Beam-helicity asymmetry measurements in the Virtual Compton Scattering reaction in the $\gamma^* N \rightarrow \Delta$ transition at $Q^2 = 0.20$ (GeV/c)$^2$

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We report on new beam-helicity asymmetry measurements ($A_h$) of the $H(e, e'p)\gamma$ reaction in the $\Delta(1232)$ resonance at $Q^2 = 0.20$ (GeV/c)$^2$. The measurements were performed at MAMI and were carried out simultaneously with the measurement of the $H(e, e'p)\pi^0$ reaction channel. It is the lowest $Q^2$ for which the $A_h$ for the virtual Compton scattering (VCS) reaction has been measured in the first resonance region. The measured asymmetries have been compared and have been found to be well described by dispersion-relation (DR) calculations for VCS. The sensitivity of the data to the Generalized Polarizabilities (GPs) of the proton and to the amplitudes associated with the nucleon excitation to the $\Delta(1232)$ has been explored through the DR formalism. The measured asymmetries have been found to exhibit a much higher sensitivity to the GPs while it is suggested that future measurements of higher statistical precision will offer stronger constraints to theoretical calculations and will provide valuable insight towards a more complete understanding of the GPs of the proton and of the $\pi N$ amplitudes.

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A fundamental question of nuclear physics is the description of the internal structure of the nucleon. While the small distance structure of the nucleon is adequately described by point-like quarks and gluons, its description at larger distance can involve both quark and baryon-meson degrees of freedom. The study of the structure of the nucleon can be pursued by the exploration of a number of complementary reactions and through the measurement of various type of observables. Polarization observables have been proven a very valuable tool towards this direction in the recent years. Such observables have been explored at higher energies to access the generalization of parton distributions through the exclusive deep virtual compton scattering reaction and for the study of the transverse spin structure of the nucleon in semi-inclusive deep inelastic scattering while at lower energies they can provide significant sensitivity to various amplitude interferences through the exploration of pion- and photon-electroproduction reactions.

One of the reaction mechanisms sensitive to the electromagnetic structure of the nucleon is the Virtual Compton Scattering (VCS) reaction. VCS off the proton refers to the reaction $\gamma^* p \rightarrow e' p$, which is accessed experimentally through photon electroproduction $ep \rightarrow e'p$, and is the coherent sum of the Compton process and the Bethe-Heitler (BH) process. The BH process refers to the photon emission by the incoming or outgoing electron and it adds coherently to the VCS amplitude. The Compton amplitude decomposes into a Born term, characterized by a proton in the intermediate state, and a Non-Born term containing all other intermediate states; the Born part is given in terms of nucleon ground state properties and the non-Born part contains all nucleon excitations and meson-loop contributions. The BH and Born amplitudes are entirely calculable, with the proton electromagnetic form factors as inputs.

The VCS has been proven in the recent years a valuable reaction, complementary to elastic scattering and to pion-production, which has provided new insights on the nucleon internal structure. Previous experiments, both below and above the pion threshold, have focused on the study of the generalized polarizabilities (GPs) of the proton $[1, 2, 3, 4]$ and the exploration of the res-
amplitude and to the understanding of its $Q^2$ dependence. Through the $A_h$ measurements one can test the theoretical models mostly towards their prediction of the imaginary part of VCS. Towards this direction we exploit the Dispersion-Relation (DR) calculation \cite{8,9} for virtual Compton scattering. In this model the VCS non-Born contribution is given in terms of dispersive integrals relating the real and imaginary parts of the amplitude. The imaginary part is calculated, through the unitarity relation, from the scattering amplitudes of electro- and photo-production on the nucleon, taking into account the dominant contribution from $\pi N$ intermediate states. The DR model has two free parameters, $\Lambda_\alpha$ and $\Lambda_\beta$, related to the dipole electric and magnetic GPs, respectively, while the amplitudes for $\gamma^{(*)} p \rightarrow \gamma \pi$ entering the unitarity relation are taken from the MAID-2007 \cite{10} model. A measurement of $A_h$ offers a strong cross-check of the dispersion formalism for VCS.

The experiment was performed at the Mainz Microtron MAMI utilizing an 855 MeV longitudinally polarized electron beam with an average beam current of 25 $\mu$A employed on a 5 cm long liquid-hydrogen target. The longitudinal beam polarization was $\approx 75\%$ throughout the experiment. The A1 magnetic spectrometers \cite{11} were used for the proton and electron detection; Electrons and protons were detected in coincidence with spectrometers A and B respectively. The detector package in each spectrometer includes a set of vertical drift chambers for particle tracking and scintillator detectors for timing and particle identification measurements while a Cerenkov counter was also used for the electron identification.

The $H(\vec{e}, e' p) \gamma$ reaction was performed at $Q^2 = 0.20$ (GeV/c)$^2$ and at $W = 1210$ MeV. The measurement of the $H(\vec{e}, e' p) \gamma$ reaction channel was performed simultaneously with the measurement of the $H(\vec{e}, e' p) \pi^0$ chan-

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{The coincidence time spectrum for the $H(\vec{e}, e' p) \gamma$ reaction.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{The derived missing mass spectrum, plotted as a function of the square of missing mass shows the superb resolution achieved, essential to isolating the small photon decay branch of the $\Delta(1232)$ Resonance. Channels for $M^2 < 0.01 GeV^2$ have been multiplied by a factor of twenty.}
\end{figure}
The measured beam-helicity asymmetries $A_h$ as a function of $\phi_{\gamma'\gamma}$. The errors correspond to the statistical and the total experimental uncertainties. The DR calculation is presented along with the data. At the top panels the sensitivity to the $\pi N$ amplitudes is explored (with the re-fit resulting from [12]). At the bottom panels the sensitivity to the GPs is investigated.

