Recent Results in Real and Virtual Compton Scattering at Jefferson Lab

Charles E. Hyde-Wright

Old Dominion University
Norfolk VA 23529 USA

chyde@odu.edu
Compton Scattering
Different physics highlighted in different kinematic domains.

Real Compton Scattering
Forward limit
Dispersion Relations,

Low Energy Theorem:
GDH Sum Rule
Electric, Magnetic, & Spin Polarizabilities

High Energy,
Wide Angle Compton Scattering
s-\(M^2\), \(M^2-u\), \(-t \gg \Lambda_{QCD}^2\)

\[
\begin{align*}
s &= (q+p)^2, \\
u &= (p-q')^2 \\
t &= (q-q')^2
\end{align*}
\]
Virtual Compton Scattering

Low Energy Theorem:
(P. Guichon et al)
Generalized Polarizabilities
Dispersion Relations,
(B. Pasquini et al)

Deeply Virtual Compton Scattering
s-M^2, Q^2 >> \Lambda_{QCD}^2
-t << Q^2
Generalized Parton Distributions
Spatial imaging of quarks & gluons

Wide angle Compton Scattering
s,Q^2, -t large, no constraint on u.

\[ s = (q+p)^2, \]
\[ Q^2 = -q^2, \]
\[ u = (p-q')^2 \]
\[ t = (q-q')^2 \]
Jefferson Lab
Continuous Electron Beam Accelerator Facility

Hall A
High Resolution Spectrometers (HRS$^2$)

VCS: $H(e,e'p)X$
100μA $e^-$ on 15 cm liquid $H_2$ target

RCS: $H(\gamma,\gamma'p)$
$\leq$ 40μA $e^-$ on Cu radiator + 15 cm liquid $H_2$ target
Wide Angle Compton Scattering

- **Asymptotic limit:** \(s - M^2, -t, M^2 - u \to \infty \) …
  - “pure” Perturbative QCD (G.Farrar & S.J.Brodsky…)

- **Sub-asymptotic:** \(s - M^2, -t, M^2 - u \leq 10 \text{ GeV}^2\)
  - Conjecture: Handbag dominance (Feynman mechanism)
  - Radyushkin, Kroll: Factorized ansatz (GPD).
    - Quark propagator \((xP + k_\perp + q)^2 \to xP \cdot q\)
  - G.Miller, unfactorized
    - Exact Klein-Nishina amplitude
      - Constituent Quarks
    - Wave function ansatz
E99-114 data
Jefferson Lab E99-114
H(γ,γ)p

- 10-40μA beam on 6% radiator and 1g/cm² H₂ (mixed γ+e beam)
- Recoil Proton detected in HRS
  - Focal Plane Polarimeter
- Scattered photon detected in 700 element Pb-Glass array
- Scattered electron deflected by magnet and detected in Pb-Glass.
Electron, Compton, $\pi^0$ events

- 2-D plot of position of EM shower, relative to elastic prediction from recoil proton kinematics
RCS Differential Cross Sections
JLab E99-114, 25 kinematic points w/ statistical errors.
2 gluon exchange pQCD calculations only generate a small piece of the scattering amplitude, even with highly asymmetric Distribution Amplitudes
Proton Spectrometer and Focal Plane Polarimeter

\[ \Theta_{adj} = 86^\circ \cdot E_p (GeV) \cdot \frac{\Theta_{input}}{3.56} \]

in E99-114 \( \Theta_{adj} \) at focal plane is 270 degree. Asymmetries are proportional to \( p_L \) and \( p_S \) of the proton polarization.

