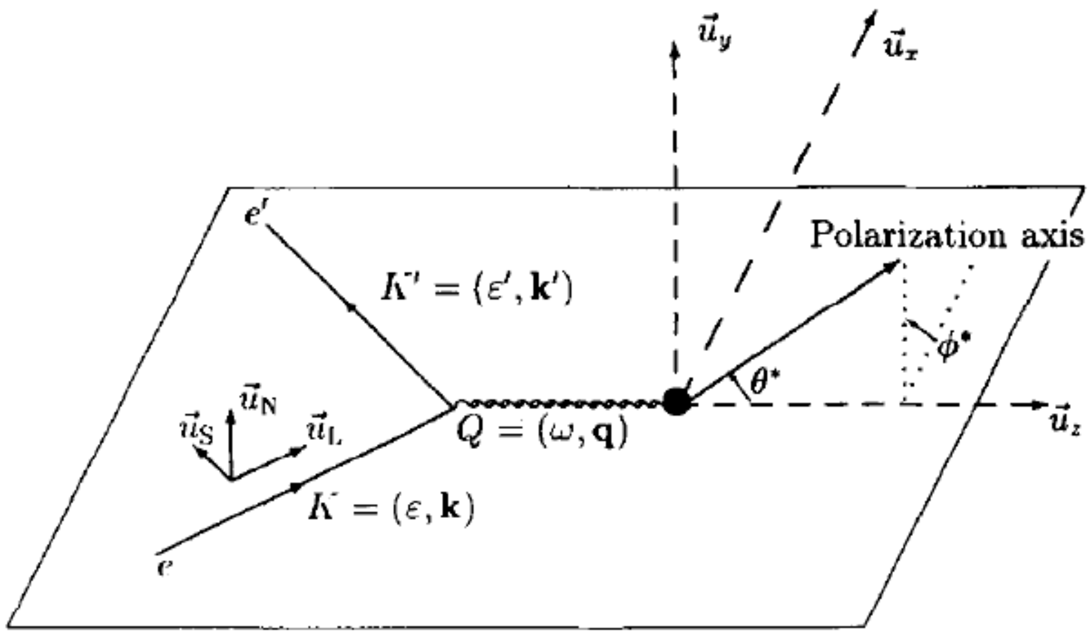

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$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)^h = \sigma_{\mathrm{Mott}}\, f_{\mathrm{rec}}^{-1} \left\{ \left(v_{\mathrm{L}} \mathcal{R}^{\mathrm{L}} + v_{\mathrm{T}} \mathcal{R}^{\mathrm{T}} + v_{\mathrm{TL}} \mathcal{R}^{\mathrm{TL}} + v_{\mathrm{TT}} \mathcal{R}^{\mathrm{TT}}\right) + h \left(v_{\mathrm{T'}} \mathcal{R}^{\mathrm{T'}} + v_{\mathrm{TL'}} \mathcal{R}^{\mathrm{TL'}}\right) \right\}$$

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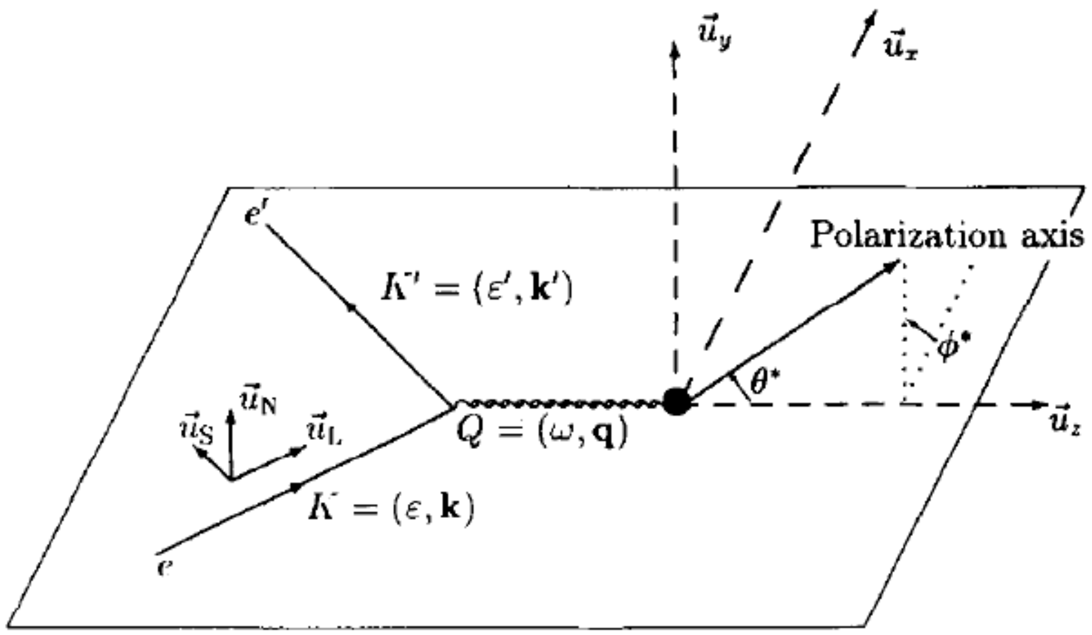

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Σ

terms occurring even if incident electrons are not polarized

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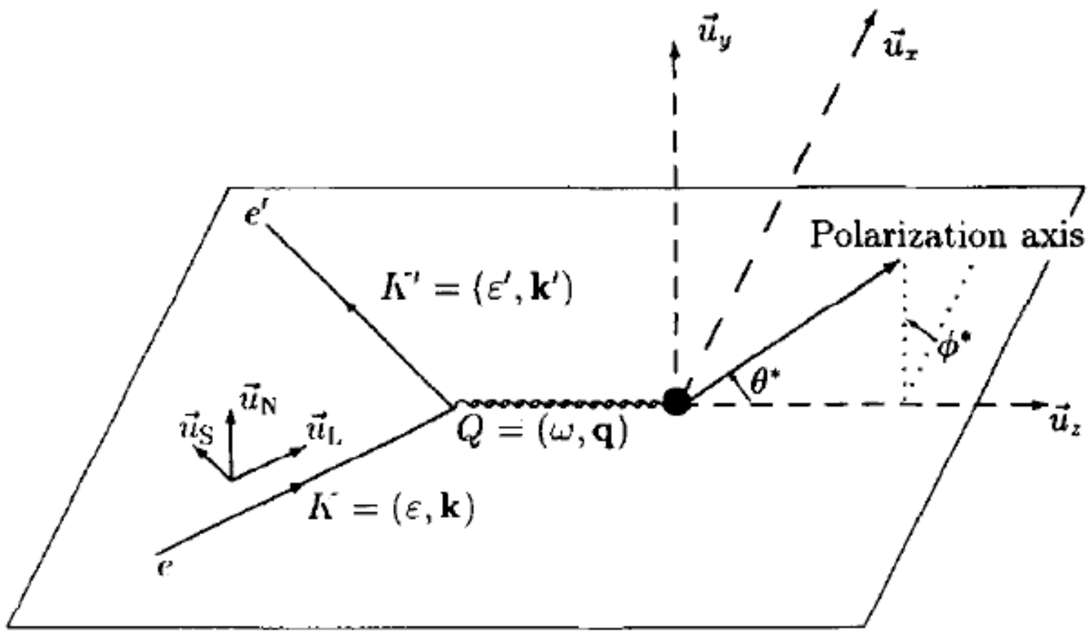

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Σ — terms occurring even if incident electrons are not polarized

Δ — terms occurring only if both target and incident electrons are polarized

Elastic scattering: ground state

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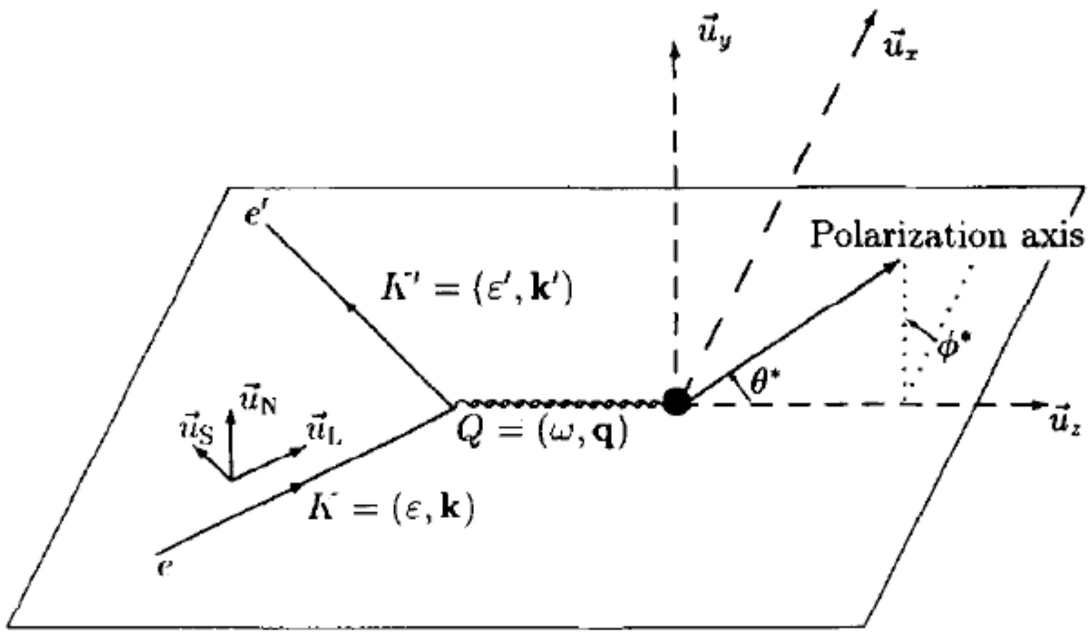

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terms occurring even if incident electrons are not polarized

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terms occurring only if both target and incident electrons are polarized

-for relativistic electrons $h = \pm 1$ and Σ/Δ separation can be carried out with two measurements for the two helicities

Elastic scattering: ground state

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$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)^h = \sigma_{\mathrm{Mott}}\, f_{\mathrm{rec}}^{-1} \left\{ \left(v_{\mathrm{L}}\mathcal{R}^{\mathrm{L}} + v_{\mathrm{T}}\mathcal{R}^{\mathrm{T}} + v_{\mathrm{TL}}\mathcal{R}^{\mathrm{TL}} + v_{\mathrm{TT}}\mathcal{R}^{\mathrm{TT}}\right) + h\left(v_{\mathrm{T}'}\mathcal{R}^{\mathrm{T}'} + v_{\mathrm{TL}'}\mathcal{R}^{\mathrm{TL}'}\right)\right\}$$

v's: electron kinematic factors; involve: $q_\mu, \mathbf{q}, \theta_{\mathrm{e}}, \quad (\omega = 0)$

e.g.: $v_{\mathrm{L}} = \dfrac{q_\mu^4}{\mathbf{q}^4}\,; \qquad v_{\mathrm{TT}} = -\dfrac{1}{2}\dfrac{q_\mu^2}{\mathbf{q}^2}\,; \qquad v_{\mathrm{TL}'} = -\dfrac{1}{\sqrt{2}}\dfrac{q_\mu^2}{\mathbf{q}^2}\tan\dfrac{\theta_e}{2}$

100% target polarization:

$$f_{\mathcal{J}}^i = \frac{(2J_i)!\,\sqrt{2\mathcal{J}+1}}{(2J_i+\mathcal{J}+1)!\,(2J_i-\mathcal{J})!}$$

$$f_{\mathcal{J}}^i = \frac{\delta_{\mathcal{J},0}}{\sqrt{2J_i+1}} \quad \text{(no polarization)}$$

-nuclear response functions:

$$\mathcal{R}^{\mathrm{L}} = 4\pi \sum_{\mathcal{J}\geq 0} \xi(\mathcal{J}) P_{\mathcal{J}}(\cos\theta^*)\, f_{\mathcal{J}}^i\, \mathcal{W}_{\mathcal{J}}^{\mathrm{L}}(q)$$

$$\mathcal{R}^{\mathrm{TT}} = 4\pi \sum_{\mathcal{J}\geq 2} \xi(\mathcal{J}) P_{\mathcal{J}}^2(\cos\theta^*)\, \cos 2\phi^*\, f_{\mathcal{J}}^i\, \mathcal{W}_{\mathcal{J}}^{\mathrm{TT}}(q)$$

$$\mathcal{R}^{\mathrm{TL}'} = 4\pi \sum_{\mathcal{J}\geq 1} \xi(\mathcal{J}+1) P_{\mathcal{J}}^1(\cos\theta^*)\, \cos\phi^*\, f_{\mathcal{J}}^i\, \mathcal{W}_{\mathcal{J}}^{\mathrm{TL}'}(q)$$

$$t_{\mathrm{C}J} = \langle J_i \| M_J^{\mathrm{Coul}}(q) \| J_i \rangle$$

$$t_{\mathrm{M}J} = \langle J_i \| T_J^{\mathrm{mag}}(q) \| J_i \rangle$$

$$\mathcal{W}_{\mathcal{J}}^{\mathrm{L}}(q) = \sum_{J'J\geq 0} \mathcal{X}_i^{J'J\mathcal{J}}(0,0)\, t_{\mathrm{C}J'}\, t_{\mathrm{C}J}$$

$$\mathcal{W}_{\mathcal{J}}^{\mathrm{TT}}(q) = \frac{1}{\sqrt{(\mathcal{J}-1)\mathcal{J}(\mathcal{J}+1)(\mathcal{J}+2)}} \sum_{J'J\geq 1} \mathcal{X}_i^{J'J\mathcal{J}}(1,1)\, \zeta(J'+J)\, t_{\mathrm{M}J'}\, t_{\mathrm{M}J}$$

$$\mathcal{W}_{\mathcal{J}}^{\mathrm{TL}'}(q) = \frac{2\sqrt{2}}{\sqrt{\mathcal{J}(\mathcal{J}+1)}} \sum_{J'\geq 0; J\geq 1} \mathcal{X}_i^{J'J\mathcal{J}}(0,1)\, \zeta(J'+J+1)\, t_{\mathrm{C}J'}\, t_{\mathrm{M}J}$$

Elastic scattering: ground state

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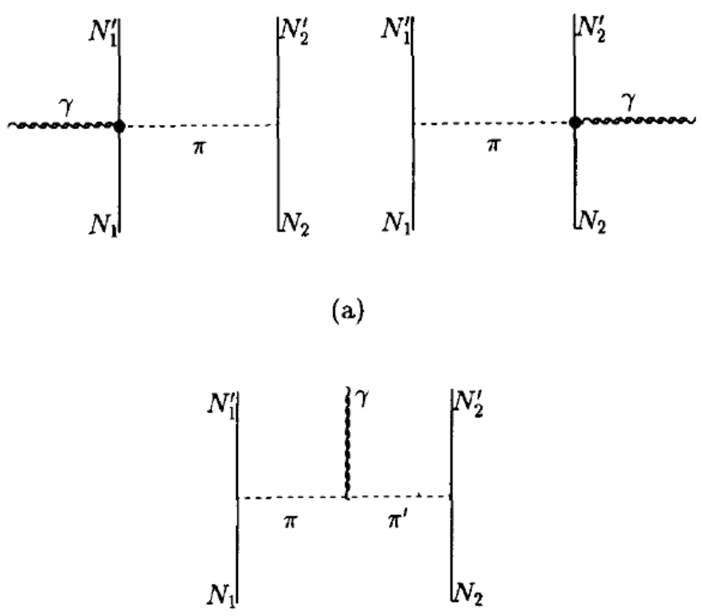
-study ^{11}B (3/2$^-$), ^{13}C (1/2$^-$), ^{15}N (1/2$^-$), ^{17}O (5/2$^+$), ^{39}K (3/2$^+$)
looking for MEC effects: distortion effects reduced
-extreme shell model (MEC effects similar to more sophisticated models including core-polarization terms)
-current operator: OB+MEC



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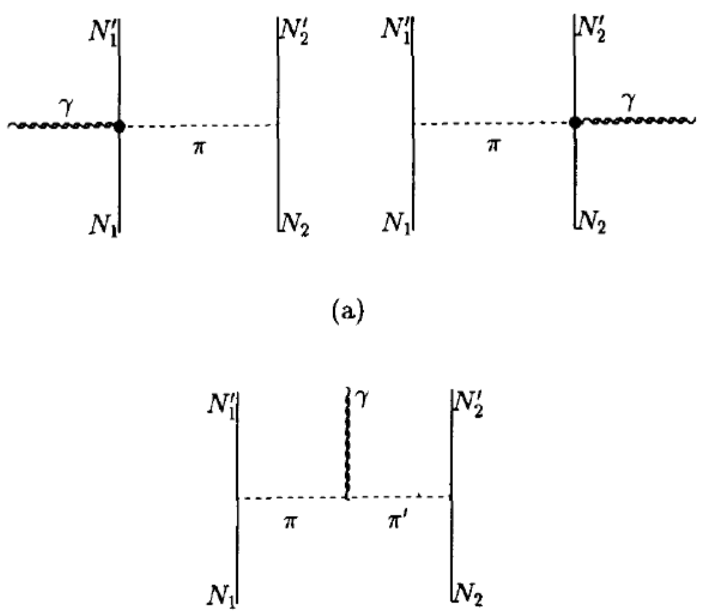

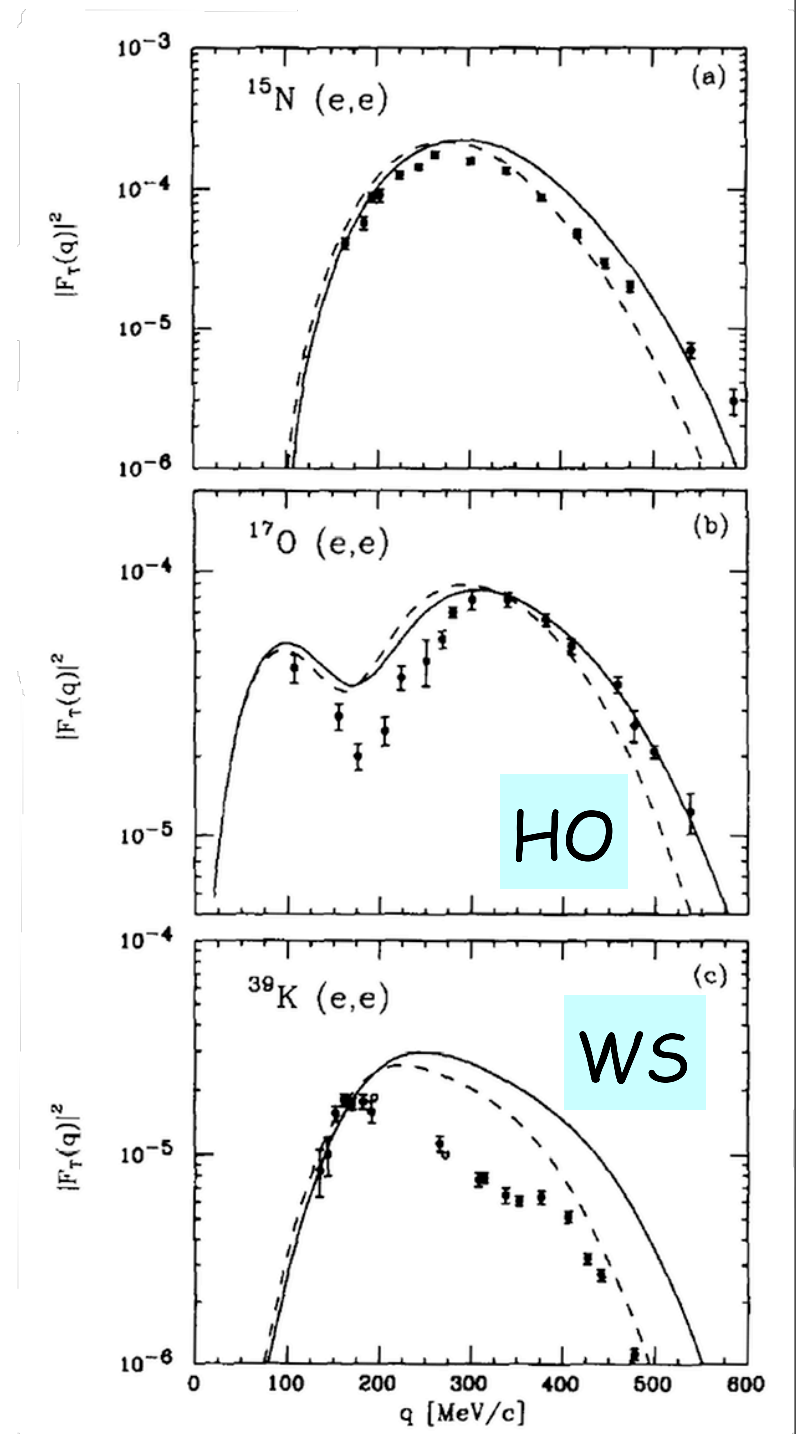

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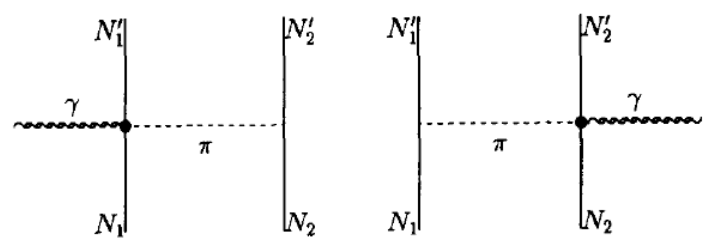
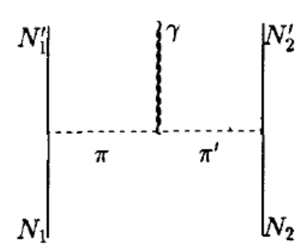


(a)

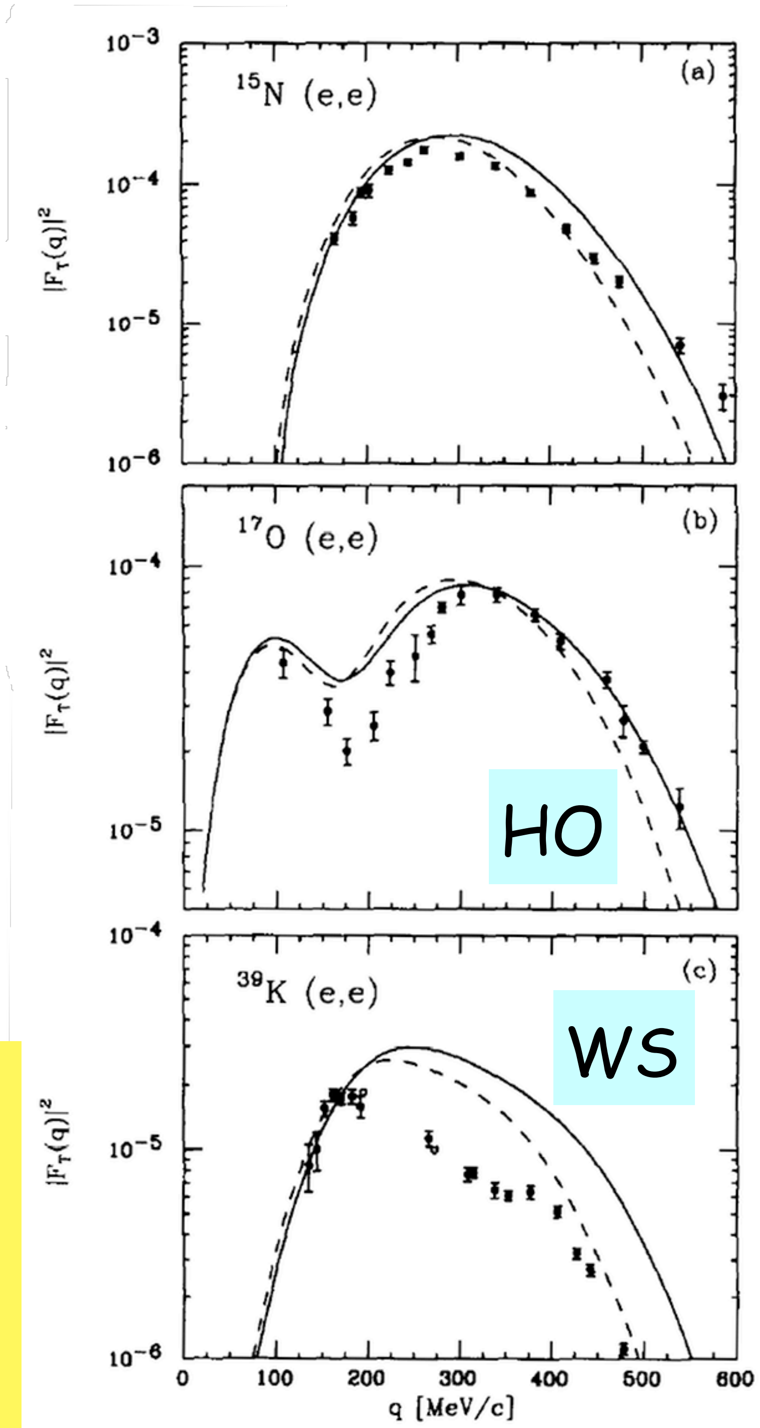


$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)^h = \Sigma_0^{\mathrm{OB}}\left(\frac{\Sigma_0}{\Sigma_0^{\mathrm{OB}}} + \overline{\Sigma} + \overline{\Delta}\right)$$

$$\Sigma_0 = 4\pi\,\sigma_{\mathrm{Mott}}\,f_{\mathrm{rec}}^{-1}\,f_0^i\,\left(v_{\mathrm{L}}\,\mathcal{W}_0^{\mathrm{L}}(q) + v_{\mathrm{T}}\,\mathcal{W}_0^{\mathrm{T}}(q)\right)$$

$$\overline{\Sigma} = \frac{\Sigma - \Sigma_0}{\Sigma_0^{\mathrm{OB}}}$$

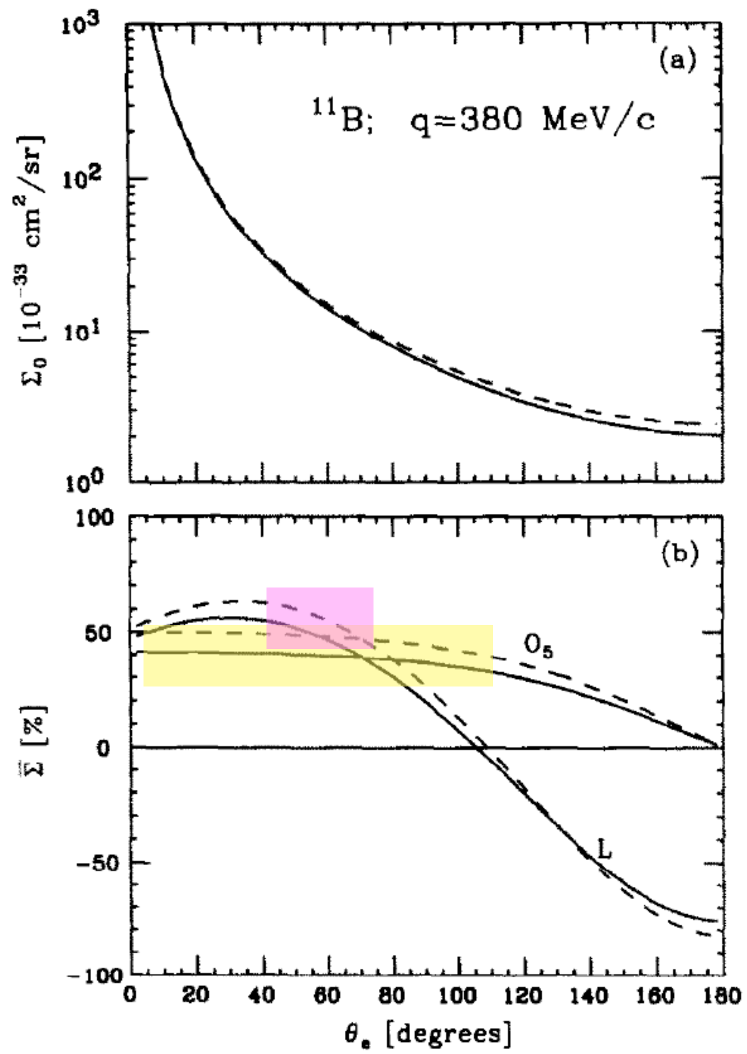
$$\overline{\Delta} = \frac{\Delta}{\Sigma_0^{\mathrm{OB}}}$$

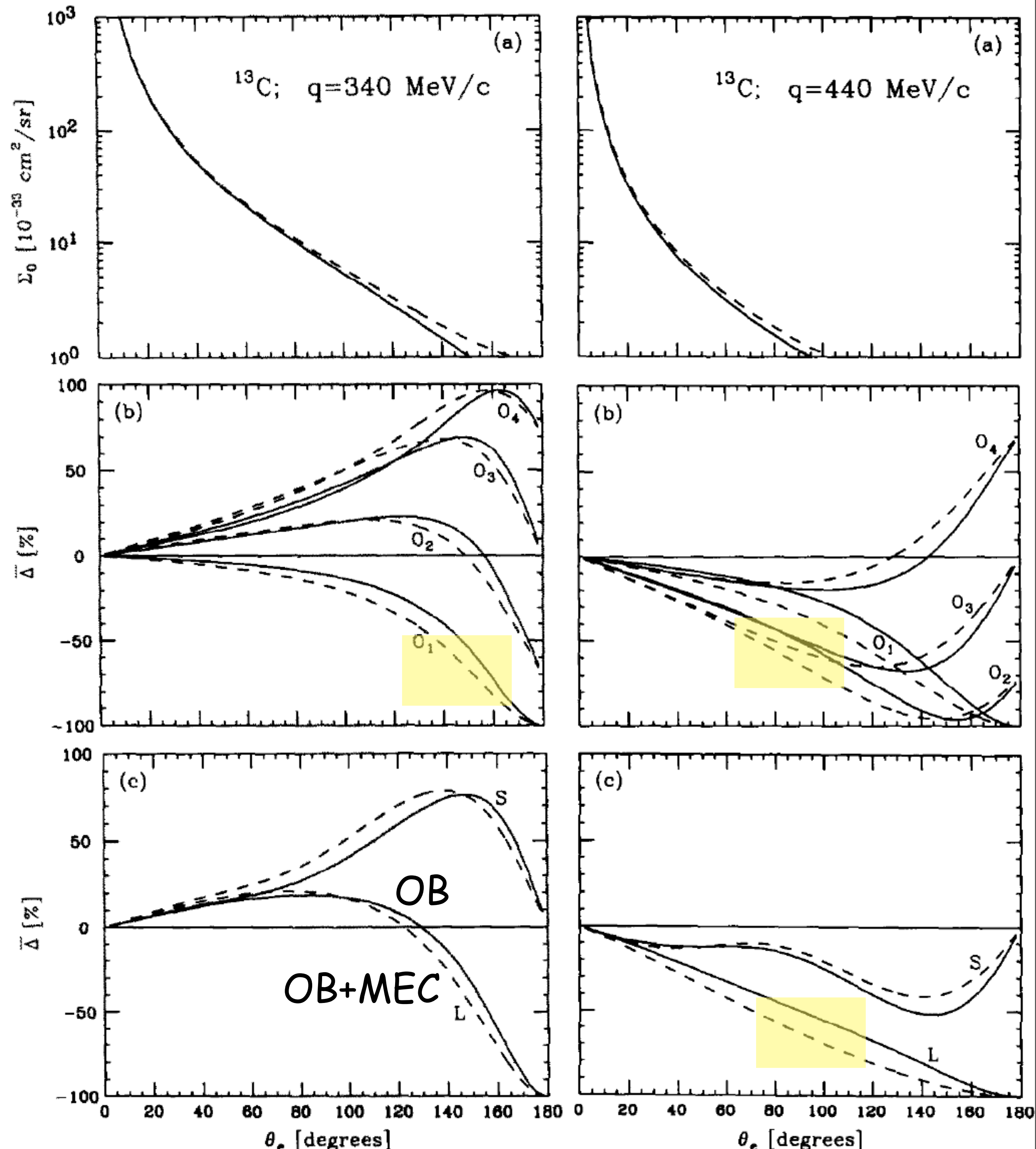


Elastic scattering: ground state

Elastic scattering: ground state

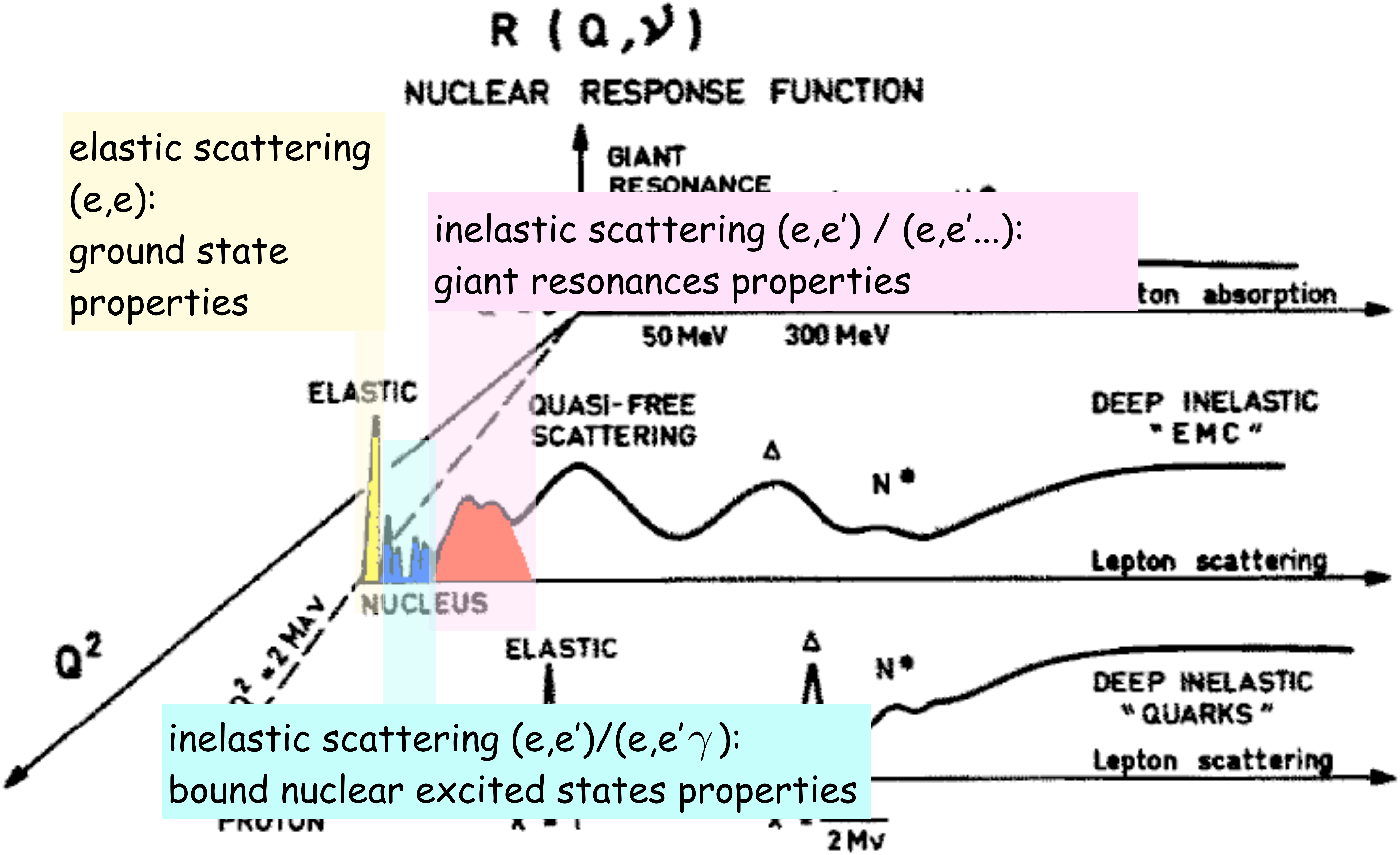
- -lower nuclear spins: ^{13}C ($1/2^-$), ^{15}N ($1/2^-$)
- -more relevant in $\overline{\Delta}$ than in $\overline{\Sigma}$
- -momentum transfers: 200-400 MeV/c
- -backward angles
- -target polarized on the scattering plane





