Nucleon Spin Polarisabilities from Deuteron Compton Scattering

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for *Deepshikha Shukla* (no thanks to US DHS)

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1. Previous Successes
2. Spin-Polarisabilities in the Deuteron
3. Per Aspera Ad Astra
4. Concluding Questions

How do constituents of the nucleon react to external fields?

How to reliably extract neutron and spin polarisabilities?

Comprehensive Theory Effort:

hg, J. McGovern (Manchester), D. R. Phillips (Ohio U), D. Choudhury Shukla (GW)

Precursors: R. Hildebrandt/T. R. Hemmert/B. Pasquini/hg. . . 2000-05, . . . ,

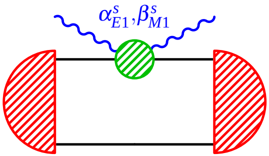
Beane/Malheiro/McGovern/Phillips/van Kolck 1999-2005; Choudhury Shukla/Phillips 2005-08

1. Previous Successes

(a) Deuteron Compton Scattering at $\omega = 0 \dots 200$ MeV

hg/Hemmert/Hildebrandt/Phillips 2004
hg/RPH/TRH 2005

– Iso-scalar α^s_{E1}, β^s_{M1} at $\mathcal{O}(\varepsilon^3)$



Full dispersion,
chirally consistent,
strong Δ para-magnetism.

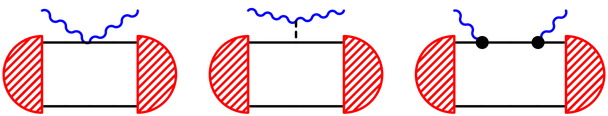
Δ in Small Scale Expansion

Hemmert/Hostein/Kambor 1998

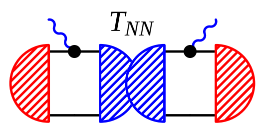
Short-distance coefficients $\delta\bar{\alpha}$, $\delta\bar{\beta}$ fit to experiment.

$\Longrightarrow$ **Determine static polarisabilities $\bar{\alpha}^s$, $\bar{\beta}^s$.**

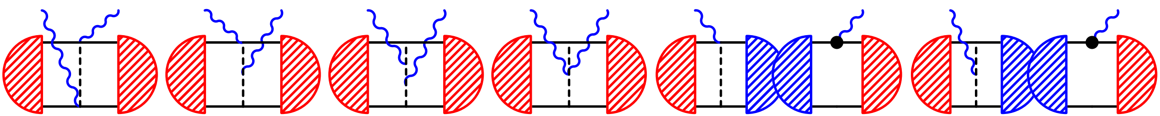
– One-body contributions



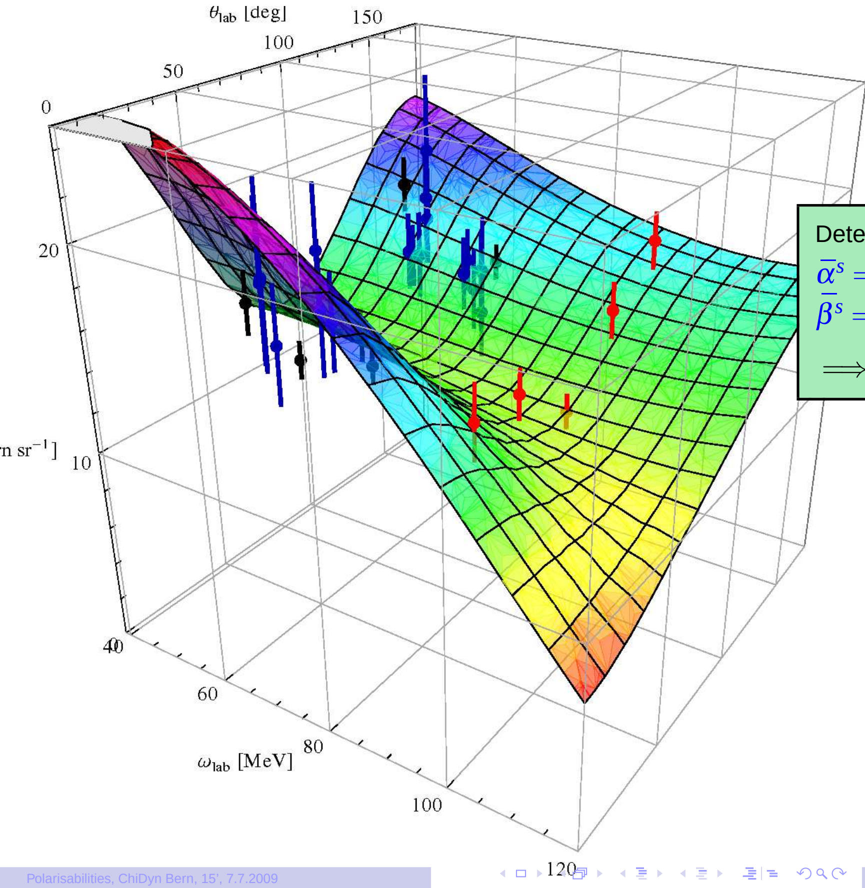
$\sum$ partial waves



– meson-exchange currents



(b) Un-Polarised Deuteron Compton Scattering



$\left.\frac{d\sigma}{d\Omega}\right|_{\rm lab}$ [nbarn/sr]

world data: 28 points

Illinois, Saskatoon, Lund

Determination using Baldin-Σ-rule:

$\bar{\alpha}^s = 11.3 \pm 0.7_{\rm stat} \pm 0.6_\Sigma \pm 1_{\rm theory}$

$\bar{\beta}^s = \ 3.2 \mp 0.7_{\rm stat} \pm 0.6_\Sigma \pm 1_{\rm theory}$

$\Longrightarrow$ **proton$\approx$ neutron polarisabilities**

Upcoming

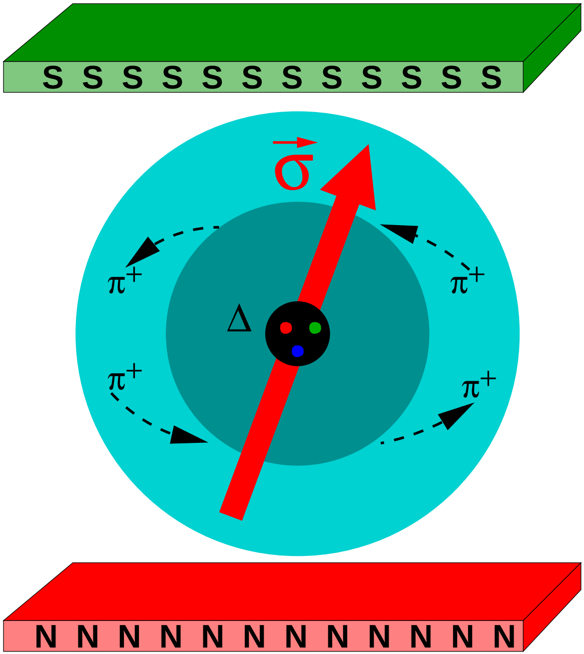
MAXlab: $[60;120]$ MeV, data taken;

HIγS: 65 MeV, approved

(a) Dynamical Polarisabilities from "Interactions": Nucleonic Faraday Effect

Response of **spin-degrees of freedom in nucleon** to real photon of definite multipolarity and non-zero energy ω.

$\Longrightarrow$ **Multipole Analysis.**



$$\mathcal{L}_{\text{pol}} = 4\pi\, N^\dagger \times$$

$$\Big\{ \tfrac{1}{2} \Big[\alpha_{E1}(\omega)\, \vec{E}^2 + \beta_{M1}(\omega)\, \vec{B}^2 \Big]$$ spin-indep dipole

$$+ \tfrac{1}{2} \Big[\gamma_{E1E1}(\omega)\, \vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \gamma_{M1M1}(\omega)\, \vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})$$

"pure" spin-dep dipole

$$-2\,\gamma_{M1E2}(\omega)\, \sigma_i\, B_j\, E_{ij} + 2\,\gamma_{E1M2}(\omega)\, \sigma_i\, E_j\, B_{ij} \Big]$$

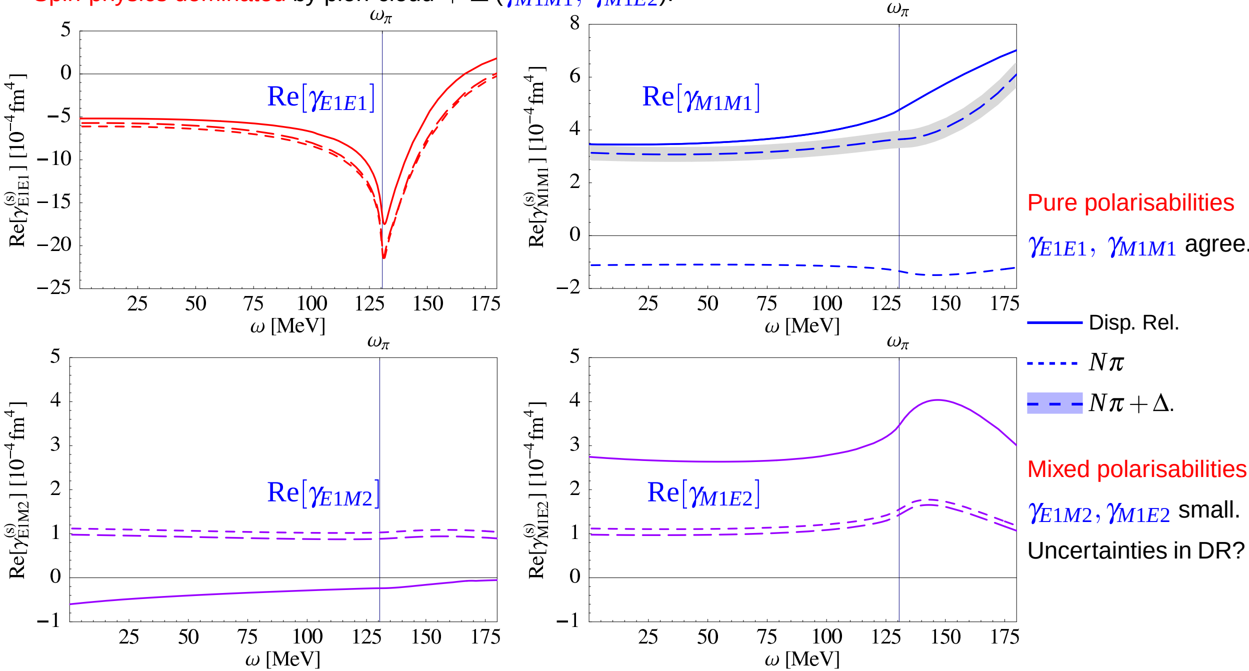
"mixed" spin-dep dipole

$$+ \ldots \Big\} N$$ quadrupole etc.

