Nucleon polarizabilities from Compton scattering

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in collaboration with Vladimir Pascalutsa



International School of Nuclear Physics

Sept. 20, 2015, Erice

Outline

1) Inelastic structure, polarizabilities, and how they matter for the proton size

2) Status of dipole scalar polarizabilities

3) Disentangling the magnetic polarizability by beam asymmetry of Compton scattering

4) Multipole analysis - in progress..

5) Summary

Traditional to Callation to Estruction Scattering

Electron-proton scattering The optical theorem relates the absorptive parts of the forward VVCS amplitud structure functions, or equivalently, the cross sections of virtual-photon absorption



eq:elstructure



$$\begin{split} & \prod T_{1}(\nu,Q^{2}) Q^{2} = -(k'-k) \\ & \prod T_{1}(\nu,Q^{2}) Q^{2} = \frac{Q_{\pi^{2}\alpha}}{x} \int_{0}^{\infty} (\nu,Q^{2}) = \nu \sigma_{T}(\nu,Q^{2}), \\ & \prod T_{2}(\nu,Q^{2}) x = \frac{Q^{2}\alpha}{\nu} (p_{2}(M_{\mu}Q^{2})) = \frac{Q^{2}\nu}{\nu^{2}+Q^{2}} [\sigma_{T}+\sigma_{L}](\nu,Q^{2}), \\ & \prod S_{1}(\nu,Q^{2}) = \frac{q_{\pi^{2}\alpha}}{\nu} (p_{2}(\nu,Q^{2})) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} [\sigma_{T}+\sigma_{T}](\nu,Q^{2}), \\ & \prod S_{1}(\nu,Q^{2}) = \frac{q_{\pi^{2}\alpha}}{\nu} (p_{2}(\nu,Q^{2})) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} [p_{\pi^{2}}(\nu,Q^{2})] \\ & \prod S_{1}(\nu,Q^{2}) = \frac{q_{\pi^{2}\alpha}}{\nu} (p_{\pi^{2}}(\nu,Q^{2})) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} [p_{\pi^{2}}(\nu,Q^{2})] \\ & \prod S_{1}(\nu,Q^{2}) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}} (p_{\pi^{2}}(\nu,Q^{2})) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} [p_{\pi^{2}}(\nu,Q^{2})] \\ & \prod S_{1}(\nu,Q^{2}) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}} (p_{\pi^{2}}(\nu,Q^{2})) = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} [p_{\pi^{2}}(\nu,Q^{2})] \\ & = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} = \frac{q_{\pi^{2}\alpha}}{\nu^{2}+Q^{2}} [$$

These unitarity relations hold in the physical region, where the Bjorken variable unit interval: $x \in [0, 1]$.

The structure functions describing the purely elastic scattering are given in te FFs:

$$f_1^{\text{el}}(\nu, Q^2) = \frac{1}{2} G_M^2(Q^2) \,\delta(1-x),$$

$$f_2^{\text{el}}(\nu, Q^2) = \frac{1}{1+\tau} \Big[G_E^2(Q^2) + \tau G_M^2(Q^2) \Big] \,\delta(1-x),$$

$$g_1^{\text{el}}(\nu, Q^2) = \frac{1}{2} F_1(Q^2) G_M(Q^2) \,\delta(1-x),$$

$$g_2^{\text{el}}(\nu, Q^2) = -\frac{1}{2} \tau F_2(Q^2) G_M(Q^2) \,\delta(1-x),$$

where $\tau = Q^2/4M^2$ and $G_E(Q^2)$, $G_M(Q^2)$ are the Sachs FFs,

$$G_E = F_1 + \tau F_2, \quad G_M = F_1 + F_2.$$

Furthermore, δ is the Dirac delta-function, such that

$$\delta(1-x) = \nu_{\rm el} \, \delta(\nu - \nu_{\rm el}), \quad \text{with } \nu_{\rm el} = Q^2/2M = 2M\tau.$$

Nadiia Krupina

In the asymptotic limit, $Q^2 \rightarrow \infty$, and fixed x, the structure functions are relatively distribution functions. We are, however, interested in the limit where Q and ν are Vladimir Pascalutsa