MEC effects larger than 20%

Outline

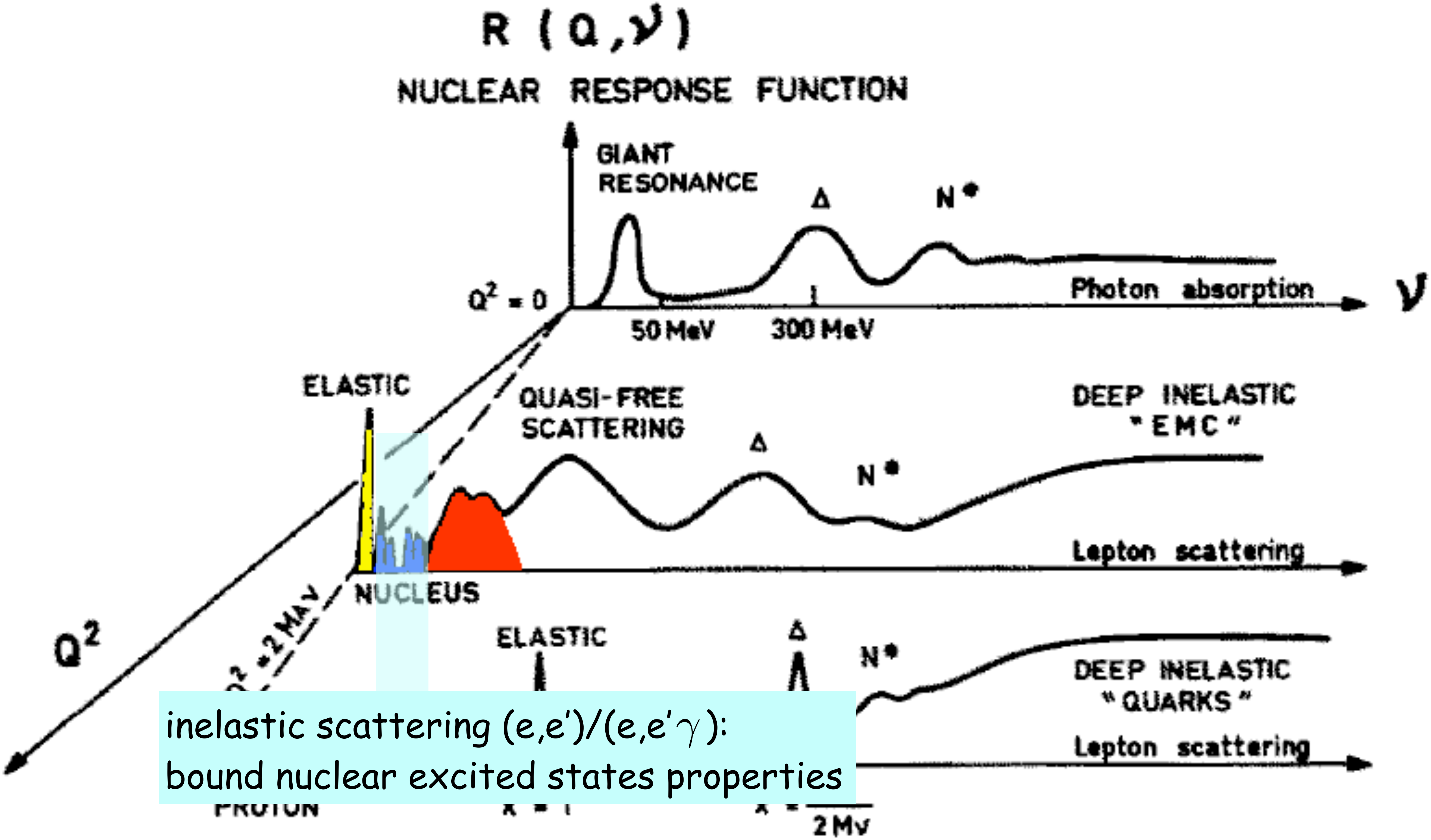


elastic scattering (e,e): ground state properties

inelastic scattering (e,e') / (e,e'...): giant resonances properties

inelastic scattering (e,e')/(e,e'γ): bound nuclear excited states properties

Outline



inelastic scattering (e,e')/(e,e'γ):
bound nuclear excited states properties

Inelastic scattering: bound excited states

inclusive (e,e') experiments

Inelastic scattering: bound excited states

inclusive (e,e') experiments

nuclear states

-collective states: involve the excitation of many nucleons

-particle-hole states: formed by excitation of one or a few particles

Inelastic scattering: bound excited states

inclusive (e,e') experiments

nuclear states

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 4\pi\,\sigma_{\mathrm{Mott}}\,f_{\mathrm{rec}}^{-1}\left[\frac{q_\mu^4}{\mathbf{q}^4}\sum_{\lambda=0}^{\infty}|F_\lambda^{\mathrm{C}}(q)|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right)\sum_{\lambda=1}^{\infty}\left(|F_\lambda^{\mathrm{E}}(q)|^2+|F_\lambda^{\mathrm{M}}(q)|^2\right)\right]$$

$$F_\lambda^{\mathrm{C}}(q) = \frac{1}{\sqrt{2J_i+1}}\int_0^\infty \mathrm{d}r\,r^2\,j_\lambda(qr)\,\rho_\lambda(r)$$

$$\rho_\lambda(r) = \int \mathrm{d}\Omega\,\langle J_f\|\rho(\mathbf{r})\,Y_\lambda(\hat{\mathbf{r}})\|J_i\rangle$$

$$F_\lambda^{\mathrm{E}}(q) = -\frac{1}{\sqrt{(2J_i+1)(2\lambda+1)}}\int_0^\infty \mathrm{d}r\,r^2\sum_{s=-1,1} s\sqrt{\lambda+\delta_{s,-1}}\,j_{\lambda+s}(qr)\,J_{\lambda,\lambda+s}(r)$$

$$F_\lambda^{\mathrm{M}}(q) = \frac{1}{\sqrt{2J_i+1}}\int_0^\infty \mathrm{d}r\,r^2\,j_\lambda(qr)\,J_{\lambda,\lambda}(r)$$

$$J_{\lambda,\lambda'}(r) = i\int \mathrm{d}\Omega\,\langle J_f\|\mathbf{J}(\mathbf{r})\cdot\mathbf{Y}_{\lambda\lambda'}(\hat{\mathbf{r}})\|J_i\rangle$$

Inelastic scattering: bound excited states

inclusive (e,e′) experiments

nuclear states

-collective states: involve the excitation of many nucleons

-particle-hole states: formed by excitation of one or a few particles

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 4\pi\,\sigma_{\mathrm{Mott}}\,f_{\mathrm{rec}}^{-1}\left[\frac{q_\mu^4}{\mathbf{q}^4}\sum_{\lambda=0}^{\infty}|F_\lambda^{\mathrm{C}}(q)|^2 + \left(-\frac{1}{2}\frac{q_\mu^2}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right)\sum_{\lambda=1}^{\infty}\left(|F_\lambda^{\mathrm{E}}(q)|^2+|F_\lambda^{\mathrm{M}}(q)|^2\right)\right]$$

$$F_\lambda^{\mathrm{C}}(q) = \frac{1}{\sqrt{2J_i+1}}\int_0^\infty \mathrm{d}r\,r^2\,j_\lambda(qr)\,\rho_\lambda(r)$$

$$\rho_\lambda(r) = \int \mathrm{d}\Omega\,\langle J_f\|\rho(\mathbf{r})\,Y_\lambda(\hat{\mathbf{r}})\|J_i\rangle$$

$$F_\lambda^{\mathrm{E}}(q) = -\frac{1}{\sqrt{(2J_i+1)(2\lambda+1)}}\int_0^\infty \mathrm{d}r\,r^2\sum_{s=-1,1} s\sqrt{\lambda+\delta_{s,-1}}\,j_{\lambda+s}(qr)\,J_{\lambda,\lambda+s}(r)$$

$$F_\lambda^{\mathrm{M}}(q) = \frac{1}{\sqrt{2J_i+1}}\int_0^\infty \mathrm{d}r\,r^2\,j_\lambda(qr)\,J_{\lambda,\lambda}(r)$$

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-natural $[\Pi=(-1)^J]$ parity transitions: $\rho_\lambda,\quad J_{\lambda,\lambda+1},\quad J_{\lambda,\lambda-1}$ calculated from $F_\lambda^{\mathrm{C}},\quad F_\lambda^{\mathrm{E}}$

-unnatural $[\Pi=(-1)^{(J+1)}]$ parity transitions: $J_{\lambda,\lambda}$ calculated from F_λ^{M}

-extraction of densities: similar situation to charge density in (e,e) experiments

-form factors include contributions from all multipoles: $J_i=0\longrightarrow\lambda=J_f$

Inelastic scattering: bound excited states

inclusive (e,e′) experiments - collective states: the 3^- at 2.615 MeV in ^{208}Pb

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microscopic view: excitation of many particle-hole pairs

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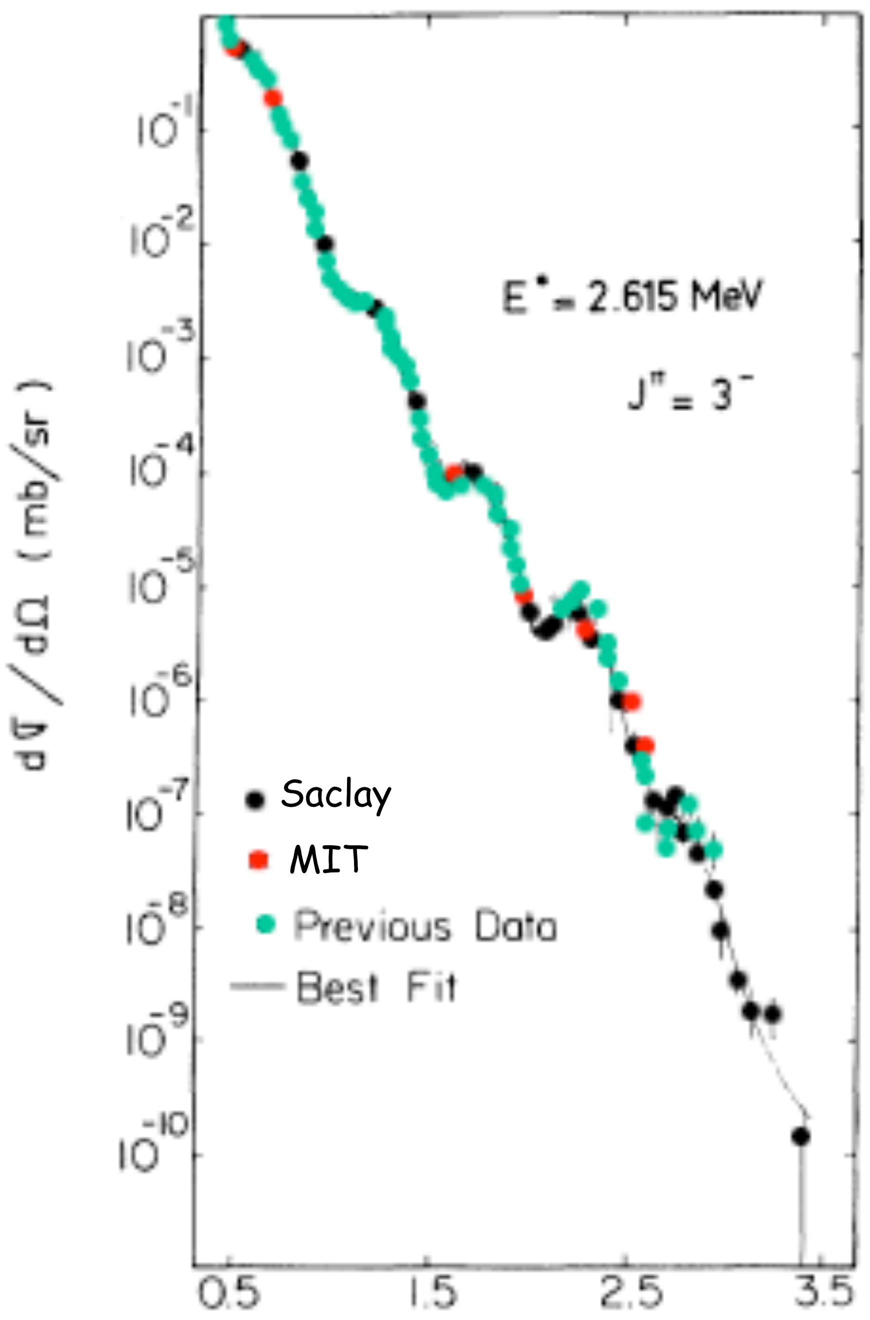


Inelastic scattering: bound excited states

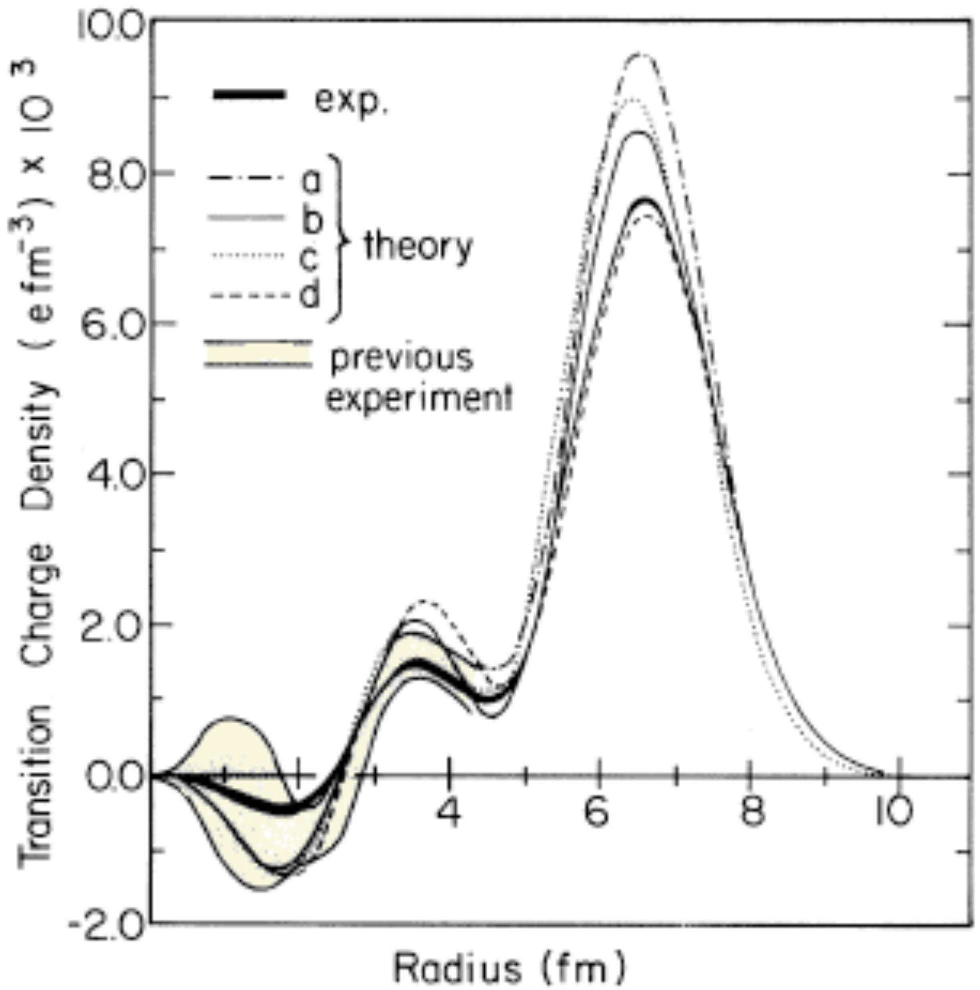
inclusive (e,e′) experiments - collective states: the 3^- at 2.615 MeV in ^{208}Pb

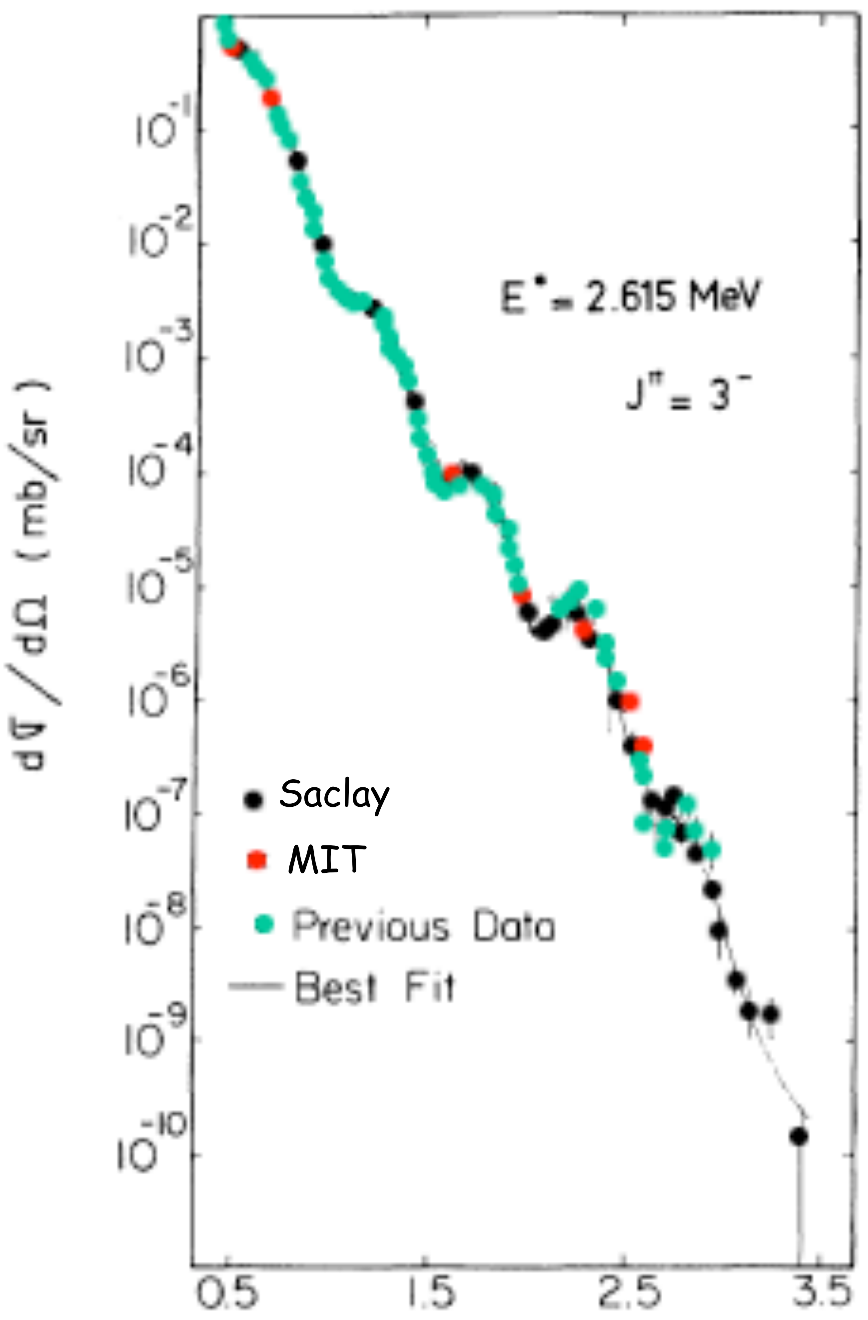
microscopic view: excitation of many particle-hole pairs

-transition density is obtained using the Fourier-Bessel expansion:

$$\rho_\lambda(r) = \begin{cases} \sum_k A_k\, q_k^{[\lambda-1]}\, j_\lambda(q_k^{[\lambda-1]} r)\,, & r \le R_c \\ 0, & r > R_c \end{cases}$$

$R_c q_k^{[\lambda]}$ is the k-th zero of $j_\lambda(z)$





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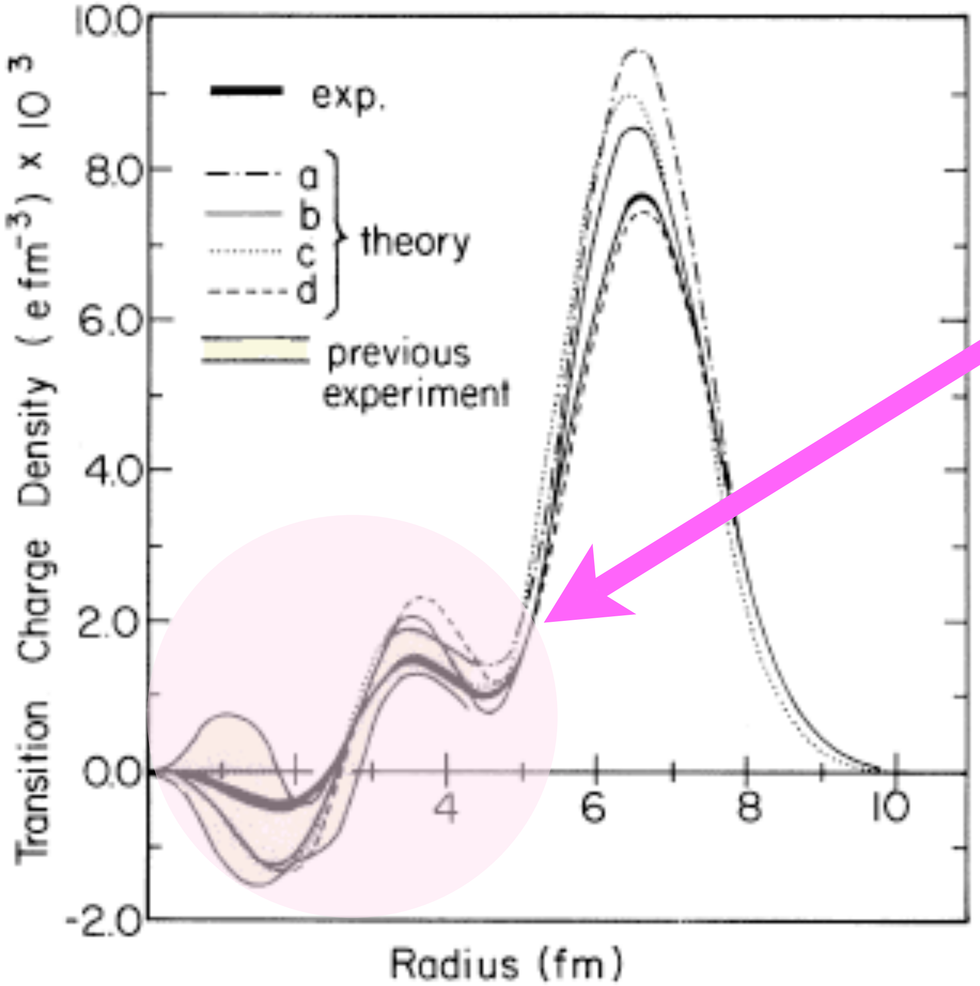
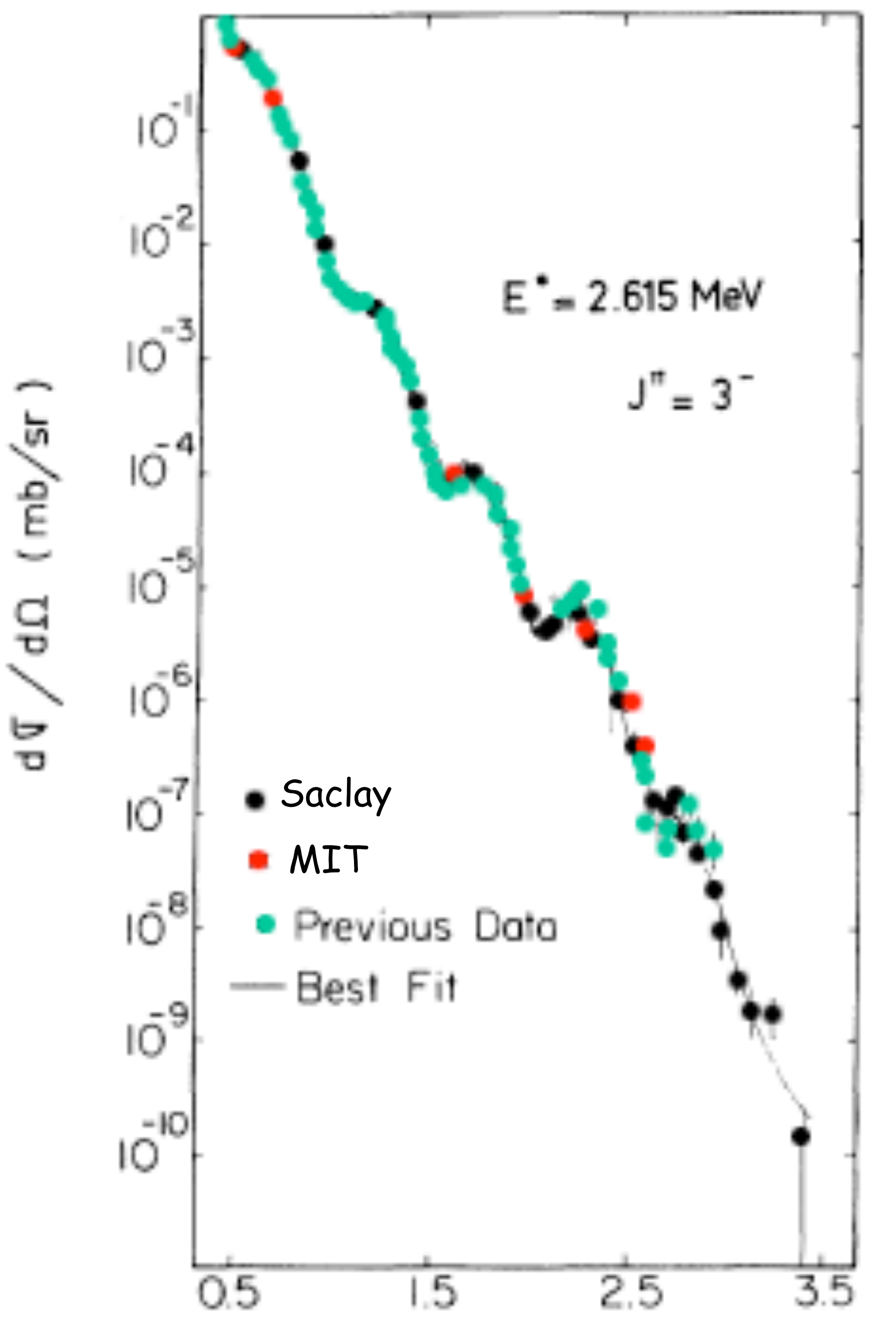


structure explained only in terms of indiviual nucleon orbits: the experimental accuracy requires microscopic models



Inelastic scattering: bound excited states

inclusive (e,e') experiments: other collective states

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5^- states in ^{208}Pb

TRANSITION CHARGE DENSITY

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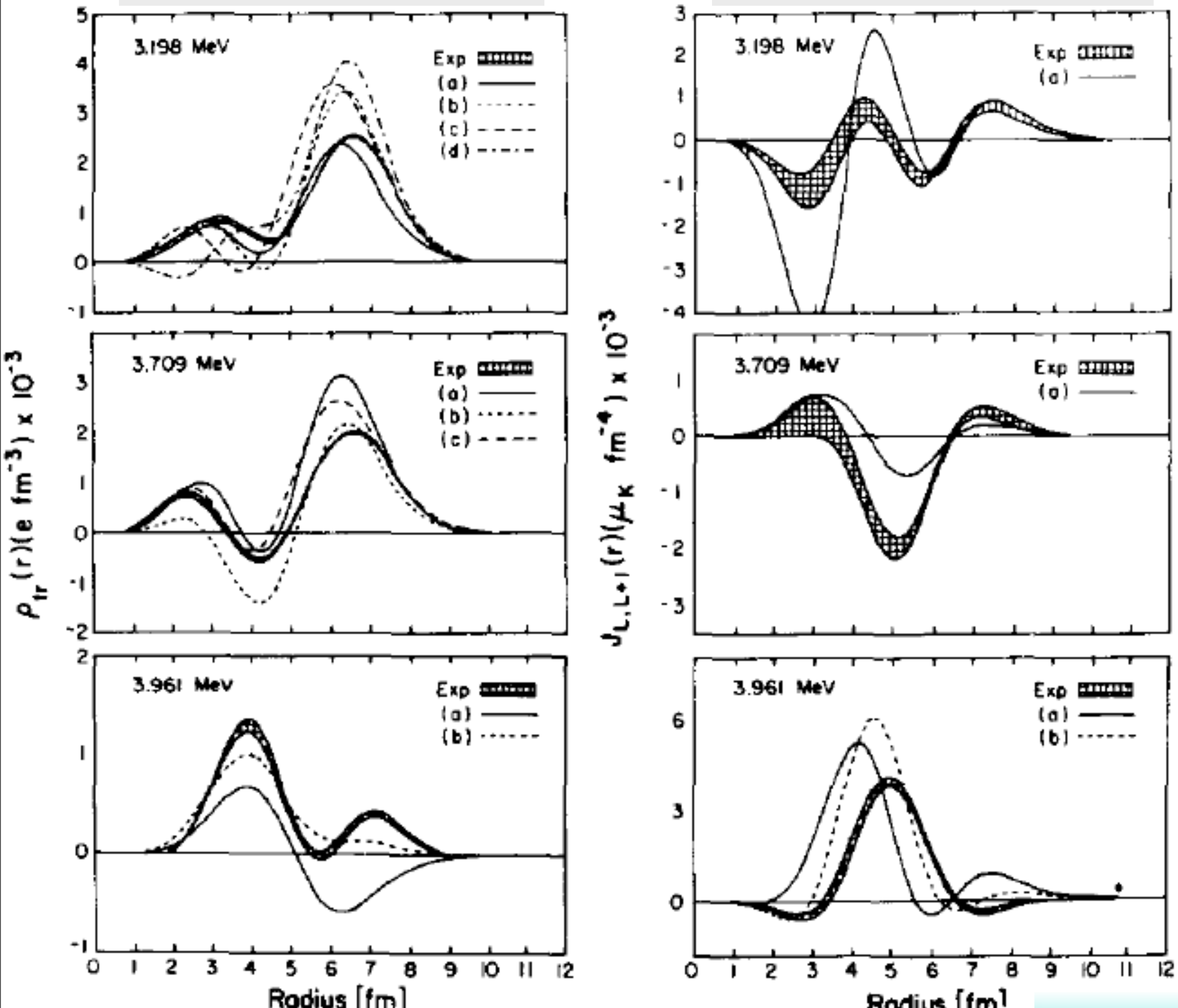

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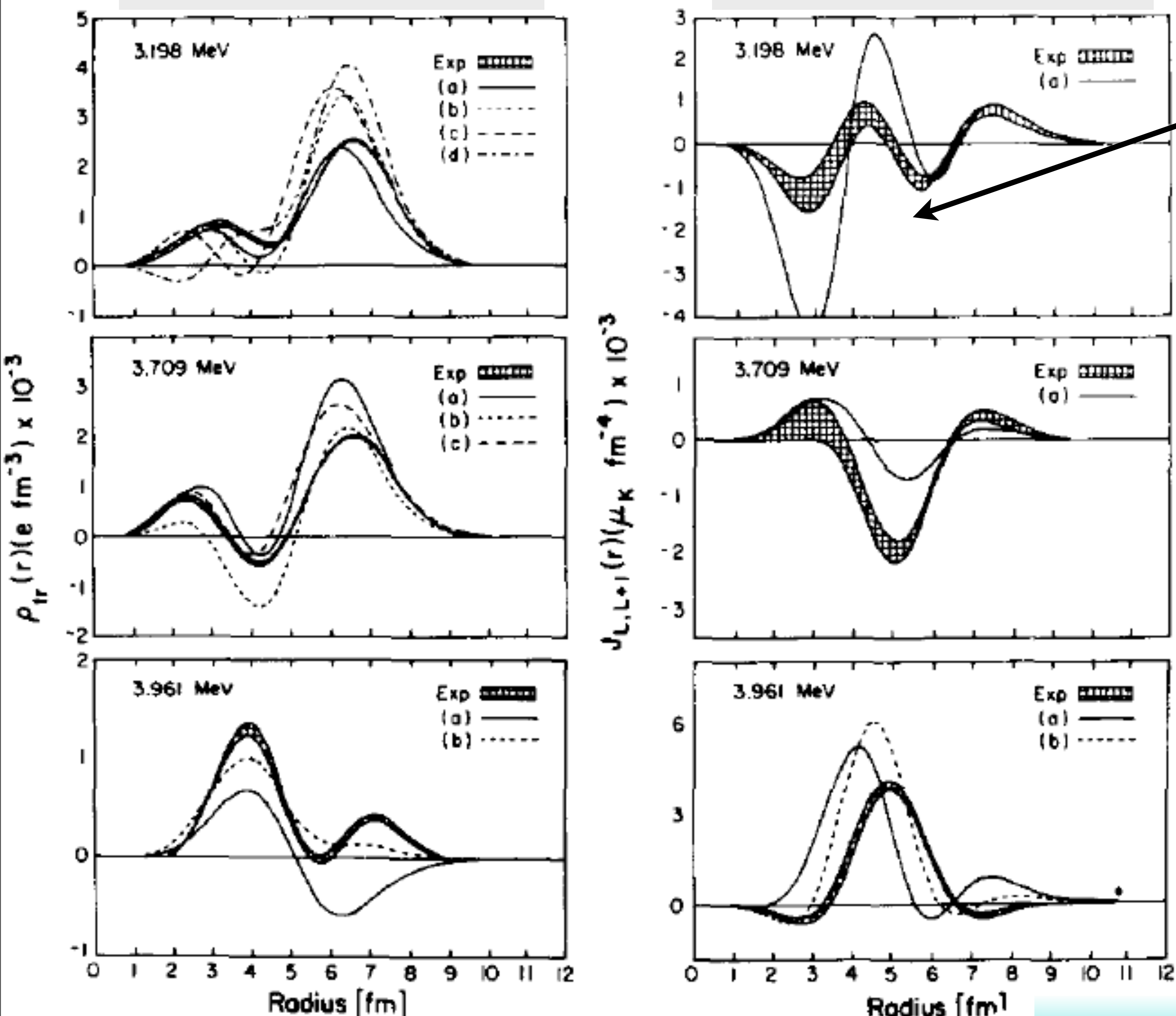

larger discrepancies wiht calculations:

