Virtual Compton scattering measurements in the $\gamma^* N \rightarrow \Delta$ transition

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We report on new H$(e, e' p)\gamma$ measurements in the $\Delta(1232)$ resonance at $Q^2 = 0.06$ (GeV/c)^2 carried out simultaneously with H$(e, e' p)\pi^0$. It is the lowest Q^2 for which the virtual Compton scattering (VCS) reaction has been studied in the first resonance region. The VCS measured cross sections are well described by dispersion-relation calculations in which the multipole amplitudes derived from H$(e, e' p)\pi^0$ data are used as input, thus confirming the compatibility of the results. The derived resonant magnetic dipole amplitude $M_{1+}^{3/2} = (40.60 \pm 0.70_{\text{stat+sys}})(10^{-3}/m_{\pi^+})$ at $W = 1232$ MeV is in excellent agreement with the value extracted from H$(e, e' p)\pi^0$ measurements.

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During the past three decades an extensive effort has been devoted to the study of the $\gamma^* N \rightarrow \Delta$ transition to precisely determine the resonant amplitudes involved in the process [1]. According to spin-parity selection rules, only magnetic dipole ($M_{1+}^{3/2}$) and electric quadrupole ($E_{1+}^{3/2}$) or Coulomb quadrupole ($S_{1+}^{3/2}$) multipoles are allowed to contribute to this transition. The magnetic dipole amplitude $M_{1+}^{3/2}$ dominates, a manifestation of the spin flip character of the transition. The presence of quadrupole amplitudes identifies and helps elucidate the origins of the nonspherical components in the nucleon wave function [2–26]. It is the complex quark-gluon and meson cloud dynamics of hadrons that give rise to nonspherical components in their wave function which at the classical limit and at large wavelengths will correspond to a "deformation."

Up until now only the dominant H$(e, e' p)\pi^0$ and the H$(e, e'\pi^+)n\Delta$ reaction channels, with branching ratios of approximately 66 and 33%, respectively, have been utilized for the determination of the resonant amplitudes in the transition. In this work, we present results obtained for the first time from the weak H$(e, e' p)\gamma$ channel. The different nature of this reaction channel, being purely electromagnetic, and the fact that it was measured simultaneously with the dominant H$(e, e' p)\pi^0$ channel [15], allows for important tests of the reaction framework and of the systematic uncertainties of the extracted resonant amplitudes. The measurement was made possible because of the excellent quality of the MAMI beam and the superb resolution and wide acceptance of its spectrometers which yielded a high resolution missing mass spectrum with the γ and π^0 simultaneously measured and widely separated (see Fig. 1).

The magnetic dipole amplitude is accurately known and the existence of nonspherical components in the nucleon wave function has been established through the extraction of resonant quadrupole amplitudes in the pion-electroproduction channels [25]. However, the control and quantification of the model error of the resonant amplitudes as well as the understanding and significance of the various interfering channels in the transition ("background channels") are still open issues and of major importance. The exploitation of the H$(e, e' p)\gamma$ reaction channel can be of central importance toward this direction. The resonant amplitude contributions are isolated within different theoretical frameworks in the pion- and photon-electroproduction channels. Background contributions, which need to be known for the determination of the weak quadrupole resonant amplitudes, are of different natures for these channels and therefore present different theoretical problems. Thus an important cross-check on the model dependence of the analysis is offered through the comparison of the results obtained from the photon- and the pion-electroproduction reactions.

In pion-electroproduction the reaction cross section can be factorized into a virtual photon flux and a sum of partial cross

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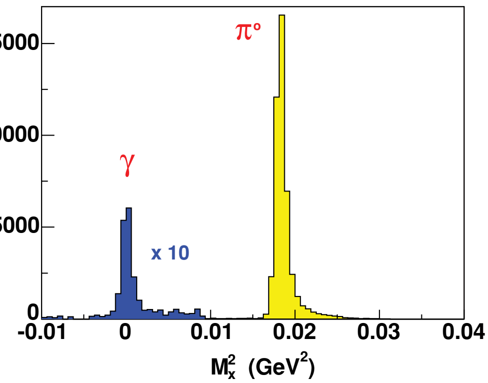

