Polarizabilities of the Nucleons: Past and Future

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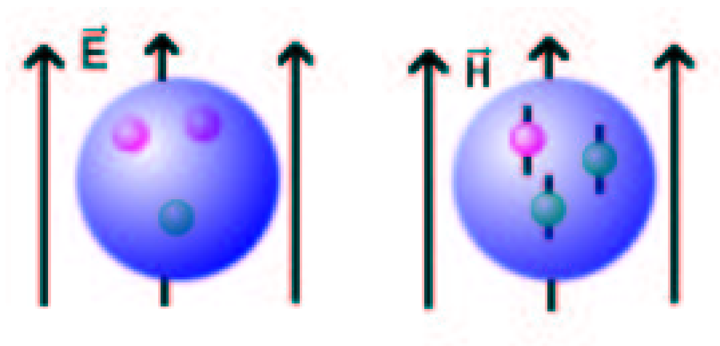
1. The "Basics" of Nucleon Polarizabilities
2. Free Nucleons
   (a) Proton
   (b) Neutron (Deuteron)
3. Mass > 2

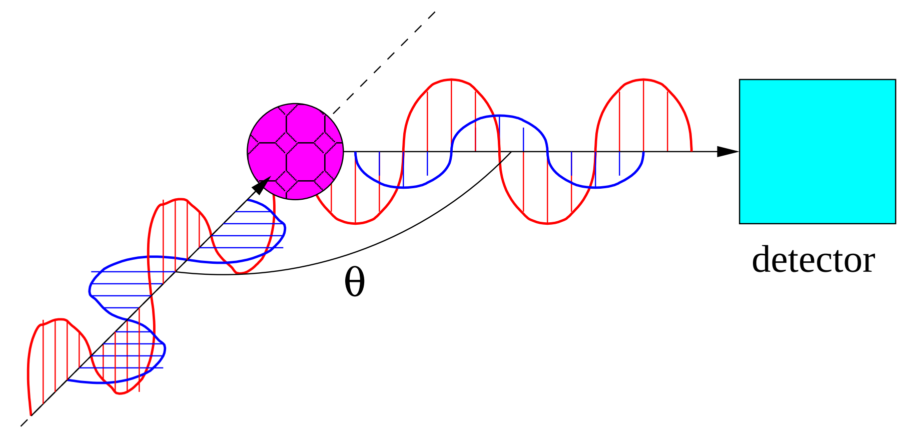
The "Basics" of Nucleon Polarizabilities

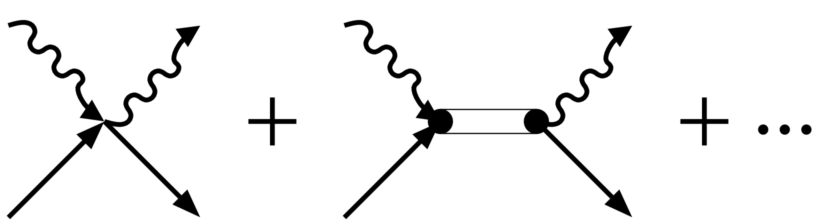
- represent response of nucleon constituents to external fields.



$\vec{p} = \alpha \vec{E}$ $\qquad$ $\vec{m} = \beta \vec{H}$

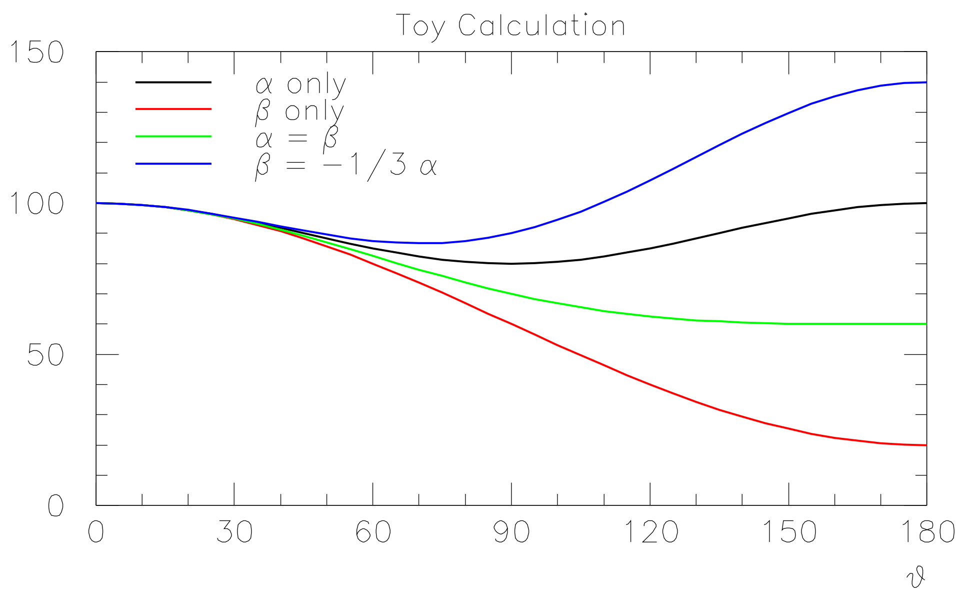
- Compton scattering





- Moments $\rightarrow$Polarizabilities

$$2\sum\frac{|\langle d_z\rangle|^2}{\omega}\rightarrow\overline{\alpha}\approx 12\times 10^{-4}\mathrm{fm}^3;$$
$$2\sum\frac{|\langle \mu_z\rangle|^2}{\omega}\rightarrow\overline{\beta}\approx 2\times 10^{-4}\mathrm{fm}^3$$
$$\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega}_{Born}+(\frac{k'}{k})^2\{r_0 k^2\{\underbrace{(\overline{\alpha}+\overline{\beta})(1+\cos\theta)^2}_{forward}+\underbrace{(\overline{\alpha}-\overline{\beta})(1-\cos\theta)^2}_{backward}\}\}$$



- strong limits on forward angle cross sections

  – sum rule: $\overline{\alpha}+\overline{\beta}=\frac{1}{2\pi}\int_{m_\pi}^{\infty}\frac{\sigma_{tot}(\omega')}{\omega'^2}d\omega'$