-relativistic effects, MEC, ... play a more important role in currents

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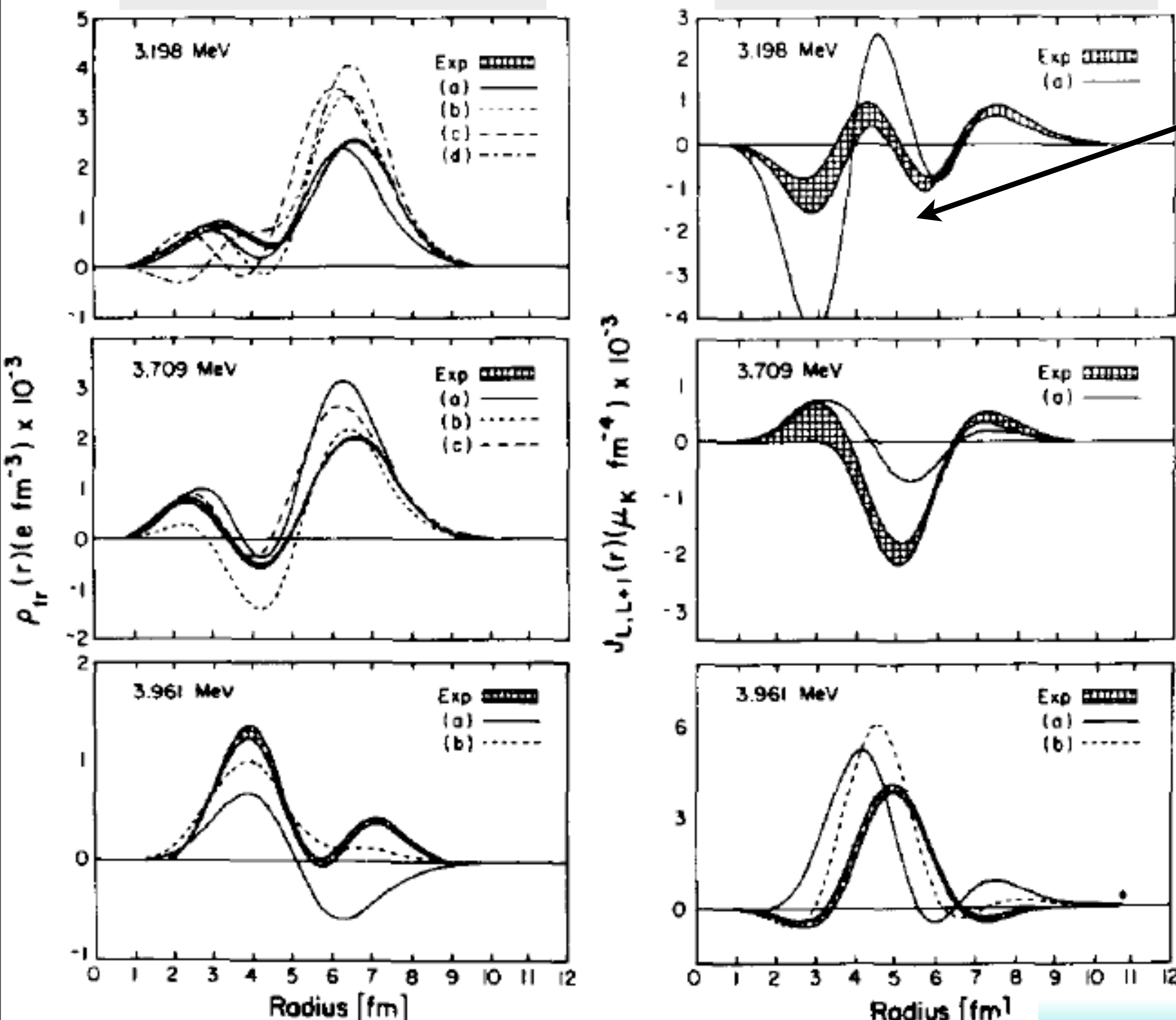

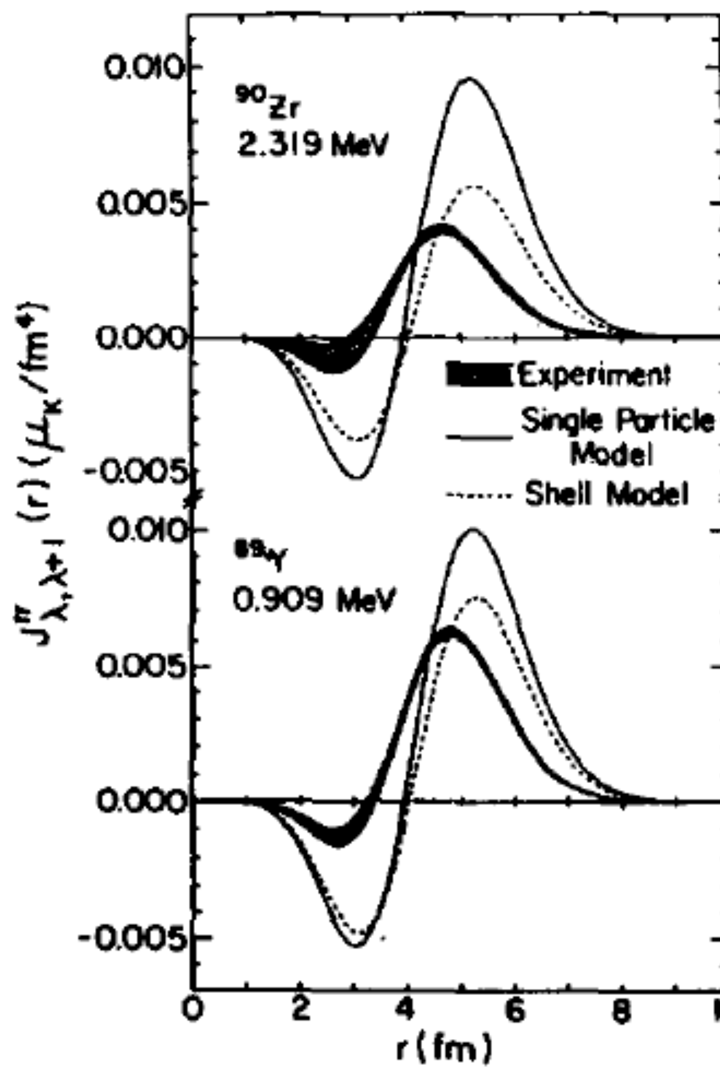

Inelastic scattering: bound excited states

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inclusive (e,e') experiments - particle-hole states: the high-spin states in ^{208}Pb

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inclusive (e,e') experiments - particle-hole states: the high-spin states in ^{208}Pb

high-spin states identified

in (e,e') experiments:

-E10, E12, M12, M14 in ^{208}Pb

-E7, M7, M10 in ^{90}Zr

-M8 in nickel region

-M5, E8 in ^{48}Ca

-M4 in ^{16}O

Inelastic scattering: bound excited states

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common characteristic:

very few particle-hole states contribute to their wave function due to the high multipolarity

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discovered in (e,e') experiments by:

Lichtenstadt et al. Phys. Rev. Lett. 40 (1978) 1127; Phys. Rev. C 20 (1979) 427

Observation of 12^- Magnetic Spin States in ^{208}Pb

J. Lichtenstadt, J. Heisenberg, C. N. Papanicolas, and C. P. Sargent
Bates Linear Accelerator Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

A. N. Courtemanche and J. S. McCarthy
University of Virginia, Charlottesville, Virginia 22901
(Received 16 February 1978)

States at 6.42-, 6.75-, and 7.06-MeV excitation have been observed in electron scattering on ^{208}Pb. The transverse character of the excitation cross section has been established. The states have been interpreted as the $\nu(i_{13/2}^{-1}j_{15/2})_{12^-,14^-}$ and the $\pi(h_{11/2}^{-1}i_{13/2})_{12^-}$ single-particle hole excitations of the ^{208}Pb ground state, on the basis of the measured momentum-transfer dependence and the magnitude of the cross section.

High-spin states of $J^\pi = 12^-, 14^-$ in ^{208}Pb studied by (e,e')

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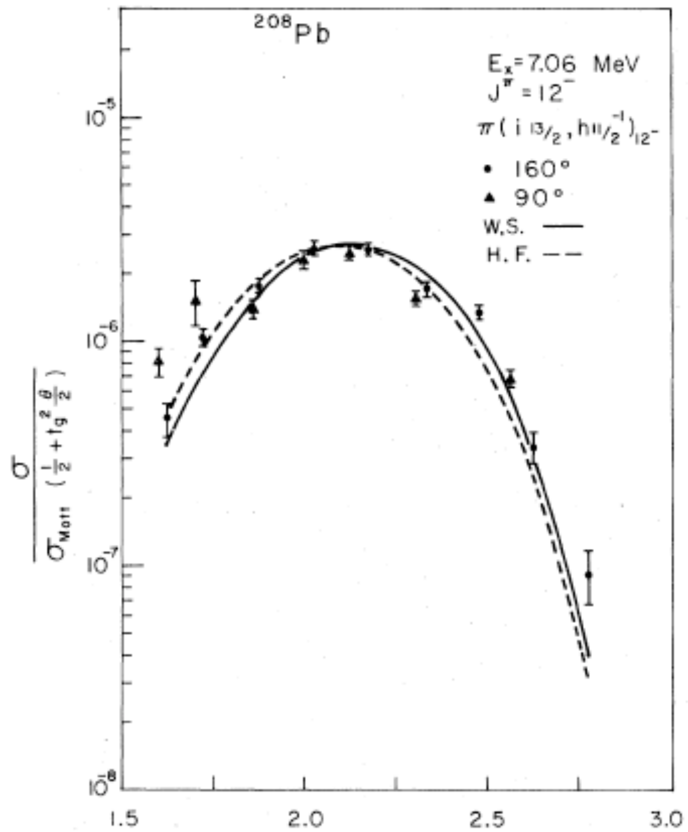
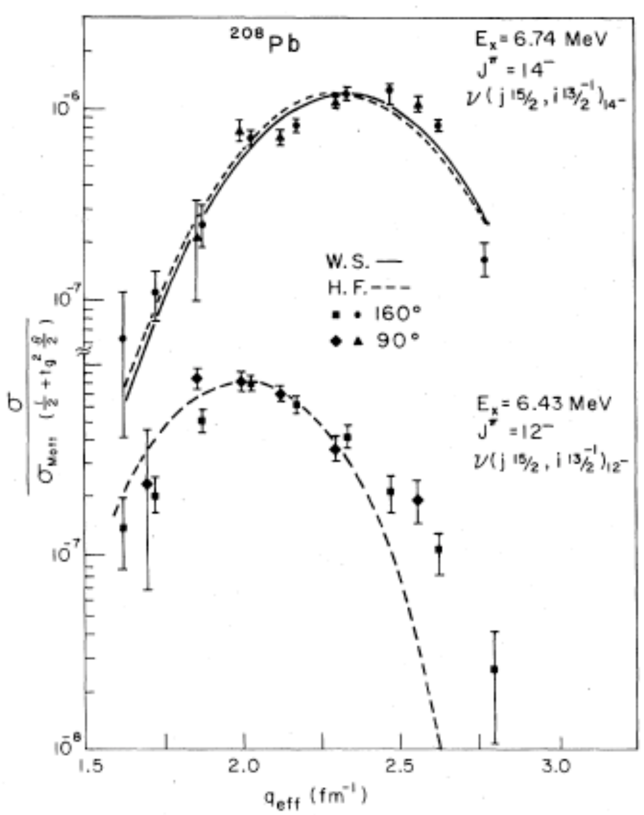
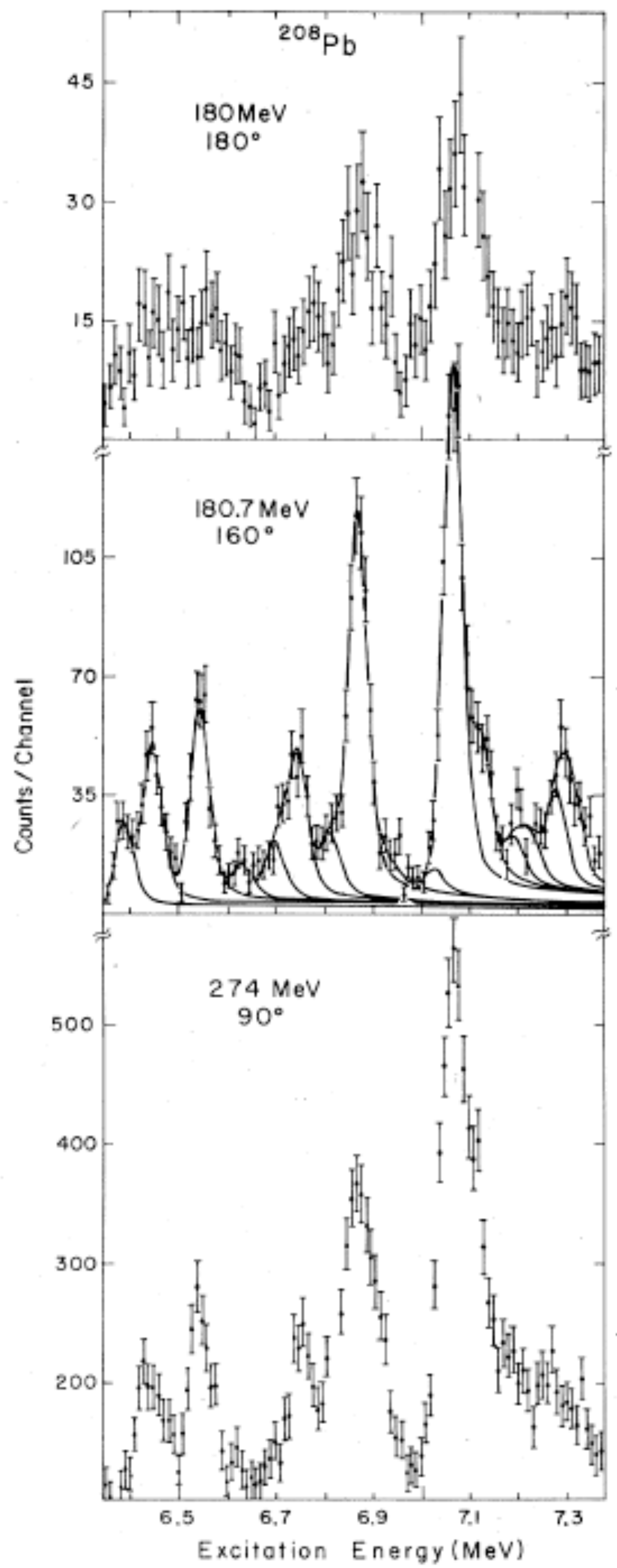
Inelastic electron scattering cross sections for the excited states at 6.43, 6.74, and 7.06 MeV in ^{208}Pb were measured with high resolution. The measurements were done in forward and backward directions covering the momentum transfer range of $0.3 < q < 2.5$ fm^{-1}. The state at 7.06 MeV was identified as the $\pi(i_{13/2}h_{11/2}^{-1})_{12-}$ and the states at 6.74 and 6.43 MeV as the $\nu(j_{15/2}i_{13/2}^{-1})_{14-,12-}$, respectively. The identification was based on four criteria: (a) the agreement between the q dependence of the measured form factor with that of Hartree-Fock single particle-hole prediction, with no adjustment of radial parameters, (b) the absence of a longitudinal form factor, (c) the relative magnitude of the observed levels, and (d) the excitation energies being close to the single p-h energies. The measured strength of each state was found to be 50% of the single p-h prediction.

Inelastic scattering: bound excited states

inclusive (e,e') experiments - particle-hole states: the high-spin states in ^{208}Pb







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Inelastic scattering: bound excited states

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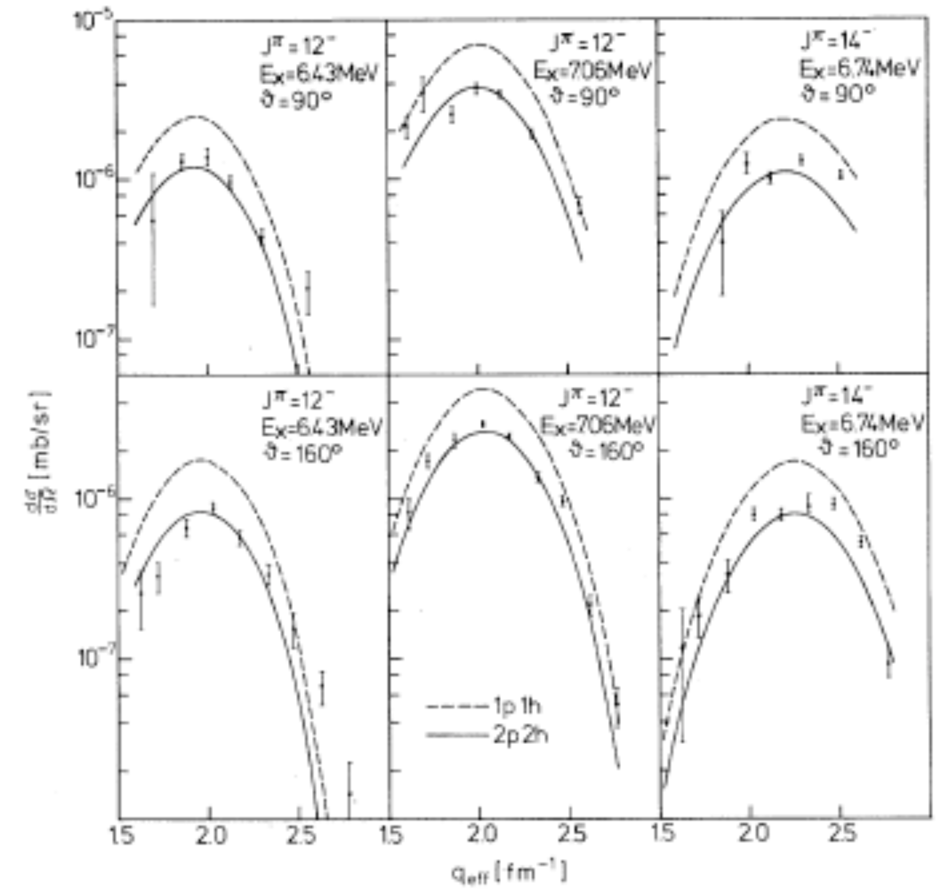
Krewald, Speth, Phys. Rev. Lett. 45 (1980) 417



-residual interaction: $\delta + \pi + \rho$

$$
\begin{aligned}
V(q) \quad = \quad & C_0 \left(f_0 + f_0' \,\boldsymbol{\tau}\cdot\boldsymbol{\tau}' + g_0 \,\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' + g_0' \,\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' \,\boldsymbol{\tau}\cdot\boldsymbol{\tau}' \right) \\
& + 4\pi \,\boldsymbol{\tau}\cdot\boldsymbol{\tau}' \left[\frac{f_\pi^2}{m_\pi^2} \left(\frac{1}{3} \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' - \frac{\boldsymbol{\sigma}\cdot\mathbf{q}\,\boldsymbol{\sigma}'\cdot\mathbf{q}}{m_\pi^2 + q^2} \right) \right. \\
& \qquad \left. + \frac{f_\rho^2}{m_\rho^2} \left(\frac{2}{3} \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' - \frac{\boldsymbol{\sigma}\times\mathbf{q}\,\boldsymbol{\sigma}'\times\mathbf{q}}{m_\rho^2 + q^2} \right) \right]
\end{aligned}
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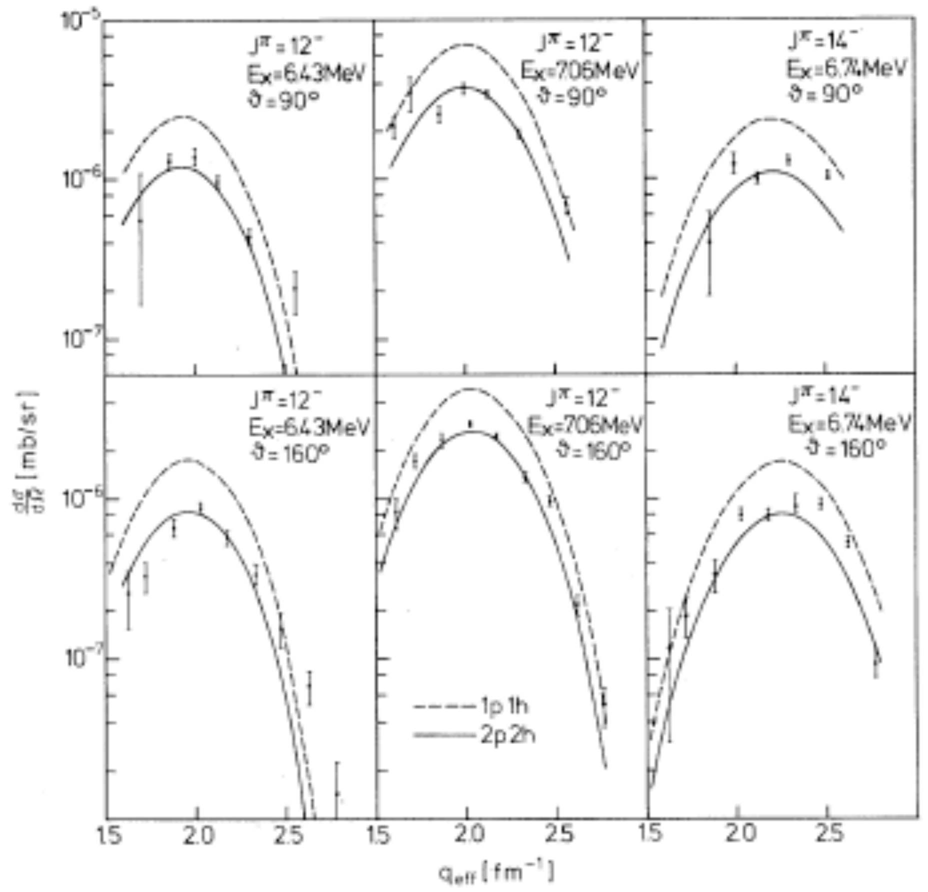

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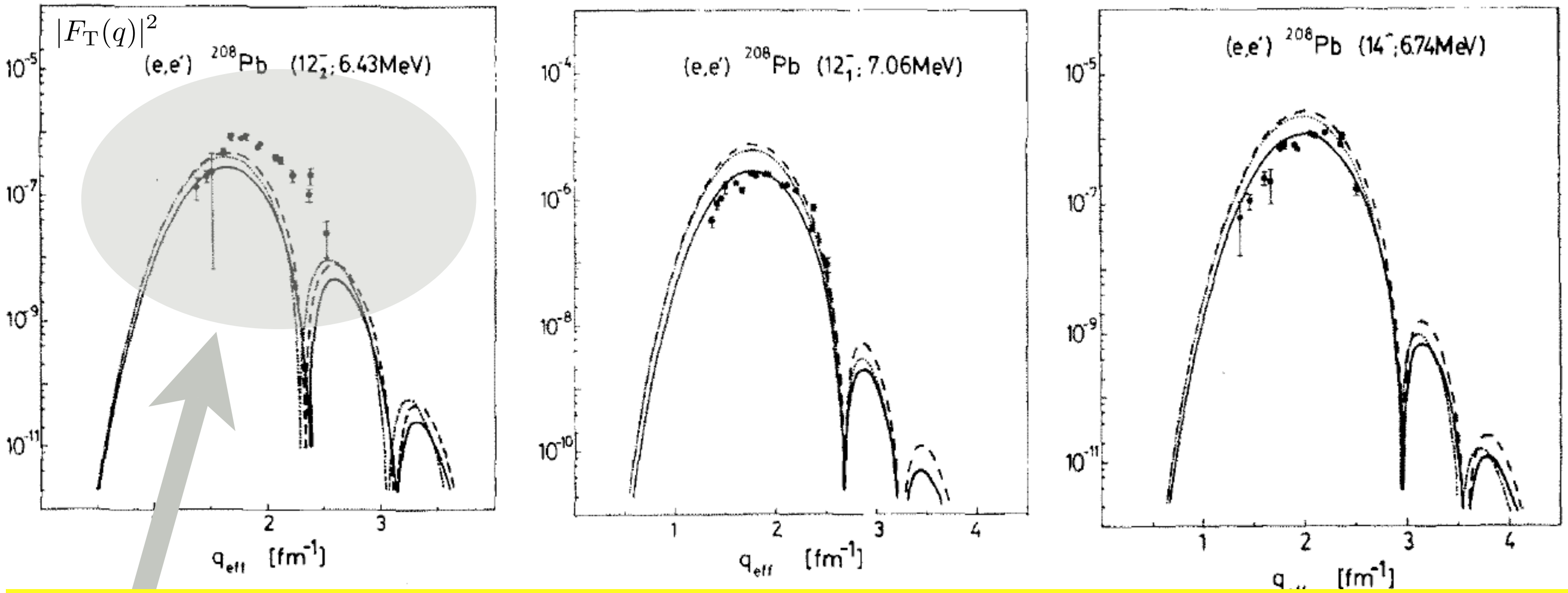

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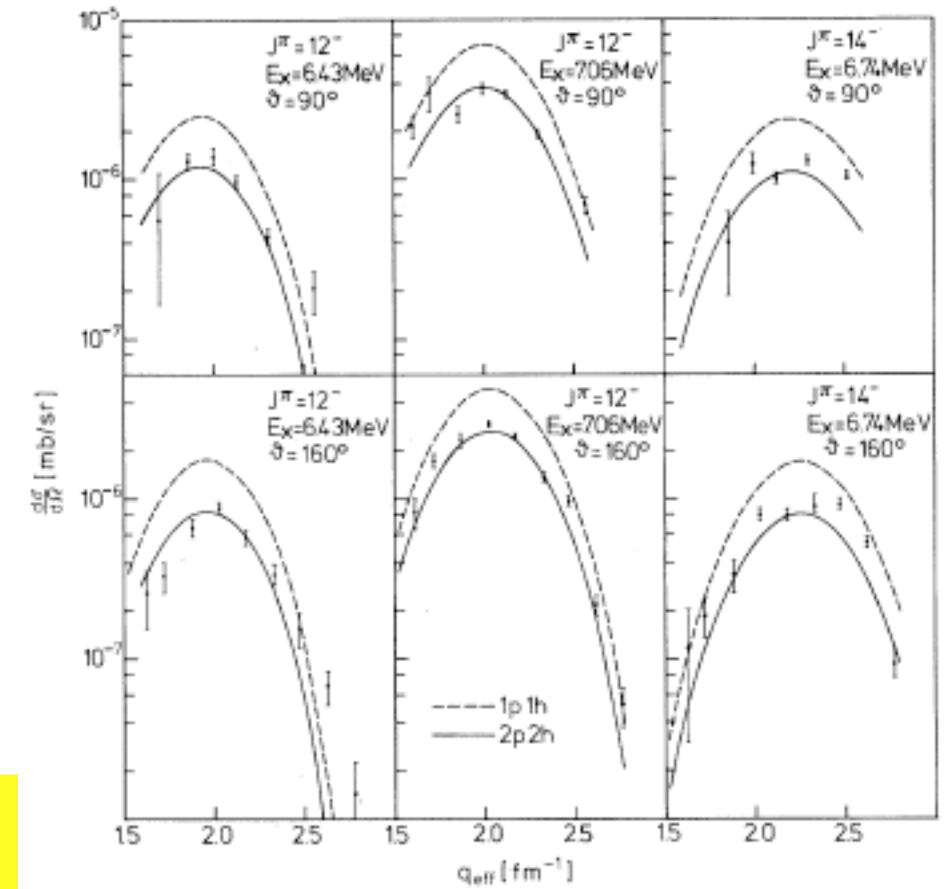

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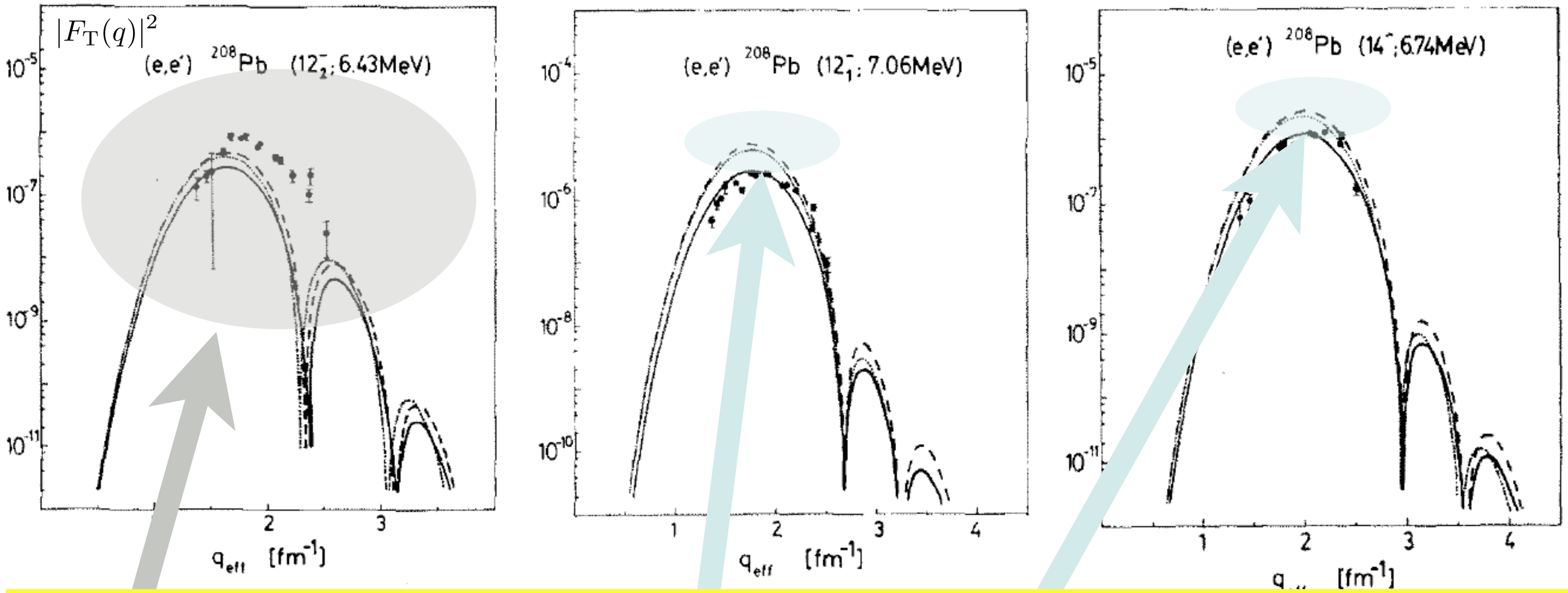

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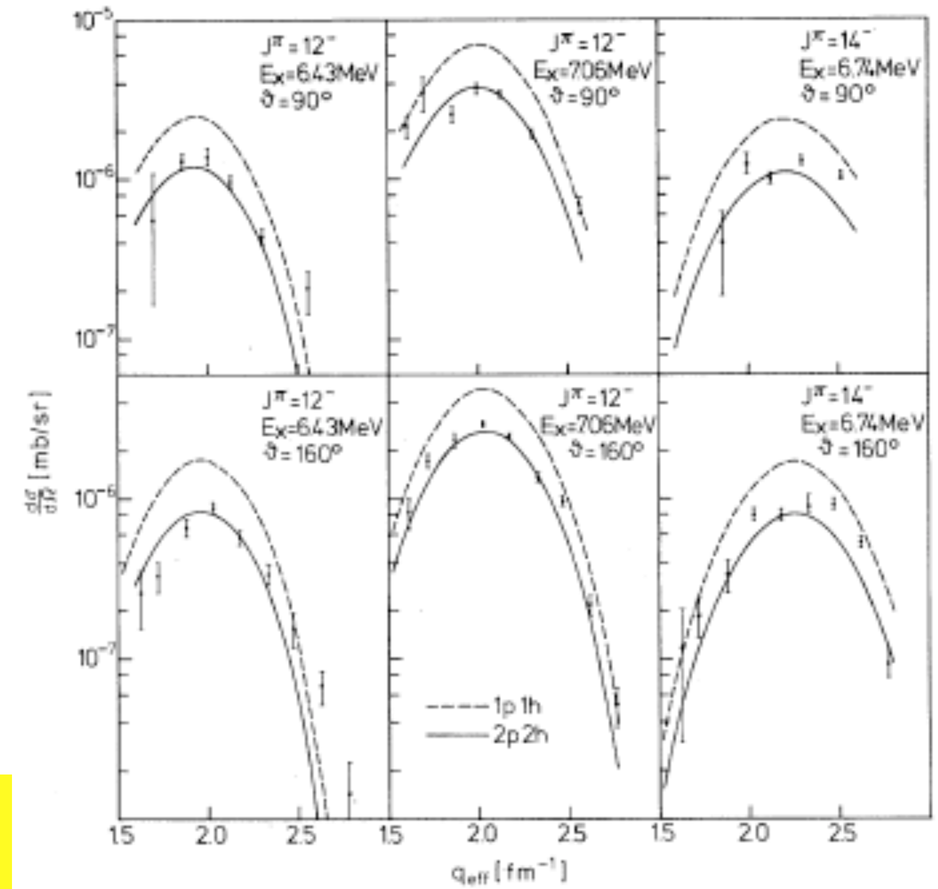