Asymmetries for Pion and Compton processes
Longitudinal Polarization Transfer in RCS

\[ K_{LL} = p(\gamma, \gamma \vec{p}) \quad E_\gamma = 3 \text{GeV} \]

- Experimental evidence for Handbag mechanism
  - CQM & GPD Calculations
- pQCD (2Gluon exchange) strongly ruled out
Handbag Amplitude: Klein-Nishina Scaling at fixed \(-t\)?

\[ \theta_{\gamma\gamma} \leq 100^\circ \]

\[
\frac{d\sigma_{RCS}}{d\sigma_{KN}} = \frac{2\hat{s}\hat{u}}{\hat{s}^2 + \hat{u}^2} R^2_\lambda(t) + \frac{(\hat{s} - \hat{u})^2}{\hat{s}^2 + \hat{u}^2} \left[ R^2_V(t) + \frac{-t}{4m^2} R^2_T(t) \right]
\]
$\gamma p \rightarrow \gamma p$

**E99-114 Statistical errors only**

Light Front Cloudy Bag Model
(only 3-quark content included at large $x$ for RCS)

Handbag amplitude & Wavefunction ansatz

\[ \Phi(k_1,k_2,k_3) = \frac{(\text{spin})^N}{\left[ M_{123}^2 + \beta^2 \right]^\gamma} \]

Parameters $\beta, \gamma, m_q$ fitted to $H(e,e')p$

Real Compton Scattering
Data. JLab E99-114 Preliminary
Cross section scaling at fixed $\theta_{\gamma\gamma}^{\text{CM}}$

$$\frac{d\sigma}{dt} \rightarrow \frac{f(\theta)}{s^n}$$

$n+2 =$ Sum of # of elementary fields in initial & final state

$p_\perp$ largest at $\theta^{\text{CM}}=90^\circ$
Future Prospects for RCS

- Ales Psaker, A. Radyushkin (ODU):
  - Improved treatment of $k_\perp$ in handbag amplitude
- C. Weiss: Massless quarks in constituent quark wavefunction of proton.

- Measurement of $A_{LL}$ at 4 GeV and 120° (Hall C)
- Double kinematic range in $s$ and $t$ with JLab @ 12 GeV
Low Energy Compton Scattering

\[ \vec{E}_{\text{Incident}} \]

\[ \vec{e} \cdot \vec{R}_{\text{CM}} \]

\[ \alpha E \vec{E} \]

Power radiated: \[ P = \frac{2}{3c^3} \left| \frac{\partial^2 \vec{d}}{\partial t^2} \right|^2 \]

Center of Mass motion and induced dipole: \[ \frac{\partial^2 \vec{d}}{\partial t^2} = \frac{e^2}{m} \vec{E} - \alpha E \omega^2 \vec{E} \]
Forward and Backward Low Energy Scattering Amplitudes


\[
\frac{1}{8\pi M} T_{fi}(0^\circ) = \epsilon_f^* \cdot \epsilon_i \left[ -\frac{e^2}{4\pi M} + \omega^2 (\alpha_E + \beta_M) + \mathcal{O}(\omega^4) \right] 
+ i\sigma \cdot \epsilon_f^* \times \epsilon_i \left[ -\omega \frac{e^2}{4\pi} \frac{\kappa^2}{2M^2} + \omega^3 \gamma_0 + \mathcal{O}(\omega^5) \right] 
\]

\[
-\gamma_0 = \gamma_{E1} + \gamma_{M1} + \gamma_{E2} + \gamma_{M2}
\]

\[
\frac{1}{8\pi M} T_{fi}(\pi) = \epsilon_f^* \cdot \epsilon_i \left[ -\frac{e^2}{4\pi M} + \omega \omega' (\alpha_E - \beta_M) + \mathcal{O}(\omega^4) \right] 
+ i\sqrt{\omega \omega'} \sigma \cdot \epsilon_f^* \times \epsilon_i \left[ -\omega \frac{e^2}{4\pi} \frac{\kappa^2 + 4\kappa + 2}{2M^2} + \omega \omega' \gamma_0 + \mathcal{O}(\omega^4) \right] 
\]

\[
\gamma_\pi = -\gamma_{E1} + \gamma_{M1} + \gamma_{E2} - \gamma_{M2}
\]

Compton Scattering Cross Section

\[
\frac{d\sigma}{d\Omega \gamma \gamma_{\text{Lab}}} = \left| \frac{1}{8\pi M} \frac{\omega_f}{\omega_i} T_{fi} \right|^2
\]
Real Compton Scattering & Proton Polarizabilities

World Data: (1960 - 2001, Moscow, Saskatoon, Illinois, Mainz)