  – Optical Theorem + Dispersion Relations

$$\frac{d\sigma}{d\Omega}=|T(\omega,\theta)|^2$$
$$\Im m\, T(\omega,0)=\frac{\omega}{4\pi}\sigma_{tot}(\omega')$$
$$\Re e\, T(\omega,0)-\Re e\, T(0,0)=\frac{\omega^2}{2\pi^2}P\int_0^{\infty}\frac{\sigma_{tot}(\omega')}{\omega'^2-\omega^2}d\omega'$$

$\rightarrow$ ‘fun’ is at backward angles

- reality: $k > 50$ MeV, other factors and higher order effects (e.g. Babusci et al. PRC 58)

k^2: $\overline{\alpha}, \overline{\beta}$

κ - anomalous magnetic moment

k^3: κ, $\overline{\alpha}, \overline{\beta}$

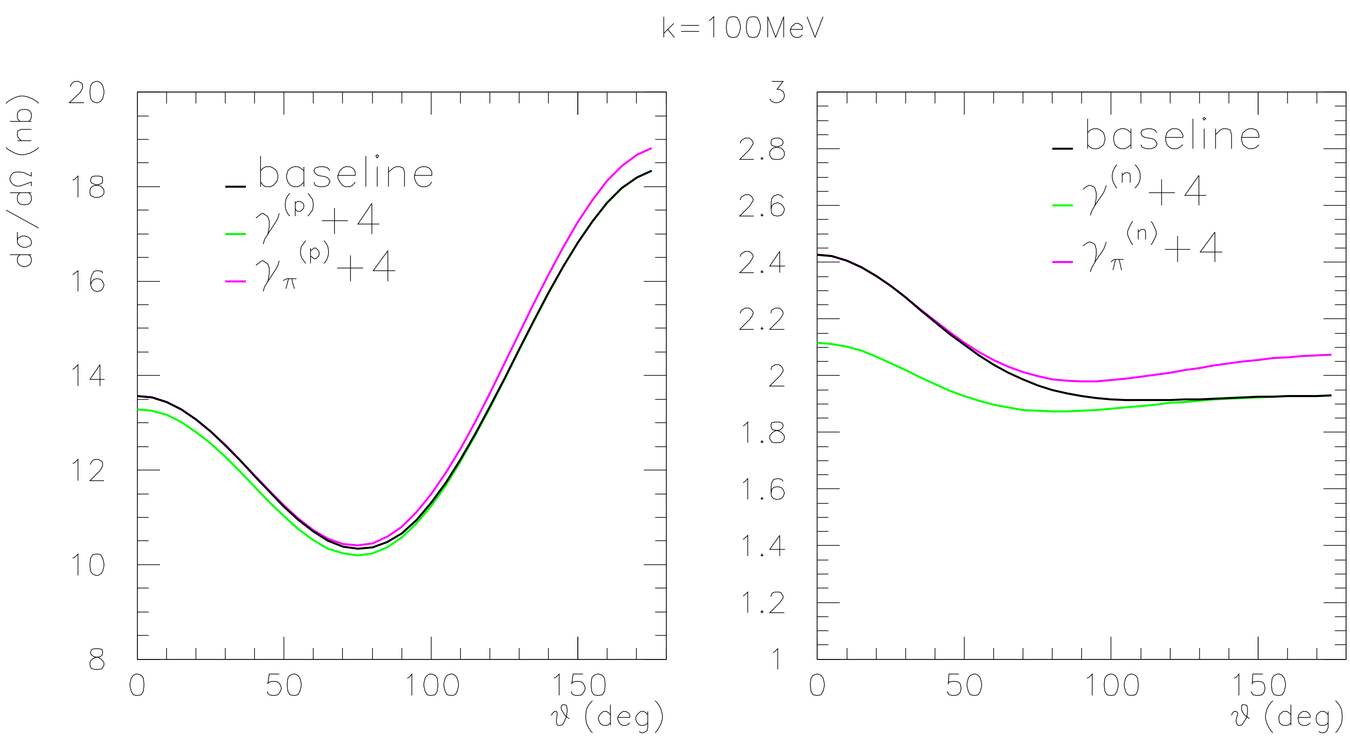
$\gamma_{E1}, \gamma_{M1}, \gamma_{E2}, \gamma_{M2}$ - “spin” polarizabilities

k^4: κ, $\overline{\alpha}, \overline{\beta}$, $\gamma_{E1}, \gamma_{M1}, \gamma_{E2}, \gamma_{M2}$

$\alpha_{E\nu}, \beta_{M\nu}$ - “dispersion” or “dynamic dipole” polarizabilities