The measured beam-helicity asymmetries $A_h$ are presented in Fig. 3. Both the statistical and the total experimental uncertainties are exhibited. The results are dominated by the statistical uncertainties since the data acquisition time was optimized for the measurement of the $\pi^0$ channel which is characterized by a much higher count rate. The systematic uncertainties are driven mainly by the uncertainty of the central momenta and the spectrometer angles as well as from the uncertainty introduced to the final results by the variation of the analysis cuts. The central momenta and spectrometer angle uncertainties were varied in the analysis procedure in order to quantify the corresponding uncertainties. The deviations introduced to the extracted values of $A_h$ resulting primarily from the variation of the size of the kinematical phase space bins (polar and azimuthal angles, invariant mass and four-momentum transfer), and of the coincidence-time and missing-mass analysis cuts were quantified as the corresponding analysis cuts systematic uncertainties. A cut on the target length is also applied in the analysis to ensure the elimination of any contribution resulting from background processes coming from the target walls. Detector inefficiencies and dead-times are canceled out in the asymmetry. Moller polarimeter measurements provided the measurement of the longitudinal beam polarization with a relative uncertainty better than 2%; this uncertainty results to a corresponding
systematic uncertainty to the $A_h$. In order to extract the final $A_h$ result a theoretical model has to be used to project the finite phase space to point kinematics; for this part the DR [8, 9] model was used. The projection introduces a corresponding uncertainty due to the uncertainty of the description of the theoretical model but this uncertainty is rather small, at the order of $\approx 0.1\%$ in absolute magnitude for the extracted asymmetries. Radiative corrections [14, 15] have also a negligible effect to the asymmetry. The overall systematic uncertainties, for all of the experimental points, are approximately 50% of the corresponding statistical uncertainty.

The results are compared to the predictions of the DR [8, 9] calculation as exhibited in Fig. 3. The DR calculation is found to describe successfully the data, although the experimental errors are rather big. The $A_h$ has been extracted at various $\phi_{\gamma N}$ angles thus providing the opportunity to explore its azimuthal angle dependence which is not known analytically. The data support a $\sin \phi_{\gamma N}$-like dependence as expected from the pure VCS contribution in the numerator of the asymmetry. The sensitivity of the DR calculation to both the $\pi N$ amplitudes and to the GPs of the proton is also explored (top and bottom panels of Fig. 3 respectively). The default DR calculation is using the MAID $\pi N$ amplitudes; the calculation is also presented with the values of the three $N \rightarrow \Delta$ resonant amplitudes re-fitted utilizing the $\pi^0$ channel measurements [12] at the same kinematics. As exhibited in Fig. 3(a) and Fig. 3(b) the sensitivity to the resonant amplitudes is quite small. A re-fit including also the $S_{0+}$ amplitude, in addition to the three resonant ones, was also performed; the sensitivity to the $S_{0+}$ amplitude is provided through the fifth-structure function $a_{1F}'$ measurements of the $\pi^0$ channel [12]. Although this re-fit differentiated significantly the value of $S_{0+}$, the result of the corresponding DR calculation practically coincided with the DR calculation utilizing only the resonant amplitudes re-fit. The DR sensitivity to the GPs has also been explored as exhibited in Fig. 3 (panels (c) and (d)). The DR calculation has been explored by applying a rather small variation of $\pm 0.1$ to the $\Lambda_\alpha$ and $\Lambda_d$ (the two parameters related to the dipole electric and magnetic GPs respectively) with respect to the central corresponding values of 0.7 and 0.5. It is evident that the $A_h$ offers a much higher sensitivity to the GPs compared to the $\pi N$ amplitudes. The highest sensitivity is exhibited to the electric polarizability. Nevertheless, the uncertainty of the data is rather big to allow us to significantly constrain these parameters. The fact that our uncertainties are driven by statistical errors is suggesting that future dedicated measurements of higher statistical precision will be able to offer strong constraints to the electric polarizability, at the present kinematics. It is quite interesting that the interplay of the amplitudes to the GPs is quite different in the present measurement compared to a previous measurement of $A_h$ [3] at different kinematics; the previous results [3], which are at higher $Q^2$ kinematics and at forward polar angles, exhibit higher sensitivity to the $\pi N$ amplitudes compared to the GPs.

In conclusion we have performed measurements of the beam-helicity asymmetry $A_h$ for virtual compton scattering in the $\Delta(1232)$ region accessing a new lowest $Q^2$. The experimental results, which provide access to the imaginary part of the VCS, have tested the DR formalism for VCS, where the imaginary part of the VCS amplitude is connected through unitarity to the $\gamma^* \rightarrow \pi N$ amplitudes, and we have found that the calculation is in good agreement with the data which show, although within rather large uncertainties, a $\sin \phi_{\gamma N}$ dependence of the $A_h$. The sensitivity to both the GPs and to the $\pi N$ amplitudes has been explored, while also taking into account the simultaneously measured pion electro-production channel at the same kinematics, and the highest sensitivity is exhibited to the generalized electric polarizability $\alpha_E$. It is suggested that future $A_h$ measurements of higher statistical precision that will explore a wide range of the $[Q^2, \theta_{\gamma N}]$ phase-space can offer new valuable input towards a more complete description of the GPs of the proton and of the $\pi N$ amplitudes.

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