Development of NPS for the DVCS experiments in Hall C at Jefferson Lab

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LC2019

Parallel 1 : Hadronic structure - GPDs
• Deeply Virtual Compton Scattering (DVCS) for GPDs
• Neutral Particle Spectrometer (NPS) for DVCS experiments in Hall C
• NPS simulations and crystal optical properties measurement
Generalized Parton Distributions

Form Factors: via elastic scattering
- charge & magnetization spatial distribution

Parton distribution: via deep inelastic scattering
- Longitudinal momentum & helicity distribution of partons

Generalized Parton Distributions: via exclusive reactions
- Transverse position distribution and longitudinal momentum of partons
Deeply Virtual Compton Scattering

\[ \gamma^* p \rightarrow p' \gamma \]

\[ Q^2 = -q^2 \]
\[ \nu = \frac{p \cdot q}{M} \]
\[ x_B = \frac{Q^2}{2M \nu} \]
\[ \xi \sim \frac{x_B}{2 - x_B} \]

At high \( Q^2 \), DVCS amplitudes can be factorized into 2 parts
«Hard Part»: Perturbatively calculable
«Soft Part»: Nucleon structure \( \rightarrow \) Parameterized by GPDs
Deeply Virtual Compton Scattering

\[ \text{DVCS process and BH process entangle } \rightarrow \text{ Need to separate each term to extract the GPDs} \]

\[\sigma \propto |BH|^2 + |DVCS|^2 + \text{Interference} \]

Calculable from QED

\[\sim 1\]

\[\sim \frac{1 + \cos \varphi}{P_1(\varphi)P_2(\varphi)}\]

\[I \propto (\frac{E_b}{\nu})^3\]

\[|\text{DVCS}|^2 \propto (\frac{E_b}{\nu})^2\]

At fixed \(Q^2\) and \(\nu = Q^2/(2Mx_B)\)
DVCS experiments in Hall C

Reach higher! : further test the $Q^2$ dependence of the observables

Different beam energies : separate $|DVCS|^2$ and Interference term

Reach lower value of $x_B$ : Cross-check with CLAS, CLAS12 and COMPASS

Need a full kinematic region to better understand the GPDs

Thomas Jefferson National Accelerator Facility (Jefferson Lab), Virginia, USA.
12 GeV continuous electron beam. 4 experimental halls with different setups

Highest precision data in the kinematic domain accessible with an 11GeV beam

<<Kinematic region accessible by JLab 11GeV beam>>
Neutron Particle Spectrometer (NPS) in Hall C

\[ e \ p \rightarrow e'p'\gamma \]

\[ \gamma^* \ p \rightarrow p'\gamma \]

(Exclusive process)

To detect neutral particles \( (\gamma, \pi_0) \), NPS will be installed on to the SHMS. SHMS will be used as a cantilever.

HMS detects scattered electrons
NPS detects neutral particles

HMS : High Momentum Spectrometer
SHMS : Super High Momentum Spectrometer
Neutron Particle Spectrometer (NPS) in Hall C

Highest luminosity ($\sim 10^{38} \text{cm}^{-2}\text{s}^{-1}$) of DVCS ever before with smallest angle (for the high $Q^2$ data) possible
- Creates big amount of background to the calorimeter
  → Introduce sweeping magnet to reduce the background

Calorimeter:
1080 (30X36) PbWO$_4$ blocks
each crystals: 2X2X20 cm3, $\sim$670 gram

Target chamber
Beam direction
Sweeping magnet
Out-going Beam-pipe
Calorimeter
Contributions for the NPS

• **Geant4 simulation**
  - Energy resolution simulation
  - Dose rate calculation
  - Acceptance calculation

• **Optical properties measurement of PbWO$_4$ crystals**
  - Radiation hardness measurement
  - Optical bleaching
• Energy resolution simulation
  - Decision of the design of the NPS

• Radiation dose rate calculation
  - Estimate dose rate on the NPS to take the radiation damage into account
    - How often we need to cure the crystals
    - What is the maximum luminosity we can tolerate
    - Effect of background on detector resolution

• Precise calculation of the detector acceptance
  - Work in progress
NPS Energy Resolution Simulation