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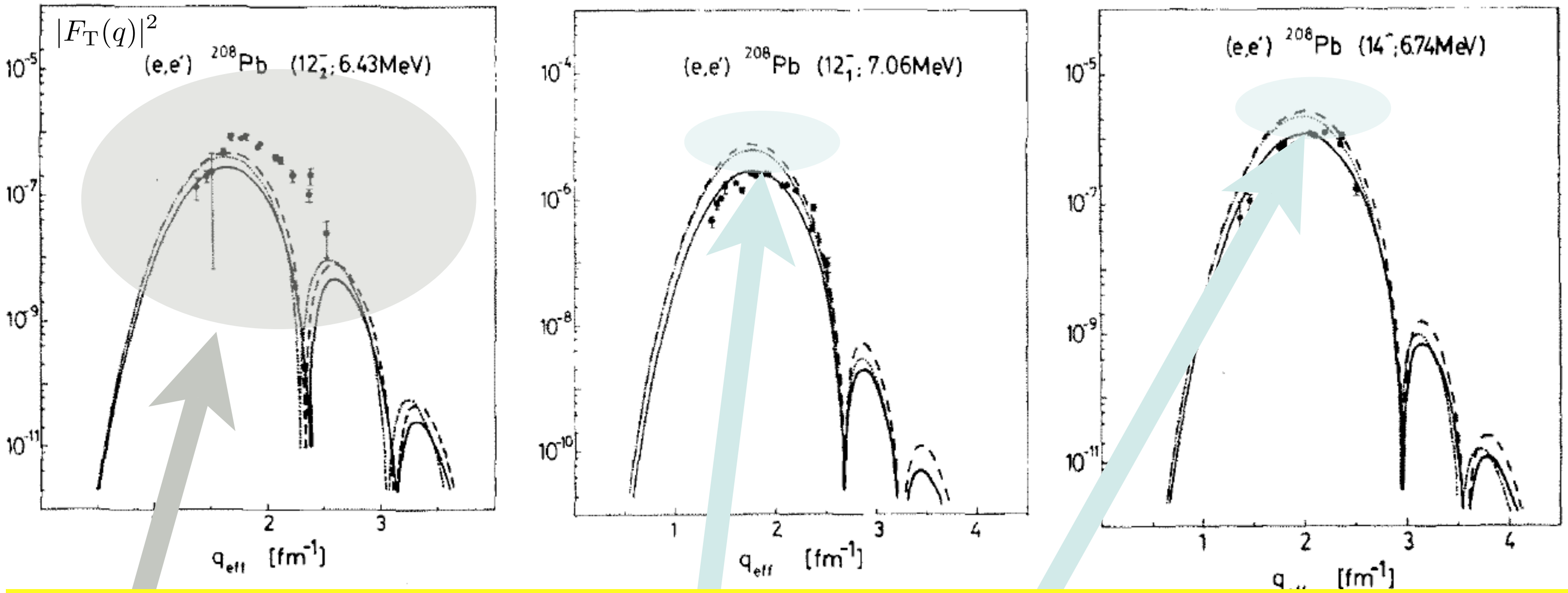

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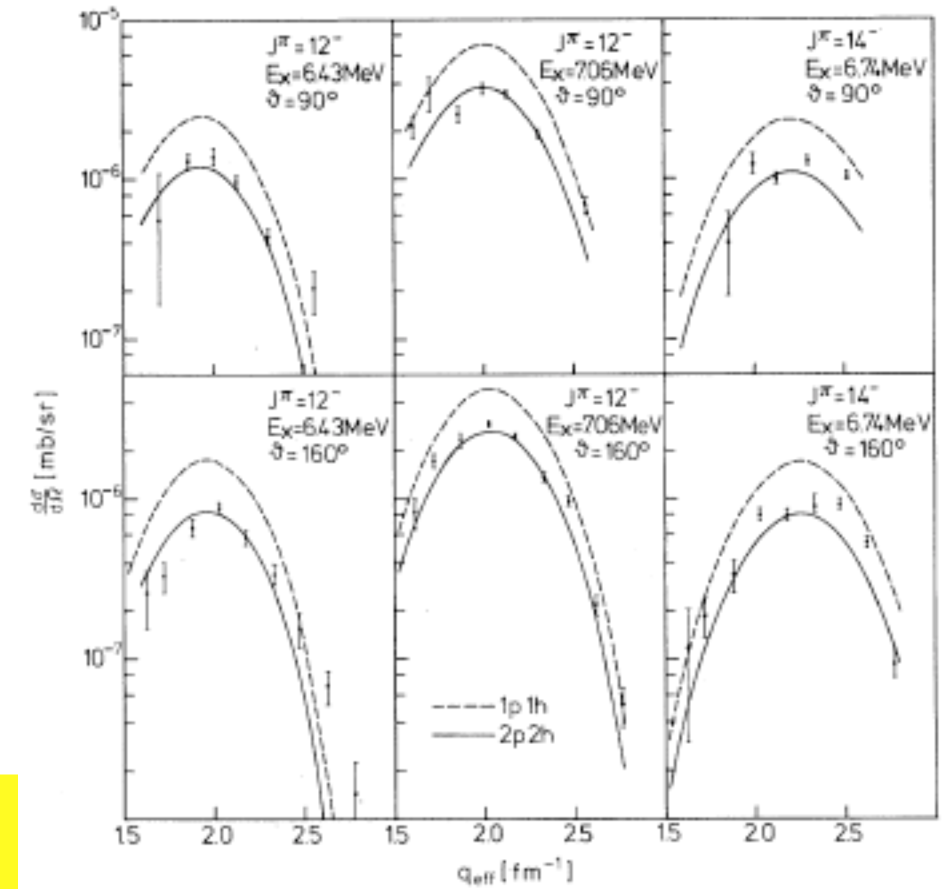

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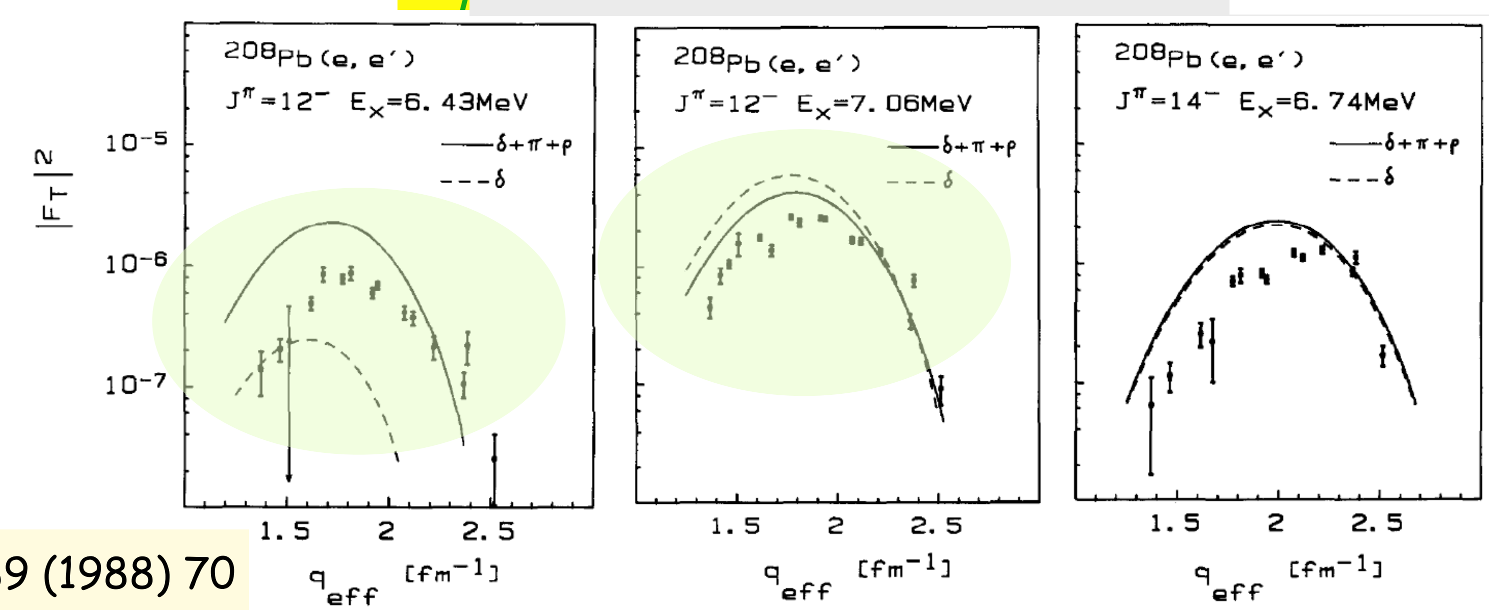

Lallena, Nucl. Phys. A 489 (1988) 70

Inelastic scattering: bound excited states

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|12^-; 6.43\ \mathrm{MeV}\rangle &= \sqrt{(1-a)^2}\,|\nu(1j_{15/2}\,1i^{-1}_{13/2})_{12^-}\rangle + a\,|\pi(1i_{13/2}\,1h^{-1}_{11/2})_{12^-}\rangle \\
|12^-; 7.06\ \mathrm{MeV}\rangle &= -a\,|\nu(1j_{15/2}\,1i^{-1}_{13/2})_{12^-}\rangle + \sqrt{(1-a)^2}\,|\pi(1i_{13/2}\,1h^{-1}_{11/2})_{12^-}\rangle
\end{aligned}
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Inelastic scattering: bound excited states

Hintz, Lallena, Sethi Phys. Rev. C 45 (1992) 1098

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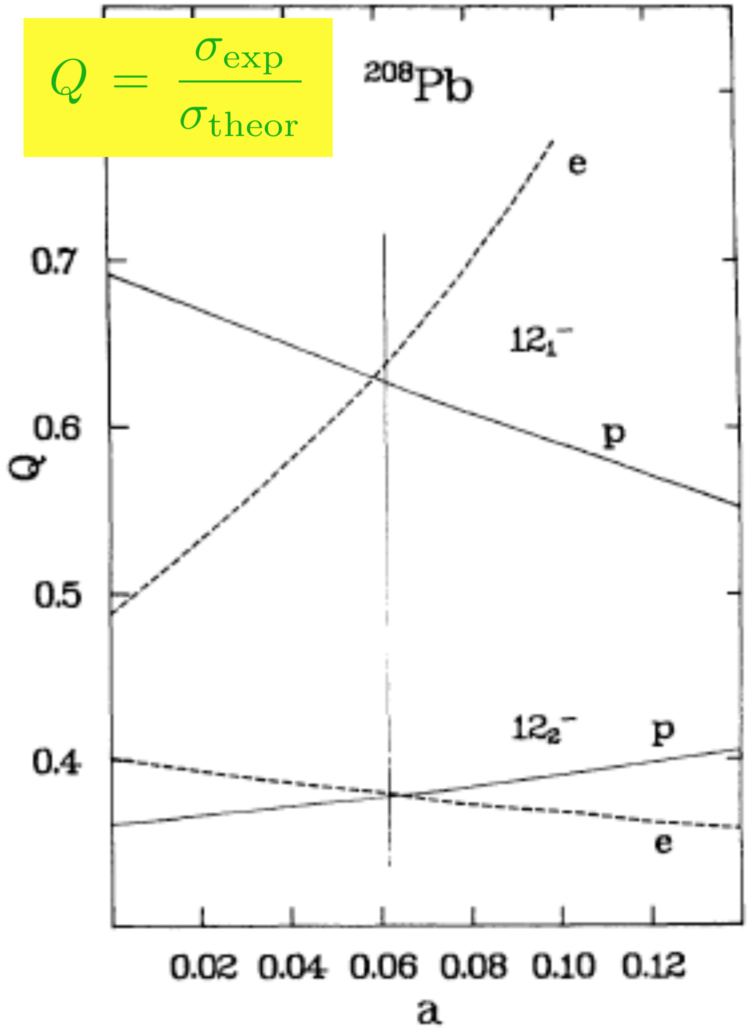
$$Q = \frac{\sigma_{\exp}}{\sigma_{\mathrm{theor}}}$$



Inelastic scattering: bound excited states

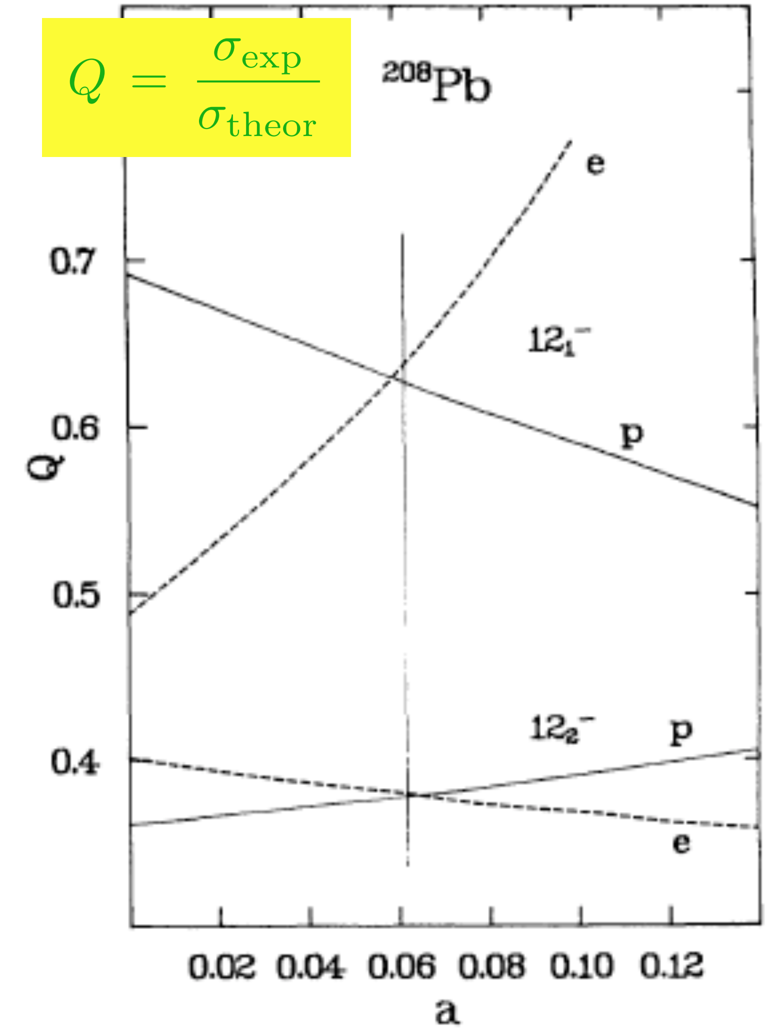
Hintz, Lallena, Sethi Phys. Rev. C 45 (1992) 1098

residual interaction: $V(q) = V_{\rm LM} + V_\pi^{\sigma\tau} + V_\pi^{\rm T} + V_\rho^{\sigma\tau} + V_\rho^{\rm T}$

$$V(q) = C_0\,(f_0 + f_0'\,\boldsymbol{\tau}\cdot\boldsymbol{\tau}' + g_0\,\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' + g_0'\,\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}'\,\boldsymbol{\tau}\cdot\boldsymbol{\tau}')$$
$$+ 4\pi\,\boldsymbol{\tau}\cdot\boldsymbol{\tau}'\left[\frac{f_\pi^2}{m_\pi^2}\left(\frac{1}{3}\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' - \frac{\boldsymbol{\sigma}\cdot\mathbf{q}\,\boldsymbol{\sigma}'\cdot\mathbf{q}}{m_\pi^2+q^2}\right) + \frac{f_\rho^2}{m_\rho^2}\left(\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' - \frac{\boldsymbol{\sigma}\times\mathbf{q}\,\boldsymbol{\sigma}'\times\mathbf{q}}{m_\rho^2+q^2}\right)\right]$$

g_0, g_0' chosen to reproduce the energies of the two 1⁺ states at 5.85 MeV and 7.30 MeV in ^{208}Pb

$$Q = \frac{\sigma_{\rm exp}}{\sigma_{\rm theor}}$$



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Hintz, Lallena, Sethi Phys. Rev. C 45 (1992) 1098

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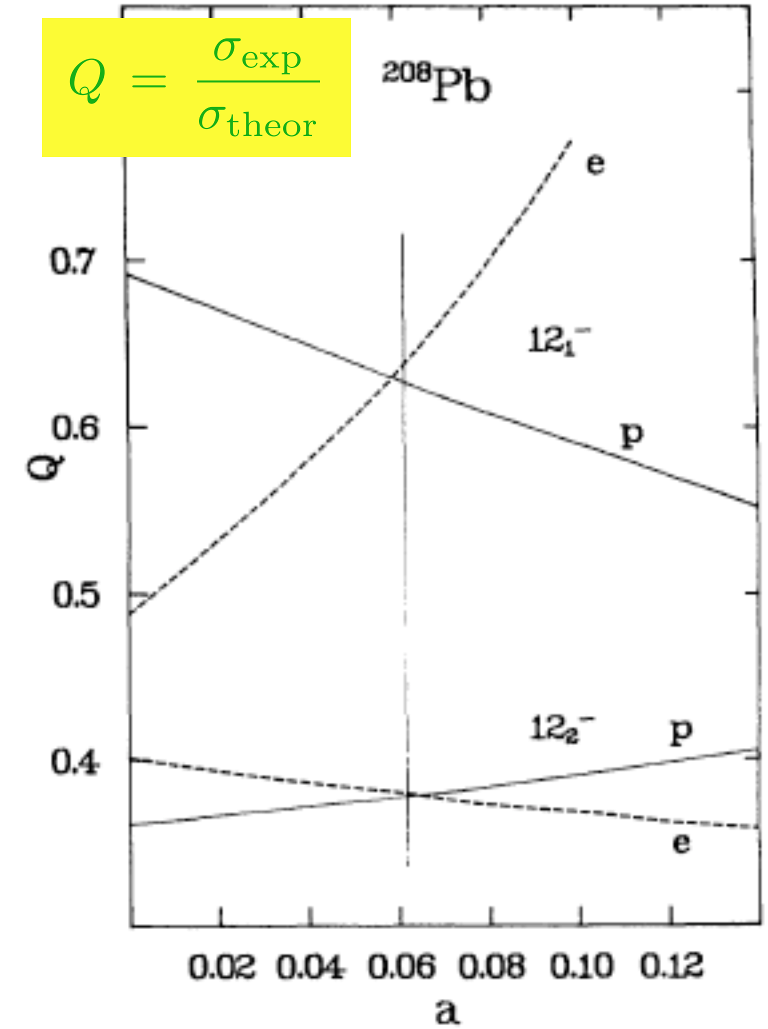
$$V(q) = C_0\,(f_0 + f_0'\,\boldsymbol{\tau}\cdot\boldsymbol{\tau}' + g_0\,\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' + g_0'\,\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}'\,\boldsymbol{\tau}\cdot\boldsymbol{\tau}') + 4\pi\,\boldsymbol{\tau}\cdot\boldsymbol{\tau}'\left[\frac{f_\pi^2}{m_\pi^2}\left(\frac{1}{3}\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' - \frac{\boldsymbol{\sigma}\cdot\mathbf{q}\,\boldsymbol{\sigma}'\cdot\mathbf{q}}{m_\pi^2+q^2}\right) + \frac{f_\rho^2}{m_\rho^2}\left(\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}' - \frac{\boldsymbol{\sigma}\times\mathbf{q}\,\boldsymbol{\sigma}'\times\mathbf{q}}{m_\rho^2+q^2}\right)\right]$$

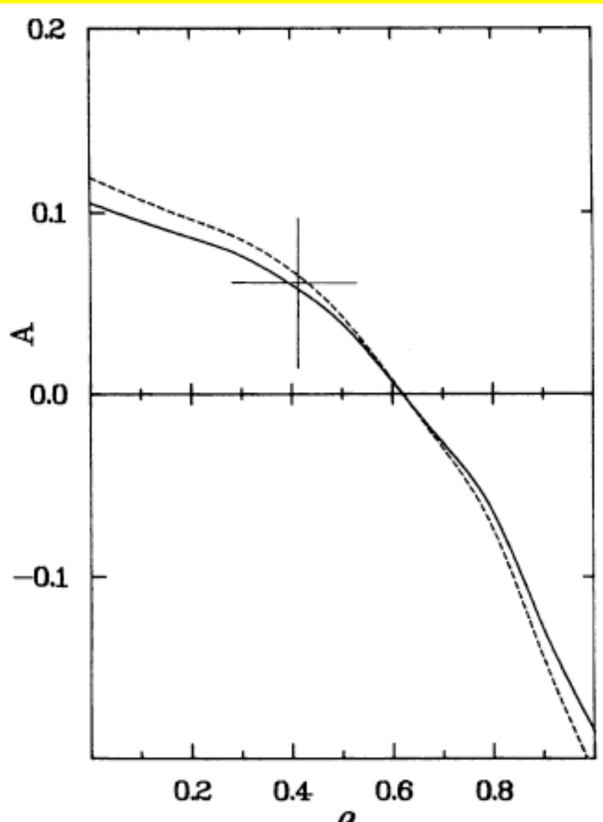
$$|\Psi_N(RPA)> = Q_N^\dagger|\Psi_0(RPA)>$$

$$Q_N^\dagger = \sum_{ph} X_{ph}(N)a_p^\dagger a_h - Y_{ph}(N)a_h^\dagger a_p$$

$$V(q) = V_{\rm LM} + V_\pi^{\sigma\tau} + V_\rho^{\sigma\tau} + \beta\,(V_\pi^{\rm T} + V_\rho^{\rm T})$$

$$Q = \frac{\sigma_{\rm exp}}{\sigma_{\rm theor}}$$





-the tensor interaction is too strong to be used in RPA calculations (~30%)

Nakayama, Phys. Lett. B165 (1985) 239
Co', Lallena, Nucl. Phys. A 510 (1990) 139

-but (p,p') requires of an additional reduction

Drozdz, Tain, Wambach, Phys. Rev. C34 (1986) 345

Inelastic scattering: bound excited states

Hintz, Lallena, Sethi Phys. Rev. C 45 (1992) 1098

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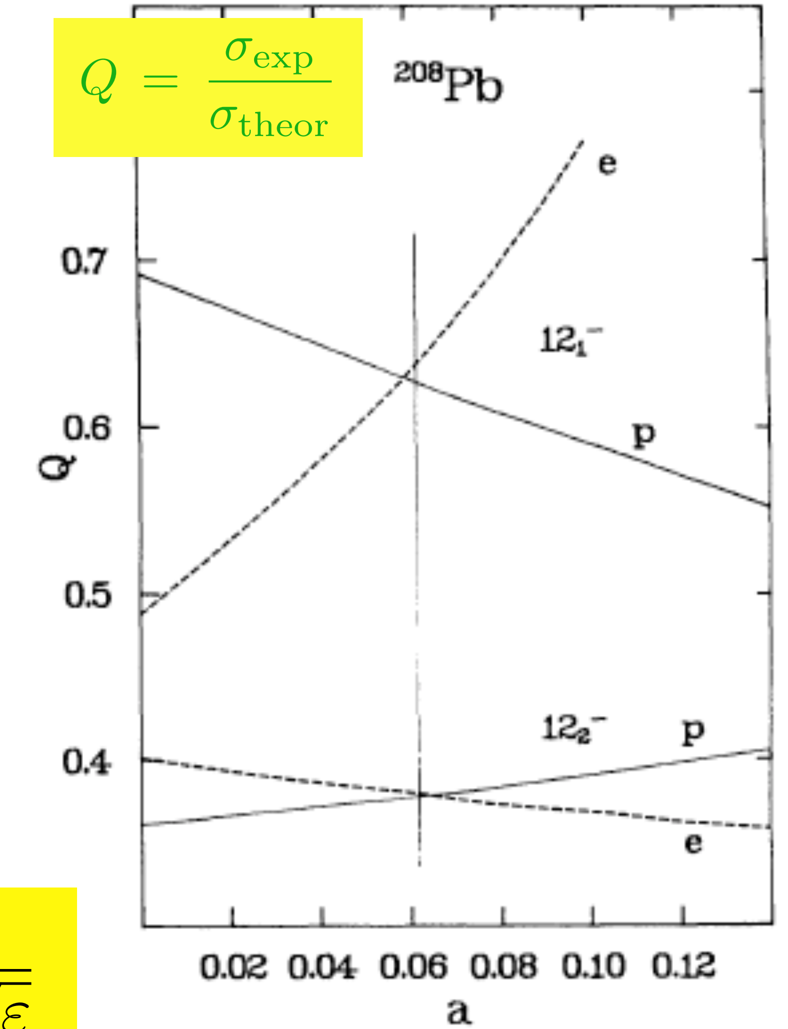
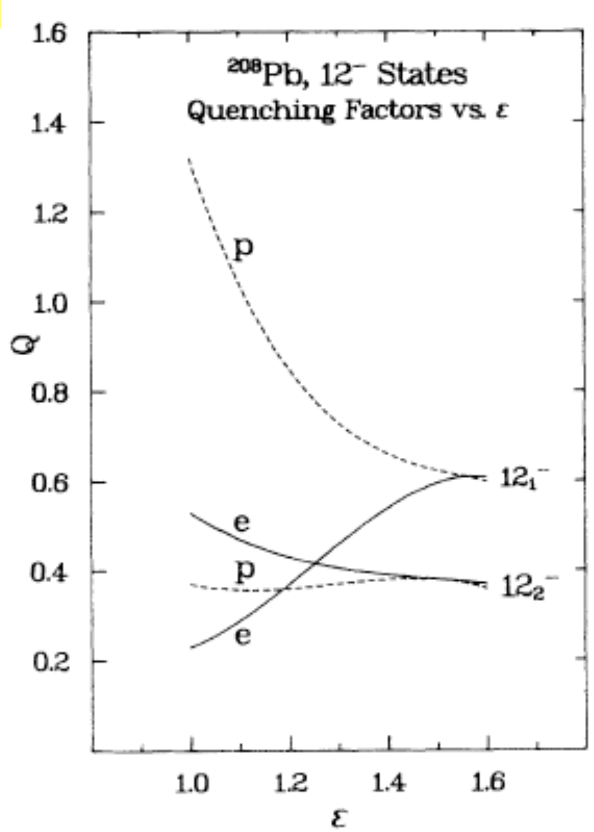


$$V(q) = V_{\rm LM} + V_\pi^{\sigma\tau} + V_\pi^{\rm T} + \varepsilon\,(V_\rho^{\sigma\tau} + V_\rho^{\rm T}(m_\rho^*))\,, \qquad \frac{m_\rho^*}{m_\rho} = \frac{1}{\sqrt{\varepsilon}}$$



$\varepsilon = 1.6 \qquad \left(\frac{m_\rho^*}{m_\rho} = 0.79\right)$ permits a consistent description of both (p,p') and (e,e') quenching factors

Inelastic scattering: bound excited states

inclusive (e,e') experiments - particle-hole states:
the 1^+ state at 10.23 MeV in ^{48}Ca

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Steffen et al., Nucl. Phys. A 404 (1983) 413

FORM FACTOR OF THE M1 TRANSITION TO THE 10.23 MeV STATE IN ^{48}Ca AND THE ROLE OF THE Δ(1232)[†]

W. STEFFEN, H.-D. GRÄF and A. RICHTER
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A. HÄRTING and W. WEISE
Institut für Theoretische Physik der Universität Regensburg, D-8400 Regensburg, W. Germany

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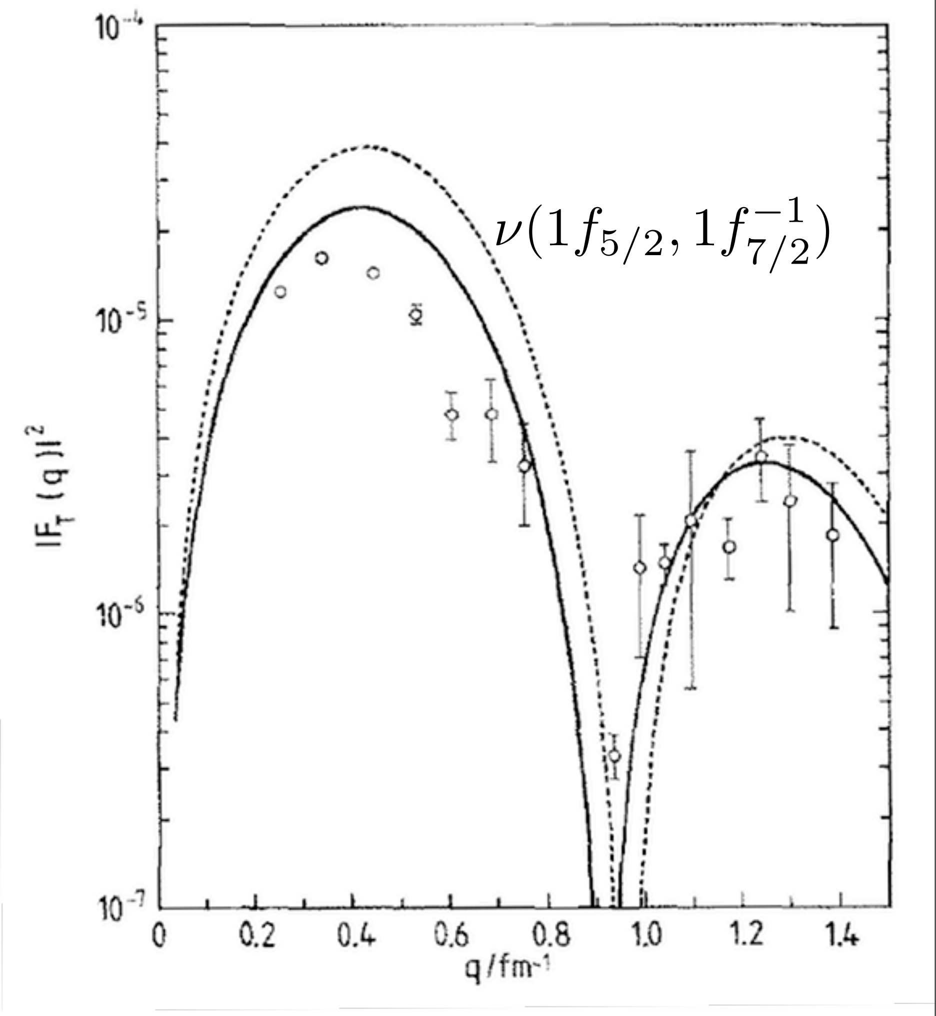

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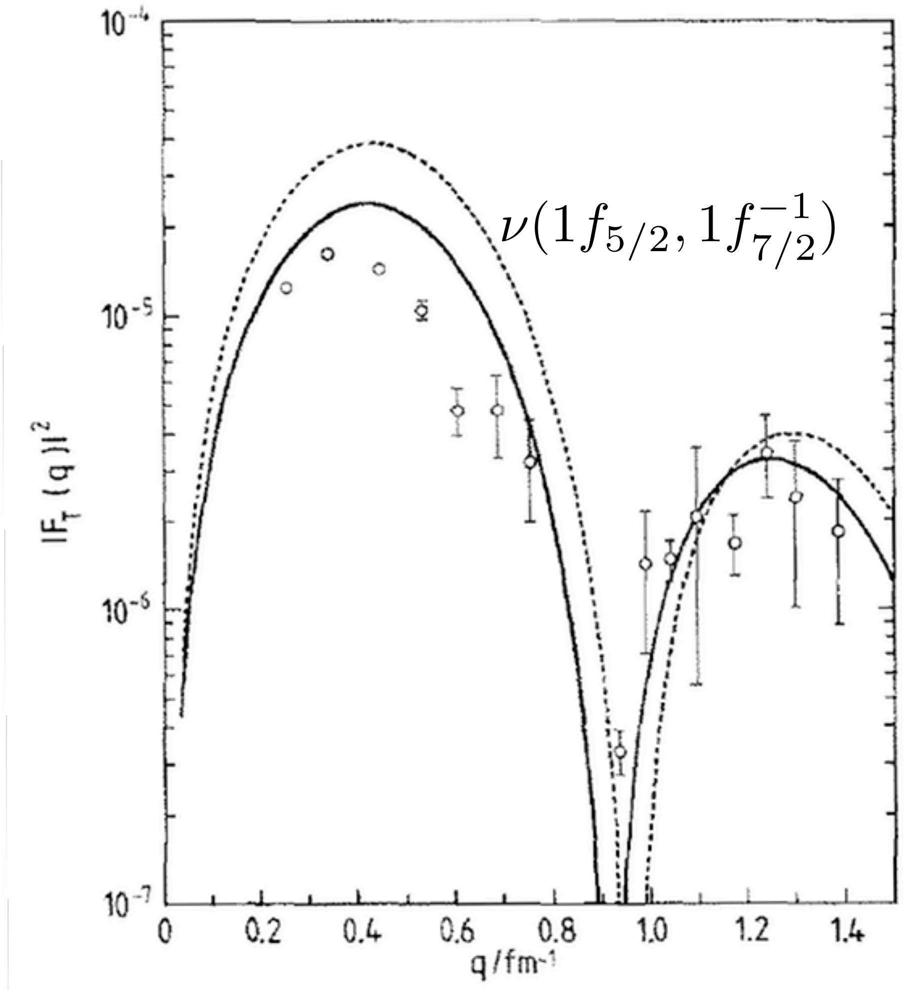

q-dependent quenching:

$\Delta - h$ effects ?