α_{E2}, β_{M2} - quadrupole polarizabilities

$k > m_\pi$: nucleon resonances, e.g. Δ



$$\gamma_0 = -\gamma_{E1} - \gamma_{M1} - \gamma_{E2} - \gamma_{M2}$$

$$\gamma_\pi = -\gamma_{E1} + \gamma_{M1} + \gamma_{E2} - \gamma_{M2}$$

Free Nucleons: Proton

- Extensively studied since at least 1950's

60 MeV (Oxley 1958)

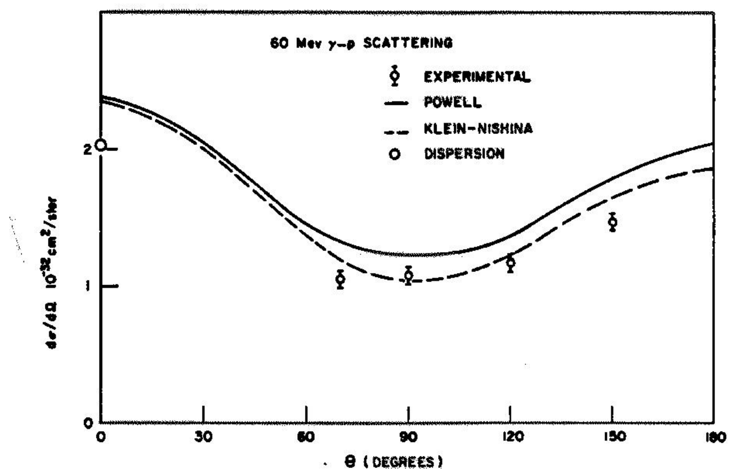
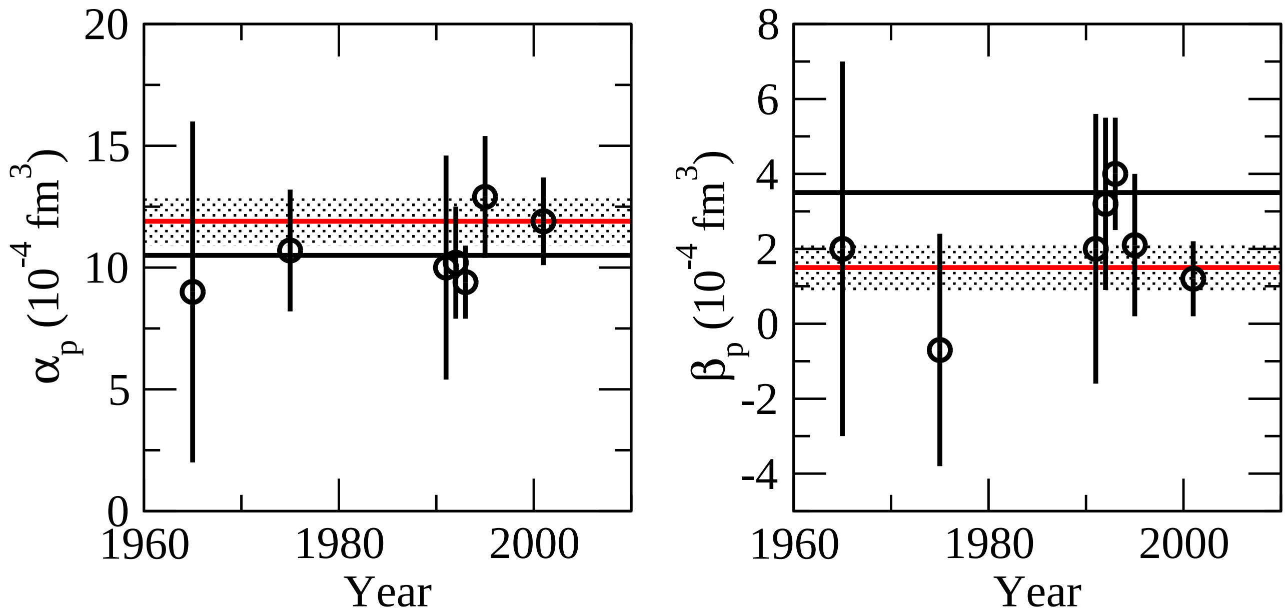


FIG. 6. Experimental and theoretical differential cross sections.

- no resonance effects until above 100 MeV
- no competing nuclear process until π_0 threshold (135 MeV CM)
- sum rule: $\alpha + \beta = 13.69 \pm 0.14$ (Babusci et al. 1998)



Olmos de Leon (Mainz):	$\overline{\alpha}^{(p)} = 11.9 \pm 0.5 \mp 0.5 \pm 0.3(model)$ $\overline{\beta}^{(p)} = 1.5 \pm 0.6 \pm 0.2 \pm 0.4(model)$
ChPt (BKM 1995)	$\overline{\alpha}^{(p)} = 10.5 \pm 2.0$ $\overline{\beta}^{(p)} = 3.5 \pm 3.6$

ChPT: Chiral Pertubation Theory

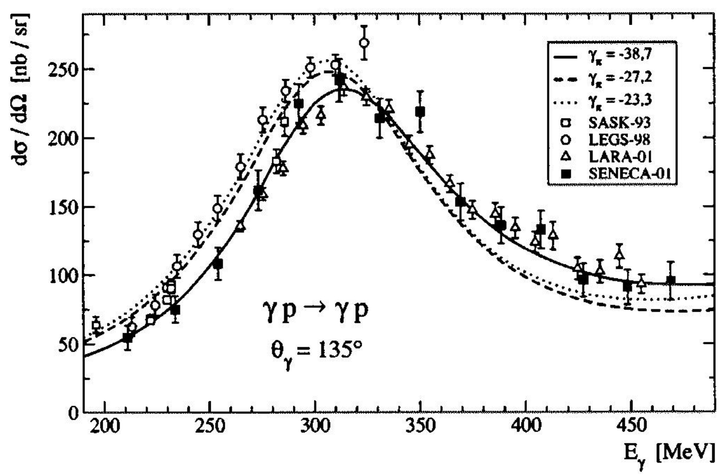
- low E expansion in zero quark mass (chiral) limit
- uses symmetries from Standard Model
  $\rightarrow$ any success of ChPT is success of QCD at low E

- spin polarizabilities remain somewhat indeterminate

1. $\gamma_\pi^{(p)}$ $(\times 10^{-4}\text{fm}^4)$

Tonnison (LEGS):	$-27.1 \pm 2.2^{+2.8}_{-2.4}\}$
Camen (Mainz):	-38.7 ± 1.8
ChPT (McGovern):	-36.6
DR (L'vov):	-39.5 ± 2.4

$\theta = 135°$ (Camen et al. 2002)



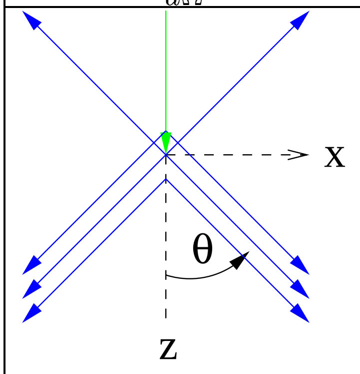
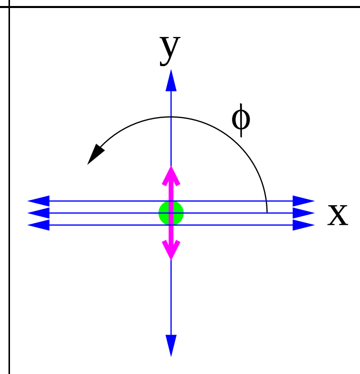
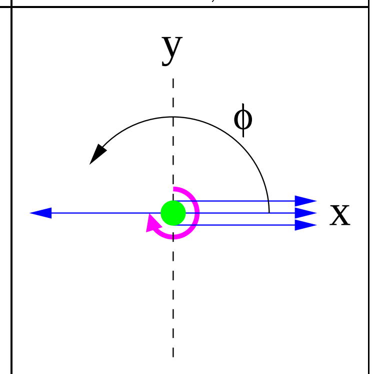
2. $\gamma_0^{(p)}$ $(\times 10^{-4}\ \text{fm}^4)$