Purpose:
- NPS is made of 1080 crystals (30X36, stacked)
- Need structures for uniform arrays → Better energy resolution
- More structure between crystals → Worse energy resolution

► Check the dependency of the energy resolution of the NPS on the distance between the crystals (gap)

Recent NPS prototype:
No material in the middle part

<<PrimEx also used PbWO₄ crystals for the calorimeter>>
11μA beam in 15cm Liquid hydrogen target (approximate luminosity : $\sim 2 \times 10^{37} cm^{-2} s^{-1}$) NPS placed 6m away from the target, 6.3°

Sweeping Magnet (SM) :
- Reduces the dose rate a factor of 3 or more
  - Reach smaller angle
  - Tolerate higher luminosity
Geant4 NPS Simulation Conclusions

• Energy resolution simulation
  - Detector structure: 0.5mm carbon material only in the front and the back side, 2cm each of the crystals

• Radiation dose rate calculation
  - Sweeping magnet: reach smaller angle for the high $Q^2$ and tolerate higher luminosity

• Full package of experimental setup is ready for the NPS acceptance calculation
PbWO$_4$ Optical Properties Measurements

- Radiation hardness measurement
  - Check crystal performance in high radiation environment
  - Impact of radiation on crystal resolution
  - Study the needs for curing

- Optical bleaching
  - Method to recover the optical properties of the crystals after the irradiation damage
PbWO$_4$ Irradiation Test

The radiation damage differs for every crystal

Picture: ~20Gy/min ~4hrs with $^{60}$Co at Laboratoire de Chimie Physique

Light transmittance measurement
Ionizing radiation creates color centers
- By electron traps or point structure defects

Relaxation of color centers
- Thermo-activation
- Injection of specific energy
  - Blue light: PMT sensitive
  - Infrared light: PMT insensitive \(\rightarrow\) possibility of curing during data taking
The crystal was irradiated with 30Gy of dose
- Applied two types of light illumination recovery
  - Infrared (IR) light with optical fiber for 2hrs
  - Blue light with optical fiber for 2hrs

→ Blue light works better in recovering the transmittance

→ Blue light for the crystal optical property damage recovery system of NPS

PbWO₄ Optical Bleaching
PbWO$_4$ Optical Properties Measurements Conclusion

- Radiation damage exists and varies with crystals
- Crystals radiation damage can be cured
  - Blue light curing (optical bleaching) via optical fiber to be used for the NPS

<<picture : Emmanuel Rindel>>
Summary

• DVCS access to the GPDs
• DVCS experiments in Hall C will exploit vast kinematic region and cross check Hall A, CLAS, HERMES and COMPASS data
• NPS is needed in Hall C in order to perform the DVCS experiment
• NPS energy resolution and dose rate calculation with Geant4
• Optical bleaching method for maintaining calorimeter’s energy and position resolution
Time Line of the NPS

• Detector construction in the 2nd half of 2019
• Delivery of NPS to Jefferson Lab at the beginning of 2020
• NPS tests at Jefferson Lab in 2020
• DVCS experiment expected in 2021
Ongoing projects

