PROCEEDINGS OF SCIENCE

Real and Virtual Compton Scattering at MAMI

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Polarizabilities are fundamental properties of hadrons and, since they are defined in the static limit, are an ideal testing ground for hadron models. They can be accessed via real or virtual Compton scattering at electron accelerators with the clean electromagnetic probe of a photon in initial and final state. The experiments are challenging, however, since the signal is small and the background is high. In this presentation the experimental program at MAMI will presented, both for real and for virtual Compton scattering.

52 International Winter Meeting on Nuclear Physics - Bormio 2014,
27-31 January 2014
Bormio, Italy

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PoS(Bormio2014)048

1. Introduction

Polarizabilities are defined as the response of a system to an external electric or magnetic field. For example, an electric field induces an electric dipole moment proportional to the field strength, and the electric polarizability α_E is defined just as the proportionality constant between field and dipole moment. Since these polarizabilities are defined for static fields, this is a rare case where the intuitive picture of classical electro-dynamics still holds for the quantum-mechanical objects like hadrons.

For hadrons, the origin of the polarizabilities is the strong interaction, leading to very "stiff" objects with a corresponding tiny polarizability which can not be measured by a static field. The same polarizabilities can be accessed, however, via a dynamic measurement by Compton scattering which is dominated in the static limit of vanishing photon moment by the polarizabilities.

In this contribution, an overview of the program to determine the polarizabilities of the proton at the Mainz Microtron (MAMI), both in real and virtual Compton scattering, is presented.

2. Real Compton Scattering

The cross section of real Compton scattering on the proton, i.e. of the reaction $\gamma + p \to \gamma + p$, is given in the low energy limit by

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} - \frac{e^2}{4\pi m_p}\left(\frac{q'}{q}\right)^2 q q' \left\{\frac{1}{2}(\bar{\alpha}+\bar{\beta})(1+\cos\theta)^2 + \frac{1}{2}(\bar{\alpha}-\bar{\beta})(1-\cos\theta)^2\right\} + \cdots,$$

i.e. the sum of electric and magnetic polarizability in forward and the difference in backward direction (σ_0 is the cross section of a point-like object, q (q') is the momentum of the incoming (outgoing) photon).

The current status of the available data is summarized by fig. 1 (from ref. [3]). The most recent measurement was by the A2/TAPS Collaboration at MAMI [2] using unpolarized Compton scattering. Also shown in this pictures are calculations in BχPT [3] and HBχPT [1] which demonstrate a principle problem of any unpolarized measurement: The measurement is performed at a finite photon momentum, while the polarizabilities have to be extracted by an extrapolation to the static limit. For the TAPS data, this was done by a dispersion relations calculation. The newer calculations could show, that they also can describe the data sets with a reasonable fit quality with a significant deviation from the extracted data points. Especially the electric polarizability α is not well extracted from unpolarized data. This clearly shows the need for an independent extraction of the polarizabilities using polarization observables. The Particle Data Group quotes a value for the polarizabilities using the Baldin Sum rule, i.e. the dispersion integral

$$\alpha + \beta = \frac{1}{2\pi^2}\int_{\omega_0}^{\infty} \frac{\sigma_{\text{total}}(\omega)}{\omega^2} d\omega,$$

and the fits in Chiral Perturbation Theory. The first aim of the MAMI real Compton scattering program is to improve the separation of α and β via polarization observables.