Ahrens: $-\frac{1}{4\pi^2}\int_{m_\pi}^{\infty}(\sigma_{3/2} - \sigma_{1/2})d\omega = -1.87 \pm 0.08 \pm 0.10$

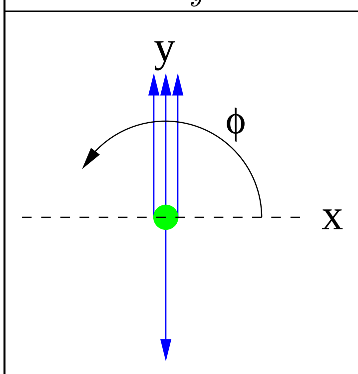
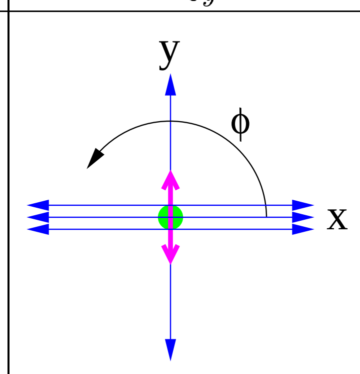
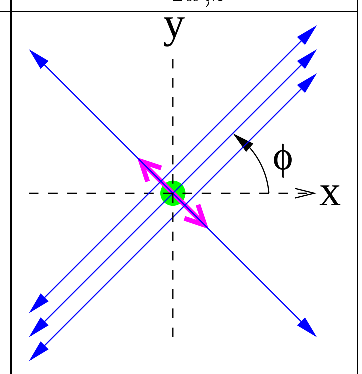
ChPT(McGovern): -3.9

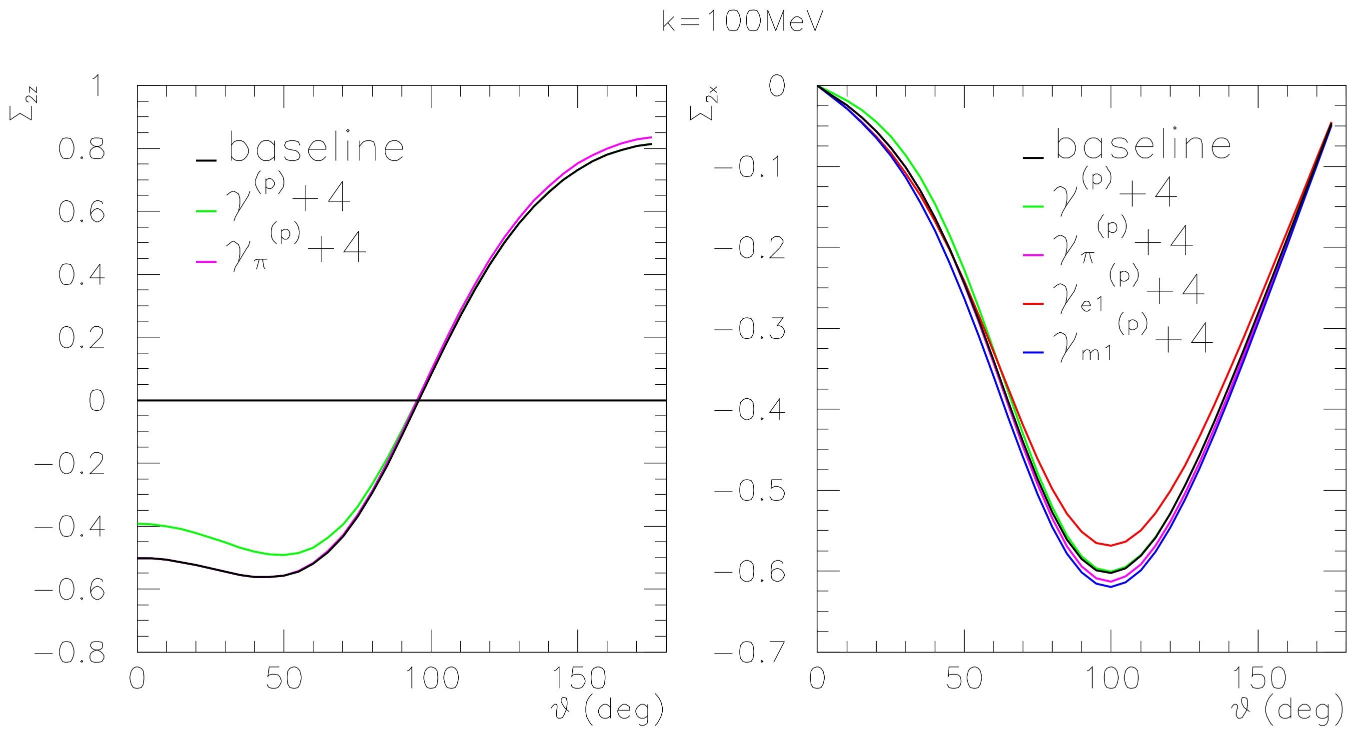
DR (Drechsel): -0.80

- Disentangling contributions
  - energy dependence
  - single and double polarization

Observable:	$\frac{d\sigma}{d\Omega}$	Σ_3	$\Sigma_{2x,z}$
			
Beam:	unpolarized	linear	circular
Target:	unpolarized	unpolarized	polarized

Additionally, above pion threshold:

Observable:	Σ_y	Σ_{3y}	$\Sigma_{1x,z}$
			
Beam:	unpolarized	linear	linear:$\phi = \pi/4$
Target:	polarized	polarized	polarized


k=100MeV
Σ2z
baseline
γ(p)+4
γπ(p)+4
ϑ (deg)
Σ2x
baseline
γ(p)+4
γπ(p)+4
γe1(p)+4
γm1(p)+4
ϑ (deg)

Neutron→Deuteron

"How similar is neutron to proton (polarizabilities)?"