$E_{ij} := \frac{1}{2}(\partial_i E_j + \partial_j E_i)$ etc.

Predicted in χEFT: No N-core contributions $\Longrightarrow$ no free parameters.

Spin-physics dominated by pion-cloud $+\,\Delta$ (γ_{M1M1}, γ_{M1E2}).



Pure polarisabilities

γ_{E1E1}, γ_{M1M1} agree.

Mixed polarisabilities

γ_{E1M2}, γ_{M1E2} small.

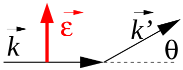
Uncertainties in DR?

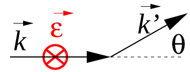
Static values (proton vs. iso-scalar)	χEFT iso-scalar	DR iso-scalar	MAMI proton	LEGS proton
$\bar{\gamma}_0 = -(\gamma_{E1E1}+\gamma_{M1M1}+\gamma_{E1M2}+\gamma_{M1E2})$	-0.7	-0.4	-1	
$\bar{\gamma}_\pi - (\pi\text{–pole}) = -\gamma_{E1E1}+\gamma_{M1M1}-\gamma_{E1M2}+\gamma_{M1E2}$	8.6	12	~ 8	~ 18

(a) Deuteron Polarisation Observables and Notebook

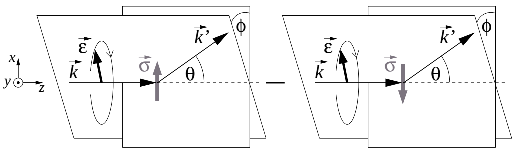
Shukla/hg/McGovern/Phillips 2009

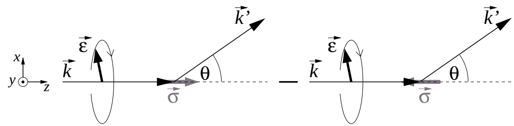
linpol. γ, unpol. deuteron:

$\left.\frac{d\sigma}{d\Omega}\right|_x^{\text{lin}}$ 

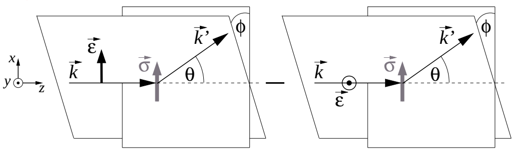
$\left.\frac{d\sigma}{d\Omega}\right|_y^{\text{lin}}$ 

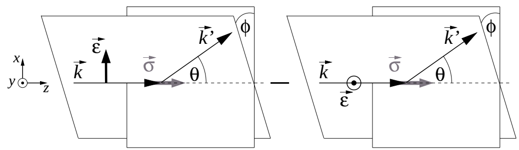
circpol. γ, vecpol. deuteron:

Δ_x^{circ} 

Δ_z^{circ} 

linpol. γ, vecpol. deuteron:

Δ_x^{lin} 

Δ_z^{lin} 

Differences Δ and asymmetries $\Sigma = \frac{\Delta}{\textbf{sum}}$

2$\times$6 observables, 6 polarisabilities, 3 kinemat. variables ω, θ, ϕ + additional Constraints:

– scalar polarisabilities α_{E1}, β_{M1}

– γ_0, γ_π (???)

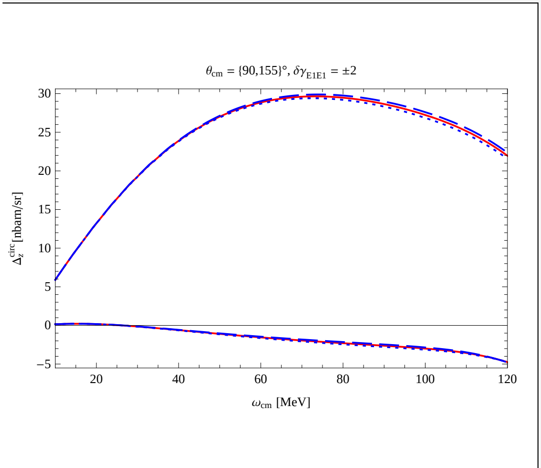
– experiment: detector settings,. . .

$\Longrightarrow$ Kill too many trees when all presented.

