Polarization Transfer in Proton Compton Scattering at High Momentum Transfer

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Compton scattering from the proton was investigated at \(s = 6.9 \text{ GeV}^2\) and \(t = -4.0 \text{ GeV}^2\) via polarization transfer from circularly polarized incident photons. The longitudinal and transverse components of the recoil proton polarization were measured. The results are in excellent agreement with a prediction based on a reaction mechanism in which the photon interacts with a single quark carrying the spin of the proton and in disagreement with a prediction of pQCD based on a two-gluon exchange mechanism.

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Real Compton Scattering (RCS) from the nucleon with \(s, -t, \) and \(-u\) values large compared to \(\Lambda_{\text{QCD}}^2\) is a hard exclusive process which provides access to information about nucleon structure complementary to high \(Q^2\) elastic form factors [1, 2] and Deeply Virtual Compton Scattering [3]. A common feature of these reactions is a high energy scale, leading to factorization of the scattering amplitude into a hard perturbative amplitude, which de-
scribes the coupling of the external particles to the active quarks, and the overlap of soft nonperturbative wave functions.

Various theoretical approaches have been applied to RCS in the hard scattering regime, and these can be distinguished by the number of active quarks participating in the hard scattering subprocess, or equivalently, by the mechanism for sharing the transferred momentum among the constituents. Two extreme pictures have been proposed. In the perturbative QCD (pQCD) approach (Fig. 1a) [4–7], three active quarks share the transferred momentum by the exchange of two hard gluons. In the handbag approach (Fig. 1b)[8–11], there is only one active quark whose wave function has sufficient high-momentum components for the quark to absorb and re-emit the photon. In any given kinematic regime, both mechanisms will contribute, in principle, to the cross section. It is generally believed that at sufficiently high energies, the pQCD mechanism dominates. However, the question of how high is “sufficiently high” is still open, and it is not known with any certainty whether the pQCD mechanism dominates in the kinematic regime that is presently accessible experimentally.

![RCS Diagrams](image)

FIG. 1: RCS diagrams for the (a) pQCD and (b) handbag reaction mechanism.

One prediction of the pQCD mechanism for RCS is the constituent scaling rule [12], whereby $d\sigma/dt$ scales as $s^{-6}$ at fixed $\theta_{CM}$. The only data in the few GeV regime from the pioneering experiment at Cornell [13] are approximately consistent with constituent scaling, albeit with modest statistical precision. Nevertheless, detailed calculations show that the pQCD cross section under-predicts the data by factors of at least ten [6], thereby calling into question the applicability of the pQCD mechanism in this energy range. On the other hand, more recent calculations using the handbag approach have reproduced the Cornell cross-section data to better than a factor of two [8, 9]. The purpose of the present experiment [14] was to provide a more stringent test of the reaction mechanism by improving significantly on the statistical precision of the Cornell data, by extending those data over a broader kinematic range, and by measuring the polarization transfer observables $K_{LL}$ and $K_{Ls}$ at a single kinematic point. The results of the latter measurements are reported in this Letter. As will be shown subsequently, these results are in unambiguous agreement with the handbag mechanism and in disagreement with the pQCD mechanism.

The present measurement, shown schematically in Fig. 2, was carried out in Hall A at Jefferson Lab, with basic instrumentation described in [15]. A longitudinally-polarized, 100% duty-factor electron beam with current up to 40 $\mu$A and energy of 3.48 GeV was incident on a Cu radiator of 0.81 mm thickness. The mixed beam of electrons and bremsstrahlung photons was incident on a 15-cm liquid H$_2$ target, located just downstream of the radiator, with a photon flux of up to $2 \times 10^{13}$ equivalent quanta/s. Quasi-real photons, which contribute 16% of total events with an average virtuality of 0.005 GeV$^2$, were treated as a part of the RCS event sample. For incident photons at a mean energy of 3.22 GeV, the scattered photon was detected at a mean scattering angle of 65° in a calorimeter consisting of an array of 704 lead-glass blocks subtending a solid angle of 30 msr and with angular resolution of 1.8 mrad and relative energy resolution of 7.7%. The associated recoil proton was detected in one of the Hall A High Resolution Spectrometers (HRS) at the corresponding central angle of 20° and central momentum of 2.94 GeV. The HRS had a solid angle of 6.5 msr, momentum acceptance of ±4.5%, relative momentum resolution of 2.5 $\times$ $10^{-4}$, and angular resolution of 2.4 mrad, the latter limited principally by scattering in the target. The trigger was formed from a coincidence between a signal from a scintillator counter in the HRS focal plane and a signal above a 500 MeV threshold in the calorimeter. In total, 15 C and 3.5 C of beam charge were accumulated for RCS production and calibration runs, respectively.