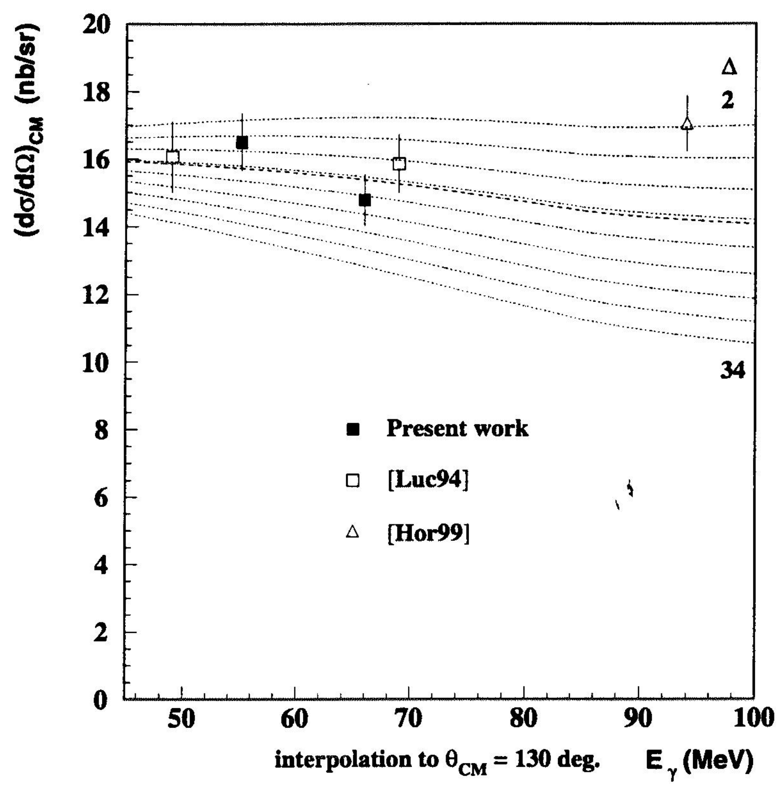
- sum rule: $\alpha^{(n)} + \beta^{(n)} = 14.40 \pm 0.66$ (Babusci et al. 1998)
- so tantalizing: polarizabilities are LO, not NLO
  - $\frac{d\sigma}{d\Omega} = (\frac{k'}{k})^2\{0 + r_0 k^2[(\alpha+\beta)(1+\cos\theta)^2 + (\alpha-\beta)(1-\cos\theta)^2]\}$
  - no quadrupole or dispersion polarizability contributions

ACK! No pure neutron targets. *sigh* Deuteron.

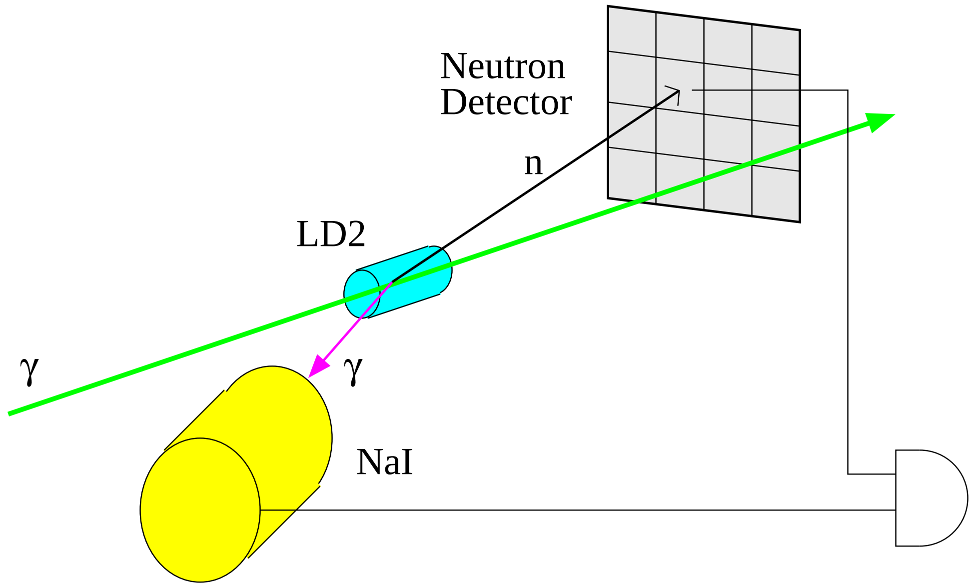
- 2 strategies to get n polarizabilities from d observations:

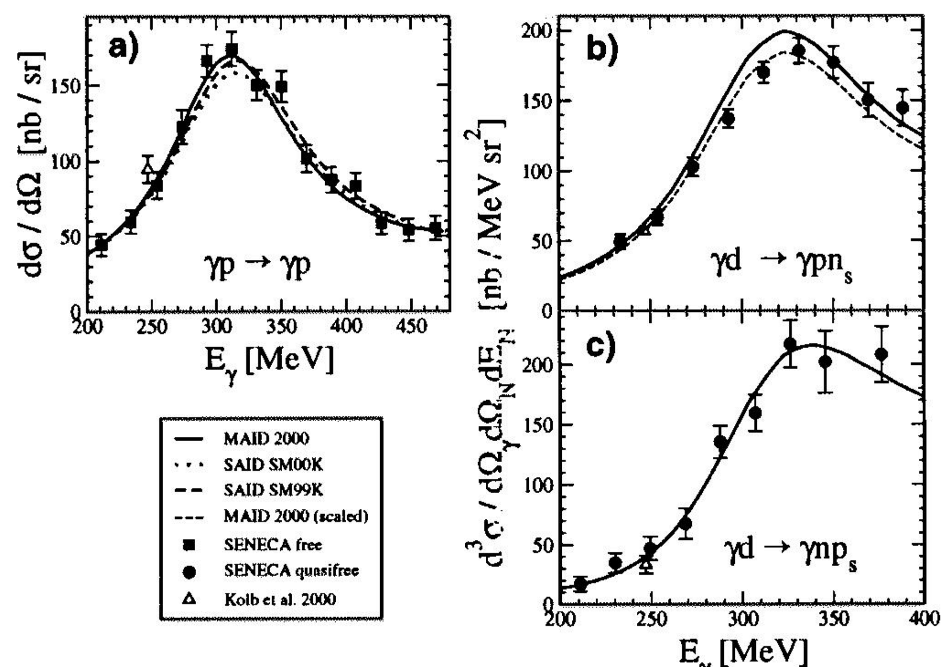
1. coherent scattering:

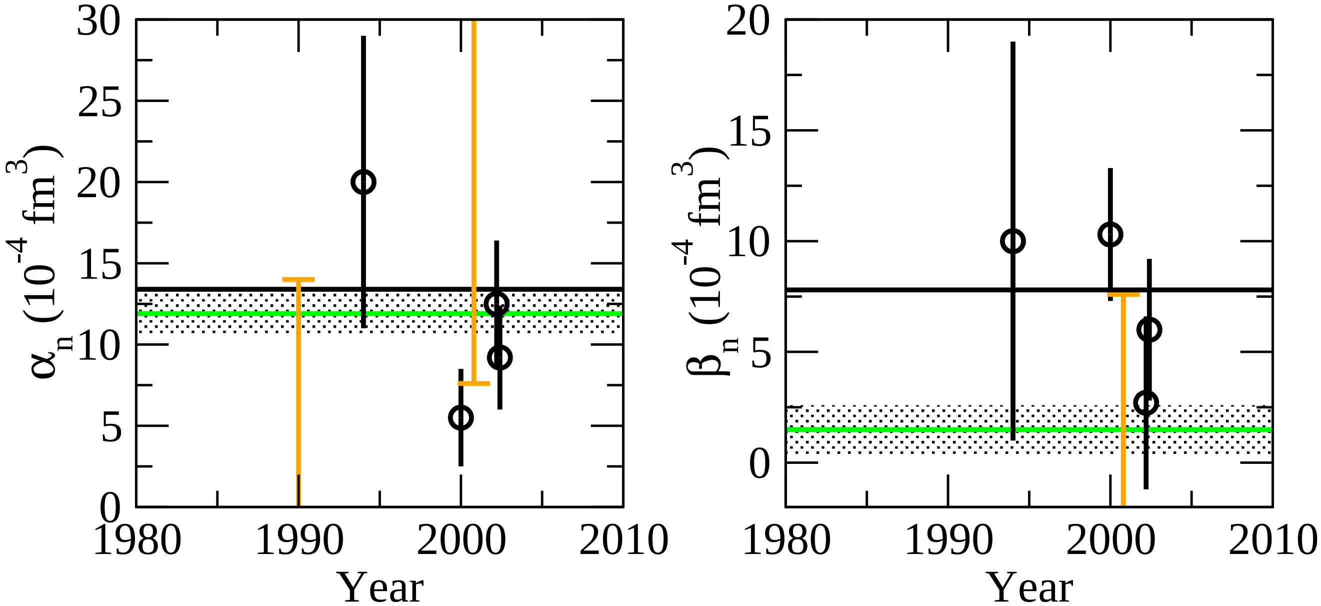
(Lundin et al. 2002)



2. quasi-free (higher E):







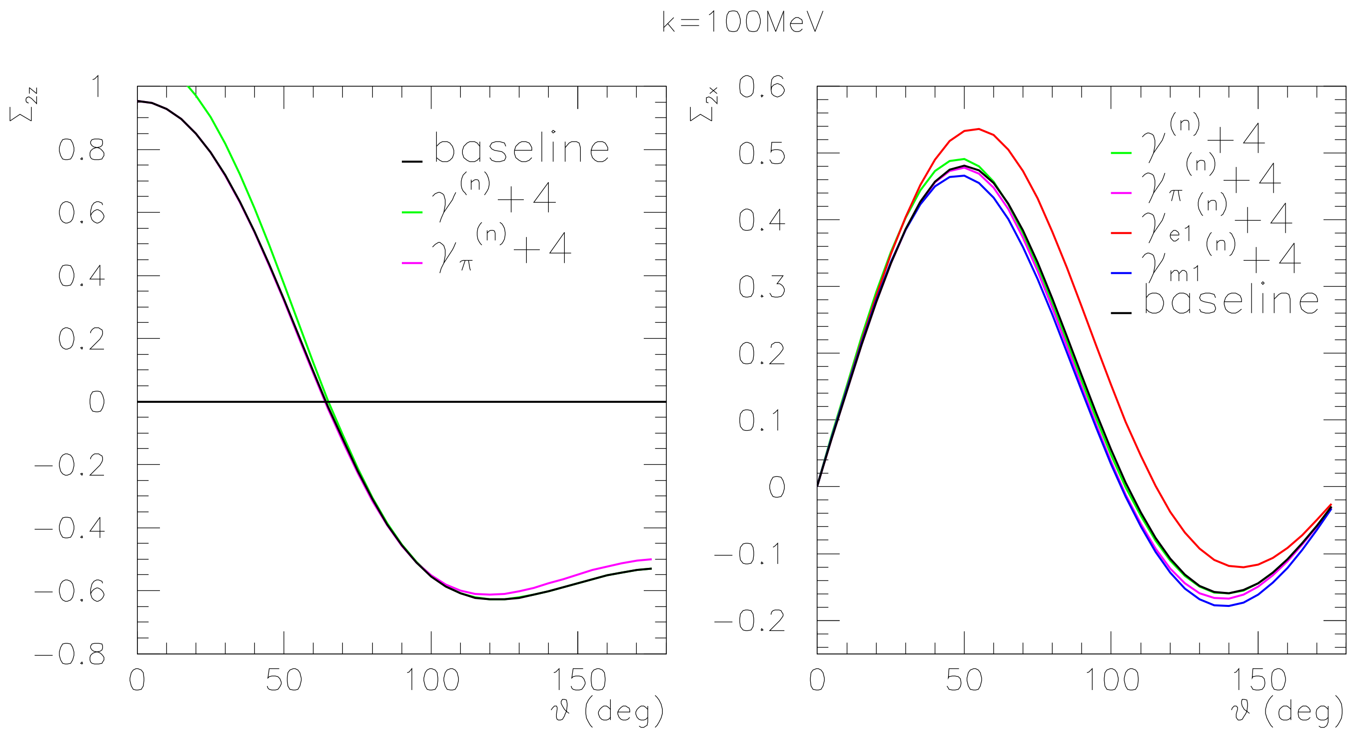
Kossert (Mainz):	$\overline{\alpha}^{(n)} = 12.5 \pm 1.8^{+1.1}_{-0.6} \pm 1.1(model)$
	$\overline{\beta}^{(n)} = 2.7 \mp 1.8^{+0.6}_{-1.1} \mp 1.1(model)$
ChPT (BKM 1995):	$\overline{\alpha}^{(n)} = 13.4 \pm 1.5$
	$\overline{\beta}^{(n)} = 7.8 \pm 3.6$