• Additional measurements on the prototype
  - Finalize the NPS design
• Software reconstruction for the NPS and acceptance calculation
Backups
<table>
<thead>
<tr>
<th>EXP. NO.</th>
<th>Hall</th>
<th>Title</th>
<th>Spokespersons</th>
<th>Institutions</th>
<th>Beam Days</th>
<th>Rating</th>
<th>PAC</th>
<th>Run Group</th>
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<tbody>
<tr>
<td>E12-13-007</td>
<td>C</td>
<td>Measurement of Semi-Inclusive $\pi^+$ Production as Validation of Factorization</td>
<td>R. Ent, T. Horn, H. Mkrtchyan, V. Tadevosyan</td>
<td>JLab, CUA, Yerevan</td>
<td>25</td>
<td>A-</td>
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<tr>
<td>E12-13-010</td>
<td>C</td>
<td>Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C</td>
<td>C. Munoz Camacho, R. Paremuzyan, T. Horn, C. Hyde, J. Roche</td>
<td>IPN Orsay, UNH, CUA, ODU, Ohio U</td>
<td>53</td>
<td>A</td>
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<tr>
<td>E12-14-005</td>
<td>C</td>
<td>Wide Angle Exclusive Photoproduction of $\pi^+$ Mesons</td>
<td>D. Dutta, M. Amaryan, H. Gao, M. Kunkel, S. Sirca, I. Strakovsky</td>
<td>Miss. State, ODU, Duke, ODU, Ljubljana, GWU</td>
<td>18</td>
<td>B</td>
<td>42</td>
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<td>E12-14-006</td>
<td>C</td>
<td>Initial State Helicity Correlation in WideAngle Compton Scattering</td>
<td>D. Keller, D. Day, J. Zhang</td>
<td>UVa</td>
<td>15</td>
<td>B</td>
<td>42</td>
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Approved Science Program with the NPS
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lead Tungsten (PbWO₄)</th>
<th>Lead Fluoride (PbF₂)</th>
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<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>8.28</td>
<td>7.66-7.77</td>
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<tr>
<td>Radiation length X₀ (cm)</td>
<td>0.89</td>
<td>0.93-0.95</td>
</tr>
<tr>
<td>Refraction index</td>
<td>2.36 (λ = 420 nm)</td>
<td>1.8-2.0</td>
</tr>
<tr>
<td></td>
<td>2.24 (λ = 600 nm)</td>
<td>(depending on λ)</td>
</tr>
<tr>
<td>Transmission range (nm)</td>
<td>340-1000</td>
<td>250 – 1100</td>
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<tr>
<td>Moliere radius (cm)</td>
<td>2.19</td>
<td>2.22</td>
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<tr>
<td>Radiation type</td>
<td>Scintillation (~13% Čerenkov)</td>
<td>Pure Čerenkov</td>
</tr>
<tr>
<td>Sensitivity to low en. bckgr.</td>
<td>Sensitive</td>
<td>Insensitive (no scintillation)</td>
</tr>
<tr>
<td>Timing property (slow/fast)</td>
<td>≈30 ns / 10 ns</td>
<td>Very fast,</td>
</tr>
<tr>
<td>τₑ, ns (%)</td>
<td>5 (73%)</td>
<td>Total pulse width &lt; 20 ns</td>
</tr>
<tr>
<td></td>
<td>14 (23%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>110 (4%)</td>
<td></td>
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<tr>
<td>Lead content (% by weight)</td>
<td>&gt; 85</td>
<td>85</td>
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<td>Hydrosopicity</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Energy resolution σₘ/E (%)</td>
<td>~2.4/√E</td>
<td>5.3/√E</td>
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<tr>
<td>Position resolution σ (mm)</td>
<td>~2.5/√E</td>
<td>~1.5/√E</td>
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<tr>
<td>Photon yields per 1 MeV</td>
<td>~140-200</td>
<td>~1.0-2.0</td>
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<td>Temperature dependence of Light Yield</td>
<td>~ -2%/°C</td>
<td>No need of temperature stabilization</td>
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<td>Critical Energy (MeV)</td>
<td>--</td>
<td>8.6–9.0</td>
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<tr>
<td>$x_B$</td>
<td>0.36</td>
<td>0.50</td>
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<tr>
<td>-------</td>
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<tr>
<td>$Q^2$ (GeV)$^2$</td>
<td>3.0</td>
<td>4.0</td>
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<tr>
<td>$k$ (GeV)</td>
<td>6.6*</td>
<td>8.8</td>
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<tr>
<td>$k'$ (GeV)</td>
<td>2.2</td>
<td>4.4</td>
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<td>$\theta_{\text{Calo}}$ (deg)</td>
<td>11.7</td>
<td>14.7</td>
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<td>$D_{\text{Calo}}$ (m)</td>
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<td>$I_{\text{beam}}$ ($\mu$A)</td>
<td>28</td>
<td>28</td>
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<tr>
<td>$N_{\text{evt}}$ (10$^5$)</td>
<td>1.5</td>
<td>8.8</td>
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<tr>
<td>$\sigma_{M^2_X}$ (GeV$^2$)</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Days</td>
<td>1</td>
<td>2</td>
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</table>
PbWO$_4$ Light Yield Measurements

Cross checking the measured LY between two different lab.

Measurement of the temperature dependence of the crystals light yield

Also, light yields differ in each crystals.

<<measurements done by Rong WANG>>