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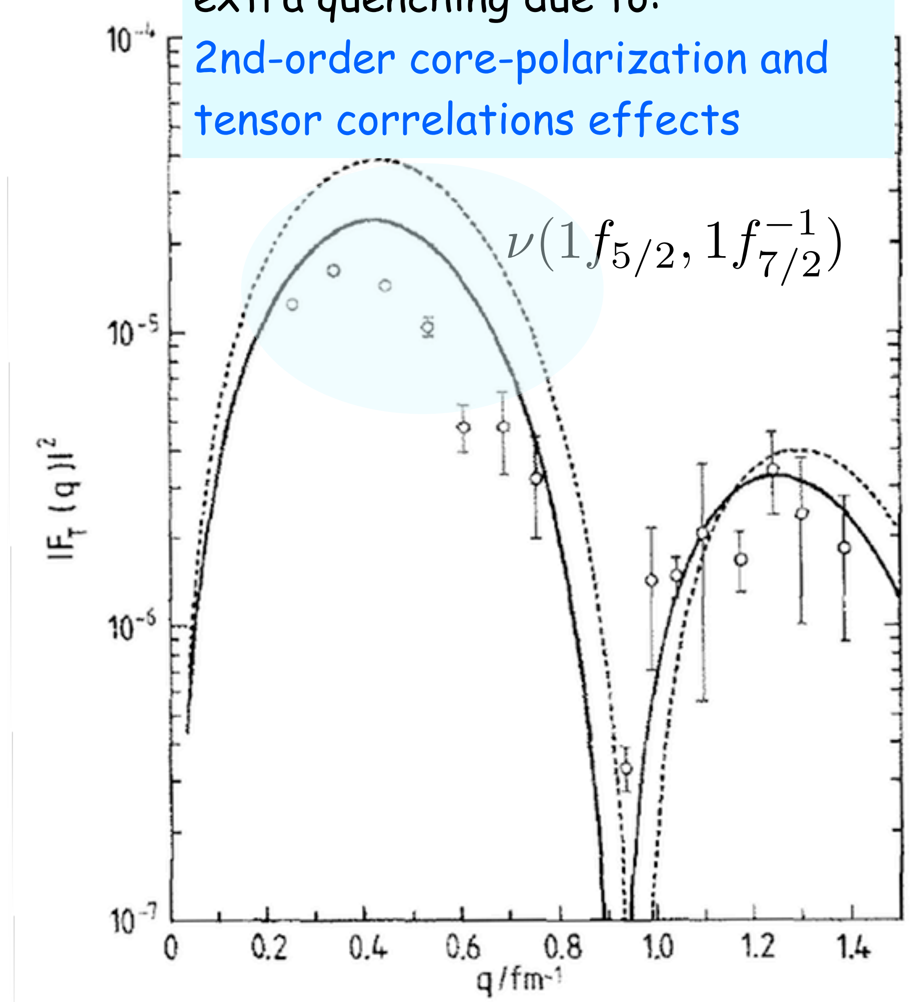
extra quenching due to:
2nd-order core-polarization and tensor correlations effects



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RPA calculation with $\delta + \pi + \rho$

Amaro, Lallena, Phys. Lett. B 261 (1991) 229

Configuration	X	Y
$\pi(2p_{1/2}, 1p_{1/2}^{-1})$	−0.073	0.025
$\pi(1f_{5/2}, 1p_{3/2}^{-1})$	0.131	0.077
$\nu(3s_{1/2}, 2s_{1/2}^{-1})$	−0.070	−0.004
$\nu(2d_{5/2}, 1d_{3/2}^{-1})$	−0.168	−0.015
$\nu(1f_{5/2}, 1f_{7/2}^{-1})$	−0.989	−0.222
$\nu(2f_{5/2}, 1f_{7/2}^{-1})$	0.064	−0.025

$A_J(\mathrm{ph}) = X_J^*(\mathrm{ph}) + (-1)^J Y_J^*(\mathrm{ph})$

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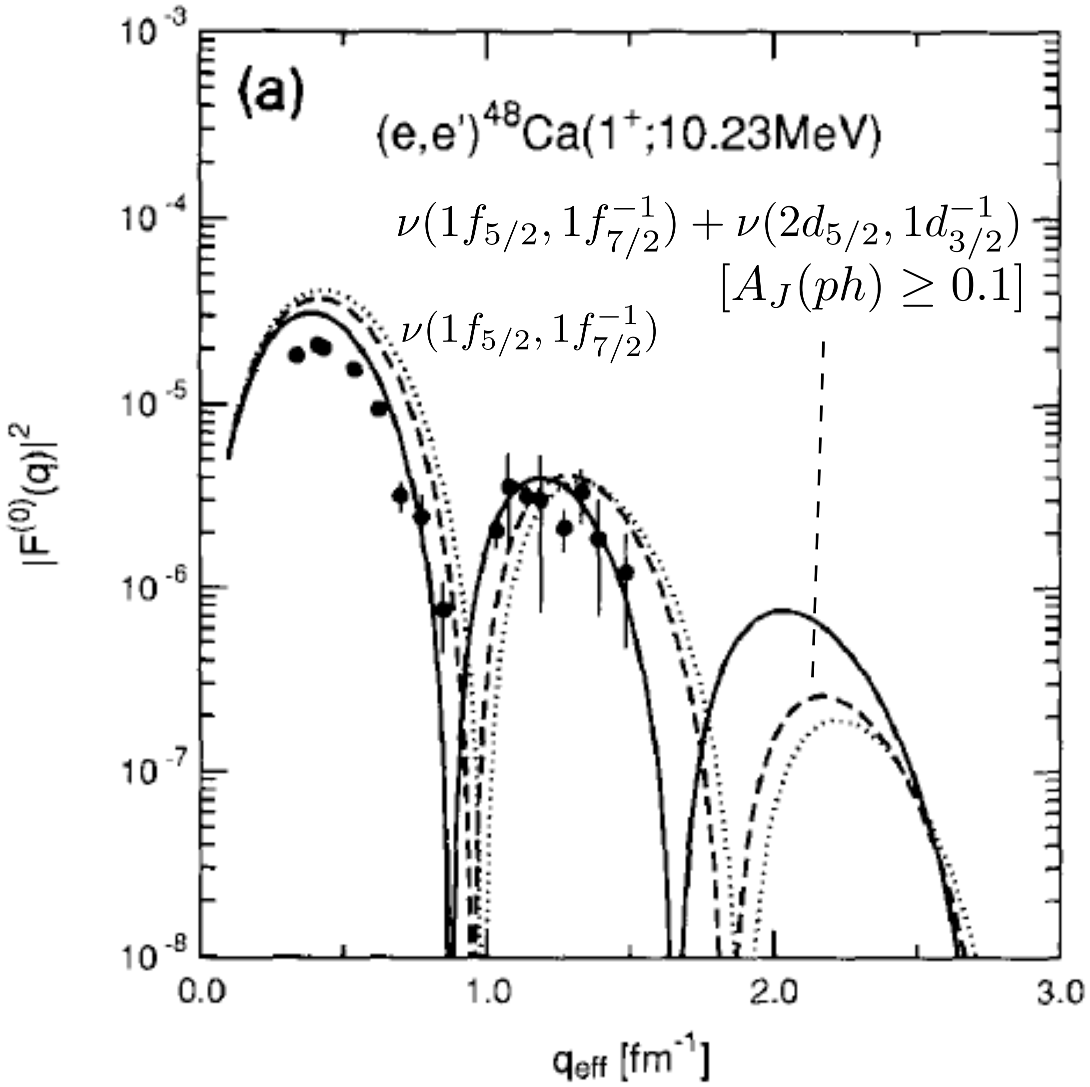

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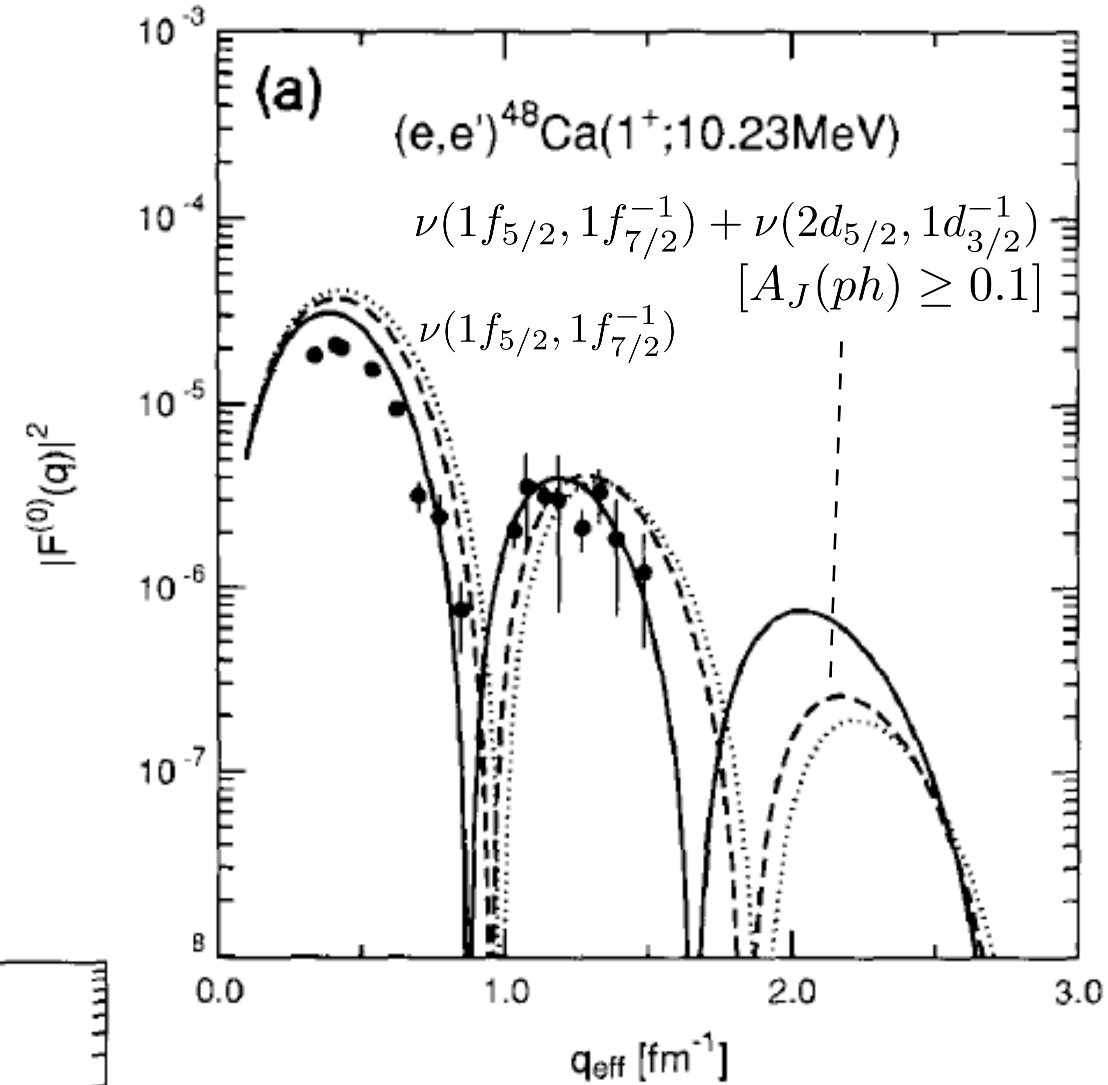

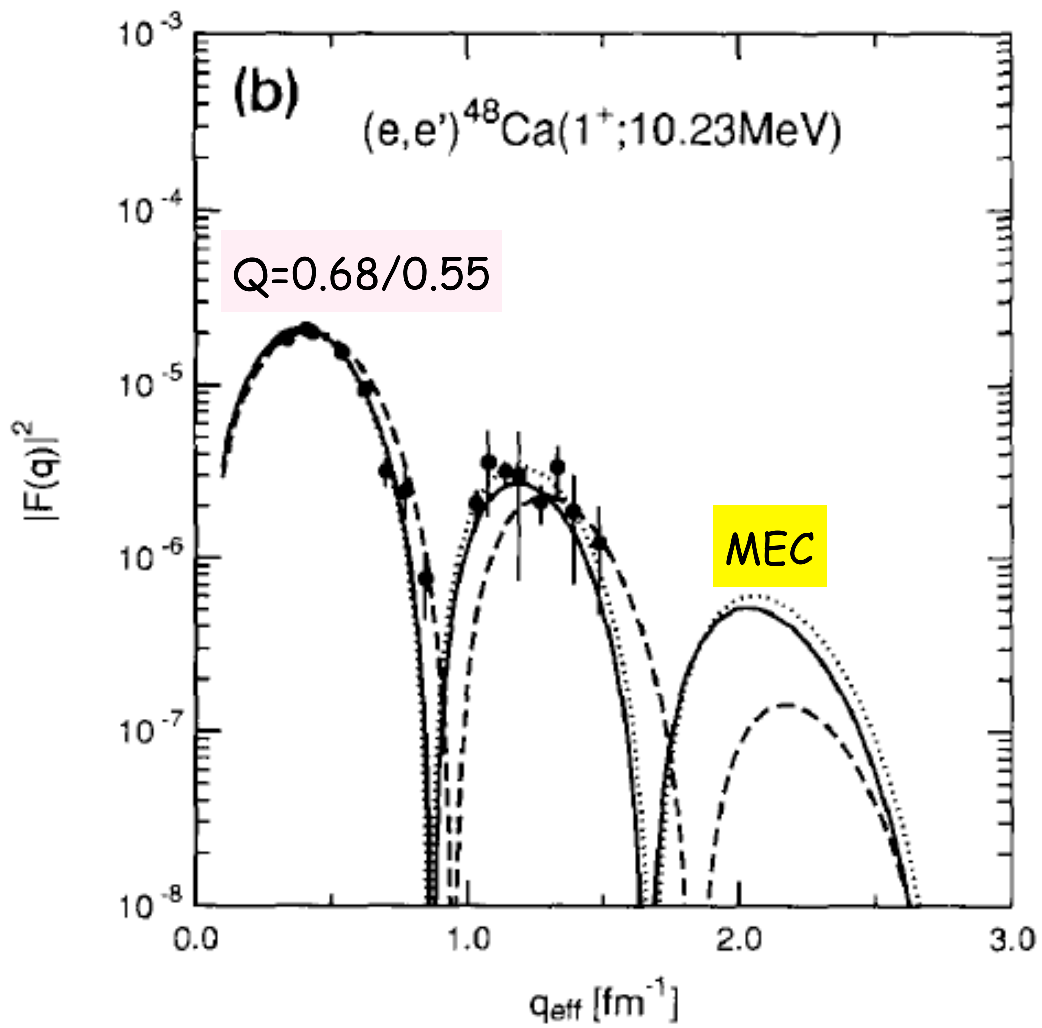

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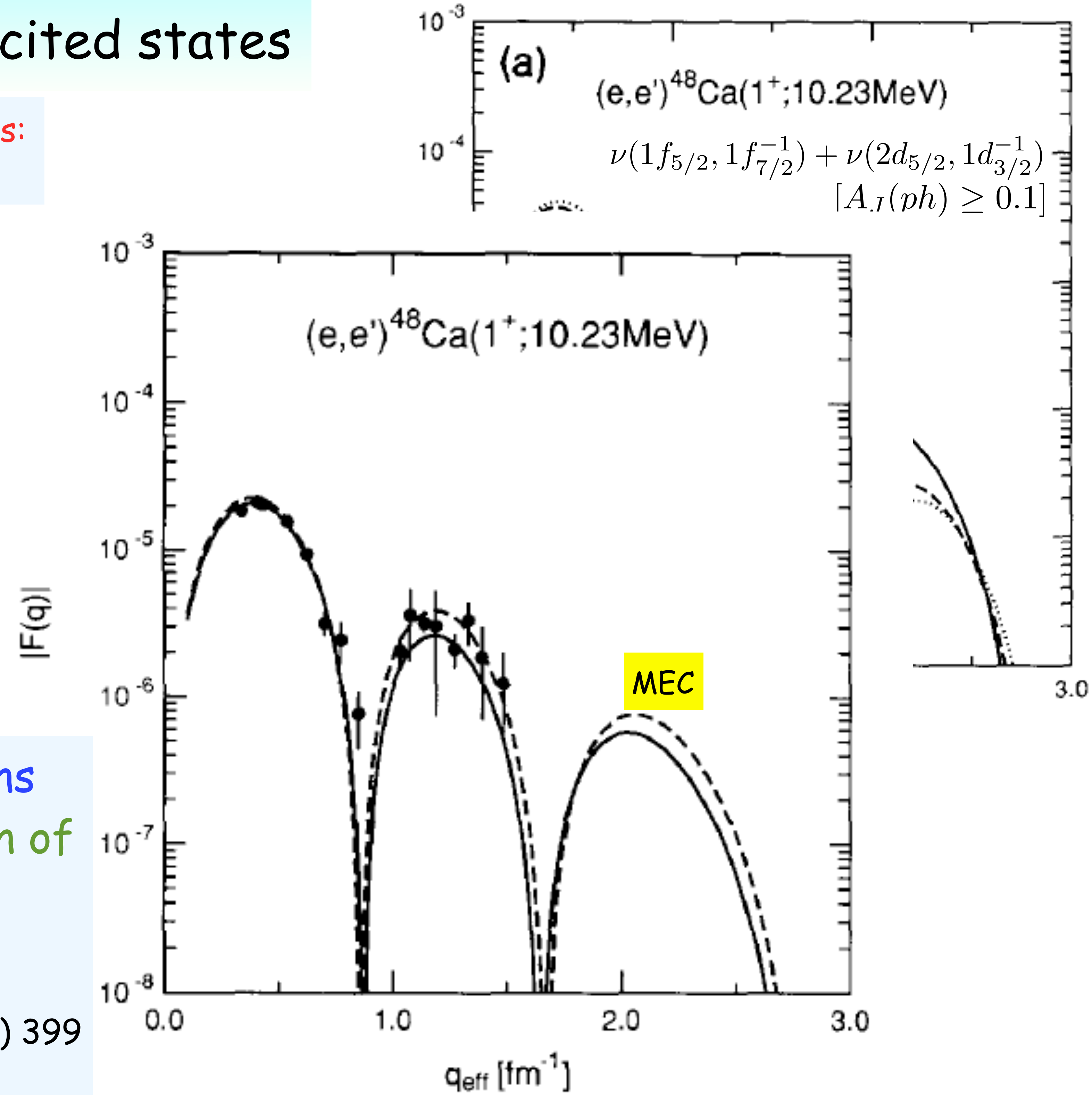

core-polarization+tensor correlations effects: phenomenological reduction of the isovector part of the magnetic moment of the nucleon

Härting, Kohno, Weise, Nucl. Phys. A 420 (1984) 399

found 0.85

q-dependent quenching:

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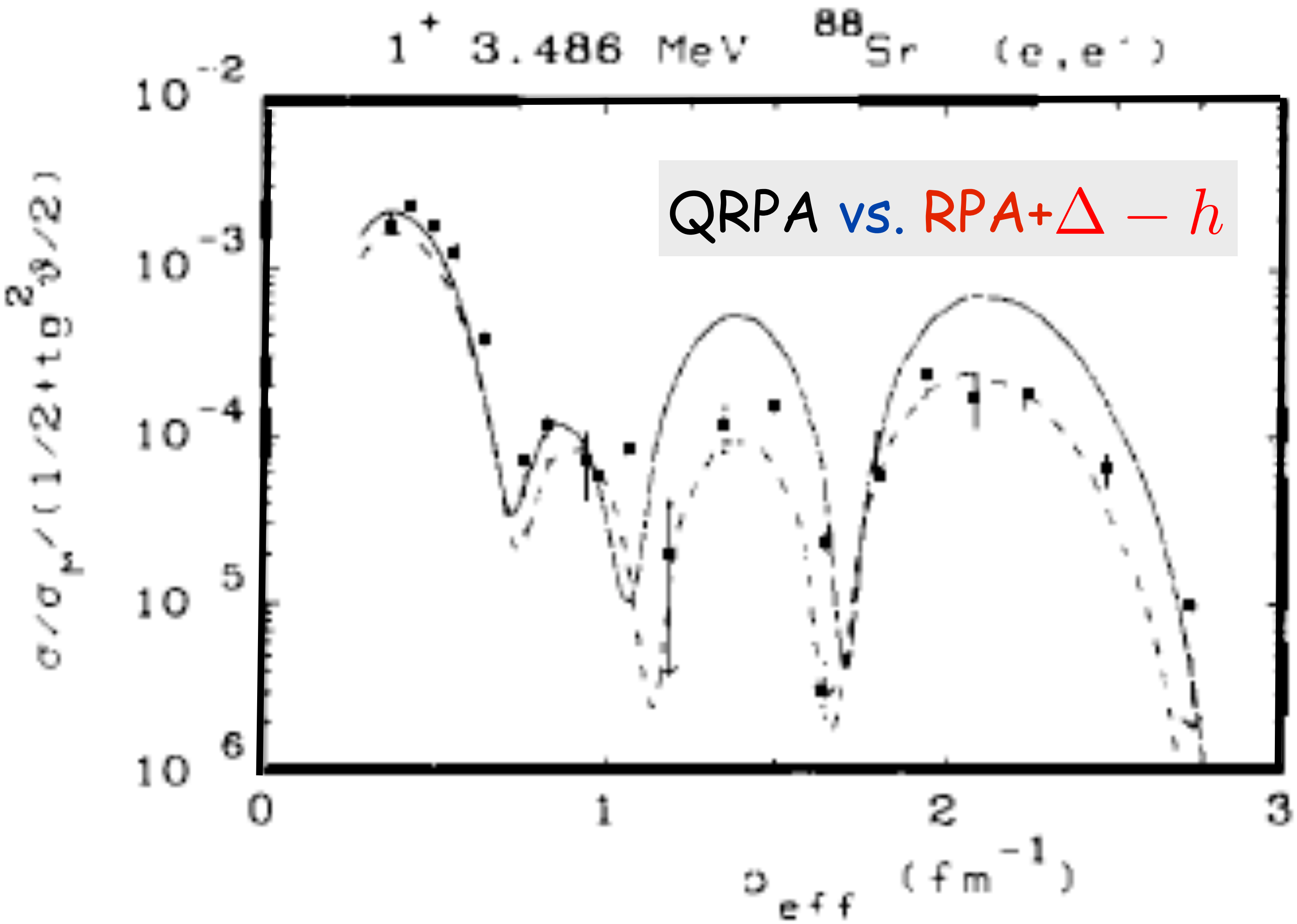
Inelastic scattering: bound excited states

Conci, Co', Speth, Phys. Lett. B 155 (1985) 318

inclusive (e,e') experiments: pairing effects

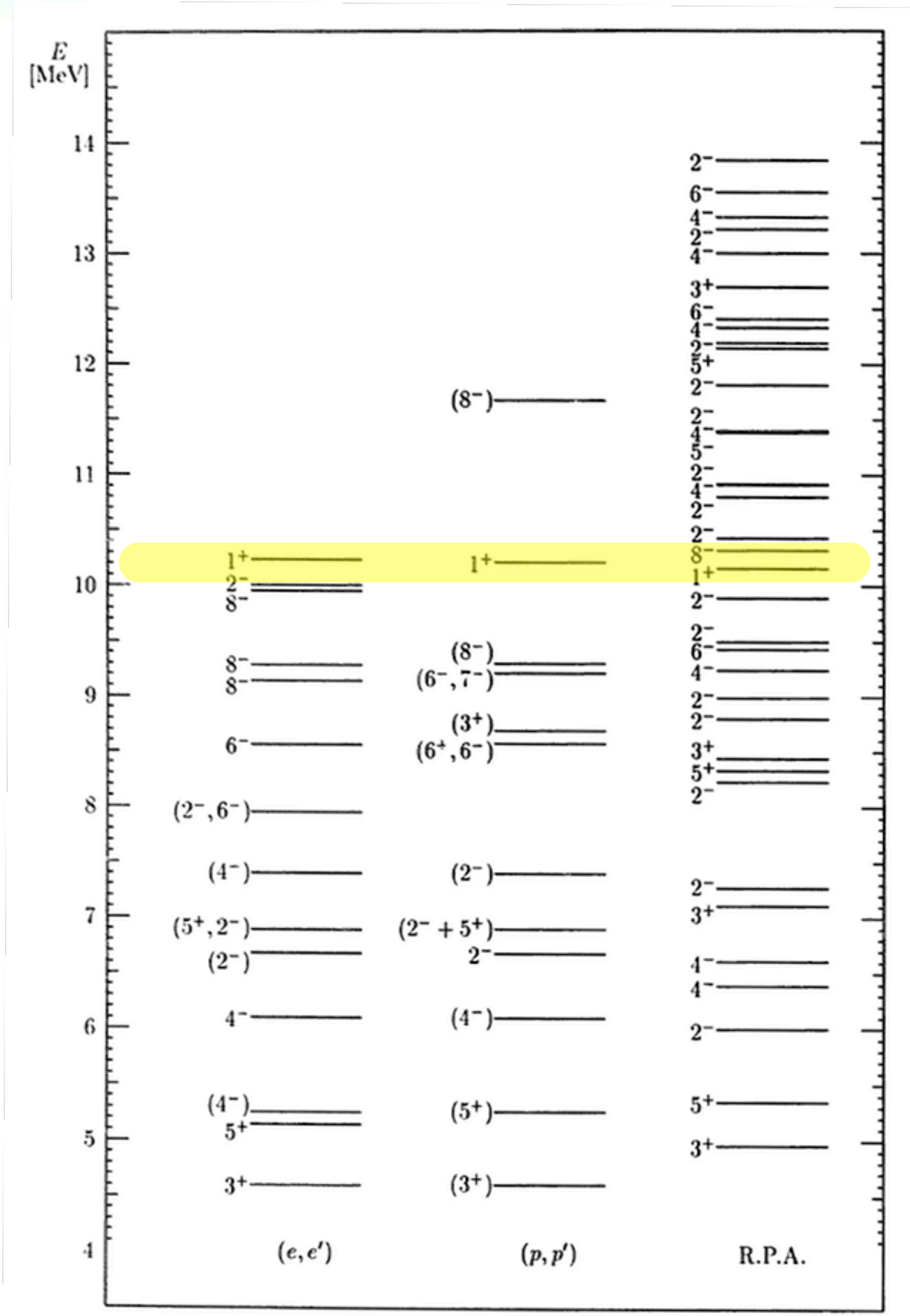
$\Delta - h$ components are not needed to explain the quenching of the data with recpect to shell-model calculations

RPA + $\Delta - h$ is unable to reproduce data above 1 fm^{-1}



Inelastic scattering: bound excited states

inclusive (e,e') experiments - magnetic states in ^{48}Ca



Inelastic scattering: bound excited states

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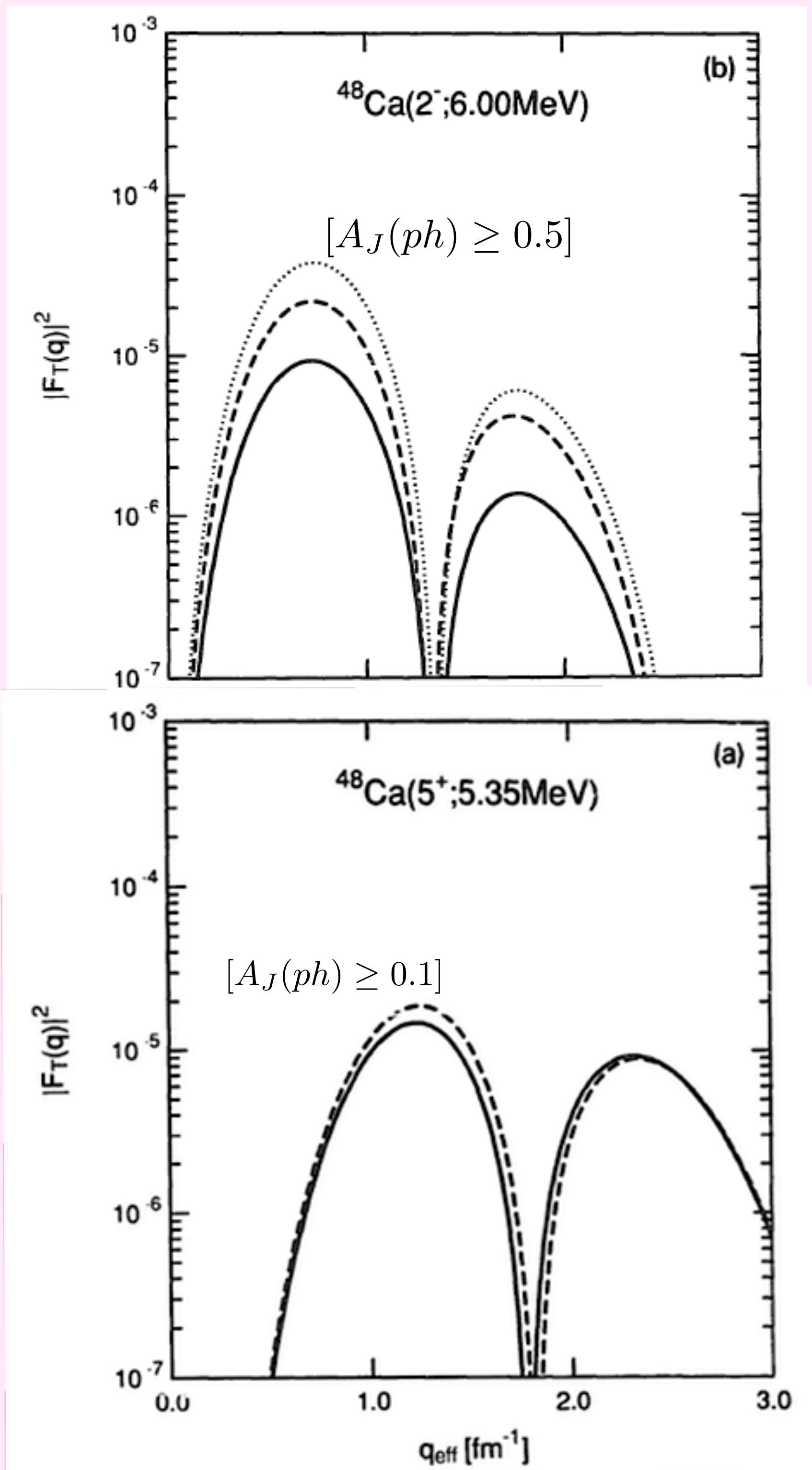
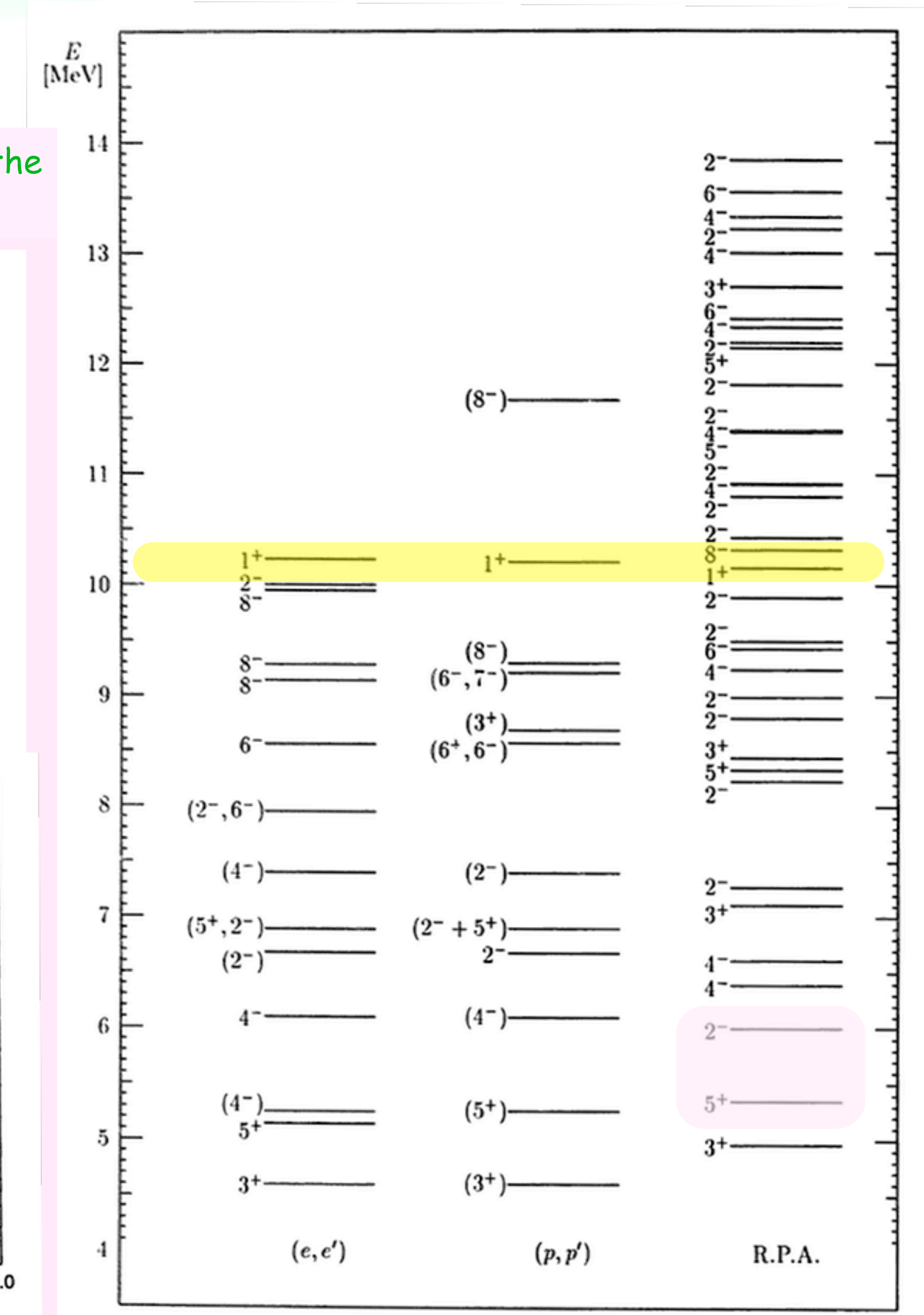
effect of the small components of the RPA wavefunction