<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>$\mathcal{O}(p^3)\chi$PT</th>
<th>$\mathcal{O}(p^4)\chi$PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_E$</td>
<td>$(12.1 \pm 0.3_{stat} \pm 0.4_{syst})$</td>
<td>12.5</td>
<td>$10^{-4} \text{ fm}^3$</td>
</tr>
<tr>
<td>$\beta_M$</td>
<td>$(1.6 \pm 0.4_{stat} \pm 0.4_{syst})$</td>
<td>1.25</td>
<td>$10^{-4} \text{ fm}^3$</td>
</tr>
<tr>
<td>$\gamma_\pi$</td>
<td>$-(36.1 \pm 2.1_{stat} \pm 0.9_{syst})$</td>
<td>$-38.3$</td>
<td>$10^{-4} \text{ fm}^4$</td>
</tr>
<tr>
<td>$\gamma_0$</td>
<td>$(1.02 \pm 0.08_{stat} \pm 0.10_{syst})$</td>
<td>4.5</td>
<td>$10^{-4} \text{ fm}^4$</td>
</tr>
</tbody>
</table>

$\mathcal{O}(p^4)\chi$PT introduces uncertainties $\approx \pm 3$ in each quoted value from phenomenological constants, esp. $\Delta$ and $N^*$ terms.

Harmonic Oscillator model: $\alpha_E \approx \alpha_{\text{QED}} \cdot \text{Volume} \cdot (b/\lambda_C)$

$\alpha_E \ll \text{Volume}$: proton is very stiff, intrinsically relativistic ($\lambda_C \approx \text{size}$)

$\beta_M \ll \alpha_E$: Strong cancellation of para- and dia-magnetism.

$N \rightarrow \Delta$ transition over saturates $\beta_M$. 
Idea of Virtual Compton Scattering for Polarizabilities:

\[ \gamma + p \text{ invariant mass } \leq M + m_\pi. \]

\[ 2\pi/q = \text{virtual-photon wavelength, controlled by experiment.} \]

Measure spatial variation of polarization inside proton:

\[ q = \text{fourier transform variable.} \]


Lvov...
Low Energy Expansion (LEX) of VCS

$q' = \text{final photon energy in } \gamma p \text{ CM frame.}$

\begin{align*}
\frac{d\sigma}{d\omega} &= \frac{d\sigma^{\text{BH+Born}}}{d\omega} + v_{LL} [ P_{LL} - P_{TT}/\epsilon ] + v_{LT} P_{LT} + \mathcal{O}(q'), \\
P_{LL} &= -\sqrt{24M} G_{E,p}(\tilde{Q}^2) P^{(C_1,C_1)0}(\tilde{Q}^2) = \frac{4M}{\alpha_{QED}} G_{E,p}(\tilde{Q}^2) \alpha_E(\tilde{Q}^2) \\
P_{TT} &= 6M(1 + \tilde{\tau}) G_{M,p}(\tilde{Q}^2) \left[ P^{(M_1,M_1)1}(\tilde{Q}^2) + \sqrt{8\tilde{\tau}} P^{(C_1,M_2)1}(\tilde{Q}^2) \right] \\
P_{LT} &= \sqrt{\frac{3}{2}} M \sqrt{1 + \tilde{\tau}} \left[ G_{E,p}(\tilde{Q}^2) P^{(M_1,M_1)0}(\tilde{Q}^2) - \sqrt{6} G_{M,p}(\tilde{Q}^2) P^{(C_1,C_1)1}(\tilde{Q}^2) \right] \\
&= -\frac{2M}{\alpha_{QED}} \sqrt{1 + \tilde{\tau}} G_{M,p}(\tilde{Q}^2) \beta_M(\tilde{Q}^2) - \text{spin G.P.}
\end{align*}

where $v_{LL}, v_{TT},$ and $\epsilon$ are kinematic factors and $\tilde{Q}^2 = Q^2$ in $q' \to 0$ limit.