(a) Deuteron Polarisation Observables and Notebook

Shukla/hg/McGovern/Phillips 2009

$\Longrightarrow$ **Interactive** *mathematic 7.0* **notebook** available from hgrie@gwu.edu



First scatt. angle θ=90°

Second scatt. angle θ=155°

Reference frame: cm | lab

Deuteron polarisation axis: x | z

Variation by ±2 of: $\delta\gamma_{E1E1}$

χEFT order: ϵ^3

Deuteron wave function: NNLO Epelbaum 650MeV | AV18

NN potential: AV18

Range y-axis: Automatic

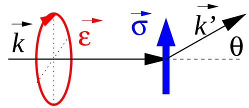
$\delta\gamma_{E1E1}=0$; $\delta\gamma_{E1E1}=+2$; $\delta\gamma_{E1E1}=-2$

(b) Spin-Polarisabilities from Circularly Pol. Photons at 125 MeV

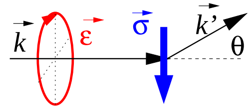
Shukla/Phillips 2005
Shukla/hg 2009

Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

difference Δ_x^{circ}, asymmetry $\Sigma_x^{\text{circ}} = \frac{\Delta_x^{\text{circ}}}{\text{sum}}$

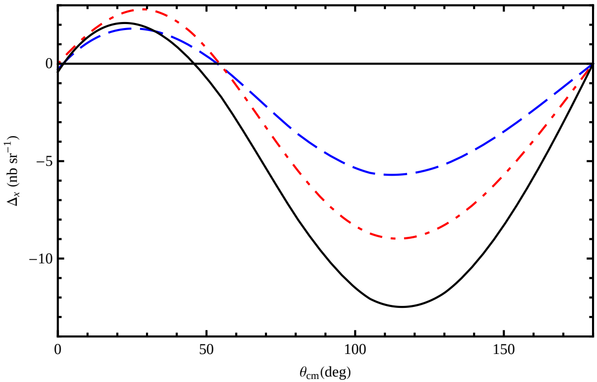


vs.



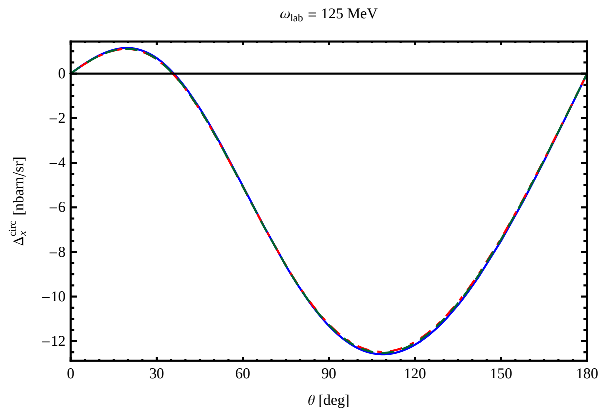
Sensitivity on Δ & NN-rescattering:

- - - - $N\pi$, no NN; - · - · $N\pi+\Delta$, no NN; —— $N\pi+\Delta+NN$



Sensitivity on wave-function:

NNLO Epelbaum 650 MeV, AV18, Nijmegen 93



– More pronounced by explicit $\Delta(1232)$

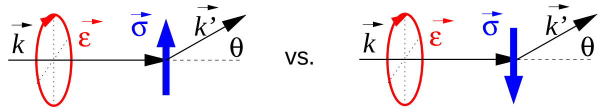
– Thomson (NN rescatt.) important even at high $\omega = 125$ MeV

– No residual deuteron wave-function dependence

– Higher pols negligible

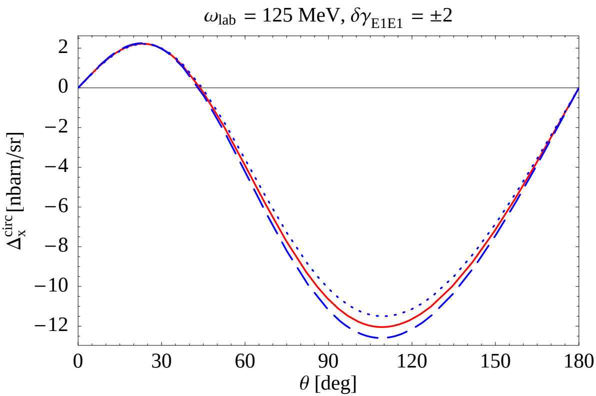
Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

difference Δ_x^{circ}, asymmetry $\Sigma_x^{\text{circ}} = \frac{\Delta_x^{\text{circ}}}{\text{sum}}$