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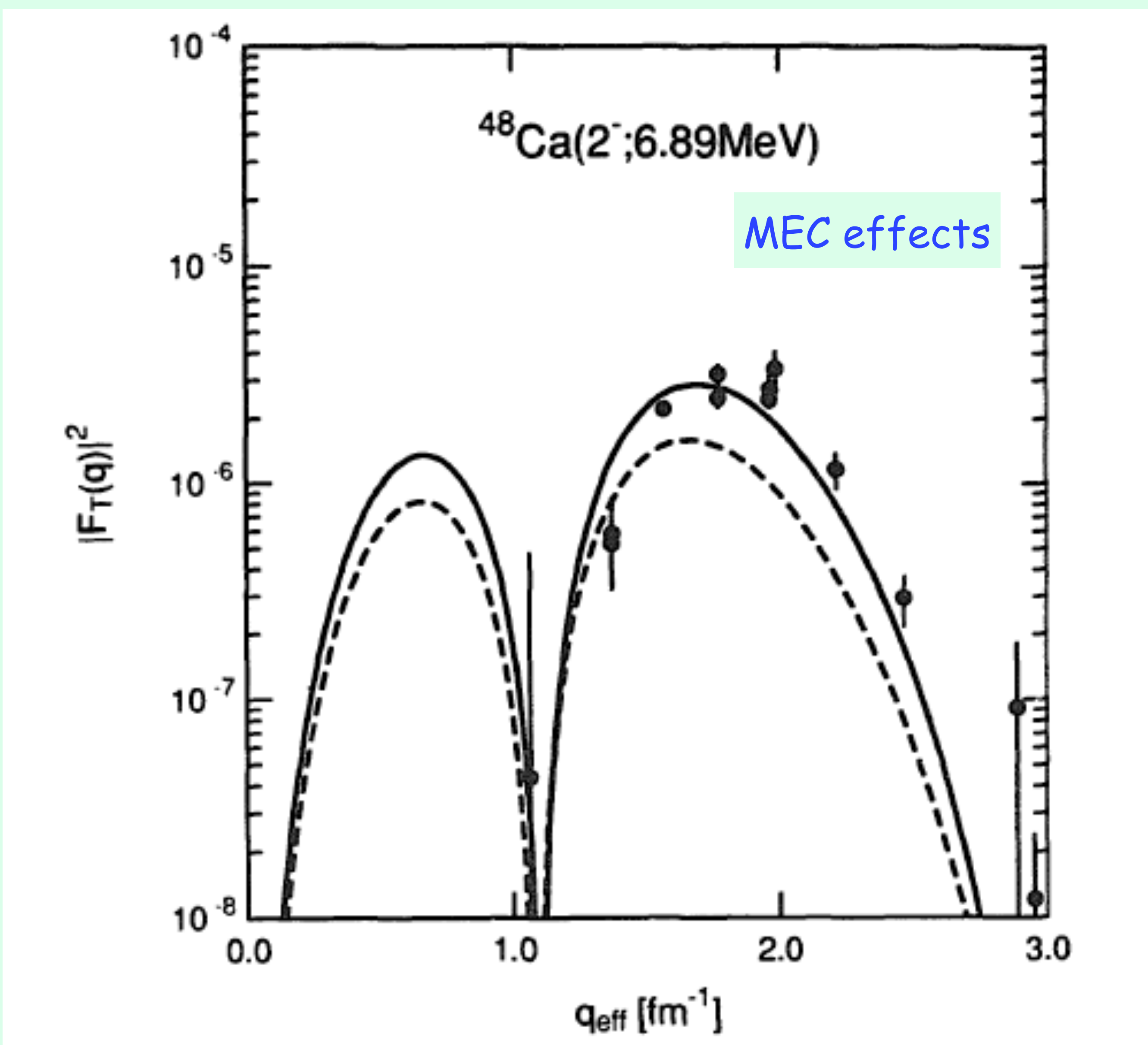
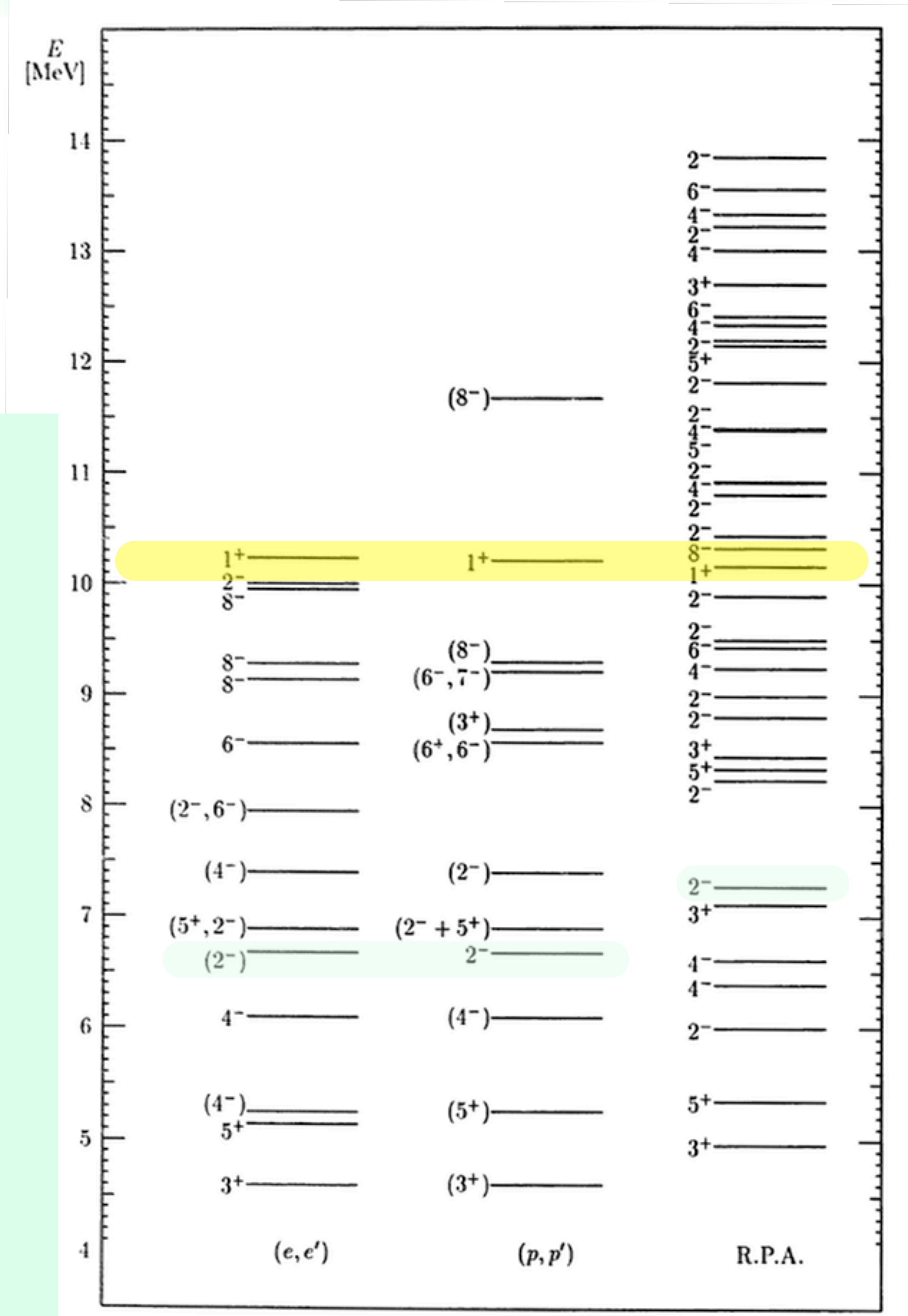
inclusive (e,e') experiments - magnetic states in ^{48}Ca





Inelastic scattering: bound excited states

inclusive (e,e′) experiments: the continuity equation

Inelastic scattering: bound excited states

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 4\pi\, \sigma_{\mathrm{Mott}}\, f_{\mathrm{rec}}^{-1}\, \frac{1}{2J_i+1} \left[\frac{q_\mu^4}{\mathbf{q}^4} \sum_{\lambda=0}^{\infty} |t_\lambda^{\mathrm{C}}(q)|^2 + \left(-\frac{q_\mu^2}{\mathbf{q}^2} + \tan^2\frac{\theta}{2} \right) \sum_{\lambda=1}^{\infty} \left\{ |t_\lambda^{\mathrm{E}}(q)|^2 + |t_\lambda^{\mathrm{M}}(q)|^2 \right\} \right]$$

$$\begin{aligned} t_\lambda^{\mathrm{C}}(q) &= \langle J_f \| M_\lambda^{\mathrm{Coul}}(q) \| J_i \rangle \\ t_\lambda^{\mathrm{E}}(q) &= -\sum_{s=-1,1} s \sqrt{\frac{\lambda+\delta_{s,-1}}{2\lambda+1}}\, t_{\lambda,\lambda+s}(q) \\ t_\lambda^{\mathrm{M}}(q) &= t_{\lambda,\lambda}(q) \end{aligned}$$

$$\begin{aligned} t_{\lambda,\lambda'}(q) &= \langle J_f \| i\, T_{\lambda\lambda'}(q) \| J_i \rangle \\ T_{\lambda\lambda'\mu}(q) &= \int \mathrm{d}\mathbf{r}\, j_\lambda(qr)\, \mathbf{Y}_{\lambda\lambda'\mu}(\hat{\mathbf{r}}) \cdot \mathbf{J}((\mathbf{r}) \end{aligned}$$

Inelastic scattering: bound excited states

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the continuity equation: $[H,\rho(\mathbf{r})]_- = i\,\nabla\cdot\mathbf{J}(\mathbf{r})$

-formulates (relativistic) charge-current conservation

-follows from gauge invariance of the electromagnetic field and its coupling to the particle field

-only three of the four multipoles are independent the fourth being restricted by CE

Inelastic scattering: bound excited states

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$$\omega = E_f - E_i$$

-usually: Siegert's theorem is satisfied!

$$\tilde{t}_{\lambda,\lambda+1}(q) = t_{\lambda,\lambda+1}(q)$$

$$\tilde{t}_{\lambda,\lambda-1}(q) = -\sqrt{\frac{\lambda+1}{\lambda}}\,t_{\lambda,\lambda+1}(q) - \sqrt{\frac{2\lambda+1}{\lambda}}\,\frac{\omega}{q}\,t_\lambda^{\mathrm{C}}(q)$$

but also:

$$\tilde{t}_{\lambda,\lambda+1}(q) = \sqrt{\frac{\lambda}{\lambda+1}}\,t_{\lambda,\lambda-1}(q) - \sqrt{\frac{2\lambda+1}{\lambda+1}}\,\frac{\omega}{q}\,t_\lambda^{\mathrm{C}}(q)$$

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Inelastic scattering: bound excited states

inclusive (e,e') experiments: the con

-if CE is satisfied all prescriptions provide the same results, but what happens if this does not occur?

-is this a way to “restore” CE?

$$\frac{d\sigma}{d\Omega} = 4\pi\,\sigma_{\rm Mott}\, f_{\rm rec}^{-1}\,\frac{1}{2J_i+1}\left[\frac{q_\mu^4}{\mathbf{q}^4}\sum_{\lambda=0}^{\infty}|t_\lambda^{\rm C}(q)|^2 + \right.$$

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$$\frac{\omega}{q}\,t_\lambda^{\rm C}(q) = -\sum_{s=-1,1}\sqrt{\frac{\lambda+\delta_{s,1}}{2\lambda+1}}\,t_{\lambda,\lambda+s}(q)$$

$$\omega = E_f - E_i$$

-usually: Siegert's theorem is satisfied!

$$\tilde{t}_{\lambda,\lambda+1}(q) = t_{\lambda,\lambda+1}(q)$$

$$\tilde{t}_{\lambda,\lambda-1}(q) = -\sqrt{\frac{\lambda+1}{\lambda}}\,t_{\lambda,\lambda+1}(q) - \sqrt{\frac{2\lambda+1}{\lambda}}\,\frac{\omega}{q}\,t_\lambda^{\rm C}(q)$$

but also:

$$\tilde{t}_{\lambda,\lambda+1}(q) = \sqrt{\frac{\lambda}{\lambda+1}}\,t_{\lambda,\lambda-1}(q) - \sqrt{\frac{2\lambda+1}{\lambda+1}}\,\frac{\omega}{q}\,t_\lambda^{\rm C}(q)$$

$$\tilde{t}_{\lambda,\lambda-1}(q) = t_{\lambda,\lambda-1}(q)$$

-corrections to calculations involving nonrelativistic wavefunctions and/or nucleon degrees of freedom are less severe in charge (v^2/c^2) than in current (v/c):

one of the two electric multipoles is eliminated by using CE

Inelastic scattering: bound excited states

inclusive (e,e') experiments:

the continuity equation - a model calculation

$$H = -\frac{\hbar^2}{2m}\nabla^2 + V_0 + \frac{\hbar^2}{2m}\frac{r^2}{b^4} + V_{\rm LS}\,\mathbf{l}\cdot\mathbf{s}$$

$$\rho(\mathbf{r}) = \sum_{k=1}^{A} \frac{1+\tau_3^k}{2}\,\delta(\mathbf{r}-\mathbf{r}_k)$$

$$\mathbf{J}^C(\mathbf{r}) = \sum_{k=1}^{A} \frac{1}{2M_k}\frac{1}{i}\frac{1+\tau_3^k}{2}\left[\,\delta(\mathbf{r}-\mathbf{r}_k)\vec{\nabla}_k + \vec{\nabla}_k\delta(\mathbf{r}-\mathbf{r}_k)\right]$$

$$\mathbf{J}^M(\mathbf{r}) = \sum_{k=1}^{A} \left(\mu_P\frac{1+\tau_3^k}{2} + \mu_N\frac{1-\tau_3^k}{2}\right)\vec{\nabla}_k\vec{\nabla}\left[\,\delta(\mathbf{r}-\mathbf{r}_k)\boldsymbol{\sigma}^k\right]$$

$$\mathbf{J}^{\rm LS}(\mathbf{r}) = \frac{1}{2}V_{\rm LS}\sum_{k=1}^{A} \frac{1+\tau_3^k}{2}\,\delta(\mathbf{r}-\mathbf{r}_k)\,\boldsymbol{\sigma}^k\times\mathbf{r}_k$$

Inelastic scattering: bound excited states

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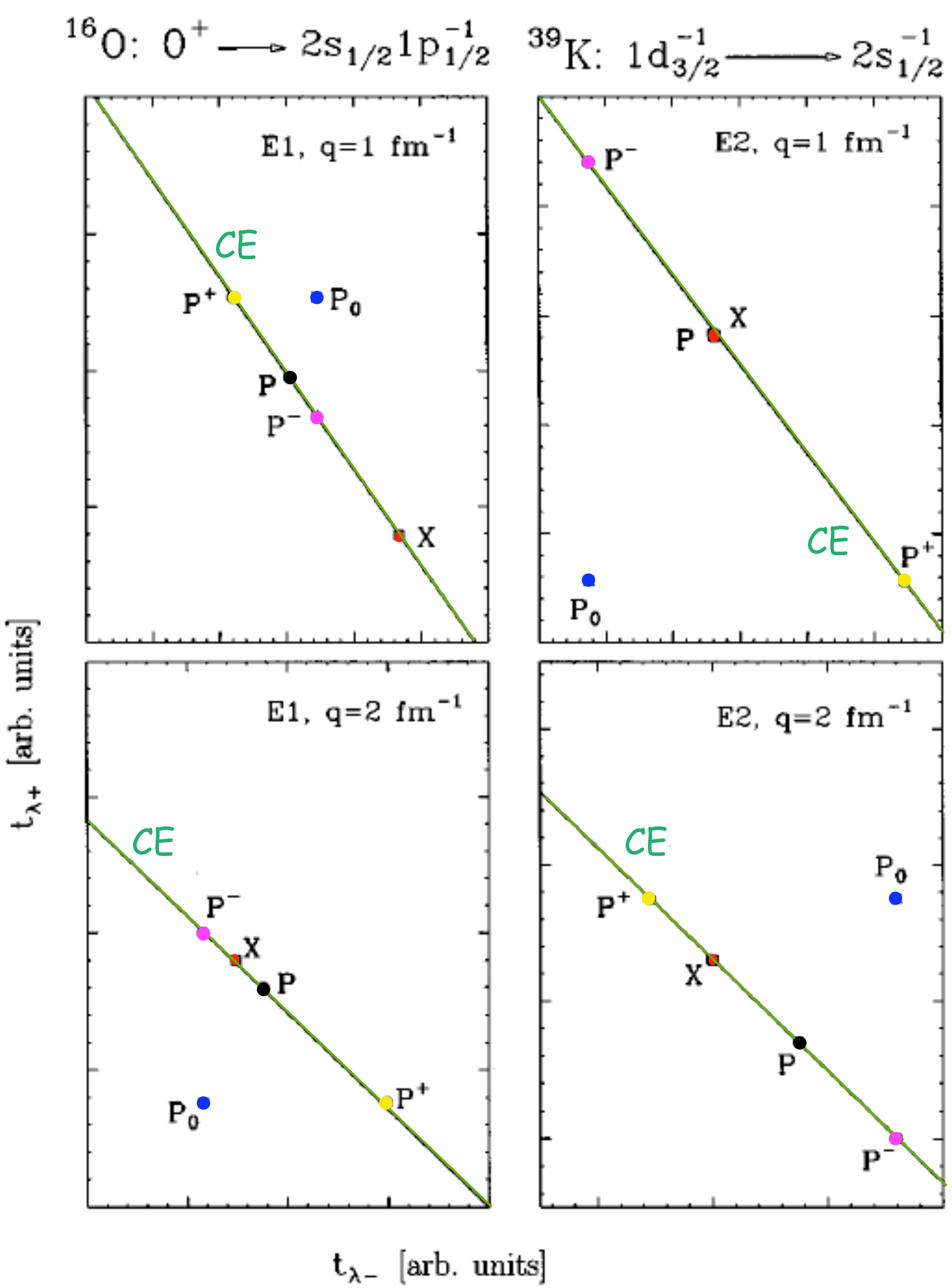

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if $\mathbf{J}(\mathbf{r}) = \mathbf{J}^{\rm C}(\mathbf{r}) + \mathbf{J}^{\rm M}(\mathbf{r}) + \mathbf{J}^{\rm LS}(\mathbf{r})$ CE is verified
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-we consider $\mathbf{J}_0(\mathbf{r}) = \mathbf{J}^{\rm C}(\mathbf{r}) + \mathbf{J}^{\rm M}(\mathbf{r})$ and we get:

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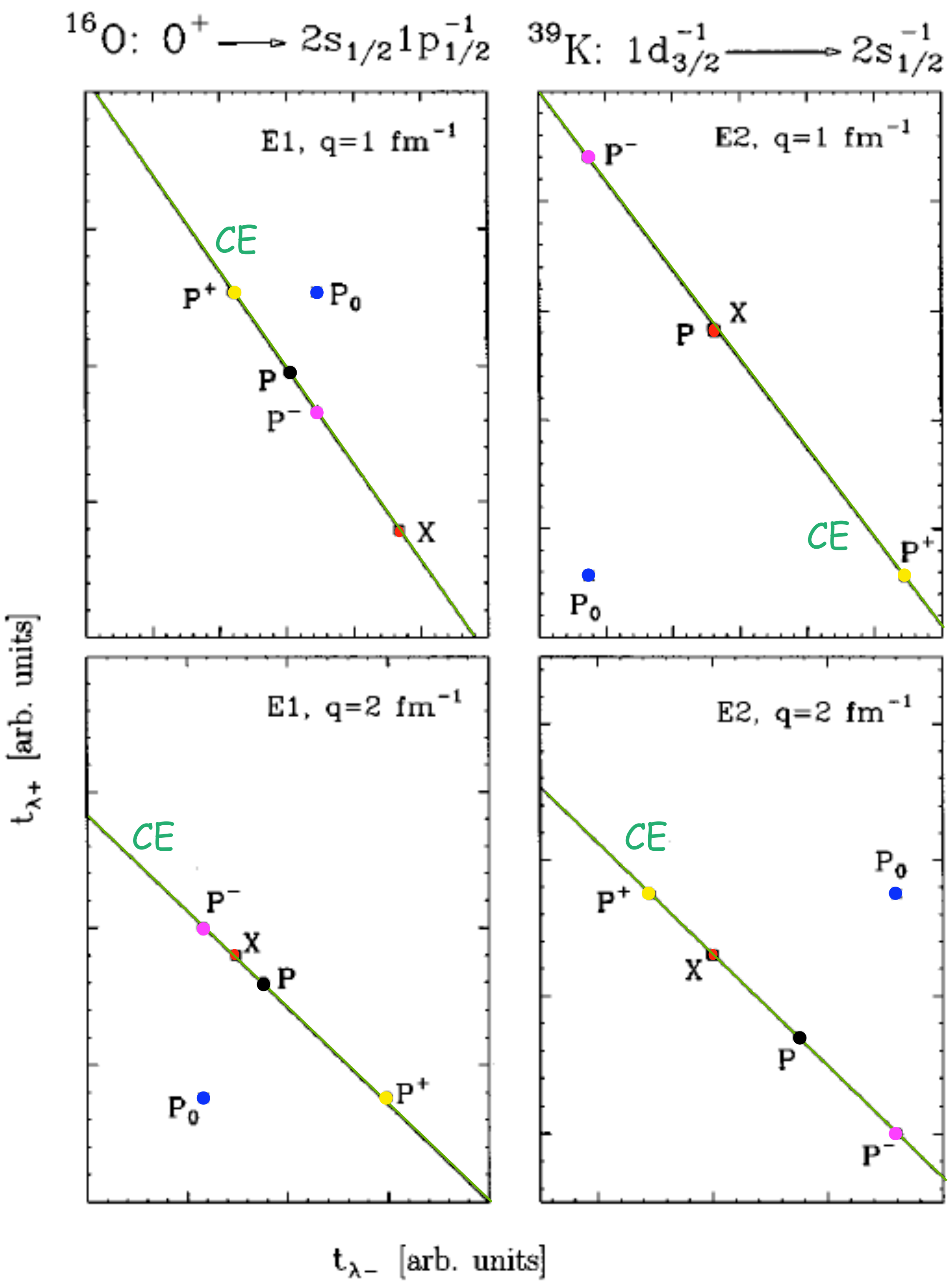
Inelastic scattering: bound excited states

inclusive (e,e') experiments:

the continuity equation - a model calculation



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P verifies CE and reproduces the electric multipole as found for P_0

Inelastic scattering: bound excited states

inclusive (e,e') experiments:

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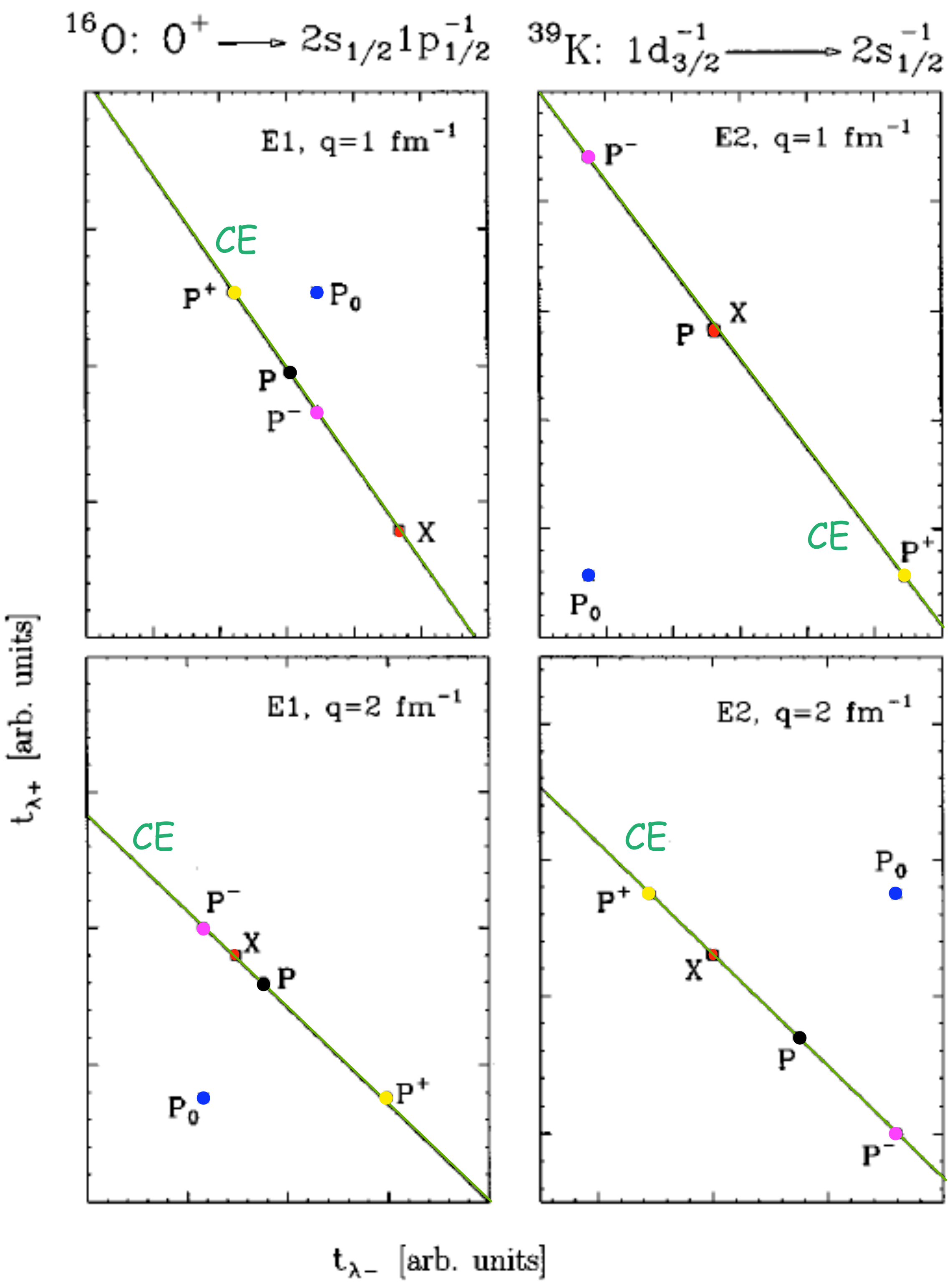

the procedures to impose CE by hand in calculations based on models that do not verify it are misleading and do not warrant better o more reasonable results

if $\mathbf{J}(\mathbf{r}) = \mathbf{J}^{\mathrm{C}}(\mathbf{r}) + \mathbf{J}^{\mathrm{M}}(\mathbf{r}) + \mathbf{J}^{\mathrm{LS}}(\mathbf{r})$ CE is verified and we get X

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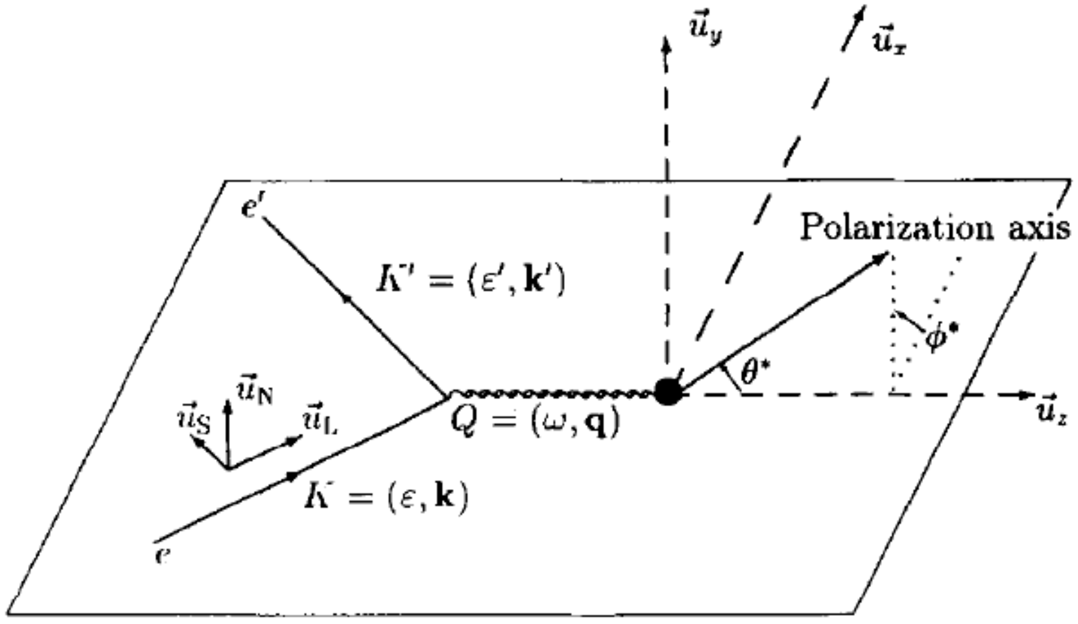
Inelastic scattering: bound excited states

inclusive (e,e′) experiments:

polarization $\vec{A}(\vec{e}, e')$



$$\left(\frac{d\sigma}{d\Omega_e}\right)^h = \Sigma_0^{OB}\left(\frac{\Sigma_0}{\Sigma_0^{OB}} + \overline{\Sigma} + \overline{\Delta}\right)$$

$$\Sigma_0 = 4\pi\,\sigma_{Mott}\, f_{rec}^{-1}\, f_0^i \left(v_L\, \mathcal{W}_0^L(q) + v_T\, \mathcal{W}_0^T(q)\right)$$

$$\overline{\Sigma} = \frac{\Sigma - \Sigma_0}{\Sigma_0^{OB}}$$

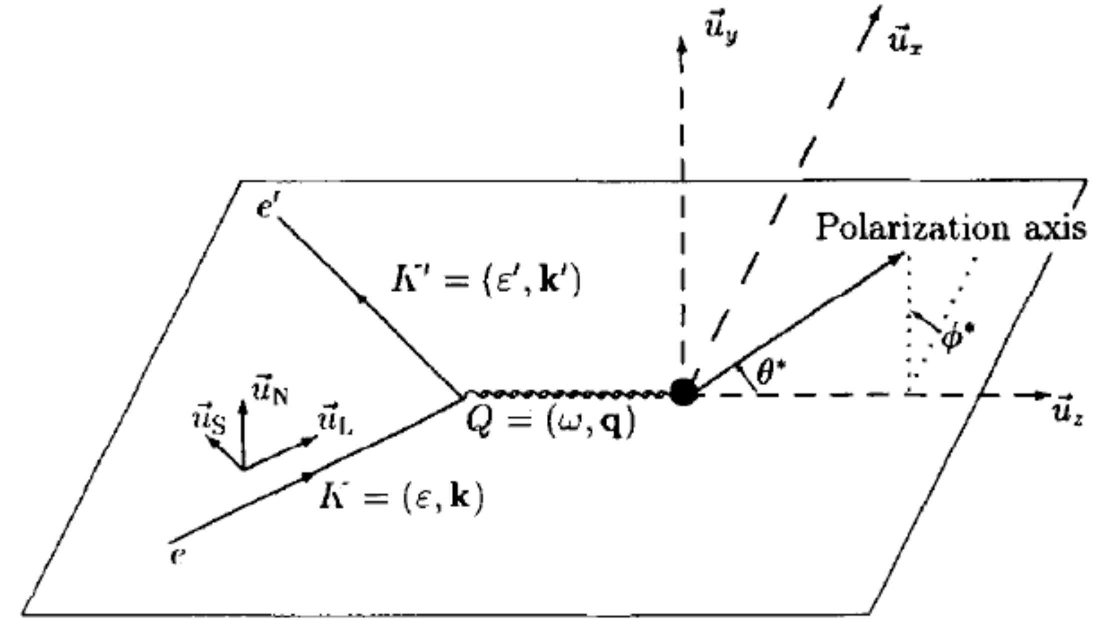
$$\overline{\Delta} = \frac{\Delta}{\Sigma_0^{OB}}$$

- -wider spectrum of possibilities than $\vec{A}(\vec{e}, e)$
- -best situation: ^{11}B
- -forward angles in $\overline{\Sigma}$ and backwards in $\overline{\Delta}$
- -momentum transfers: 60-400 MeV/c
- -target polarized on the scattering plane

Inelastic scattering: bound excited states

inclusive (e,e′) experiments:

polarization $\vec{A}(\vec{e}, e')$



$$
\begin{aligned}
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\overline{\Sigma} &= \frac{\Sigma - \Sigma_0}{\Sigma_0^{\rm OB}} \\
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\end{aligned}
$$

described in the extreme shell model

Nucleus	Transition
^{11}B	$\pi(1p_{3/2}^{-1} \rightarrow 1s_{1/2}^{-1})$
^{13}C	$\nu(1p_{1/2} \rightarrow 1d_{5/2})$
	$\nu(1p_{1/2} \rightarrow 2s_{1/2})$
^{15}N	$\pi(1p_{1/2}^{-1} \rightarrow 1p_{3/2}^{-1})$
^{17}O	$\nu(1d_{5/2} \rightarrow 2s_{1/2})$
^{39}K	$\pi(1d_{3/2}^{-1} \rightarrow 2s_{1/2}^{-1})$
	$\pi(1d_{3/2}^{-1} \rightarrow 1d_{5/2}^{-1})$