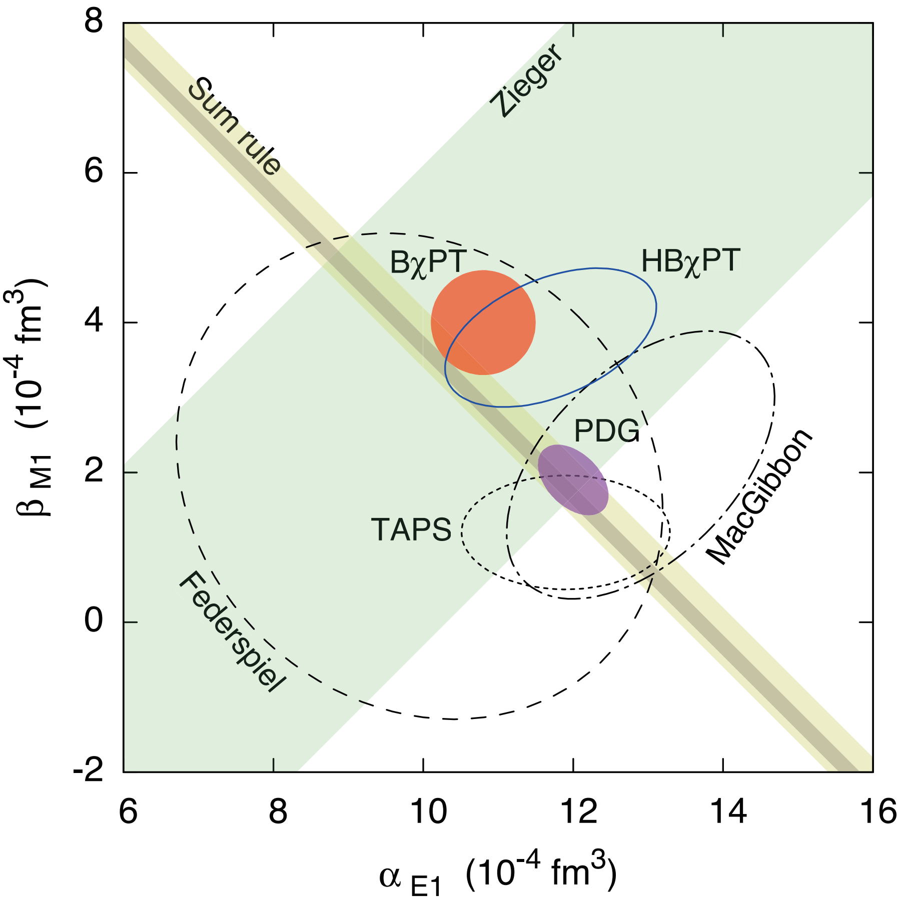

Figure 1: The current status of the scalar polarizabilities α and β of the proton. The band shows the Baldin sum rule. The most recent measurement is by TABS [2]. Also shown are calculations in BχPT [3] and HBχPT [1] and PDG value.

3. Polarization Observables

The Crystal Ball Detector of the A2 Collaboration at MAMI is a large solid angle photon detector operated at the tagged photon facility of the A2 Collaboration and is well suited for the detection of Compton scattering events. A new quality is added by the use of a polarized frozen spin target in combination with a polarized photon beam produced e.g. by coherent Bremsstrahlung on a diamond crystal. A series of experiments were started to improve the knowledge of the scalar polarizabilities and to provide first measurements of the spin polarizabilities.

With double polarization observables, the separation of the scalar polarizabilites can be improved significantly by the measurement of the observable

$$\Sigma_3 = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}$$

measuring the cross sections with transverse beam polarization oriented parallel and perpendicular

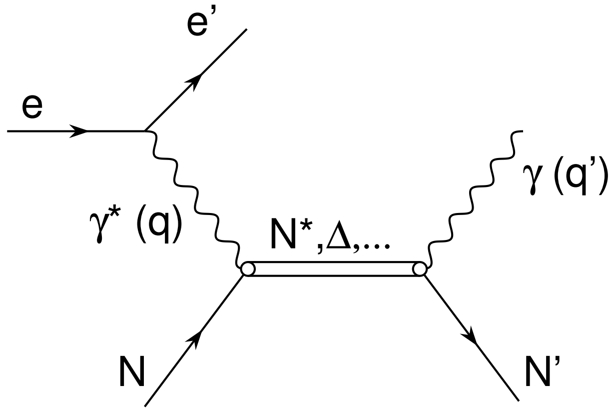

Figure 2: Virtual Compton scattering.

to the target polarization. Since the magnetic polarizability β is proportional to

$$\beta \propto \cos^2\theta \left(\frac{d\sigma_\perp}{d\Omega} - \frac{d\sigma_\perp^{\mathrm{Born}}}{d\Omega}\right) - \left(\frac{d\sigma_\parallel}{d\Omega} - \frac{d\sigma_\parallel^{\mathrm{Born}}}{d\Omega}\right)$$

it will be determined independent from α for the first time.