Potential RCS events were selected based on the kinematic correlation between the scattered photon and the recoil proton. The excellent HRS optics was used to reconstruct the momentum, direction, and reaction vertex of the recoil proton and to calculate $\delta x$ and $\delta y$, the difference in $x$ and $y$ coordinates, respectively, between the expected and measured location of the detected photon on the front face of the calorimeter. The distribution of events in $\delta x$ with a coplanarity cut of $|\delta y| \leq 10$ cm is shown in Fig. 3. The RCS events, which are in the peak at $\delta x = 0$, lie upon a continuum background primarily from the $p(\gamma, \pi^0 p)$ reaction, with the subsequent decay $\pi^0 \rightarrow \gamma\gamma$. An additional background is due to electrons from $ep$ elastic scattering, which is kinematically indistinguishable from RCS. A magnet between the target and the calorimeter (see Fig. 2) deflected these electrons horizontally by ~20 cm relative to undeflected RCS photons. The solid curve is a Monte Carlo simulation of the $\pi^0$ background.

The recoil proton polarization was measured by the focal plane polarimeter (FPP) located in the HRS. The FPP determines the two polarization components normal to the momentum of the proton by measuring the azimuthal asymmetries in the angular distribution after
scattering the proton from an analyzer, then taking the difference of these asymmetries between plus and minus electron beam helicity states. To improve the efficiency, two analyzers were utilized in the experiment, a 44-cm block of CH$_2$ and a 50-cm block of carbon. Vertical drift chambers together with front and rear straw chambers tracked the protons before, between, and after the analyzers, effectively producing two independent polarimeters with a combined product of efficiency and square of analyzing power that was measured to be 4.5 $\times$ 10$^{-3}$. For each analyzer separately, Fourier analysis of the helicity difference leads to the product of the proton polarizations at the FPP ($P_T^{fpp}$ or $P_s^{lpp}$), the circular polarization of the incident photon beam ($P_c$), and the FPP analyzing power ($A_y$):

$$N (\theta, \varphi) = N_0 (\theta) \left\{ 1 + \left[ P_c A_y (\theta) P_T^{fpp} + \alpha \right] \sin \varphi - \left[ P_{c} A_y (\theta) P_s^{fpp} + \beta \right] \cos \varphi \right\},$$

where $N_0$ is the number of protons which scatter in the polarimeter, $\theta$ and $\varphi$ are the polar and azimuthal scattering angles, and $\alpha$, $\beta$ are instrumental asymmetries. Determination of $A_y (\theta)$, $\alpha$, and $\beta$ for each analyzer was performed by measuring the polarization of the recoil proton from $ep$ elastic scattering at approximately the same momentum and by using previously determined ratio of the proton form factors [2]. The electron beam polarization was measured to be $0.766 \pm 0.026$ at the start of the experiment using a Møller polarimeter and continuously monitored throughout the production runs by observing the asymmetry due to the large $p(\gamma, \pi^0 p)$ background. An upper limit of 2% for the change of the beam polarization during the experiment was obtained from the pion data. The bremsstrahlung photon has 99% of the initial electron polarization over the energy range used [16].

To relate the proton polarization components at the focal plane to their counterparts at the target, the precession of the proton spin in the HRS magnetic elements was taken into account using a COSY model [17] of the HRS optics for the spin transport matrix. The elements of this matrix depend on the total precession angle, which was near 270° in order to optimize the determination of $K_{LL}$. The proton spin vector was then transformed to the proton rest frame, with the longitudinal axis pointing in the direction of the recoil proton in the center of mass frame [9]. In that frame, the longitudinal and transverse components of the proton polarization are just the spin transfer parameters $K_{LL}$ and $K_{LS}$, respectively.

The RCS events are selected from a small elliptical region at the origin of the $\delta x - \delta y$ plane. For each spin component, the RCS recoil polarization is given by

$$P_{RCS} = [P_{all} - (1 - R) P_{bkg}] / R,$$

where $P_{all}$ and $P_{bkg}$ are the polarizations for all events and background events in that region, respectively, and $R$ is the ratio of RCS to total events. The background polarization was measured by selecting events from regions of the $\delta x - \delta y$ plane that contain neither RCS nor $ep$ elastic events. It was determined that within the statistical precision of the measurements, $P_{bkg}$ was constant over broad regions of that plane. Results obtained with the two polarimeters were statistically consistent and were averaged. With the RCS region selected to obtain the best accuracy on $P_{RCS}$, one finds $R = 0.383 \pm 0.004$ (see Fig. 3) and the resulting polarizations are given in Table I.