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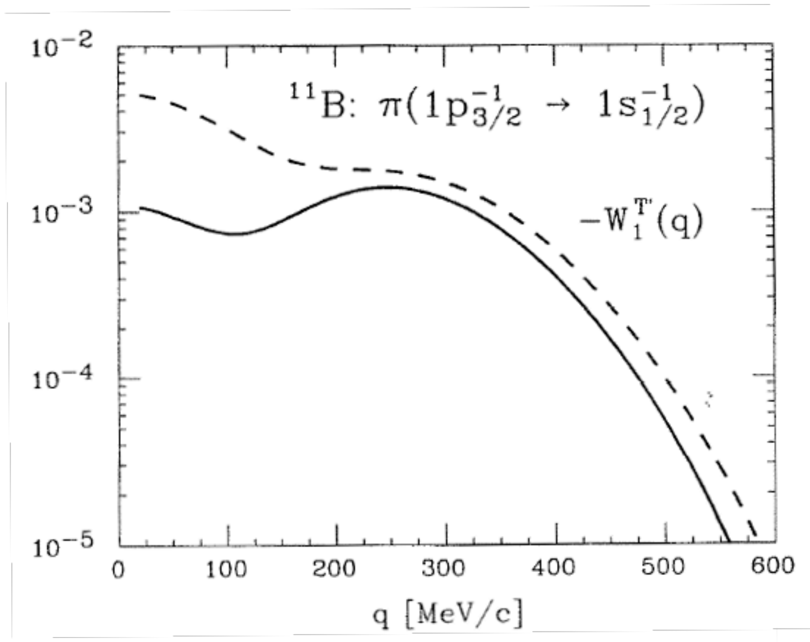
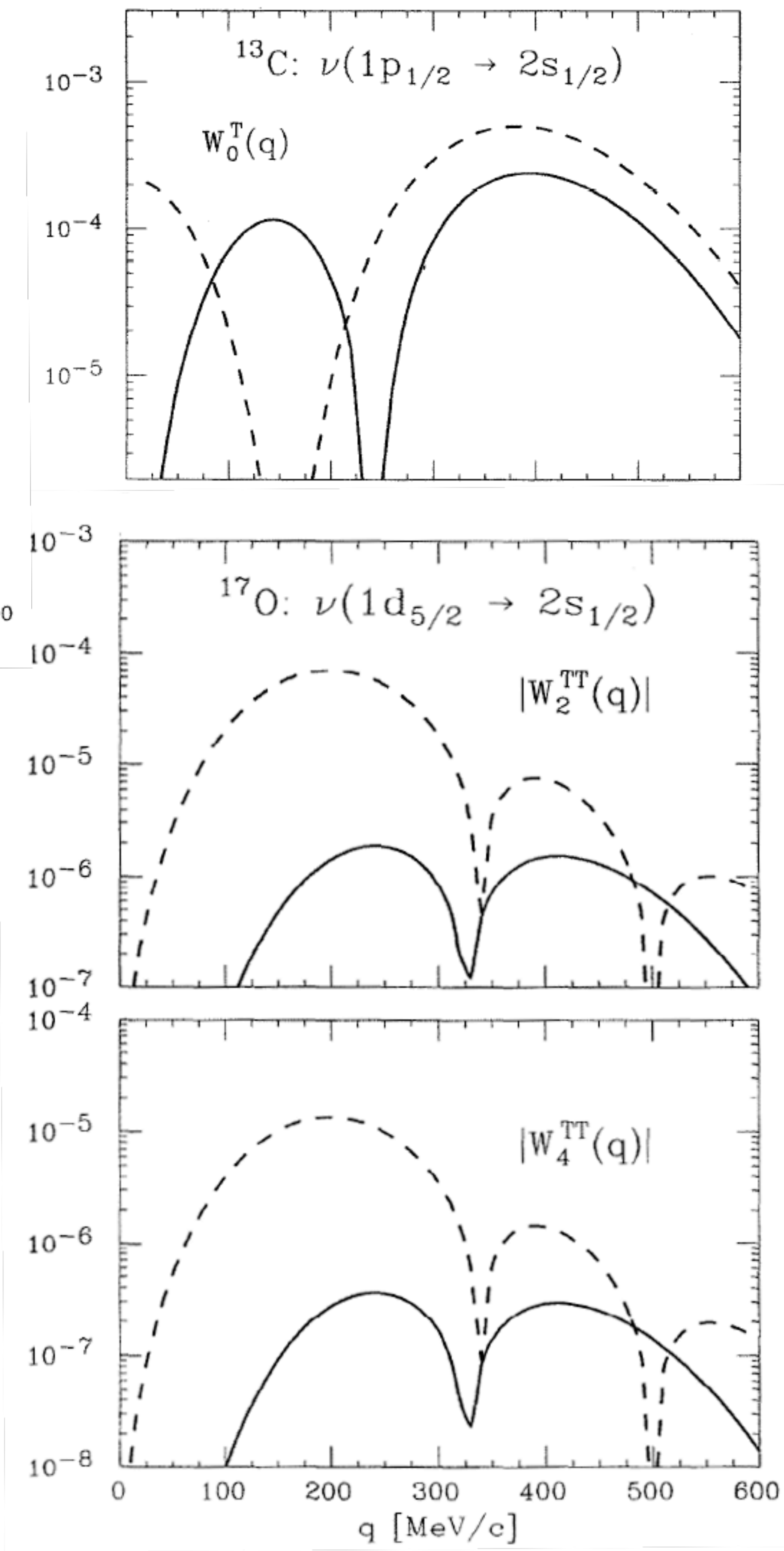
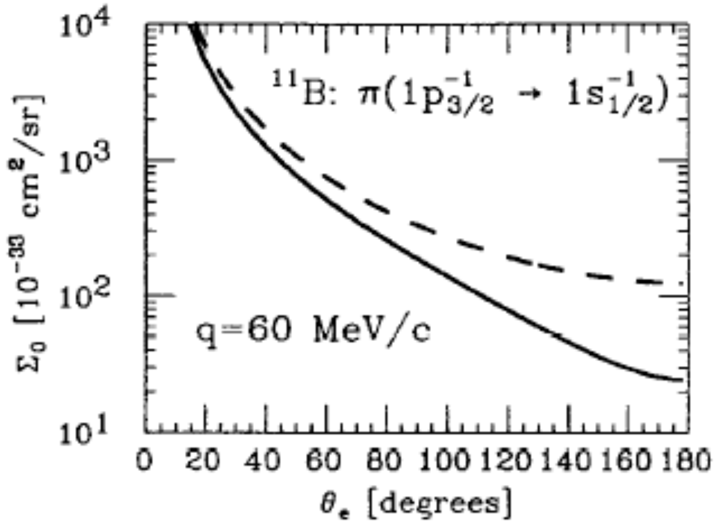
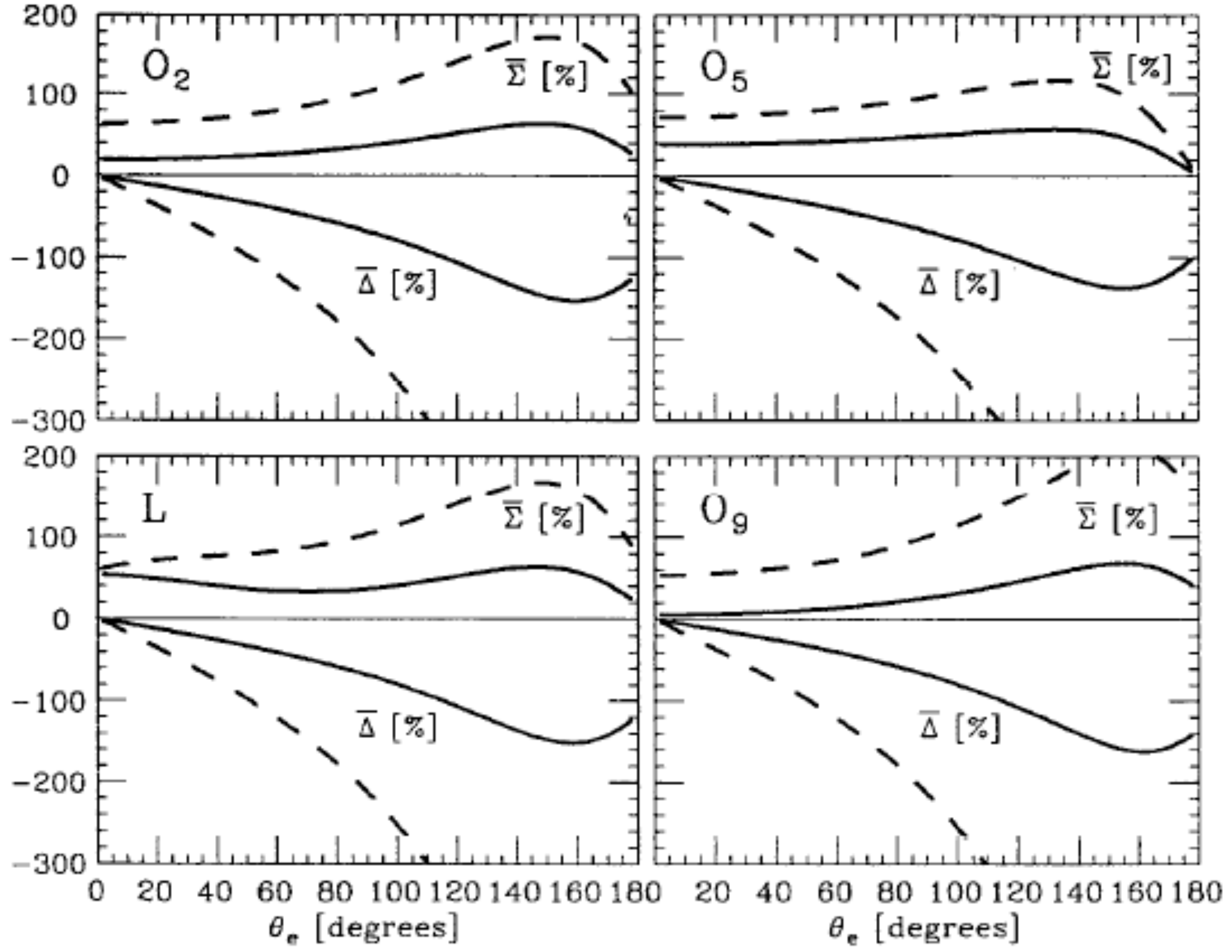
Inelastic scattering: bound excited states



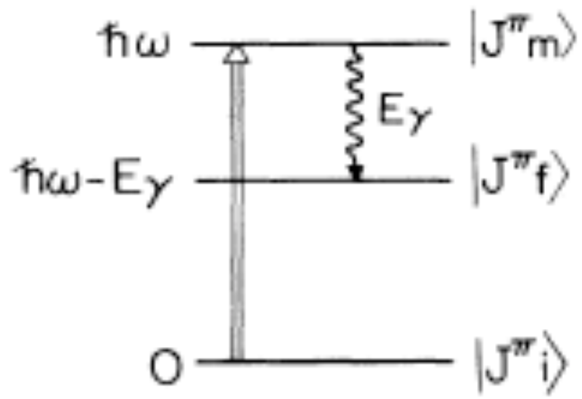


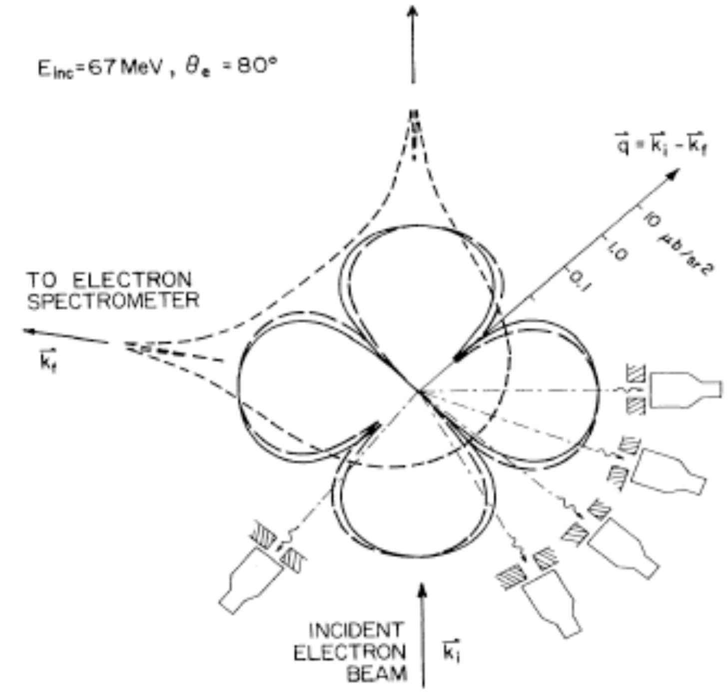




Inelastic scattering: bound excited states

(e,e'γ) experiments





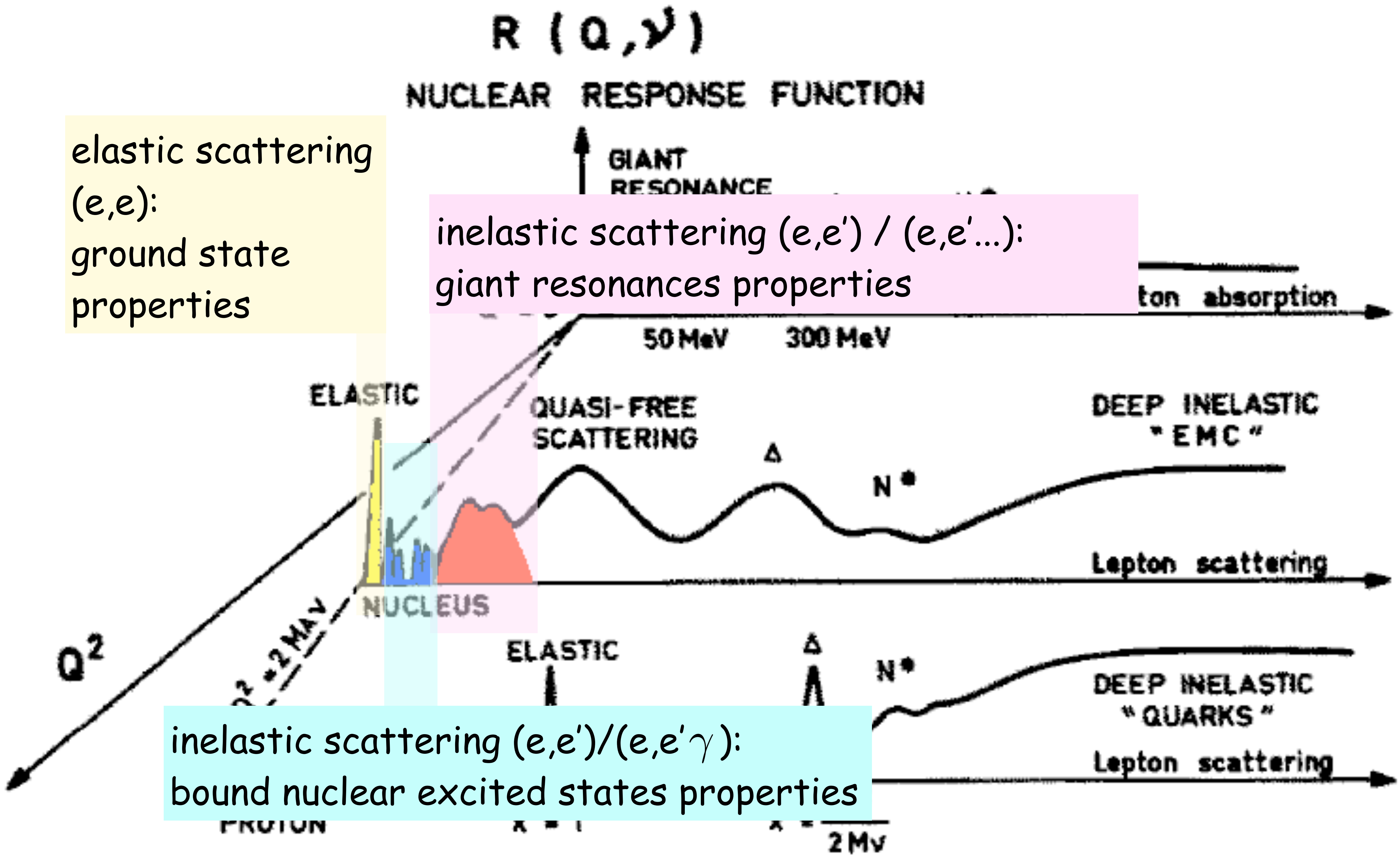
$$\frac{d^4\sigma}{d\Omega_\gamma d\Omega_e\, d\omega\, dE_\gamma} = \sigma_{\mathrm{Mott}}\left(\frac{\Gamma_{\gamma f}}{\Gamma}\right)\Big\{ V_L U_L |F_L(q)|^2 + V_T U_T |F_T(q)|^2 + V_I U_I \cos\phi_\gamma F_L(q) F_T(q) + V_S U_S \cos 2\phi_\gamma F_T(q) F_T(q) \Big\}$$

(e,e'γ) Measurements on the 4.439-MeV State of ^{12}C

C. N. Papanicolas, S. E. Williamson, H. Rothhaas,[a] G. O. Bolme, L. J. Koester, Jr., B. L. Miller, R. A. Miskimen, P. E. Mueller, and L. S. Cardman
Department of Physics and Nuclear Physics Laboratory, University of Illinois at Urbana-Champaign, Illinois 61801
(Received 21 August 1984)

The relative phase of the longitudinal and transverse form factors of the 4.439-MeV $J^\pi = 2^+$ state of ^{12}C has been measured at $q_{\mathrm{eff}} = 0.36$ and $0.46\ \mathrm{fm}^{-1}$. This phase was found to be negative, of the same sign given by Siegert's theorem in the long-wavelength limit. This measurement represents the first nuclear structure result derived through the $(e,e'\gamma)$ reaction.

Outline

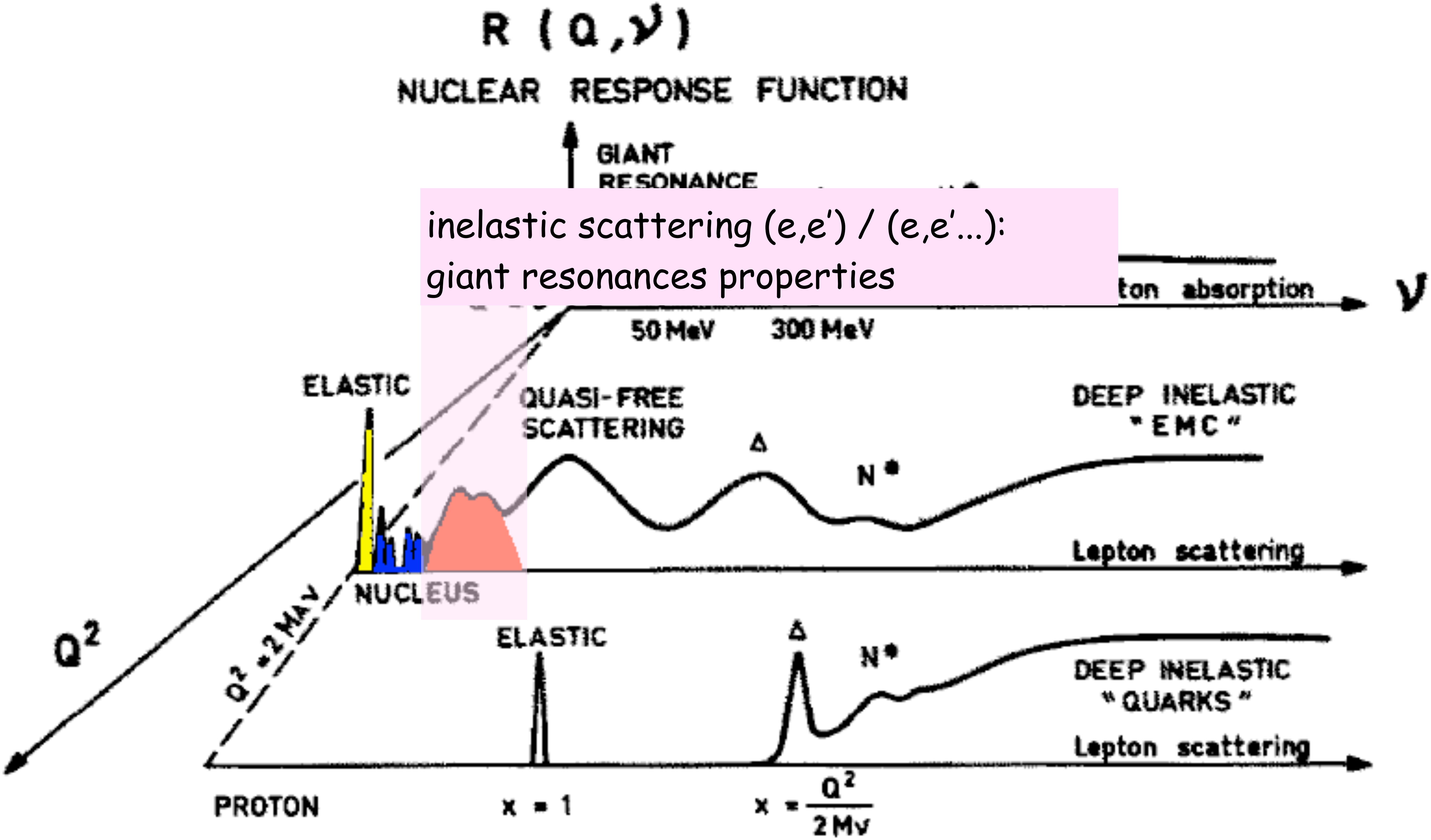


elastic scattering (e,e): ground state properties

inelastic scattering (e,e') / (e,e'...): giant resonances properties

inelastic scattering (e,e')/(e,e'γ): bound nuclear excited states properties

Outline



inelastic scattering (e,e') / (e,e'...):
giant resonances properties

Inelastic scattering: giant resonances

Co', Krewald, Nucl. Phys. A 433 (1985) 392

Inelastic scattering: giant resonances

-the nucleus is excited in the continuum

-nucleons have finite probability to be emitted after electron-nucleu collision

-all multipole contribute to cross section: inclusive experiments are unwise

-the extraction of the radiative tail is complicated

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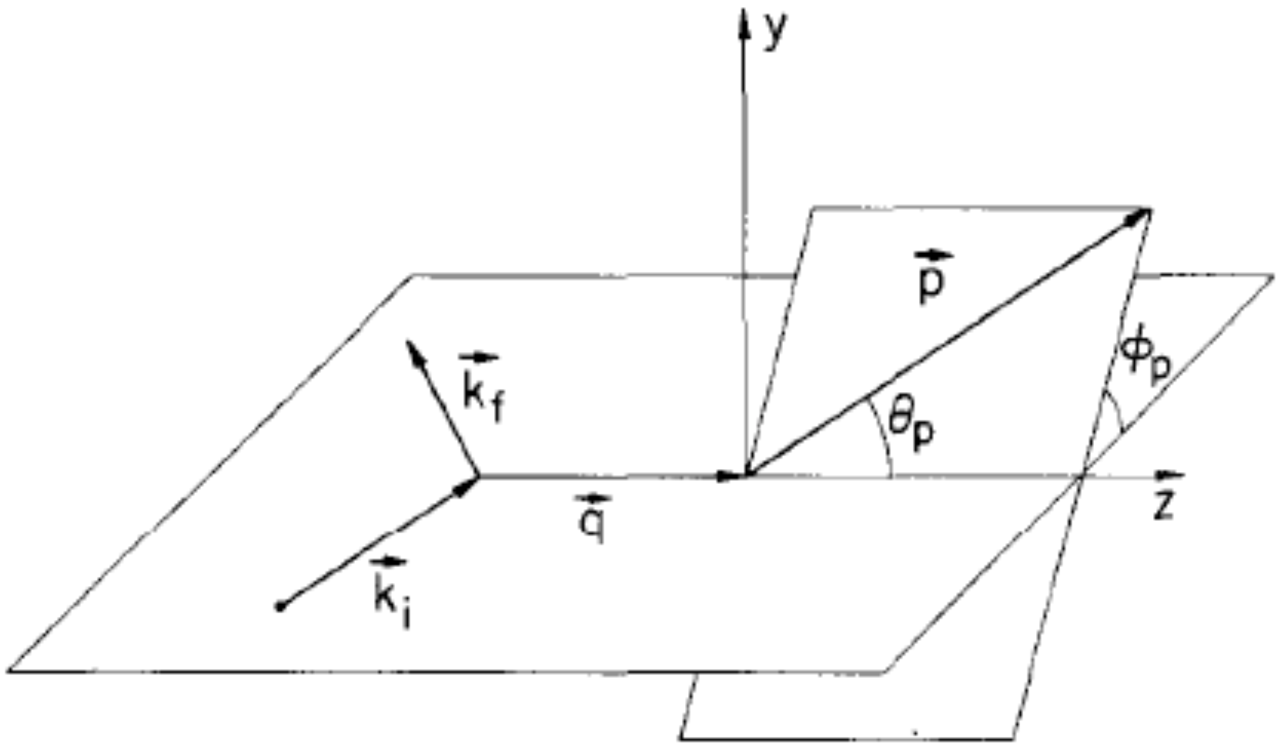

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-better in light nuclei

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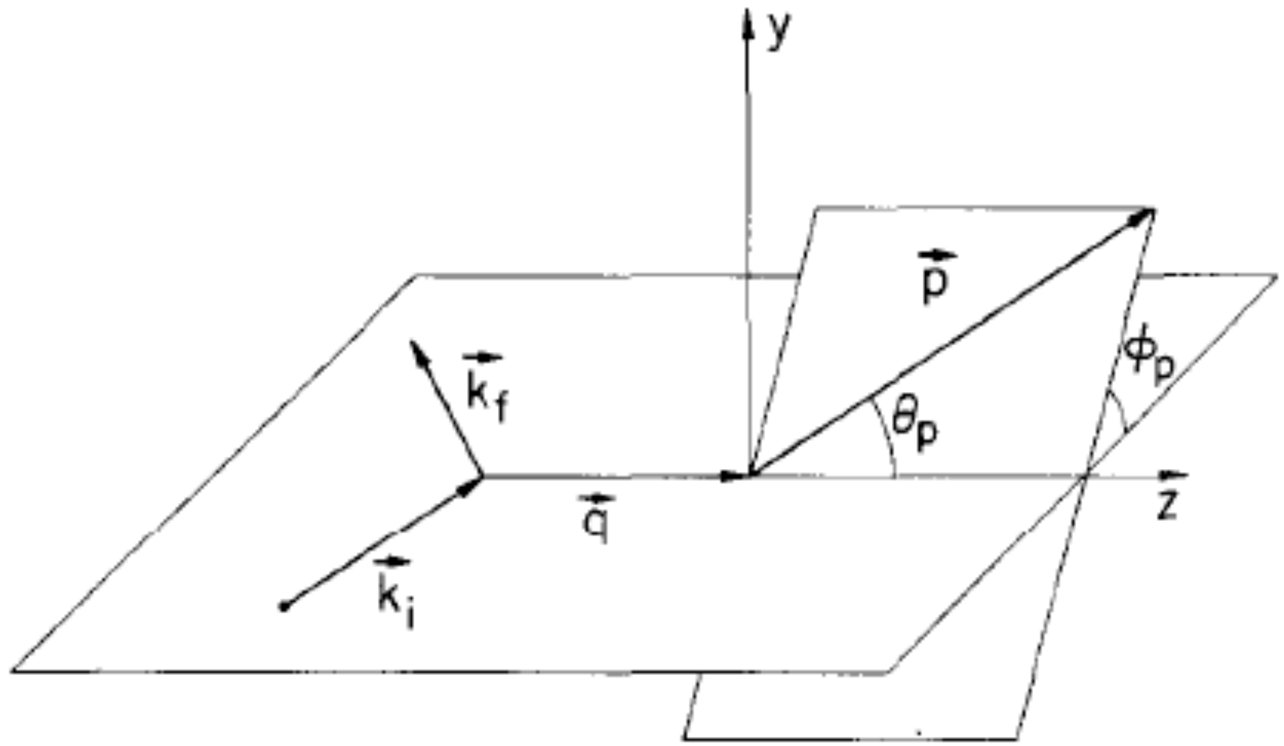

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the model:

-must describe properly nuclear excitations in the continuum

-must include the coupling between decay channels

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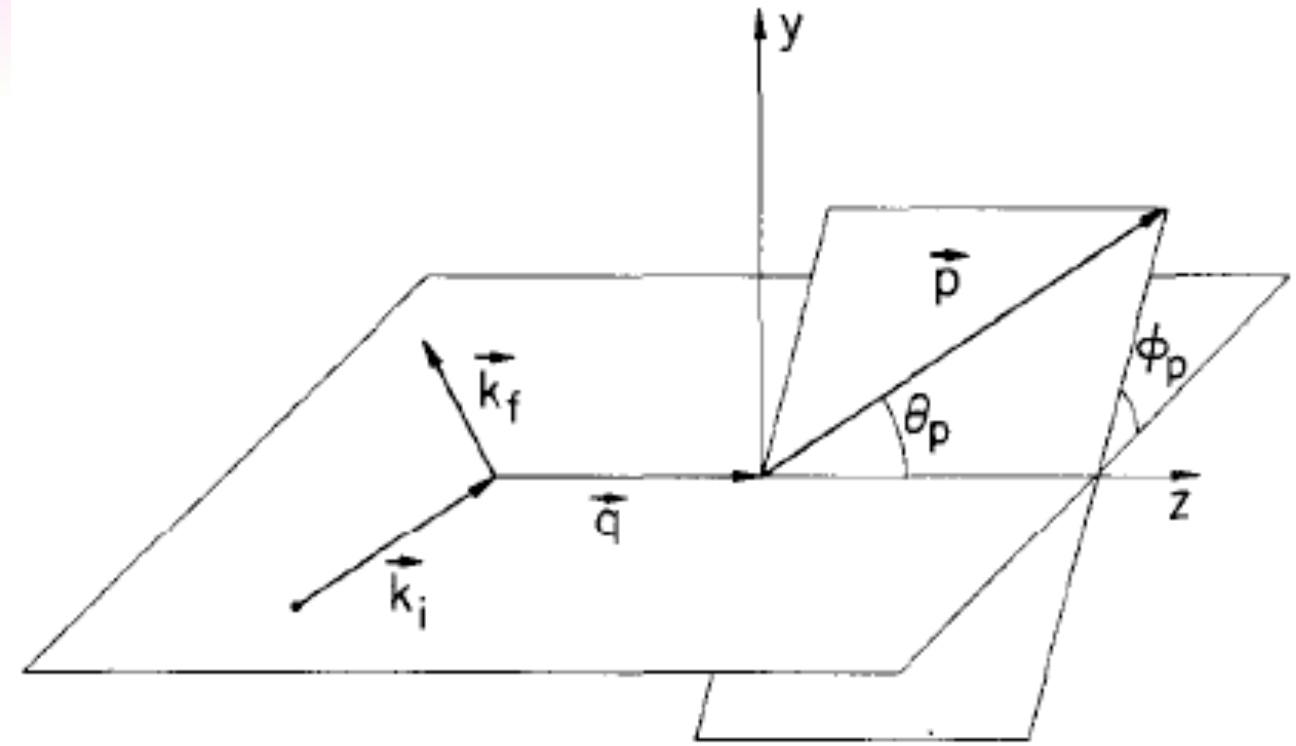

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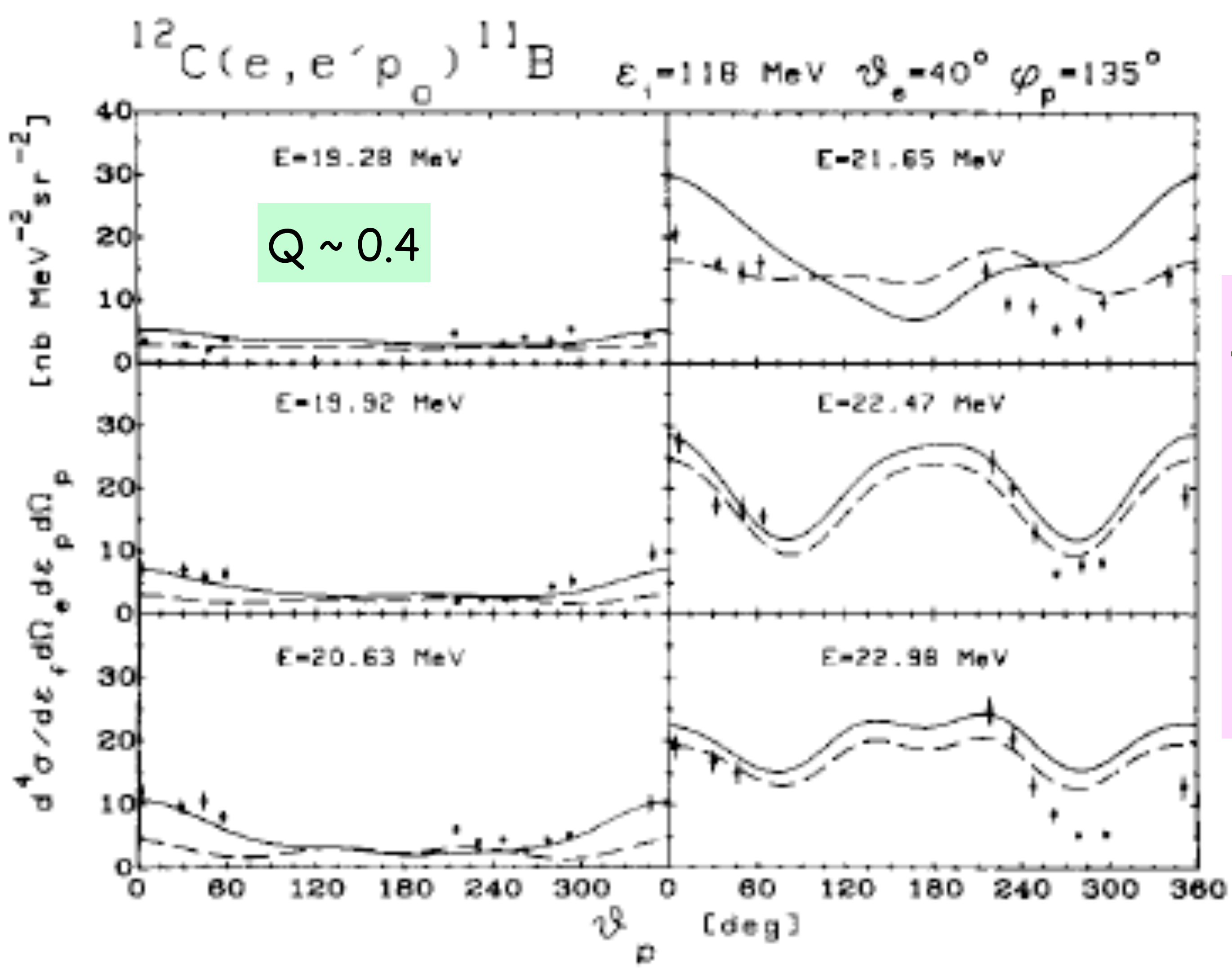

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Inelastic scattering: giant resonances

