Wide-Angle Compton Scattering

Bogdan Wojtsekhowski,
Thomas Jefferson National Accelerator Facility
These results do not appear to be reconcilable with the view of the statistical production of recoil and photo-electrons proposed by Bohr, Kramers and Slater. They are, on the other hand, in direct support of the view that energy and momentum are conserved during the interaction between radiation and individual electrons.
Regimes of Compton effect from proton

- Forward scattering at $t = 0$
- Diffractive scattering for $-t \ll \Lambda^2$
- Wide-angle scattering for $-t \sim \Lambda^2$

$s$ scaling at fixed $t/s$

$s$ and $Q^2$
Regimes of Compton effect from proton

Forward scattering amplitude:

\[ F = f_1(\omega) \cdot (\bar{\epsilon}' \cdot \bar{\epsilon}') + i\omega f_2(\omega) (\bar{\sigma} \cdot [\bar{\epsilon}' \times \bar{\epsilon}']) \]

- Forward scattering at \( t = 0 \)
- Diffractive scattering for \( t << \Lambda^2 \)
- Wide-angle scattering for \(-t \rightarrow \Lambda^2\)
  s scaling at fixed \( t/s \)

Damashek & Gilman, 1970
Regimes of Compton effect from proton

- Forward scattering at $t = 0$
- Diffractive scattering for $t << \Lambda^2$
- Wide-angle scattering for $-t \sim \Lambda^2$

$s$ scaling at fixed $t/s$

PDG, 2016
Regimes of Compton effect from proton

- Forward scattering at $t = 0$
- Diffractive scattering for $t \ll \Lambda^2$
- Wide-angle scattering for $-t \sim \Lambda^2$

s scaling at fixed $t/s$
The real photon has $Q^2=0$ and the reaction mechanism is in question.

There is a high $(-t) \gg \Lambda^2$ exchange to the “bag”, which provides crucial simplicity and a connection to the elastic Form Factors and DIS via Generalized Parton Distributions.
Physics of the nucleon

where $\xi = (p_q^+ - p'_q^+)/ (p_q^+ + p'_q^+)$

Quark dynamics of nucleon encoded in GPD functions
$H(x, \xi, t), H(\tilde{x}, \xi, t)$ hadron helicity-conserving; vector and axial-vector
$E(x, \xi, t), \tilde{E}(x, \xi, t)$ helicity-flipping; tensor and pseudo-scalar
Wide-Angle Compton Scattering

• Mechanism of the reaction is a key question

If we can measure the process: What do we learn?
What do we learn from polarization observables?

• JLab WACS experiments 2002, 2008

• Experimental results for polarization $K_{LL}$

• Motivation for further measurements

• An approach for the most productive experiment
Mechanism of the process

Two basic options for the mechanism:

Collective response - several partons are involved in high momentum interaction with the photons.

Individual response - one quark absorbs an incident photon and the same quark emits a scattered photon.
Theoretical studies of the WACS process

- Regge poles - VMD - since 1960s …, Laget
- pQCD - two-gluon - Brodsky, …, Dixon, MVh,…
- Diquark model - Guichon&Kroll 1996
- Leading quark - Brodsky et al 1972,
- GPDs (handbag) - Radyushkin, Kroll et al
- CQM - G.Miller 2004
- SCET - Kivel&Vanderhaeghen
- DSE - Eichmann

Main issues:

- Competing mechanisms
- Interplay between hard and soft processes
- Threshold for onset of asymptotic regime
- Role of the hadron helicity flip
Experimental studies of the CS process

experiments with $s > 2 \text{ GeV}^2$, low $t$
Bauer-Spital-Yennie review, RMP 50 (1978)

• DESY - 1971
• SLAC - 1971
• CEA - 1972-73, Deutsch

DESY-1971

The photon flux is $2 \times 10^8 \gamma / s$

FIG. 44. Diagram of the apparatus used by the DESY group for Compton scattering measurements (from Buschhorn et al., 1971a).
Experimental studies of the CS process

experiments with \( s > 2 \text{ GeV}^2 \), low \( t \)
Bauer-Spital-Yennie review, RMP 50 (1978)