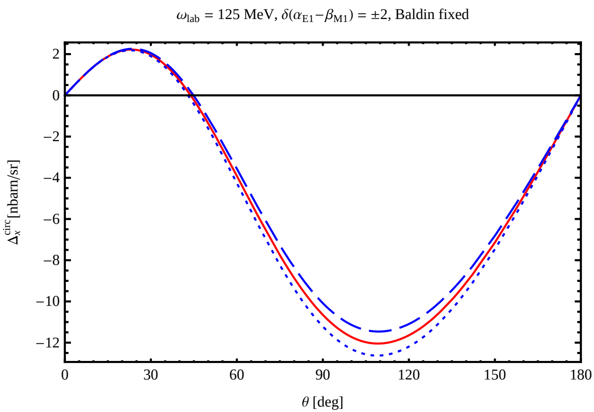
Sensitivity on γ_{E1E1}

red solid: -5.2; dashed: $-5.2+2$; dotted: $-5.2-2$



Sensitivity on nucleon $\alpha_{E1} - \beta_{M1}$; Baldin-Σ fixed

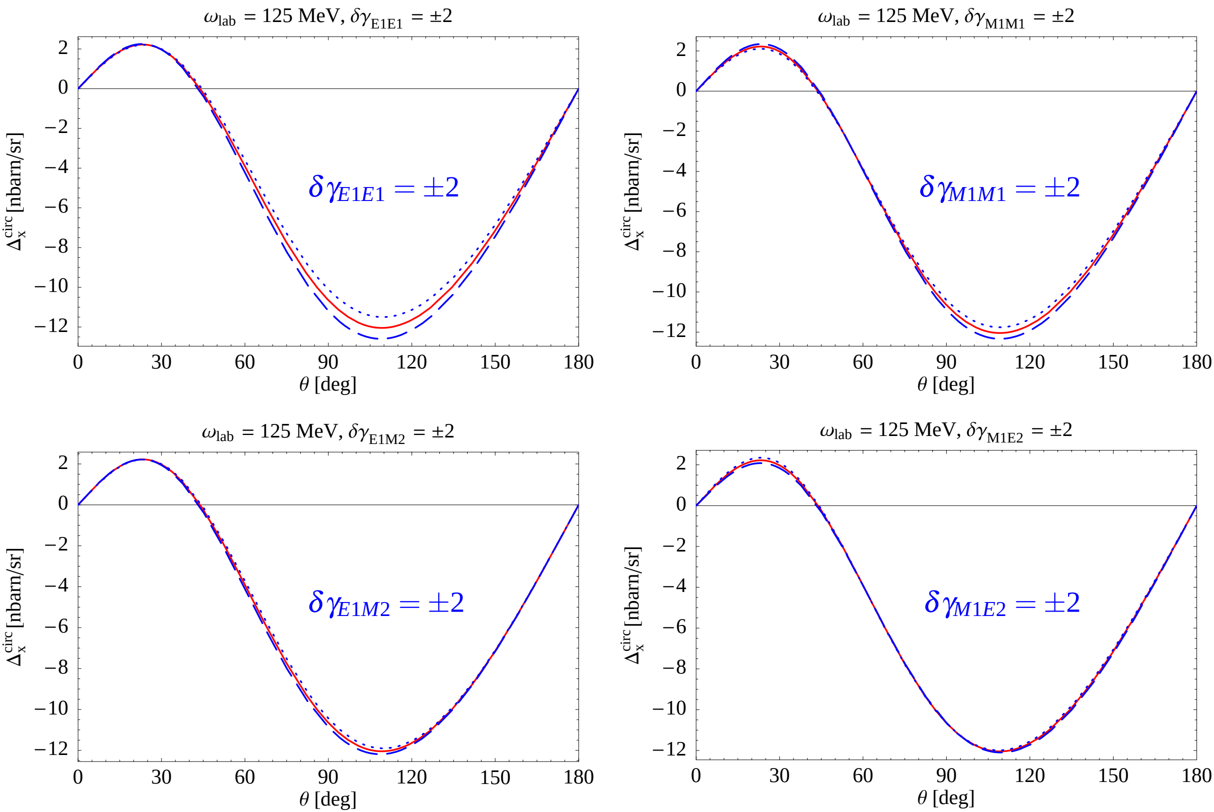
red solid: 8.2; dashed: $8.2+2$; dotted: $8.2-2$



Sensitive to γ_{E1E1}, but must nail down α_{E1}, β_{M1} at lower energy.

Similarly good signal for linear polarisation Δ_x^{lin}.

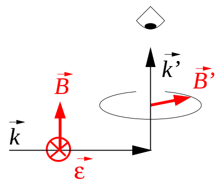
Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:



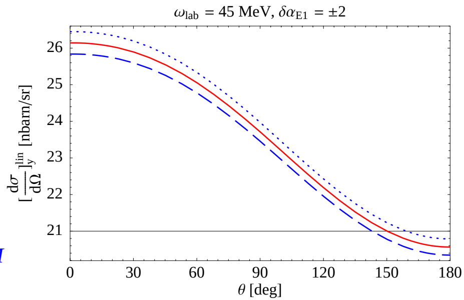
(c) Switching Off Polarisability Contributions

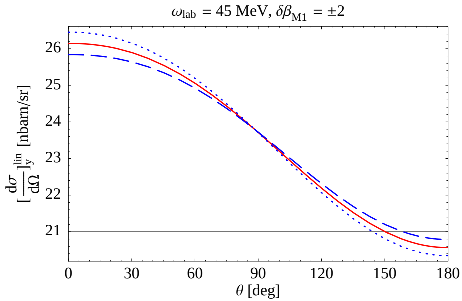
$$\mathcal{L}_{\text{pol}} = 4\pi\, N^\dagger \left\{ \frac{1}{2} \left[\alpha_{E1}(\omega)\, \vec{E}^2 + \beta_{M1}(\omega)\, \vec{B}^2 \right] + \dots \right\} N$$

Example: linearly polarised photon, $\omega = 45\ \text{MeV},\ \theta = 90^\circ$



no contribution from β_M





Unaffected by orbital ang. momentum in deuteron; Weller HIγS approved for $\omega = 65$ MeV circpol.

Only in cross-sections of special configurations; not for asymmetries!

4. Concluding Questions

(a) Comprehensive Approach to Compton Scattering

H. W. Grießhammer (GW), J. McGovern (U. of Manchester), D. R. Phillips (Ohio U.), D. Choudhury Shukla (GW⟶UNC)

Comprehensive Compton Scattering picture off p, d, ^{3}He in χEFT.

Goals: Guide and support experiments: planning and data-taking.

ongoing: MAXlab; approved/planning: **HIγS** , MAMI, S-DALINAC,. . .