Co', Lallena, Donnelly, Nucl. Phys. A 469 (1987) 684

(e,e'p) experiments in ^{40}Ca

Inelastic scattering: giant resonances

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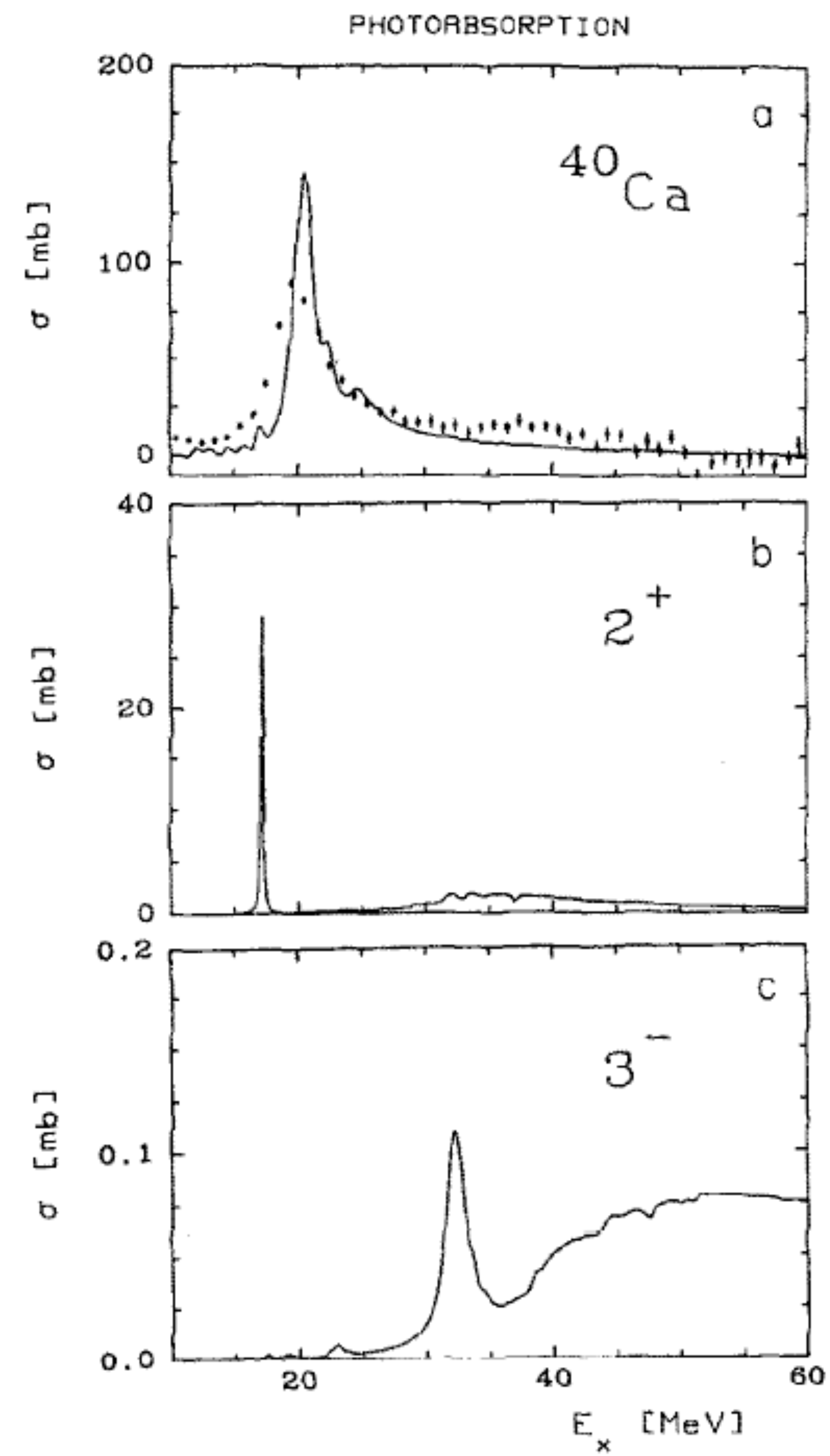

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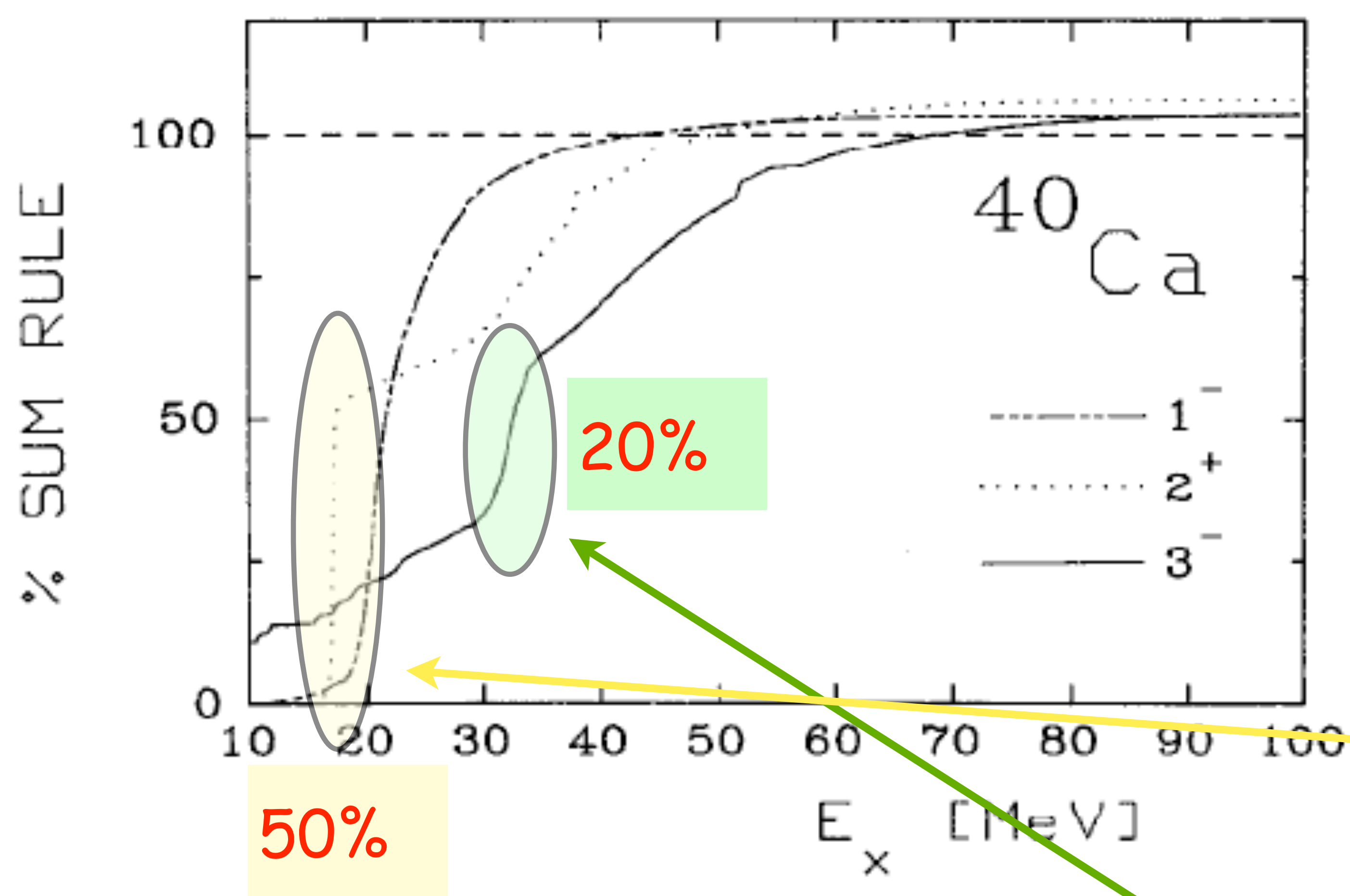

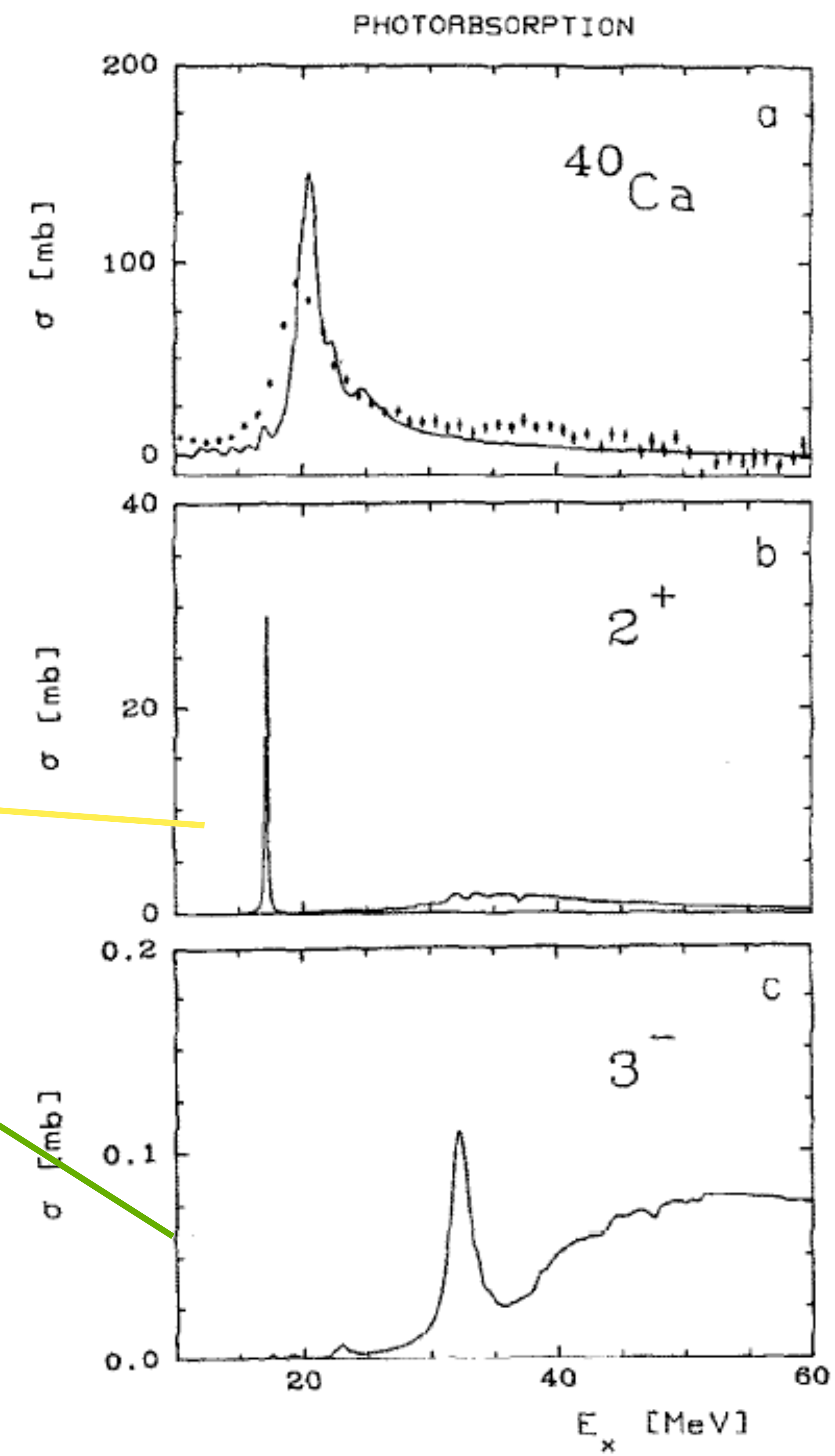

-photoabsorption cross section does not give any information about quadrupole and octupole excitations

Inelastic scattering: giant resonances

(e,e'p) experiments in ^{40}Ca

Inelastic scattering: giant resonances

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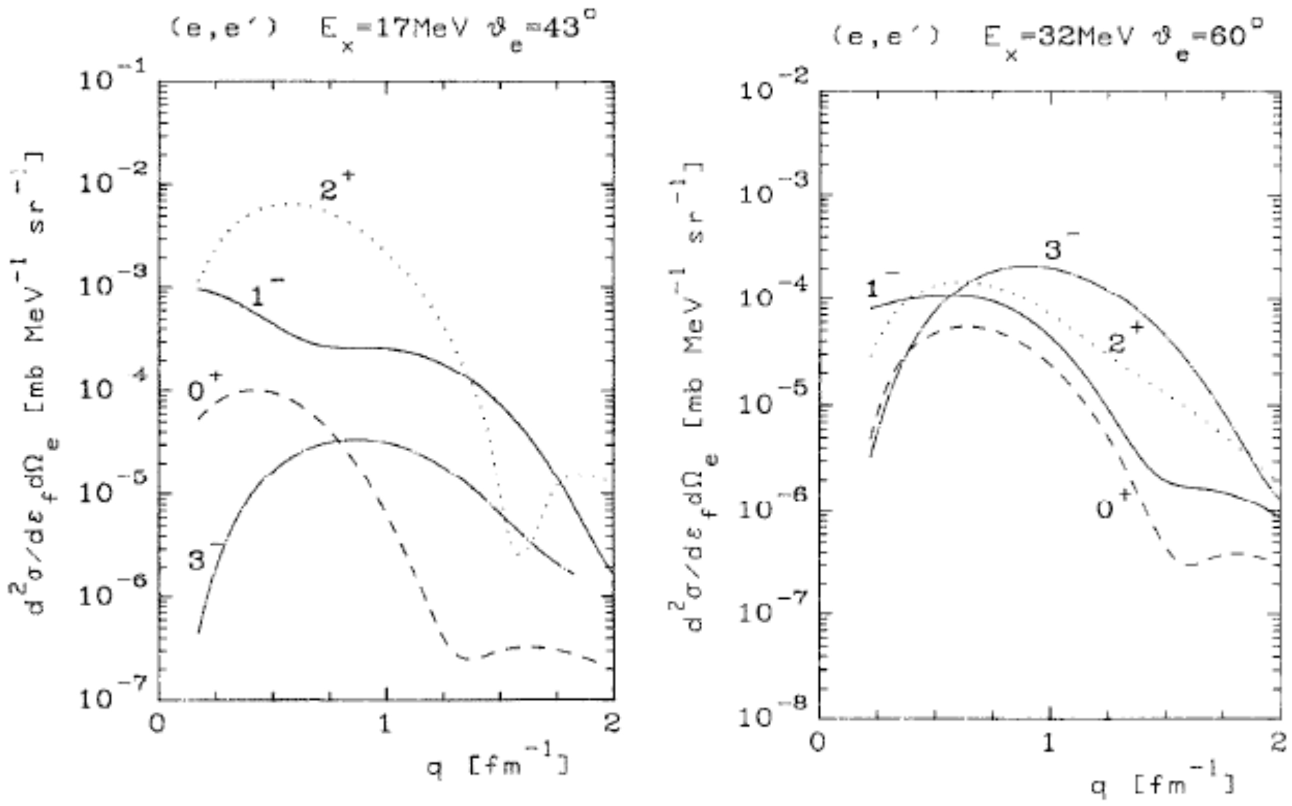

Inelastic scattering: giant resonances

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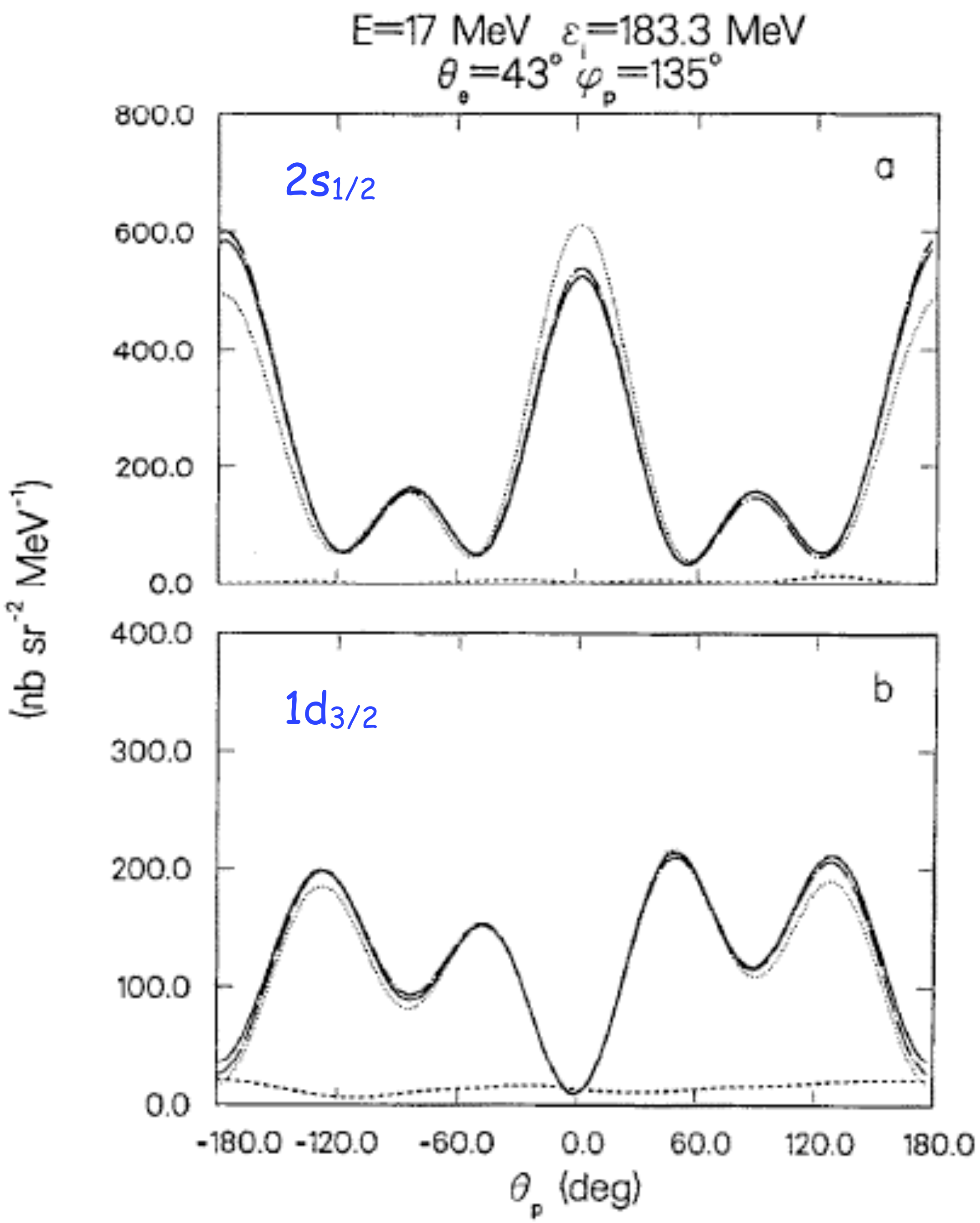

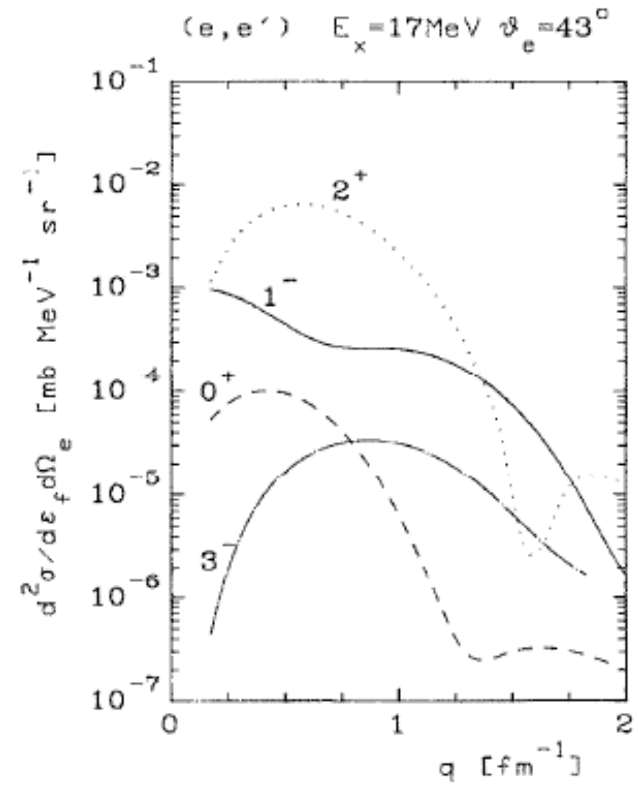

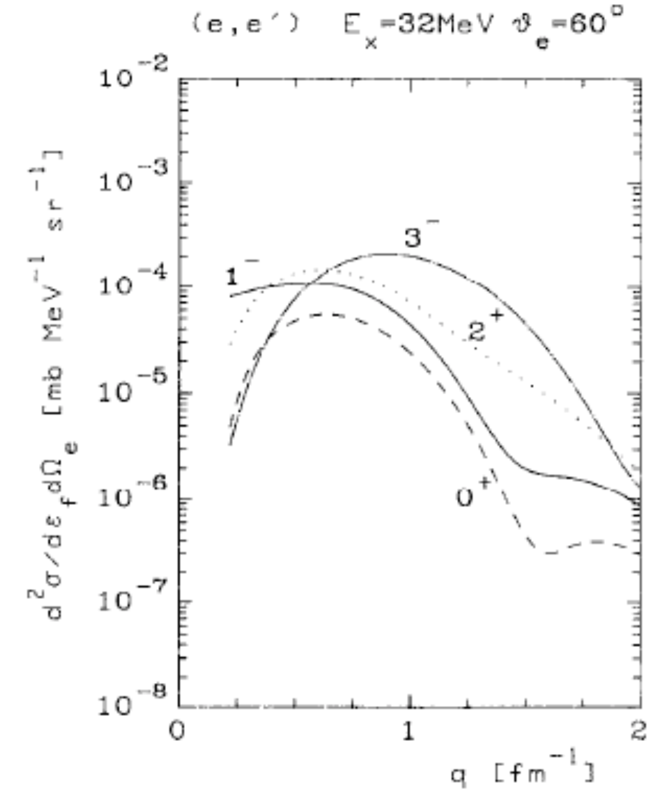

-calculation performed including all multipoles up to J=6 (both parities)

-dotted line: without 2^+

Inelastic scattering: giant resonances

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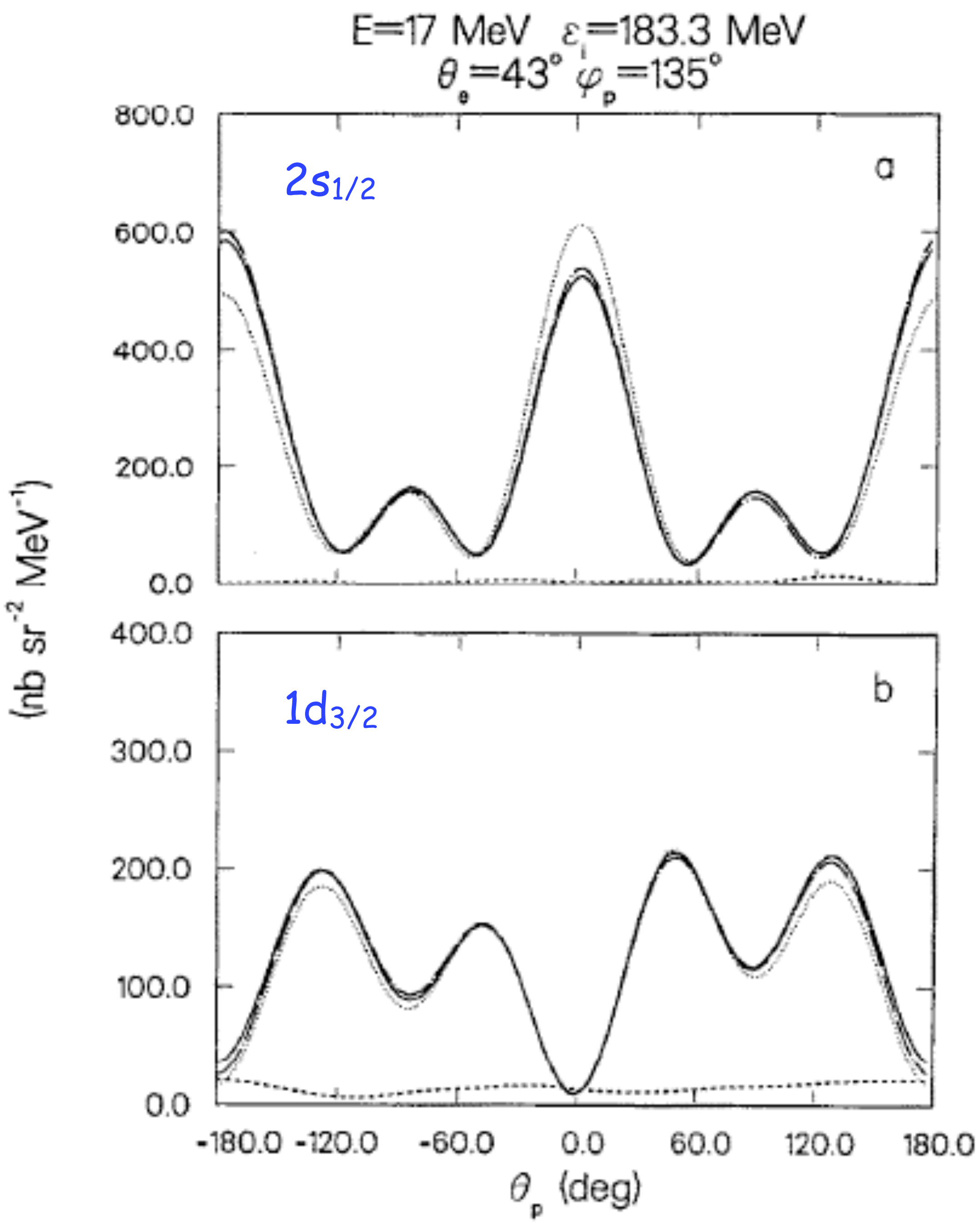

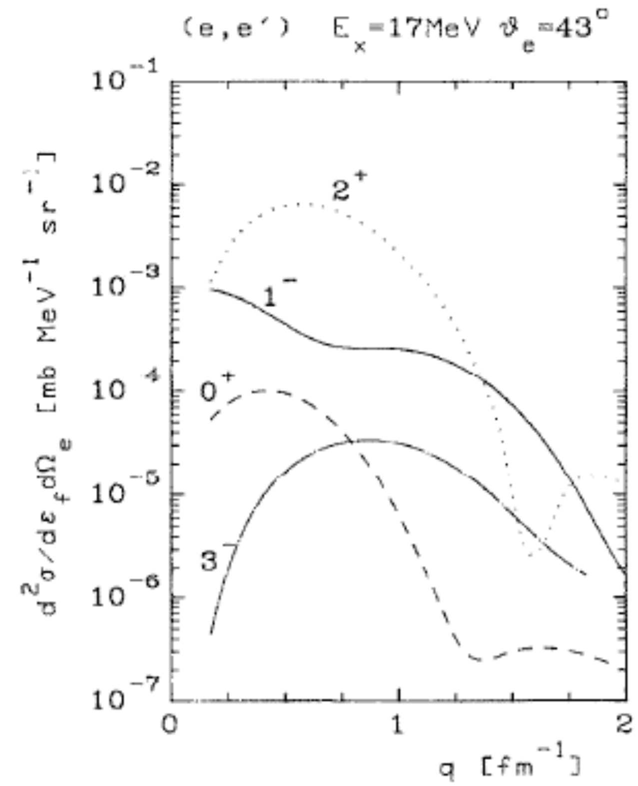

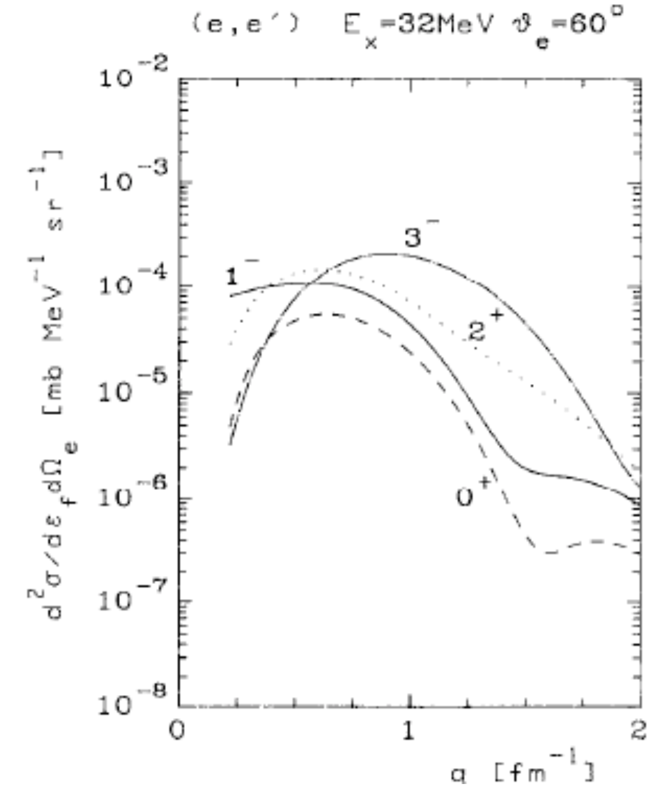

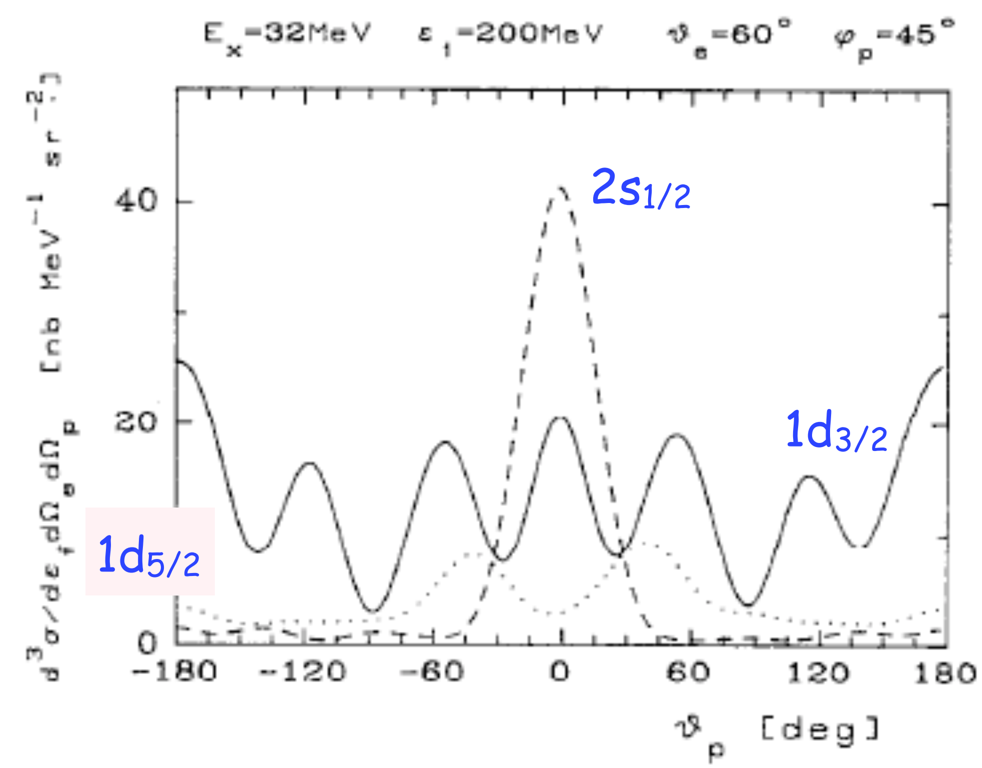

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$2s_{1/2}$: not much involved in ph configurations (quasi-free knock-out emission)

1d states: involved in nuclear collective excitations (resonant emission)

Co', Lallena, Donnelly, Nucl. Phys. A 469 (1987) 684

Inelastic scattering: giant resonances

$A(\vec{e}, e'p)$ experiments

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-it can be separated using helicity

-must be measured out-of-plane

$$\sigma/\sigma\mathrm{Mott} \propto (v_\mathrm{L} W_\mathrm{L} + v_\mathrm{T} W_\mathrm{T} + 2\, v_\mathrm{LT} W_\mathrm{LT} \cos\phi_p + 2\, v_\mathrm{TT} W_\mathrm{TT} \cos 2\phi_p) + h\, 2\, v_{\mathrm{LT}'} W_{\mathrm{LT}'} \sin\phi_p$$

fifth response function

Inelastic scattering: giant resonances

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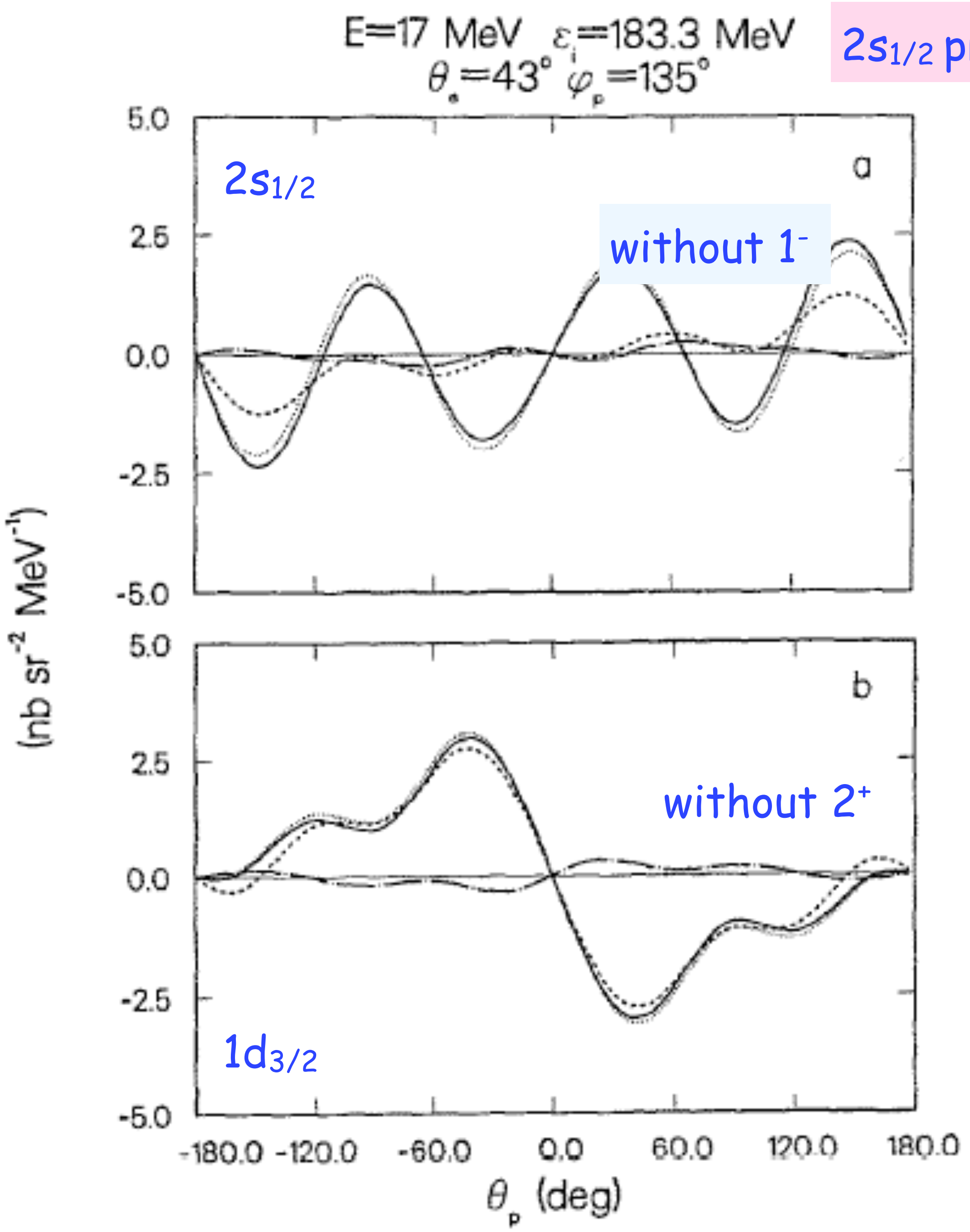

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