Introduction Traditional to Relation to Structure Function Scale $(k' - k)^2$



$$\begin{split} & \prod T_{1}(\nu,Q^{2}) Q^{2} = -(k'-k) \\ & \prod T_{1}(\nu,Q^{2}) Q^{2} = \frac{Q_{\pi^{2}\alpha}^{2} - (k'-k)}{\overline{x} + \sqrt{Q^{2}} - (2M_{N}\nu)} \\ & \prod T_{2}(\nu,Q^{2}) x = \frac{Q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu} = \frac{Q^{2}\nu}{\nu^{2} + Q^{2}} [\sigma_{T} + \sigma_{L}](\nu,Q^{2}), \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{Q_{\mu}^{2} - (k'-k)}{\nu} = \frac{(k'-k)}{\nu^{2} + Q^{2}} [\sigma_{T} + \sigma_{L}](\nu,Q^{2}), \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu} = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [\sigma_{T} + \sigma_{L}](\nu,Q^{2}), \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu} = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [\sigma_{T} + \sigma_{L}](\nu,Q^{2}), \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{2}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{2}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}} [q_{\pi^{2}\alpha}^{2} - (k'-k)] \\ & \prod S_{1}(\nu,Q^{2}) x = \frac{q_{\pi^{2}\alpha}^{2} - (k'-k)}{\nu^{2} + Q^{2}}$$

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Introduction Traditional to Relation to Structure Functions \mathcal{C}^{2} Electron-proton scattering The optical theorem relates (he apsorptive parts of 2) (he to have be approximately be a solution of virtual vVCS amplitud structure functions, or equivalently, the cross sections of virtual photon absorption



$$\begin{split} & \operatorname{Im} T_{1}(\nu, Q^{2}) Q^{2} = \frac{Q_{\pi^{2}\alpha}^{2} = -(k'-k)}{\overline{x} \sqrt{Q^{2}/(2M_{N}\nu)}} \\ & \operatorname{Im} T_{2}(\nu, Q^{2}) Q^{2} = \frac{Q_{\pi^{2}\alpha}}{\sqrt{Q^{2}/(2M_{N}\nu)}} = \frac{V_{Q^{2}\nu}}{\nu^{2} + Q^{2}} [\sigma_{T} + \sigma_{L}](\nu, Q^{2}), \\ & \operatorname{Im} S_{1}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} Q^{2}}{\nu^{2}} (\varphi_{2}^{2}(M_{\mu}Q^{2})) = \frac{\varphi_{\nu}^{2} + Q^{2}}{\nu^{2} + Q^{2}} [\sigma_{T} + \sigma_{L}](\nu, Q^{2}), \\ & \operatorname{Im} S_{1}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} Q^{2}}{\nu^{2}} (\varphi_{1}^{2}(\nu, Q^{2})) = \frac{\varphi_{\nu}^{2} + Q^{2}}{\nu^{2} + Q^{2}} [\varphi_{\nu}^{2}(\nu, Q^{2}), \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{2}^{2}(\nu, Q^{2})) = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{2}^{2}(\nu, Q^{2})) = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{1}^{2}(\nu, Q^{2})) \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{1}^{2}(\nu, Q^{2})) = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{1}^{2} - \varphi_{1}^{2}) \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{1}^{2} - \varphi_{1}^{2}) \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{\nu^{2}} (\varphi_{1}^{2} - \varphi_{1}^{2}) \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{\nu}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{1}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})} \\ & \operatorname{Im} S_{2}(\nu, Q^{2}) Q^{2} = \frac{\varphi_{1}^{2} (\varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2} - \varphi_{1}^{2})}{(\varphi_{1}^{2} - \varphi_{1}^$$

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where $Q^{\sharp}/4MQ^{2}and M_{E}^{2}(Q^{2}and G_{M}Q^{2})$, the states F_{a} re the Sachs FFs

(ii) Moments of the inelastic structure functions are related to polarizabilities, e.g. Furthermore, δ is the Dirac delta-function, such that $\alpha_{E1}(Q^2) + \beta_{M1}(Q^2) = \frac{8\alpha M_N}{Q^4} \int_0^{x_0} \mathrm{d}x \, x f_1(x) \, Q_{\nu_{\mathrm{el}}}^2 \delta(\nu - \nu_{\mathrm{el}}), \quad \text{with } \nu_{\mathrm{el}} = Q^2/2M = 2M\tau.$

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(i) Describe the response of internal structure to applied external field



Magnetic dipole polarizability





(ii) Accessed experimentally in Compton scattering





Born (elastic) contributions



non-Born contribution, given by polarizabilities

(ii) Accessed experimentally in Compton scattering





Born (elastic) contributions



non-Born contribution, given by polarizabilities

(iii) Theoretical approaches:
 Effective field theory
 Dispersion relations
 Lattice QCD