Generalized Polarizabilities (GP) $P^{(\Lambda_f,\Lambda_i)\Delta S}(\tilde{Q}^2)$, 
$(\Lambda_f, \Lambda_i) = (\text{final, initial}) \text{ Multipolarity; } \Delta S = 0, 1: \text{Proton spin flip.}$

In $\tilde{Q}^2 \to 0$ limit:

\begin{align*}
P^{(C_1,C_1)0} &\quad \rightarrow \quad -\sqrt{2/3} \quad \bar{\alpha}_E/\alpha_{QED} \\
P^{(M_1,M_1)0} &\quad \rightarrow \quad -\sqrt{8/3} \quad \bar{\beta}_M/\alpha_{QED} \\
P_{TT} &\quad \rightarrow \quad 0 \\
P^{(C_1,C_1)1} &\quad \rightarrow \quad 0
\end{align*}
Components of BETHE-HEITLER + BORN cross section

\[ d^6\sigma(\text{ep} \rightarrow \text{epy}) \]

\[ |T_{\text{BH}} + T_{\text{Born}}|^2 \]
Virtual Compton Scattering Experiments:

- MAMI: $k \leq 0.8$ GeV \hspace{1cm} q_{cm} = 0.6$ GeV/c

- Jefferson Lab: $k = 4$ GeV \hspace{1cm} Q^2 = 1.0, 1.9 GeV^2.
  hallaweb.jlab.org/physics/experiments/E93-050

- Bates-Linac: $k = 0.6$ GeV \hspace{1cm} Q^2 = 0.05 GeV^2.
  R. Miskimen, UMass-Amherst, spokesperson
Reconstruct $H(e,e'p)X$ coincidence at target

500 MHz Beam Structure

Reconstruct 1mm precision from 4mm⊗20KHz raster, with 30 KHz bandwidth Beam Position Monitor

Time Coincidence

Spatial Coincidence
Raw H(e,e’p)X Missing Mass squared (M_X^2) Spectrum
Prominent H(e,e’p)π^0 peak at M_X^2 = m_{π^2} = 20,000 MeV^2
Large unphysical background obscures for M_X^2 = 0 VCS events

Cuts to remove:
• Elastic ep→ep events. Cut on electron removes misidentified elastic events with proton punching through collimator
• H(e,e’p)X events with proton reconstructed to punch through collimator
• H(e,e’p)γ events, if assumption that γ||beam puts proton in collimator
JLab ($ep \rightarrow ep\gamma$) cross section for the lowest and highest $q'$ bin, at $40^\circ$ out-of-plane (latitude). Only statistical errors are shown. The abscissa is the azimuthal angle (or longitude). The full curve is the (BH+Born) cross section, the dashed curve includes the first-order GP effect fitted in this analysis.
LEX fit to VCS data below threshold (straight line) for each data set of JLab data. Black circles correspond to out-of-plane data, and the inner plot is a zoom on the lepton plane data (triangles).
J. Roche et al.
Dispersion Relations


I. Complete formalism for VCS cross section up to \(N\pi\pi\) threshold.
Input from
- \(\gamma N \rightarrow N\pi\) multipoles (MAID)
- \(t\)-channel \(\pi^0\) exchange
- Two low-energy subtraction “constants” (functions of \(Q^2\)):
  \(\Delta\beta(Q^2)\): \(t\)-channel \(\sigma\)-meson exchange
  \(\Delta[\alpha + \beta](Q^2)\): \(s\)-channel \(N\pi\pi\) and \(N\eta\) resonances not included in MAID.
- \(\Delta\beta\) and \(\Delta\alpha\) fitted independently to data at \(Q^2 = 1\) and \(Q^2 = 1.9\) GeV\(^2\) with dipole ansatz:

\[
\Delta\beta = \frac{\Delta\beta(0)}{[1 + Q^2/\Lambda^2_\beta]^2} \quad \Delta\alpha = \frac{\Delta\alpha(0)}{[1 + Q^2/\Lambda^2_\alpha]^2}
\]

II. Predictions of spin polarizabilities.
- Separation of \(\alpha_E\) from \([P_{LL} - P_{TT}/\epsilon]\) and \(\beta_M\) from \(P_{LT}\)

III. Interpretation of generalized polarizabilities.
$(e p \rightarrow e p \gamma)$ cross section for JLab data set I-b in six intervals of the azimuthal angle $\varphi$ (angle between lepton and hadron planes) as a function of $W$.