FIG. 1. (Color online) The derived missing mass spectrum, plotted as a function of the square of missing mass, shows the superb resolution achieved, essential to isolating the small photon decay branch of the $\Delta(1232)$ resonance. Channels for $M_x^2 < 0.01$ GeV^2 have been multiplied by a factor of ten.

sections $(\sigma_T, \sigma_L, \sigma_{LT}, \sigma_{TT}, \sigma_{LT'})$ that contain the physics of interest. This is not possible in the case of photon-electroproduction because the detected photon can emerge not only from the deexcitation of the $\Delta(1232)$ resonance but also from the incoming or scattered electron, from the Bethe-Heitler (BH) process. The virtual Compton scattering (VCS) reaction $\gamma^* p \rightarrow \gamma p$ amplitude also contains a Born component. The BH and Born contributions are well understood and precisely calculable with the nucleon electromagnetic form factors as inputs. The non-Born amplitude contains the physics of interest, which includes resonant amplitudes as well as Generalized Polarizabilities (GPs). Previous experiments have focused on either the extraction of the GPs from cross section measurements [27–29] or the study of the imaginary part of the VCS amplitude through beam helicity asymmetry measurements [30]. In this work sensitivities to the resonant amplitudes and to the GPs in the $\gamma^* p \rightarrow \Delta$ have been explored for the first time through cross section measurements.

The experiment was performed at the Mainz Microtron using the A1 magnetic spectrometers [31]. The experimental arrangement and parameters are those reported in Ref. [15]. An 855 MeV electron beam with an average beam current of 25 μA was employed on a liquid-hydrogen target. Electrons and protons were detected in coincidence with spectrometers A and B, respectively. The H$(e, e'p)\gamma$ reaction was performed at $Q^2 = 0.06$ (GeV/c)^2 and at the top of the $\Delta(1232)$ resonance. The measurements were taken for $\theta_{\gamma^*\gamma}$ values from 147° up to 180°, with $\theta_{\gamma^*\gamma}$ the polar angle in the c.m. frame between the initial and final photons of the VCS process, and for a range of azimuthal angles with respect to the electron scattering plane $\phi_{\gamma^*\gamma}$ from 180° to 360°. Parallel cross section measurements at $\theta_{\gamma^*\gamma} = 180°$ have also been performed covering a range of the $p\gamma^*$ c.m. energy W from 1135 to 1275 MeV.

To facilitate cross section extraction the data were sorted in kinematic bins of the following widths: $\Delta W =$ 15 MeV, $\Delta Q^2 = 0.014$ (GeV/c)^2, $\Delta\theta_{\gamma^*\gamma} = 8°$, and $\Delta\phi_{\gamma^*\gamma} =$ 30°. Point cross sections were derived from the finite acceptances by projecting the measured values using the Dispersion-Relation (DR) model [32]. 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 photoproduction on the nucleon, taking into account the dominant contribution from πN intermediate states. The DR model has two free parameters, Λ_α and Λ_β, 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 MAID 2003 [21]. The projection to the central kinematical values introduces an uncertainty of the order of 1% to the derived cross section values. Radiative corrections were applied to the data using Monte Carlo simulation; a detailed description of these corrections can be found in Ref. [33]. Elastic scattering data from H and ^{12}C for calibration purposes were taken at 600 MeV. The systematic uncertainties of the cross sections have been determined to be about 4%, whereas the statistical uncertainty is about 3 to 4% depending on the kinematics; thus both the systematic and the statistical errors have an equivalent contribution to the extracted cross section uncertainties.

In Fig. 2 we present the experimental results for the extracted cross sections at $\theta_{\gamma^*\gamma} = 156°$ and 147° for the measured azimuthal angles $\phi_{\gamma^*\gamma}$. In Fig. 3 the cross sections measured at $\theta_{\gamma^*\gamma} = 180°$ as a function of the invariant mass W are presented. The depicted uncertainties result from the combination of statistical and systematic errors added in quadrature. The experimental results are compared with the predictions of the DR model with input from MAID 2003 for the magnetic dipole and the electric and Coulomb quadrupole amplitudes. The sensitivity to the quadrupole amplitudes has been explored in the three "spherical solutions" where either one or both quadrupole amplitudes are set equal to zero. The sensitivity of the GPs has been explored by varying the Λ_α and Λ_β parameters (mass scale free parameters that determine the Q^2 dependence of the polarizabilities [32]); it was found to be insignificant compared to that of the resonant amplitudes.