- Need to reduce uncertainties by 4

- $\gamma_0^{(n)}$ and $\gamma_\pi^{(n)}$?
  - Not yet.

ChPT (McGovern):	$\gamma_0^{(n)} = -0.9$ $\gamma_\pi^{(n)} = 51.0$
DR (Drechsel): (L'vov):	$\gamma_0^{(n)} = -0.09$ $\gamma_\pi^{(n)} = 52.5 \pm 2.4$

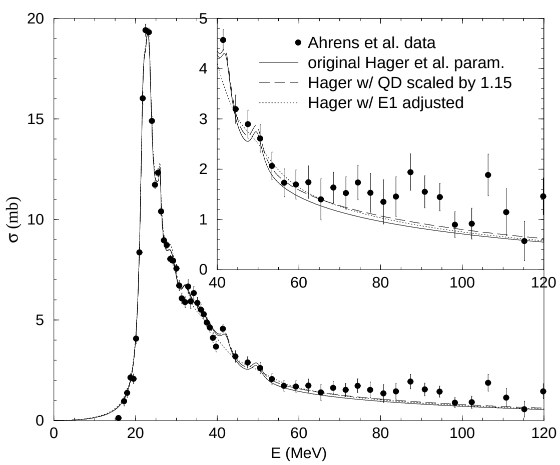
Need to improve $\alpha^{(n)}$ and $\beta^{(n)}$ situation first, or perhaps...

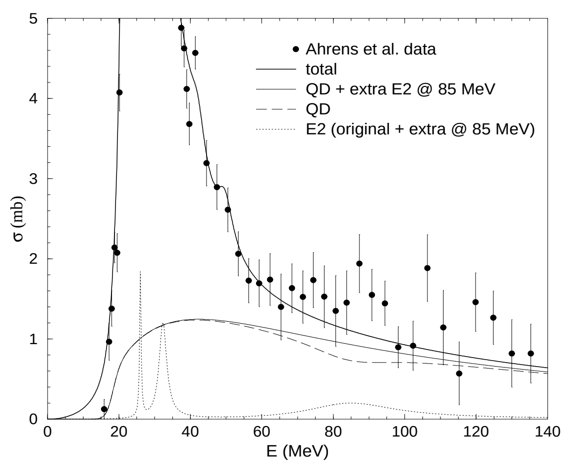


Mass > 2

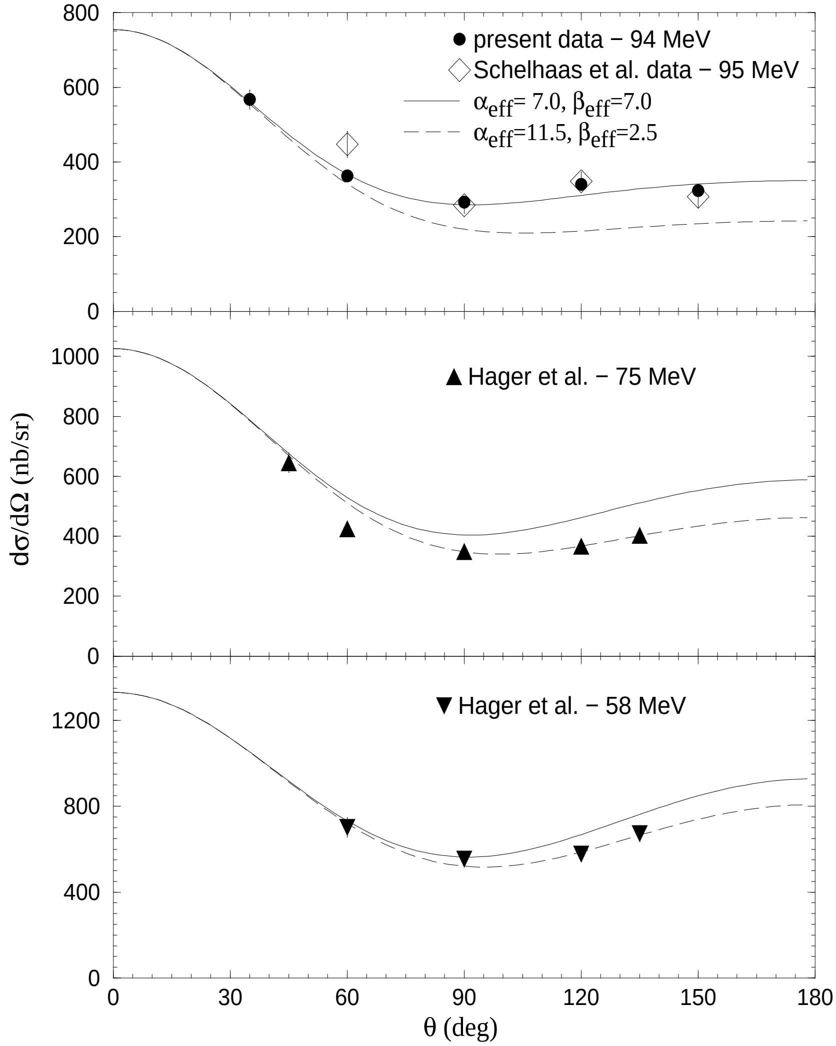
"Do polarizabilities change when nucleon is packed in with other nucleons?"