- multipole-analysis $\Longrightarrow$ map out energy-dependence of response, spin-polarisabilities.
- proton-neutron difference.
- short-distance origin of C.T.s $\delta\bar{\alpha},\ \delta\bar{\beta}$.

Done: Coding, streamlining,. . . ; **Upcoming:** χEFT with $\Delta(1232)$ at δ^4 Pascalutsa/Phillips 2003 $\longrightarrow$ J. McGovern

- Kinematics: correct π-threshold, Δ-resonance position. Next focus of attention.
- NN-rescattering: χEFT potential & deuteron wave-function fully consistent. Simple.
- Thomson limit & $\Delta(1232)$ in ^{3}He. Work!, with Bochum-Krakow.
- Breakups like $\gamma d \longrightarrow \gamma np$ (Kossert data) Long-term.

Explore knobs and handles for credible error-bars $\lesssim 0.3(?)$, exp. planning: Picture emerging.

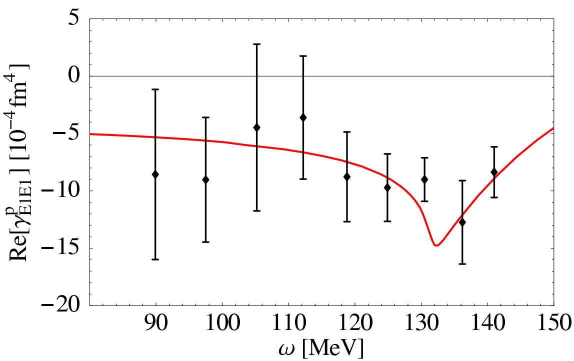

END OF
IMPROVEMENT
THANK YOU
FOR YOUR PATIENCE

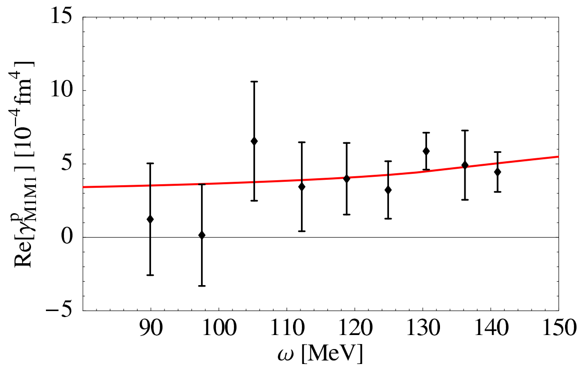
Spin-physics dominated by pion-cloud $+ \Delta$. No N-core contributions.

$$4\pi\, N^\dagger \left\{ \frac{1}{2} \left[\alpha_{E1}(\omega)\, \vec{E}^2 + \beta_{M1}(\omega)\, \vec{B}^2 \right] \right.$$ spin-indep dipole

$$+ \frac{1}{2} \left[\gamma_{E1E1}(\omega)\, \vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \gamma_{M1M1}(\omega)\, \vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}}) \right.$$ "pure" spin-dep dipole

$$\left. \left. -2\, \gamma_{M1E2}(\omega)\, \sigma_i\, B_j\, E_{ij} + 2\, \gamma_{E1M2}(\omega)\, \sigma_i\, E_j\, B_{ij} \right] + \dots \right\} N$$ "mixed" spin-dep dipole



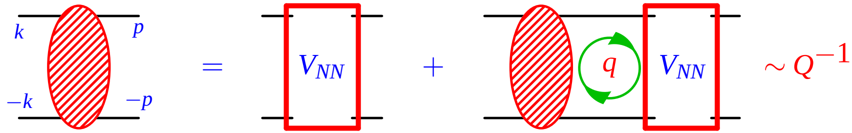


Assumptions: $\alpha_{E1}(\omega)$, $\beta_{M1}(\omega)$ well captured, only two spin-polarisabilities $\gamma_{E1E1}(\omega)$, $\gamma_{M1M1}(\omega)$ large; superficial fit to existing data.

$\Longrightarrow$ precision experiments on p, d, ^{3}He: MAXLab, TUNL/HIγS, MAMI, S-DALINAC, LARA, ...

Only phenomenological input: **Non-relativistic system with shallow (real/virtual) bound-state.**

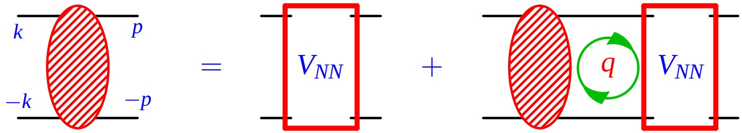
$$T_{NN}(E \sim \frac{p^2,k^2}{M}) \sim Q^{-1}$$



Power-Counting: $Q^m \qquad Q^m \qquad Q^{2m+3-2} \stackrel{!}{=} Q^m \implies m = -1$

Only phenomenological input: **Non-relativistic system with shallow (real/virtual) bound-state.**

$T_{NN}(E \sim \frac{p^2,k^2}{M}) \sim Q^{-1}$

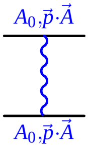


$\sim Q^{-1}$

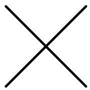
Power-Counting: Q^m $\quad Q^m \quad Q^{2m+3-2} \stackrel{!}{=} Q^m \implies m=-1$