The data reported here allow us for the first time to compare directly the results of both VCS and pion-electroproduction channels. This is achieved by using as input in the DR calculation the amplitudes (values and the uncertainties) extracted from the pion-electroproduction channel [15]. The shaded band in Figs. 2 and 3 shows the allowed range of compatibility (1σ) that is driven by the uncertainty in the magnetic dipole amplitude. By comparing the extracted VCS cross sections and the shaded band constrained by the pion-electroproduction measurements one has a direct cross-check of both reaction channels. The two reactions measure the same physical signal within different physical backgrounds, and therefore the compatibility of the derived amplitudes (or lack there of) tests their consistency and reliability. As shown in Figs. 2 and 3 the VCS results are in excellent agreement with the solutions compatible with the pion-electroproduction measurements.

The statistical accuracy of the cross section measurements allows the accurate extraction of the resonant magnetic dipole amplitude but not that of the two quadrupole multipoles. The $M_{1+}^{3/2}$ value extracted from the VCS data, within the framework of the DR calculation, of $(40.60 \pm 0.70_{\text{stat+sys}})(10^{-3}/m_{\pi^+})$ is in good agreement with the value of $(40.33 \pm 0.63_{\text{stat+sys}} \pm 0.61_{\text{model}})(10^{-3}/m_{\pi^+})$ determined

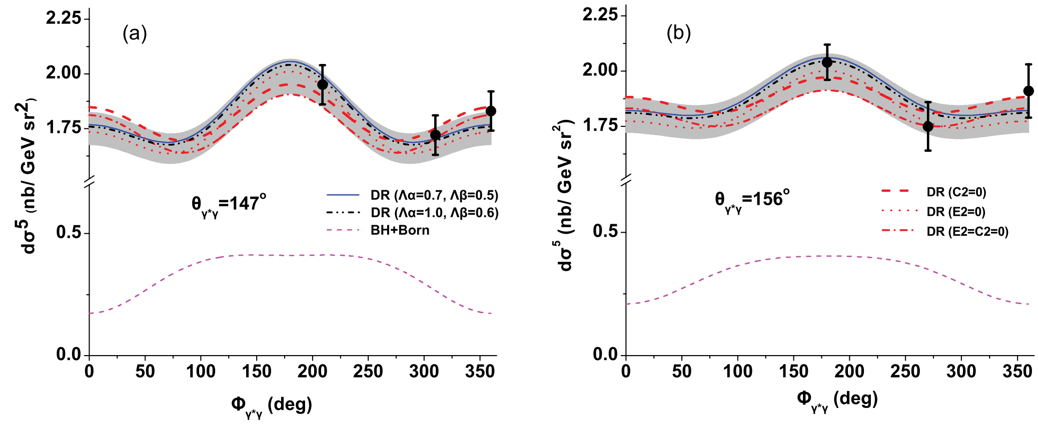

FIG. 2. (Color online) Comparison of the measured VCS cross sections at $\theta_{\gamma^*\gamma} = 147^\circ$ and 156° as a function of the azimuthal angle $\phi_{\gamma^*\gamma}$ to Dispersion Relation (DR) calculations [32] with different input. (i) Solid curves, input from the standard solutions of MAID 2003; (ii) long-dashed curves, as in (i) but with $S_{1+}^{3/2} = 0$; (iii) dotted curves, as in (i) with $E_{1+}^{3/2} = 0$; (iv) dashed-dotted curves, DR results with $S_{1+}^{3/2} = E_{1+}^{3/2} = 0$. The shaded band is derived when the dipole and quadrupole amplitudes are constrained to the values extracted from the simultaneously measured H$(e, e'p)\pi^0$ [15]. The DR calculation with the parameters $\Lambda_\alpha = 1.0$ GeV and $\Lambda_\beta = 0.6$ GeV (dash-dot-dot curves) is also shown with $\Lambda_\alpha = 0.7$ GeV and $\Lambda_\beta = 0.5$ GeV (solid curves). The uncertainties are the quadratic sum of statistical and systematic errors.

through the pion-electroproduction channel [15] and of comparable precision. The derived values are in agreement with theoretical predictions and the overall trend of the existing data as shown in Fig. 4.

