Beam spin asymmetry of $ep \rightarrow eN\pi\gamma$ reactions with the CLAS detector: pioneering experimental investigation of $\Delta$VCS

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Abstract. The Generalized Parton Distributions (GPDs) parameterize the non-perturbative content of the nucleon. They appear in the amplitude of hard exclusive processes such as DVCS on the proton ($ep \rightarrow ep\gamma$). They correlate the spatial and momentum structure of the nucleon in terms of partonic degrees of freedom. The introduction of transition GPDs extended the GPD formalism to more general final states. These GPDs can be used for instance to describe processes where the recoil nucleon is excited into a nucleon resonance. In this paper we focus on the N-$\Delta$ transition. The simplest process to access N-$\Delta$ transition GPDs is the $\Delta$VCS ($ep \rightarrow e\Delta^+\gamma$). First experimental beam spin asymmetry results associated to this process and obtained from CLAS data are presented. The $\Delta^+$ decaying into $N\pi$ pair, the analysis focused on the $ep \rightarrow eN\pi\gamma$ reactions in the $\Delta^+$ region.

1. Phenomenology of the electroproduction of a $\Delta^+$ resonance and a real photon on the proton

The $ep \rightarrow e\Delta^+\gamma$ reaction is the simplest tool to access N-$\Delta$ transition GPDs [1]. In the generalized Bjorken limit defined as

$$Q^2 \rightarrow \infty, \quad x_B \text{ fixed,} \quad t_\gamma/Q^2 \rightarrow 0, \quad W^2/Q^2 \rightarrow 0,$$

the amplitude of the $ep \rightarrow e\Delta^+\gamma$ reaction, involves two mechanisms: $\Delta$VCS described through transition GPDs and the Bethe-Heitler process where the produced photon is emitted by the incoming or outgoing electrons. Associated diagrams are shown on figure 1. The quantity $x_B$ is the Bjorken variable. The variables $Q^2$, $W$ and $t_\gamma$ are defined as:

$$Q^2 = -(k - k')^2$$

$$2M\nu = Q^2 + W^2 - M^2$$

$$t_\gamma = (p_\gamma - q)^2$$

where $k$, $k'$, $p_\gamma$ and $q$ are the four-momenta of the incoming electron, outgoing electron, produced photon and virtual photon respectively. The physical quantity $\nu$ is the virtual photon energy.
1.1. The ∆VCS process
The ∆VCS can be factorized [1] in the limit given above. This process is almost the same as DVCS, the main difference being that the recoil nucleon is excited into a ∆⁺ state. Thus the non-perturbative part of the process is described through N-∆ transition GPDs [1, 2, 3]. These functions are an extension of nucleon GPDs to final states where the recoil particle is a ∆ and contain the same type of information. This is the main motivation for studying this process: it may provide a first partonic description of the N-∆ transition as well as a 3-dimensional picture of it.

![Diagrams corresponding to the ep → e∆⁺γ reaction. On the left-hand side: ∆VCS handbag diagram. On the right-hand side: Bethe-Heitler diagram.](image)

Also in the large \( N_c \) limit, N-∆ transition GPDs are linked to nucleon GPDs with an estimated 30% accuracy [1] providing a complimentary access to these functions. The description of the ∆VCS process performed in Ref. [1] only takes into account GPDs having a significant contribution to the transition. The remaining transition GPDs entering the model are expressed in terms of nucleon GPDs through the following relations,

\[
H_M = \frac{2}{\sqrt{3}} [E^u - E^d] \quad (5)
\]

\[
C_1 = \sqrt{3} [\tilde{H}^u - \tilde{H}^d] \quad (6)
\]

\[
C_2 = \frac{\sqrt{3}}{4} [\tilde{E}^u - \tilde{E}^d] \quad (7)
\]

1.2. Beam spin asymmetry of the ep → eNπγ reactions in the ∆⁺ region
The ∆VCS and Bethe-Heitler processes interfere at the amplitude level. When using a polarized lepton beam, this results in a cross section asymmetry with respect to the incoming lepton helicity. This asymmetry, shown in figure 2, has been calculated in Ref. [1] based on the large \( N_c \) approximation as described before. These calculations take into account the contribution from non-resonant channels which are indiscernible from ∆VCS and Bethe-Heitler from an experimental point of view.

Studying the experimental ∆VCS beam spin asymmetry (BSA) means extracting experimentally the BSA of ep → eNπγ channels in the ∆⁺ region, the ∆⁺ decaying into either a pπ⁰ or a nπ⁺ pair. Corresponding experimental work is described in the next section.

2. Experiment and data analyses
2.1. Experiment
The experiment took place in 2005 at Jefferson Lab as the first part of the E01-113 experiment [4] now referred to as E06-003 [5], the first experiment dedicated to DVCS performed in Hall B.
Figure 2. Predicted beam spin asymmetry for the $ep \rightarrow eN\pi\gamma$ reactions [1]. The calculations are performed in the $\Delta^+$ region. Asymmetries are plotted as a function of the invariant mass of the nucleon-pion system, $W_{\pi N}$, for typical JLab kinematics: $E_e = 6$ GeV, $Q^2 = 2.5$ GeV$^2$, $x_B = 0.3$, $t = -0.5$ GeV$^2$, $\Phi = 90^\circ$ ($\Phi$ being the angle between hadronic and leptonic planes).