Examples: **NRQCD/NRQED** **EFT($\not\pi$)** **χEFT**

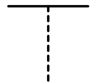
Coulomb



$\sim v^{-1}$



$C_0 \sim Q^{-1}$ $+$

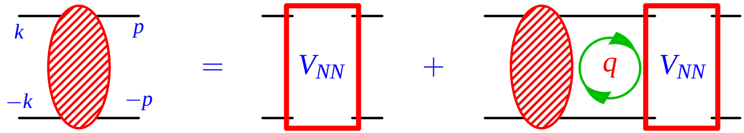


$-\frac{g_A^2}{4f_\pi^2}\,\vec{\tau}_1\cdot\vec{\tau}_2\,\frac{\vec{\sigma}_1\cdot\vec{q}\;\vec{\sigma}_2\cdot\vec{q}}{\vec{q}^{\,2}+m_\pi^2} \sim Q^{-1}$

T_{NN} non-perturbative only in bound-state dynamics: $E \sim \frac{Q^2}{M}$

Only phenomenological input: **Non-relativistic system with shallow (real/virtual) bound-state.**

$T_{NN}(E \sim \frac{p^2,k^2}{M}) \sim Q^{-1}$

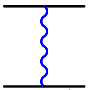


$\sim Q^{-1}$

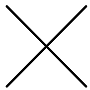
Power-Counting: Q^m $\qquad Q^m \qquad Q^{2m+3-2} \overset{!}{=} Q^m \implies m = -1$

Examples: **NRQCD/NRQED** $\qquad$ **EFT($\not\pi$)** $\qquad$ **χEFT**

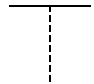
Coulomb



$\sim v^{-1}$



$C_0 \sim Q^{-1}$ $+$



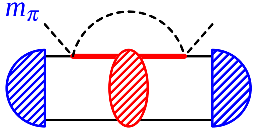
$-\frac{g_A^2}{4f_\pi^2}\,\vec{\tau}_1\cdot\vec{\tau}_2\,\frac{\vec{\sigma}_1\cdot\vec{q}\;\vec{\sigma}_2\cdot\vec{q}}{\vec{q}^{\,2}+m_\pi^2} \sim Q^{-1}$

T_{NN} non-perturbative only in bound-state dynamics: $E \sim \frac{Q^2}{M}$

$T_{NN}(E \sim Q) \sim Q^0$

$E \sim m_\pi$
Nstatic

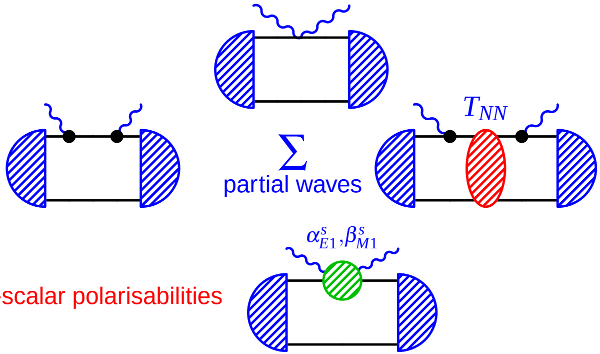
$E \sim m_\pi$



$\implies$ perturbative, 2 orders down

cf. soft photons/gluons in NRQED/NRQCD

One-body: electric, magnetic moment couplings



Iso-scalar polarisabilities

$$\omega \sim \frac{Q^2}{M} \approx 20 \text{ MeV}$$

LO Q^{-1}

LO Q^{-1}

Full LO T_{NN} pivotal for d Thomson at LO.

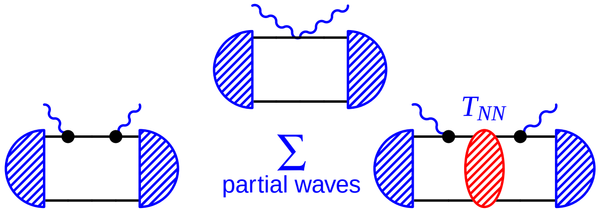
Arenhövel 1980

N^3LO

(c) Deuteron Compton Scattering at $\omega = 0 \ldots 200$ MeV

One-body: electric, magnetic moment couplings

$$\omega \sim \frac{Q^2}{M} \approx 20 \text{ MeV}$$

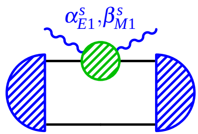


LO Q^{-1}

LO Q^{-1}

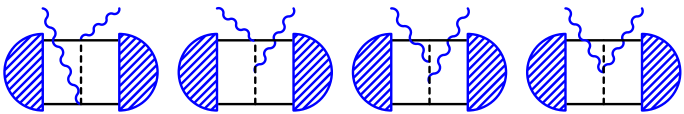
Full LO T_{NN} pivotal for d Thomson at LO.
Arenhövel 1980

Iso-scalar polarisabilities

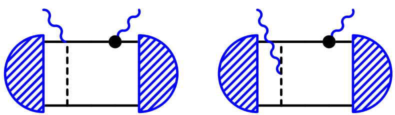


N^3LO

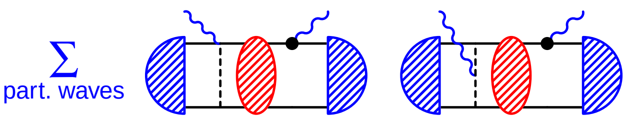
χEFT pion-exchange currents: Beane et al. 1999-2005; hg/. . . 2005