In summary, we have presented measurements of the VCS reaction in the $\Delta(1232)$ resonance region obtained simultaneously with the dominant pion-electroproduction channel at the low momentum transfer of $Q^2 = 0.06$ (GeV/c)^2. Cross sections have been extracted on the top and at the wings of the resonance, both in- and out-of-plane. The measured cross sections are found to be extremely well described by DR calculations. The sensitivity of the data to the resonant dipole and quadrupole amplitudes as well as to the GPs has been explored. At the kinematics of the measurement the effect of the GPs is inconsequential. Higher sensitivity to the quadrupole amplitudes is exhibited but the large statistical uncertainty of the cross sections does not allow for their accurate separation. Given that these results were obtained in short acquisition times optimized for the π^0 channel, future dedicated measurements of higher statistical accuracy and with an improved control of the systematic error could provide better sensitivity to the quadrupole amplitudes. Covering a wider range of proton angles will also be of value in improving the sensitivity to the resonant amplitudes. The VCS cross sections are in excellent agreement with the resonant amplitudes solution from the pion-electroproduction measurements [15], which were obtained simultaneously. This first comparison between the results from photon- and pion-electroproduction channels, provides a stringent cross-check for the extraction of the resonance multipole amplitudes, rendering further support

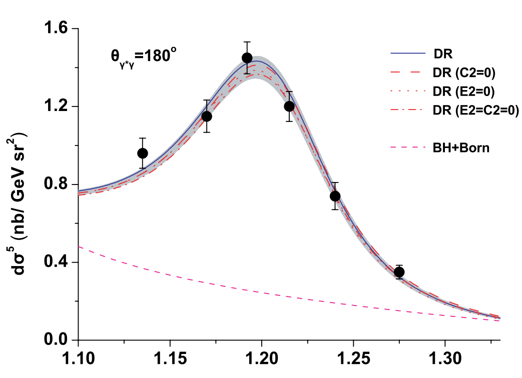

FIG. 3. (Color online) The measured VCS cross sections at $\theta_{\gamma^*\gamma} = 180^\circ$ as a function of W. The labeling conventions are the same as those in Fig. 2.

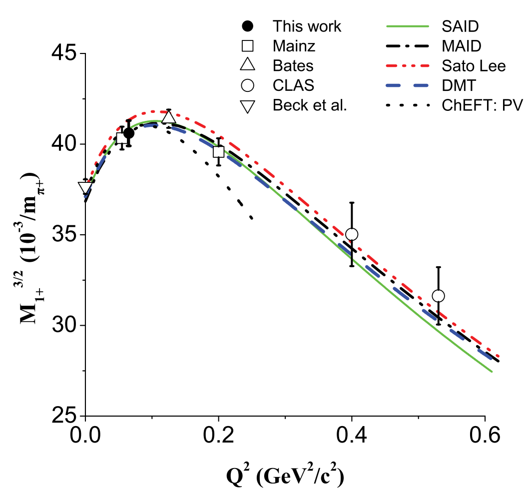

FIG. 4. (Color online) Results for $M_{1+}^{3/2}$ as a function of Q^2 from this work (VCS) and from previous pion-electroproduction experiments [3,6,12,15,24] (errors include statistical and systematic uncertainties). The two results at $Q^2 = 0.06$ (GeV/c)^2 have been shifted by 0.005 (GeV/c)^2 to be distinguishable. The theoretical predictions of MAID [21], DMT [19,20], SAID [22], Sato and Lee [18], and the ChEFT of Pascalutsa and Vanderhaeghen [34] are also shown.

to the conclusions drawn previously validating the conjectured deformation of the nucleon [3,15,25].

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