Proton radius puzzle





A. Antognini et al., Science **339**, 417 (2013).

Proton radius puzzle





A. Antognini et al., Science 339, 417 (2013).

 $[R_E^{\mu \rm H} = 0.84087(39)\,\rm{fm}]$



Muonic Hydrogen Lamb shift





Vladinvira Bassial passatut Sucle Ruete Very Low WStar RG15 20 Psaka Mary 2012, 2015

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Theory: BChPT - Lensky & Pascalutsa, EPJC (2010) HBChPT - McGovern, Phillips & Griesshammer, EPJA (2013)



Baldin sum rule

$$F_{E1} + \beta_{M1} = \frac{1}{2\pi^2} \int_{\nu_{thr}}^{\infty} d\nu' \frac{\sigma_{tot}(\nu')}{\nu'^2} \simeq 14 \times 10^{-4} \text{fm}^3$$

$$f_{00} = \int_{0}^{00} \int_{0}^{0} \int_$$

1

0

0

0.5

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EPJA (2013)

2

1.5

V (GeV)



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Experiments at MAMI and HIGS facilities

<u>Past experiments</u>: measured <u>unpolarized cross sections</u> of Compton scattering to extract alpha and beta from the angular dependence. (a la Rothenbluth separation of GE, GM)

LEX:
$$\frac{d\sigma^{(\text{NB})}}{d\Omega} = -2\pi Z^2 \frac{\alpha}{M} \left(\frac{\nu'}{\nu}\right)^2 \nu \nu' \left[2\alpha_{E1} \left(1 + \cos^2\theta\right) + 4\beta_{M1} \cos\theta\right] + O(\nu^4)$$



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Extraction of beta from beam asymmetry

PRL 110, 262001 (2013) PHYSICAL REVIEW LETTERS

week ending 28 JUNE 2013

Separation of Proton Polarizabilities with the Beam Asymmetry of Compton Scattering

Nadiia Krupina and Vladimir Pascalutsa

PRISMA Cluster of Excellence Institut für Kernphysik, Johannes Gutenberg–Universität Mainz, 55128 Mainz, Germany (Received 3 April 2013; published 25 June 2013)

We propose to determine the magnetic dipole polarizability of the proton from the beam asymmetry of low-energy Compton scattering based on the fact that the leading non-Born contribution to the asymmetry is given by the magnetic polarizability alone; the electric polarizability cancels out. The beam asymmetry thus provides a simple and clean separation of the magnetic polarizability from the electric one. Introducing polarizabilities in a Lorentz-invariant fashion, we compute the higher-order (recoil) effects of polarizabilities on beam asymmetry and show that these effects are suppressed in forward kinematics. With the prospects of precision Compton experiments at the Mainz Microtron and High Intensity Gamma Source facilities in mind, we argue why the beam asymmetry could be the best way to measure the elusive magnetic polarizability of the proton.

DOI: 10.1103/PhysRevLett.110.262001

PACS numbers: 13.60.Fz, 14.20.Dh, 25.20.Dc

Definition:
$$\Sigma_3 \equiv \frac{d\sigma_{||} - d\sigma_{\perp}}{d\sigma_{||} + d\sigma_{\perp}}$$

$$LEX: \qquad \Sigma_3 \equiv \frac{d\sigma_{||} - d\sigma_{\perp}}{d\sigma_{||} + d\sigma_{\perp}} \stackrel{\text{LEX}}{=} \Sigma_3^{(\text{Born})} - \frac{4\beta_{M1}}{Z^2 \alpha_{em}} \frac{\cos\theta \sin^2\theta}{(1 + \cos^2\theta)^2} \,\omega^2 + O(\omega^4) \qquad \begin{array}{l} \text{(applicability region}\\ \text{Energy} < 100 \text{ MeV} \end{array}$$

Low energy measurement of beam asymmetry can be used to extract magnetic polarizability independently of electric one

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Extraction of beta from beam asymmetry

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(applicability region Energy<100 MeV)

Low energy measurement of beam asymmetry can be used to extract magnetic polarizability independently of electric one

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Applicability of LEX



At 100 MeV NNLO BChPT and LEX curves coincide for forward angles - 'LEX regime'

Preliminary results from MAMI



Multipole expansion

Dynamical polarizabilities:

where f_{EE}^{L+} denotes the multipole with the angular momentum of the initial photon L and the initial and final photons are both in an electrical mode.

The values of scalar polarizabilities can be obtained by extrapolation of dynamical polarizabilities to zero energy.





ii) Low energy measurement of the beam asymmetry can be used to extract the magnetic polarizability independently from the electric one.



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Thank you for listening