NLO



NLO

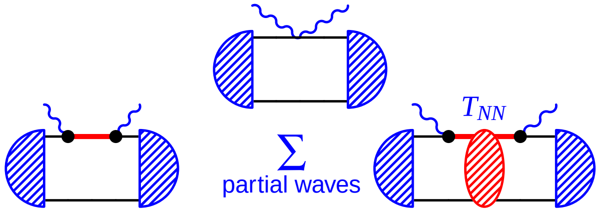


Full LO T_{NN} pivotal for total **zero** NLO contrib. to LET. Arenhövel 1980

(c) Deuteron Compton Scattering at $\omega = 0 \ldots 200$ MeV

One-body: electric, magnetic moment couplings

$\omega \sim \frac{Q^2}{M} \approx 20$ MeV $\quad \omega \sim Q \approx 100$ MeV

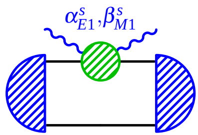


LO Q^{-1} (at $\omega \sim Q^2/M$)

LO Q^{-1} ↘ NLO, N^3LO (at $\omega \sim Q$)

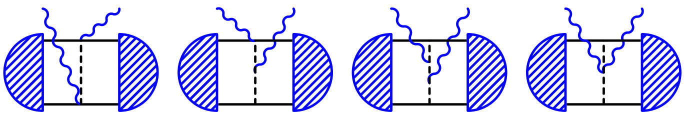
> Full LO T_{NN} pivotal for d Thomson at LO.
> Arenhövel 1980 ↘ N^3LO, perturbative

Iso-scalar polarisabilities

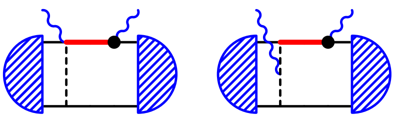


N^3LO ↗ NLO

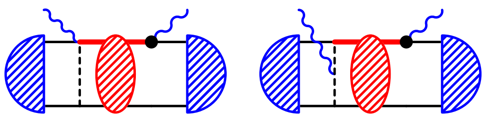
χEFT pion-exchange currents: Beane et al. 1999-2005; hg/. . . 2005



NLO → NLO



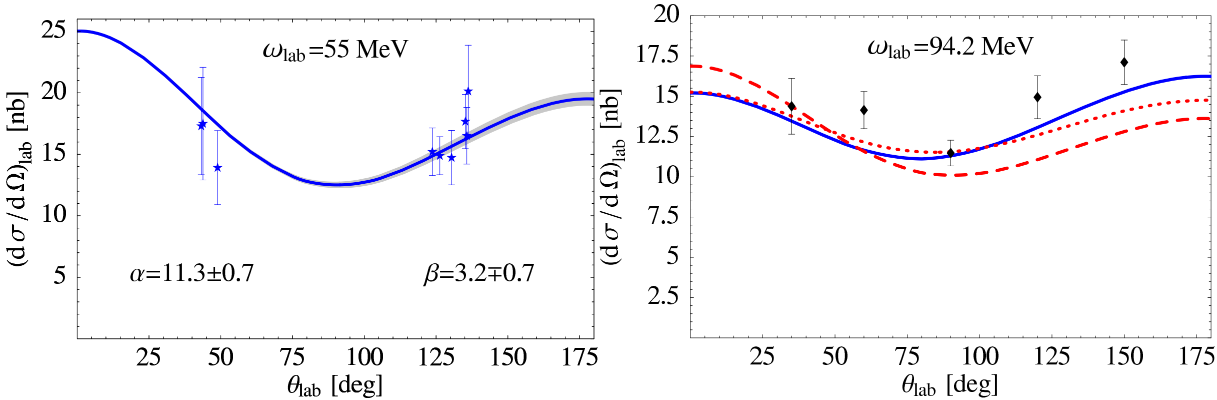
NLO ↘ N^2LO



> Full LO T_{NN} pivotal for total **zero** NLO contrib. to LET. Arenhövel 1980 ↘ N^3LO, pert.

(d) Determine Neutron Polarisabilities

Illinois ○, Lund ⋆, Saskatoon ◆ — $N\pi$ only (LO); ⋯ $N\pi$ only (NLO fit Beane et al.); — $N\pi + \Delta +$ stat. error



constrained: $\bar{\alpha}^s = 11.3 \pm 0.7_{\text{stat}} \pm 0.6_{\Sigma} \pm 1_{\text{theory}}$ $\quad\bar{\beta}^s = 3.2 \mp 0.7_{\text{stat}} \pm 0.6_{\Sigma} \pm 1_{\text{theory}}$

Proton hg/…2003: $\bar{\alpha}^p = 11.0 \pm 1.4_{\text{stat}} \pm 0.4_{\Sigma} \pm 1_{\text{theory}}$ $\quad\bar{\beta}^p = 2.8 \mp 1.4_{\text{stat}} \pm 0.4_{\Sigma} \pm 1_{\text{theory}}$

previous ranges: $[6 \ldots 18]$ $\quad[-4 \ldots 9]$

estimate theory uncertainty ($\lesssim \pm 1$): higher-order $1N$; AV18 vs. LO χEFT, d wave-fu., with vs. without T_{NN}.

$\Longrightarrow$ neutron $\approx$ proton polarisabilities