- DESY - 1971
- SLAC - 1971
- CEA - 1972-73, Deutsch

experiments with \(-t > 1 \text{ GeV}^2\) (WACS regime)

- Cornell - 1975
- JLab Hall A - 2002
- JLab Hall C - 2008

Main issues:
- Competing reaction – pion-0 photo-production
- Low cross section and small solid angle
- Low efficiency & analyzing power of the proton polarimetry
- Low limit on the polarized target luminosity

The photon flux is

\[ 1.5 \times 10^{10} \frac{\gamma}{s} \]
\[ \sim 2 \times 10^{13} \frac{\gamma}{s} \]
Mixed $e/\gamma$ beam $\rightarrow$ rates $\sim 1300$ higher than “clean” $\gamma$
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Two-body kinematics

Electron Beam $\rightarrow$ Proton Arm $\rightarrow$ Target $\rightarrow$ Polarimeter

Radiator $\rightarrow$ Magnet $\rightarrow$ Calorimeter $\rightarrow$ Veto

$10^{13}$ photons/sec

$\gamma$ intensity vs. energy

Delta Y vs Delta X

Ep events

Two-body kinematics

Delta X coordinate in calo.

Ep events

"pion" events

RCS events

B. Wojtsekhowski

SPIN2016, September 27, 2016
Polarization transfer $K_{LL}$

$E_\gamma = 3.2$ GeV, $\theta_{cm} = 120^\circ$ ($s = 6.9$, $t = -4$ GeV$^2$)

$K_{LL}$ is an average value of the longitudinal proton spin in the $\gamma p$ cm system for 100% circular polarization of incident photon.

$$K_{LL} = \frac{1}{2} \left\{ \frac{\sigma (+,\uparrow) - \sigma (+,\downarrow)}{\sigma (+,\uparrow) + \sigma (+,\downarrow)} - \frac{\sigma (-,\uparrow) - \sigma (-,\downarrow)}{\sigma (-,\uparrow) + \sigma (-,\downarrow)} \right\}$$

Raw asymmetry for ep and $\gamma p$ events

raw asymmetry is of 0.05, systematics is below $10^{-4}$
E99-114 experiment in 2002

- Deflecting magnet
- Photon detector
- Exit beam line
- Proton spectrometer
- Hydrogen target
- Electron Beam
- Deflecting magnet
Compton scattering with GPD

In the GPD approach, interaction goes with a single quark, and the handbag diagram dominates.

\[ \frac{d\sigma}{dt} = \frac{d\sigma}{dt}_{KN} \left( \frac{1}{2} \left[ R^2_v + \frac{-t}{4m^2} R^2_T + R^2_A \right] - \frac{us}{s^2 + u^2} \left[ R^2_v + \frac{-t}{4m^2} R^2_T - R^2_A \right] \right) \]

\[ K_{LL} = A_{LL} \quad K_{LL} \frac{d\sigma}{dt} \equiv \frac{1}{2} \left[ \frac{d\sigma(+, \uparrow)}{dt} - \frac{d\sigma(-, \uparrow)}{dt} \right] \]

- Test of the handbag predictions to the <10% level is an important task.
- The $K_{LL} (A_{LL})$ asymmetry is an observable of choice to test a reaction mechanism.
- The NLO corrections are supposed to vary as $1/s$ (e.g. N.Kivel & M.Vanderhaeghen).
FFs, GPDs and Polarization Observables

\[
\frac{d\sigma^{KN}_{LL}}{dt} A_{LL}^{KN} = \frac{2\pi \alpha_{em}^2}{(s-m^2)^2} \\
\times \left[ -\frac{s-m^2}{u-m^2} + \frac{u-m^2}{s-m^2} - \frac{2m^2t^2(s-u)}{(s-m^2)^2(u-m^2)^2} \right],
\]