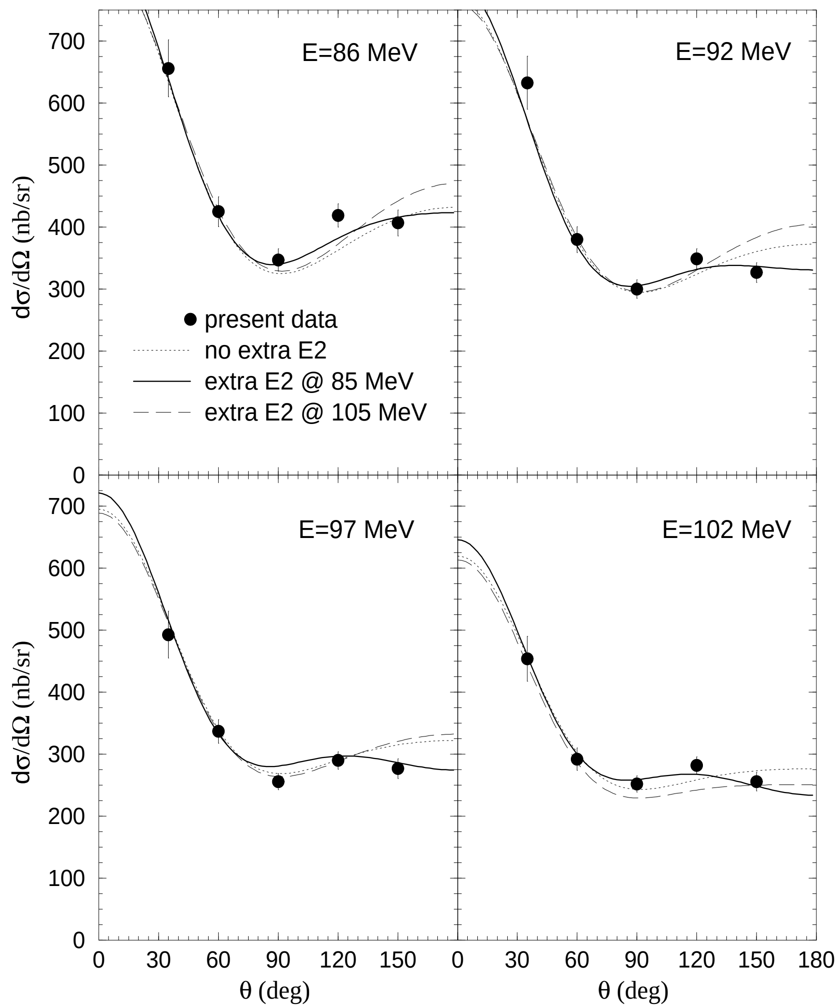
- Need to extend single nucleon paradigm:
  - $$\begin{array}{lll} \bar{\alpha}^{(p,n)} & \rightarrow \bar{\alpha}_N = \frac{Z\alpha^{(p)}+N\alpha^{(n)}}{Z+N}(= 12.2 \pm 2.0) & \rightarrow \tilde{\alpha}_N = \bar{\alpha}_N + \Delta\bar{\alpha} \\ \bar{\beta}^{(p,n)} & \rightarrow \bar{\beta}_N = \frac{Z\beta^{(p)}+N\beta^{(n)}}{Z+N}(= 2.1 \pm 1.9) & \rightarrow \tilde{\beta}_N = \bar{\beta}_N + \Delta\bar{\beta} \end{array}$$
  - $T(\omega,\theta) = R_{GR}(\omega,\theta) + R_{QD}(\omega,\theta) + R_S^{(1)}(\omega,\theta) + R_S^{(2)}(\omega,\theta)$
  - Schematically: $R_\nu(\omega,\theta) = R_{\nu DR}(\omega,0) g_{\lambda n}(\theta) F_\mu(q)$
- Inputs:
  - $F_\mu(q)$ - form factors including meson-exchange effect
  - $\sigma_{tot}(\omega) \rightarrow \sigma_{tot\nu}(\omega)$; ν =QD, E1, M1, E2
  - $\tilde{\alpha}$ and $\tilde{\beta}$





Carbon (Schelhaas et al. 1990, Hager et al. 1995, Warkentin et al. 2001)





- Problems:

    1. Inconsistencies between data sets
    2. Electric Quadrupole (E2) strength: data suggests significant strength around 85 MeV which drastically affects fit results
    3. form factor parameters (e.g. meson-exchange, charge distribution) have little effect on angular distributions but large effect on fit parameters $\tilde{\alpha}$ and $\tilde{\beta}$
    4. inconsistencies in total absorption cross section

Summary

Proton:

- $\alpha^{(p)}$ and $\beta^{(p)}$ are known to good precision
- $\gamma_0^{(p)}$ via sum rule, but not Compton yet; $\gamma_\pi^{(p)}$ still in contention; no measurement of individual $\gamma_i \rightarrow$ polarization

Neutron:

- $\alpha^{(n)}$ and $\beta^{(n)}$ has improved but uncertainty leaves open questions on effect of $\gamma_i^{(n)}$ and "$\beta^{(n)} = \beta^{(p)}$?"
- $\gamma_i^{(n)}$ unmeasured, difficult... polarization?

Multi-nucleon systems:

- not clear if polarizabilities change in nuclear environment
- messy, requires much more intensive measurements: many energies, many angles (, polarized beam or targets?)

General:

- To get good results, a Compton scattering experiment should:
  1. Cover large range of angles, extreme angles (e.g. 30° and 150°)
  2. Cover multiple energies, over fair to large range.