The result for $K_{LL}$ is shown in Fig. 4 along with the results of relevant calculations. In the handbag calculation using Generalized Parton Distributions (GPD),

$$K_{LL} \simeq \frac{R_A}{R_V} K^{KN}_{LL} \left\{ 1 - \frac{1}{2} \frac{E^2}{\left( 1 + E^2 \right)^2 \left( 1 - \frac{Q^2}{4 M^2} \right)^{-1}} \right\}^{-1},$$

where $R_A, R_V$ are axial and vector form factors, respectively, that are unique to the RCS process [9]. The experimental result implies the ratio $R_A / R_V = 0.81 \pm 0.11$. 

FIG. 2: Schematic layout of the RCS experiment.

FIG. 3: Distribution of events in $\delta x$ (points) with a coplanarity cut $|\delta y| \leq 10$ cm. The RCS and $ep$ elastic events form the peaks at $\delta x = 0$ and -20 cm, respectively, and the photo-pion events the underlying continuum. A Monte Carlo simulation of the latter events is indicated by the solid curve. The difference between the data and simulation is shown by the points with uncertainties.
TABLE I: Proton recoil polarizations. For the RCS polarization the first uncertainty is statistical; the second is systematic and dominated by the background subtraction.

|   | $P_{alt}$ | $P_{bg}$ | $P_{RCS} = K_{LL}$ ($K_{LS}$) |
|---|-----------|-----------|-------------------------------|
| L | 0.588±0.030 | 0.532±0.006 | 0.678±0.083±0.04 |
| S | 0.340±0.029 | 0.480±0.006 | 0.114±0.078±0.04 |

FIG. 4: Our result for $K_{LL}$ compared with calculations in different approaches: ASY and COZ both from pQCD [7], GPD [18], extended Regge model [19], and CQM [11]. The curve labeled KN is $K_{LL}^{KN}$, the Klein-Nishina asymmetry for a structureless proton.

The excellent agreement between the experiment and the GPD-based calculation, shown with a range of uncertainties due to finite mass corrections [20], and the close proximity of each to $K_{LL}^{KN}$ are consistent with a picture in which the photon scatters from a single quark whose spin is in the direction of the proton spin. The RCS form factors are certain moments of the GPD’s $H$ and $H$ [8, 9], so our result provides a constraint on relative values of these moments. An alternative handbag-type approach using constituent quarks (CQM) [11], with parameters adjusted to fit $G_E^p$ data [2], is also in excellent agreement with the datum. Also in good agreement is a semi-phenomenological calculation using the extended Regge model [19], with parameters fixed by a fit to high-$t$ photoproduction of vector mesons. On the other hand, the pQCD calculations [7], shown for both the asymptotic (ASY) and the COZ [21] distribution amplitude, disagree strongly with the experimental point, suggesting that the asymptotic regime has not yet been reached.

A non-zero value of $K_{LS}$ implies a proton helicity-flip process, which is strictly forbidden in leading-twist pQCD. In the GPD-based approach [10], $K_{LS}/K_{LL} \approx (-\hat{t}/2M)R_T/R_V$, where $\hat{t}$ is the four-momentum transfer in hard subprocess of the handbag diagram, $M$ is the proton mass, and $R_T$ is a tensor form factor of the RCS process. From the experimental result for $K_{LS}$, we estimate $R_T/R_V = 0.21 \pm 0.11 \pm 0.03$, where the first uncertainty is statistical and the second is a systematic due to the mass correction uncertainty in calculating $\hat{t}$ [20]. A value of 0.33 was predicted for $R_T/R_V$ [10] based on hypothesis $R_T/R_V = F_2/F_1$, the ratio of the Dirac and the Pauli electromagnetic form factors. Although the uncertainties are large, the present data suggest that $R_T/R_V$ may fall more rapidly with $-t$ than $F_2/F_1$, $K_{LL}$ vanishes in the CQM-based handbag calculation [11].

In conclusion, the polarization transfer observables, $K_{LL}$ and $K_{LS}$ were measured for proton Compton scattering in the wide-angle regime at $s = 6.9$ GeV$^2$ and $t = -4.0$ GeV$^2$. $K_{LL}$ and $K_{LS}$ are in good agreement with calculations based on the handbag reaction mechanism.

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