5.776 GeV polarized electron beam impinging a LH$_2$ target was used. Data were collected using the CEBAF Large Acceptance Spectrometer [6]. The photon acceptance of the CLAS detector (Fig. 3) was increased by adding a new calorimeter (Fig. 4) aiming at detecting photons at very forward angles where the majority of DVCS photons is expected.

Figure 3. Exploded view of the standard CLAS detector.

Figure 4. Image of the new inner calorimeter.

2.2. Data analyses: $ep \rightarrow eN\pi\gamma$ in the $\Delta^+$ region

Both the $ep \rightarrow ep\pi^0\gamma$ and $ep \rightarrow en\pi^+\gamma$ reactions in the $\Delta^+$ region were analysed and the corresponding BSAs extracted [7]. The particle identification was performed according to standard CLAS procedure as described in Ref. [7].

Event identification A previous analysis [8] of the $ep \rightarrow en\pi^+\gamma$ channel concluded that the non-detection of the final state photon made it difficult to disentangle the signal, $en\pi^+\gamma$ events, from background contributions. That is why all final state particles are detected in this analysis.
Then selection cuts are applied to several quantities, such as missing masses. For the $ep \rightarrow ep\pi^0\gamma$ analysis, the sideband method (a detailed example of which can be found in Ref. [9]) is used as a complimentary tool to subtract the combinatorial background under the $\pi^0$ mass peak and identify the $\pi^0$s. The invariant mass of the nucleon-pion system (illustrated on Fig. 5, r.h.s for the $ep \rightarrow en\pi^+\gamma$ channel), $W_{\pi N}$, is then used to define the $\Delta^+$ region by selecting events in the range:

$$1.08 \leq W_{\pi N}(\text{GeV}) \leq 1.32$$

(8)

Figure 5. Invariant mass $W_{\pi^+ n}$ of the nucleon-pion system for the $ep \rightarrow en\pi^+\gamma$ channel. On the left-hand side is the invariant mass before applying the selection cuts, on the right-hand side after. After event selection, the $\Delta^+$ peak around 1.2 GeV is clearly visible. The second and third peaks around 1.45 and 1.7 GeV are associated with the second and third resonance regions respectively.

A background arising from double pion electroproduction is remaining after applying selection cuts for $ep \rightarrow eN\pi\pi$ events. It is coming from $ep \rightarrow ep\pi^0\pi^0$ events for the $ep \rightarrow ep\pi^0\gamma$ channel and from $ep \rightarrow en\rho^+ \rightarrow en\pi^+\pi^0$ and $ep \rightarrow en\pi^+\pi^0$ for the $ep \rightarrow en\pi^+\gamma$ reaction. The subtraction of these background contributions is the last step of the BSA extraction. The background is estimated and then subtracted by using both Monte-Carlo simulations and exclusive $ep \rightarrow eN\pi\pi$ data. It amounts to an average of 30% for the $ep \rightarrow ep\pi^0\gamma$ analysis and of 45% for the $ep \rightarrow en\pi^+\gamma$ study and varies with the kinematics. Further details concerning the analyses may be found in Ref.[7].

Beam spin asymmetry results. The BSA of the $ep \rightarrow eN\pi\gamma$ channels in the $\Delta^+$ region is presented as a function of the angle $\Phi$ on Fig 6. It is the first time such asymmetries are extracted. Despite the size of the statistical uncertainties the asymmetries are clearly non-zero. The asymmetry goes from positive to negative for the $ep \rightarrow ep\pi^0\gamma$ channel and varies from negative to positive for the $ep \rightarrow en\pi^+\gamma$ reaction. The observed behaviour may be interpreted as the first experimental observation of the $\Delta VCS$ process through its interference with Bethe-Heitler.

The relatively low amount of statistics which is the major limitation of these analyses and the subsequent fact that data are integrated over most of the accessible phase space makes it difficult to performed a further detailed interpretation of the results.
Figure 6. Beam spin asymmetry of $ep \rightarrow eN\pi\gamma$ channels. On the left-hand side is the BSA of the $ep \rightarrow e\pi^0\gamma$ reaction, on the left-hand side of the $ep \rightarrow e\pi^+\gamma$ channel. Asymmetries are plotted as a function of $\Phi$ and shown in arbitrary unit. The error bars are statistical.

3. Conclusion
A pioneering investigation of $\Delta$VCS performed with CLAS data was shown. The clear $\Phi$-dependency observed for the beam spin asymmetry of $ep \rightarrow eN\pi\gamma$ reactions in the $\Delta^+$ region may be interpreted as the first experimental observation of $\Delta$VCS. The low amount of statistics is the major limit of the analyses. It calls for future detailed analysis of this process to be performed on a dedicated experiment optimized for these particular channels. Contextually these results may be considered equivalent to the first observation of DVCS [10, 11, 12]. If they were confirmed experimentally in an independent way, it would give a new insight on the N-$\Delta$ transition by granting access to a first partonic description of this transition.

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