4. Spin-Polarizabilities

While there is an intuitive picture of the scalar polarizabilities from classical electro-dynamics, the measurement of polarizabilites via photon absorption and emission implies the existence of higher order polarizabilities by adsorption and emission via higher order multipoles. In real Compton scattering there exist four spin polarizibilities γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, and γ_{M1E2}, where the first index indicates the multipole of the adsorption and the second index indicates the multipole of emission.

Up to now there exist no data on these spin polarizabilites, only on the combinations

$$\begin{aligned}\gamma_0 &= -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2} &= -\frac{1}{4\pi^2}\int_{\nu_{\mathrm{thr}}}^{\infty} \frac{\sigma_{3/2}(\nu) - \sigma_{1/2}(\nu)}{\nu^3} d\nu\} \\ \gamma_\pi &= -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}\end{aligned}$$

data exists from experiments measuring the Gerassimov-Drell-Hearn sum rule.

The spin polarizabilities will be measured e.g. with circular polarized beam on linear polarized beam

$$\Sigma_{2x} = \frac{\sigma_{+x}^{\circlearrowright} - \sigma_{+x}^{\circlearrowleft}}{\sigma_{+x}^{\circlearrowright} + \sigma_{+x}^{\circlearrowleft}}$$

which is sensitive to γ_{E1E1} or via

$$\Sigma_{2z} = \frac{\sigma_{+z}^{\circlearrowright} - \sigma_{+z}^{\circlearrowleft}}{\sigma_{+z}^{\circlearrowright} + \sigma_{+z}^{\circlearrowleft}}$$

which is sensitive to γ_{M1M1}. Finally, an overall fit of all polarization observables will disentangle all four spin polarizabilities.