(9)

\[
\frac{d\sigma^{KN}_{LL}}{dt} K_{LL}^{KN} = \frac{2\pi \alpha_{em}^2}{(s-m^2)^2} \\
\times \left[ -\frac{s-m^2}{u-m^2} + \frac{u-m^2}{s-m^2} - \frac{4m^2t^2(m^4-su)}{(s-m^2)^3(u-m^2)^2} \right],
\]

\[
R_v(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} H^a(x,0,t)
\]

\[
R_A(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} \text{sign}(x) \hat{H}^a(x,0,t)
\]

\[
R_T(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} E^a(x,0,t)
\]

M.Diehl & P.Kroll

B. Wojtsekhowski
FFs, GPDs and Polarization Observables

\[ R_v(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x,0,t) \]
\[ R_A(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} \text{sign}(x) \hat{H}^a(x,0,t) \]
\[ R_T(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} E^a(x,0,t) \]

for \( m=0 \)
\[ K_{LL}^{KN} = \frac{s^2 - u^2}{s^2 + u^2} \]
\[ A_{LL} = K_{LL} = K_{LL}^{KN} \frac{R_A}{R_v} \left[ 1 - \frac{t^2}{2(s^2 + u^2)} \left( 1 - \frac{R_A^2}{R_v^2} \right) \right]^{-1} \]

M.Diehl & P.Kroll

B. Wojtsekhowski

SPIN2016, September 27, 2016
GEp/GMp two-photon effect and WACS

\[ \frac{d\sigma}{dt} = \frac{\pi \alpha^2}{s^2} |R(s, t)|^2 (-su) \left( \frac{1}{2} |C_2(s, t)|^2 + \frac{1}{2} |C_4(s, t)|^2 + |C_6(s, t)|^2 \right) \]

Plan for E12-14-003

B. Wojtsekhowski

SPIN2016, September 27, 2016
Physics Motivation: study of $K_{LL}$

E99-114
$s=6.9$, $t=-4.0$, $u=-1.1$ GeV$^2$

Strong evidence for handbag mechanism

PRL 94, 242001 (2005)
Physics Motivation and a surprise

New measurement at large (doubled) s, t, u values is necessary to clarify the mechanism of WACS.

E99-114
s=6.9, t=-4.0, u= -1.1 GeV^2

E07-002
s=7.8, t=-2.1, u= -4.0 GeV^2

Strong evidence for additional physics

PRL 115, 152001 (2015)
Physics Motivation and a big surprise

\[ \Delta \text{E99-114} \]
\[ \Delta \text{E07-002} \]
\[ \text{in-Nishina} \]
\[ \text{M} \]
\[ \Delta \text{E} \]

E99-114
\[ s=6.9, \ t=-4.0, \ u= -1.1 \text{ GeV}^2 \]

E07-002
\[ s=7.8, \ t=-2.1, \ u= -4.0 \text{ GeV}^2 \]

3.4 \( \sigma \) from the CQM
5.5 \( \sigma \) from the GPD band
Physics Motivation and a big surprise

E99-114
s=6.9, t=-4.0, u= -1.1 GeV²

E07-002
s=7.8, t=-2.1, u= -4.0 GeV²

What is the origin of large $K_{LL}$?
Quark OAM?
Diquark u-d correlations?
GPD analysis (per Diehl&Kroll)

\[ H^q_v(x, t) = q_v(x) \exp\left[ t f_q(x) \right], \]
\[ E^q_v(x, t) = e^q_v(x) \exp\left[ t g_q(x) \right], \quad (33) \]

with an \( x \) dependent width specified by the profile functions \( f_q(x) \) and \( g_q(x) \). For polarized quarks we assume

\[ \tilde{H}^q_v(x, t) = \Delta q_v(x) \exp\left[ t f_q(x) \right], \quad (34) \]

the same \( f_q(x) \) for \( H(x, 0, t) \) and \( \tilde{H}(x, 0, t) \)

\[ f_q(x) = \alpha'_q (1 - x)^3 \log(1/x) + B_q (1 - x)^3 \]
\[ + A_q x (1 - x)^2, \]
P.Kroll recently pointed out that:

The current GPD fit is on the lower edge of $F_A$ data.
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With a larger $F_A$ it will not be a big difficulty to explain both JLab $K_{LL}$ data points.
GPD analysis (per Diehl & Kroll)

P. Kroll recently pointed out that:

The current GPD fit is on the lower edge of $F_A$ data.