The curves are 1-$\sigma$ DR fits to total of 700 data points.
RCS: Olmos de Leon et al [MAMI],

VCS: J. Roche et al [MAMI-A1], G. Laveissiere et al [JLab E93050].

Dashed Curves are total $\chi$PT, Solid curves are $\chi$PT for $P_{LL}$ and scalar part of $P_{LT}$ only.

Dotted curves are $\chi$PT for $P_{TT}$ and spin-flip part of $P_{LT}$.

DotDashed Curves are Dispersion Relation $\pi N$ predictions for $P_{TT}$ and spin-flip part of $P_{LT}$.
Generalized Polarizabilities:

Obtained by subtracting DR predictions for spin-flip polarizabilities from data.

Solid curves are $\chi$PT for $\alpha_E$ and $\beta_M$.

DotDashed curves are $\pi N$ contributions to $\alpha_E$ and $\beta_M$.

Dashed curves are $\sigma$-meson (pion-cloud) exchange term $\Delta \beta$ (fitted).

Dipole parameter $\Lambda_\beta < \Lambda$(elastic): Indicative of large size of pion cloud.

Dotted curve is $\Delta[\alpha + \beta]$ term, fitted with dipole ansatz to $Q^2 = 0 \& 1 \text{ GeV}^2$ data.
\[ \Delta[\alpha + \beta] = \alpha_E - \alpha_E^{\pi N} + \Delta \beta \]
\[ \Delta[\alpha + \beta] = F_2^{asy} \text{ amplitude in DR.} \]
Spatial distribution not the same as \( G_E \).

Dashed Curve is \( \sigma \)-exchange term \( \Delta \beta \),
Dipole paramater \( \Lambda \beta < \Lambda \) (elastic).
Indicative of large size of pion cloud.
Contributions to $\Delta[\alpha + \beta](Q^2)$

$\gamma^* p \rightarrow N^*$ Amplitudes: L. Tiator, et al., nucl-th 0310041

- $A_{1/2}^p N(1535)S_{11}$
- $S_{1/2}^p N(1535)S_{11}$
- $A_{3/2}^p N(1520)D_{13}$
- $A_{1/2}^p N(1520)D_{13}$
Conclusions and Prospects for VCS/Generalized-Polarizabilities

• Low Energy Expansion analysis of data up to $N\pi$ threshold and Dispersion Relation Analysis of data up through $N\pi\pi$ threshold give consistent results.

• DR interpretation of Generalized Polarizabilities:
  – Diamagnetism shows large spatial size, as expected from pion cloud.
  – Large contribution to Electric Polarizability from excitations beyond $N\pi$, with non-trivial $Q^2$ dependence.
  – Two photon amplitude is not dominated by low energy excitations.

• New Results soon from
  – Low $Q^2$ Bates experiment;
  – Single and Double Spin asymmetries at MAMI

• Future experiments with MAMI upgrade.
VCS(Q^2=1GeV^2) dσ(γ*,γ) at large −t:
(for θ_{γγ}≈180°, −t ≈ W^2 = s)

- Resonance form-factors at Δ and S11, D13
- Evidence for compton scattering from point-like objects for W ≈ 2 GeV?; or
- Evidence for Nucleon pole dominance of u-channel Regge: \mathcal{F} \propto s^{a(u)}?
Normal Beam Asymmetry from 2γ-exchange

- Preliminary data from HAPPEX on the proton and He-4 targets
- Measures absorptive part of Compton scattering amplitude, integrated over photon virtualities and W
- Calculations by Afanasev&Merenkov

Normal beam asymmetry for elastic ep-scattering

Unitarity-based model predictions

\[ A_{\text{ Normal}} \times 10^{-6} \]

\[ E_e = 3 \text{ GeV} \]

Normal beam asymmetry for elastic e⁻⁴He scattering

Unitarity-based model predictions

\[ E_e = 3 \text{ GeV} \]

\[ Q^2, \text{ GeV}^2 \]

\[ A_{\text{ Normal}} \times 10^{-6} \]