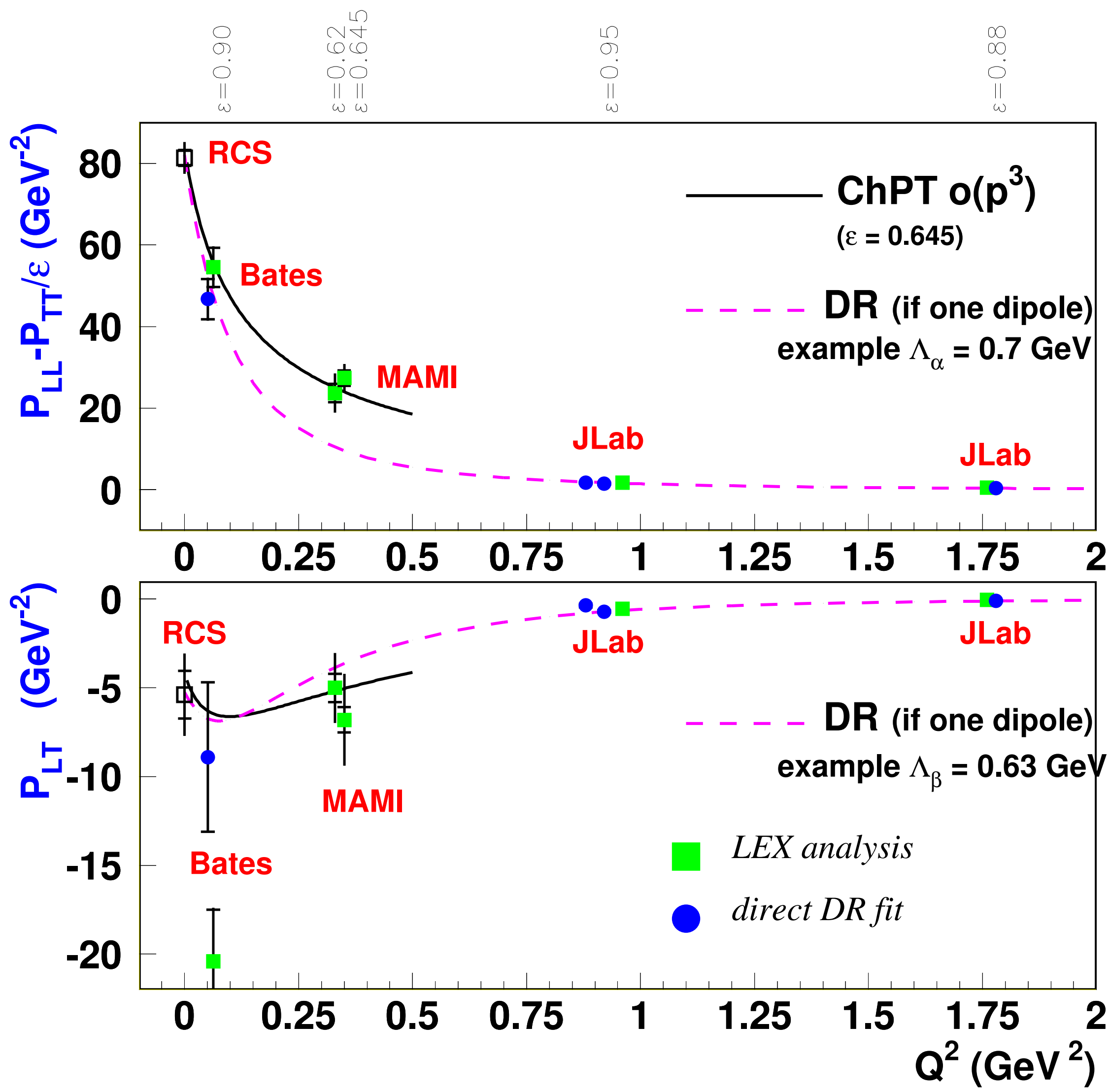

Figure 3: Data on Virtual Compton scattering from MAMI [5], JLab [6], and Bates [7]. The lines show calculations in Chiral Perturbation Theory (ChPT) [8] and calculations using Dispersion Relations (DR) [9].

5. Virtual Compton Scattering

The concept of real Compton scattering can be extended by using a virtual photon in the initial state. Fig. 2 shows the corresponding graph of the virtual Compton scattering amplitude. The polarizabilities, again defined in the limit of vanishing outgoing photon momentum, are now dependent on the four momentum transfer Q^2 of the virtual photon and are called generalized polarizabilities. These generalized polarizabilities (GPs) can be interpreted as related to the fourier-transform of the spatial distribution of the polarizabilities [4].

While the GPs can be calculated in different models at the same level as the real polarizabilities, the experimental access is more challenging than in real Compton scattering experiments. The reason is, that the VCS amplitude is covered by an overwhelming background of radiative photon emission of the incoming or outgoing electron, the so called Bethe-Heitler process. This cross section of the Bethe-Heitler-Background is several orders larger in most directions of the photon emission with sharp peaks in the direction of the incoming or the outgoing electron. An experiment on VCS is only possible using magnetic spectrometers with limited acceptance in the kinematical region where the interference between Bethe-Heitler process and VCS is sizable. The effect of the GPs is even there only on the percent level.

Nevertheless, there are now several data points available from MAMI [5], JLab [6] and Bates [7].

Fig. 3 summarizes the current status of the data on unpolarized VCS. While the domain of JLab is the higher Q^2 region, the MAMI data point is at an intermediate value of the four-momentum transfer of $Q^2 = 0.33\,\mathrm{GeV}^2/c^2$. While there is no reliable model available to predict the Q^2 dependence of the GPs over the full Q^2 range, the Bates point bridging the MAMI point and the Real Compton point seems to indicated a surprising rapid variation with Q^2.

However, all data points were taken in different experiments with significant differences in kinematical conditions. Also the analysis with dispersion relations (denoted DR in fig. 3) or using low energy expansion (denoted LEX) differs for the data points. Therefore a program was started at the A1 Collaboration at MAMI to cover several Q^2 points, including the Bates value, within a single series of experiments with comparable conditions. Also special care was taken to select a kinematical region were the differences between the different approaches to extract the GPs are minimized.

6. Conclusions

Polarizabilities are fundamental properties of the nucleon and provide a stringent testing ground for hadron models and ab initio calculations.

First results on electric and magnetic polarizabilities will be soon complemented by new measurements of the spin polarizabilities by the A2 Collaboration at MAMI, giving access for the first time to the full set of polarizabilities for the real photon case and disentangling the spin response of the proton to an electro-magnetic field.

In addition, the spatial structure of the nucleon will be tested by new experiments by the A1 Collaboration to investigate the Q^2 dependence of the electric and magnetic Generalized Polarizabilities in the Virtual Compton Scattering process, leading to new constrains on the spatial distribution of the polarizabilities.

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