With a larger $F_A$ it will be not a big difficulty to explain both JLab $K_{LL}$ data points.

High $-t$ value of $F_A$ could be obtained via GPDs modeling from the WACS $K_{LL}$ values.

$$K_{LL} \propto R_A / R_V$$

$$R_A \propto \int_{-1}^{1} \frac{\tilde{H}(x,0,t)}{x} dx$$

The same GPD is in the axial form factor.
GPD analysis (per Diehl&Kroll)

\[ K_{LL} \propto \frac{R_A}{R_V} \]

\[ R_A \propto \int_{-1}^{1} \frac{\tilde{H}(x,0,t)}{x} \, dx \]

The same GPD is in the axial form factor.

P.Kroll recently suggested:

"With regard to the difficult measurement of the axial form factor at large \(-t\) I still think that from a measurement of ALL or KLL one may extract RA and perhaps the axial form factor (through on GPD analysis) at larger \(-t\)."
WACS experimental considerations

- **$K_{LL}$**
  - Beam intensity: $2 \times 10^{13} \, \gamma/s$
  - Polarimeter: figure-of-merit $\sim 0.001$
  - Solid angle of apparatus: HRS/HMS $\sim 6$-$7 \, \text{msr}$

- **$A_{LL}$**
  - Beam intensity: $6 \times 10^{11} \, \gamma/s$ (novel source)
  - Target polarization: $\sim 0.9$
  - Solid angle of apparatus: SBS $\sim 70 \, \text{msr}$

Overall performance $\sim 250$ better for $A_{LL}$
Plan to measure $A_{LL}$

focused on max $s$ and $\theta_{cm} \sim 90^\circ$

Compact Photon Source

1.2$\mu$A $e^-$

8.8 GeV

$10\%$ X0

photon flux is $6 \times 10^{11}$ $\gamma$/s

target polarization is 0.9

solid angle is 70 msr

Super Bigbite Spectr.

Neutral Particle Spectr.
Summary

- Large $K_{LL}$ at $\theta_{cm} = 70^\circ$: WACS is not as simple as expected, even in the range of s/t/u projected GPD/SCET applicability.

A large acceptance spectrometer and a high resolution calorimeter allow a 10-fold increase in the acceptance.

A novel scheme of a photon source-electron-dump allows a 10-fold increase in the photon intensity.

With a factor of 100 of productivity gain, the $A_{LL}$ could be measured at $s = 9 & 11 & 13 & 15 \text{ GeV}^2$ at $\theta_{cm} \sim 90^\circ, 120^\circ$
Proposed Experimental Setup

focused on max s and $\theta_{cm} \sim 90^\circ$

A floor plan:

the 3D model used in GEANT simulation of physics, radiation and magnetic field calculations
Compact Photon Source

Distance to target ~200 cm
photon beam diameter on the target ~ 0.9 mm

1.2 µA e⁻
8.8 GeV

B ~ 2.5T

2mm opening

3cm NH₃

Novel concept allows high photon intensity and low radiation
Kinematic range

Detector acceptance will cover wide kinematic range in “one set”.

\[s: \ 8.0 - 16.0 \ \text{GeV}^2\]
\[-t: \ 3.0 - 7.0 \ \text{GeV}^2\]
\[-u: \ 3.0 - 7.0 \ \text{GeV}^2\]

\[\theta_{\text{cm}}: \ 80^\circ - 100^\circ\]

\[<\theta_{\text{cm}} > \sim 90^\circ\]
The systematics for the $A_{LL}$ is projected to be less than 0.03 (absolute):

The ep elastic data $A_{LL} \rightarrow$ product of the beam and target polarizations, $\delta(P_t^*P_b) \sim 4\%$; the beam pol. via Moller measurement, $\sim 1\%$; the target pol. via NMR, $\delta P_t \sim 5\%$. 

High statistical accuracy

Good systematic accuracy