Probing the Nucleus with Linearly Polarized Photons

Daniel Brandenburg (BNL/CFNS) → for the STAR Collaboration

The VI\textsuperscript{th} conference on the initial stages
Of high-energy nuclear collisions

January 10 -15th, 2021
Talk Outline

1. Introduction
   o Ultra-peripheral heavy-ion collisions (UPC)
   o Strong electromagnetic fields and transverse linearly polarized photons

2. Angular modulations of diffractive $\rho^0 \rightarrow \pi^+\pi^-$ in UPCs

3. Comparison between Au+Au and U+U collisions

4. Comparison to theoretical models

5. Summary
Ultra-Peripheral Collisions

Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic fields

• $\gamma\gamma \rightarrow l^+l^-$ : photon-photon fusion
  • One photon from the field of each nucleus interacts
  • Second order process in $\alpha$
  • $Z\alpha \approx 1 \rightarrow$ High photon density with highly charged nuclei

• $\gamma P \rightarrow \rho^0, J\psi, etc.$ : Photo-nuclear production of vector mesons ($J^P = 1^-$)
  • Photon from the EM field of one nucleus fluctuates to a $q\bar{q}$ pair, interacts with pomeron
  • Photon quantum numbers $J^{PC} = 1^{--}$

Transverse linearly polarized photons

- Extreme Lorentz contraction of EM fields $\rightarrow$ Quasi-real photons should be linearly polarized in transverse plane $(\vec{E} \perp \vec{B} \perp \vec{k})$

- Polarization vector: aligned radially with the “emitting” source

- Well defined in the photon position eigenstates

- Event average, washes out polarization effects, since $\vec{b}$ is random from one event to next
Polarization Sensitive Observable

\[ \Delta \phi = \Delta \phi[(e^+ + e^-), (e^+ - e^-)] \approx \Delta \phi[(e^+ + e^-), e^+] \text{ (for small pair } p_T) \]

Sensitive to polarization through quantum space-momentum correlations

Birefringence effects:

Recently realized, collision of linearly polarized photons leads to a \( \cos(4\Delta \phi) \) modulation in polarized \( \gamma \gamma \to e^+e^- \) process [1]

The corresponding vacuum LbyL scattering[2] is expected to display a \( \cos(2\Delta \phi) \) modulation

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Birefringence of the QED Vacuum

polarized $\gamma \gamma \rightarrow e^+ e^-$ [1] leads to $\cos(4\Delta \phi)$ modulations in

$$\Delta \phi = \Delta \phi[(e^+ + e^-), (e^+ - e^-)] \approx \Delta \phi[(e^+ + e^-), e^+]$$

### Table 1: The top row reports the total measured cross-section within STAR acceptance for

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Measured</th>
<th>QED</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-A_{4\Delta \phi}(%)$</td>
<td>16.8 $\pm$ 2.5</td>
<td>16.5</td>
<td>18.8 / 16</td>
</tr>
</tbody>
</table>

### Table 2: The result from fits to various possible sources of contamination. For each source, the systematic uncertainties added in quadrature. The theory calculations where applicable. The uncertainties reported here are the statistical and

<table>
<thead>
<tr>
<th>Source of</th>
<th>Measured QED</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h\gamma$</td>
<td>0.9 $\pm$ 0.35 (MeV/$c^2$)</td>
</tr>
<tr>
<td>$e^+ e^-$</td>
<td>3.4 $\pm$ 0.004 (stat.)</td>
</tr>
</tbody>
</table>

### Figure

- $0.45 < M_{ee} < 0.76$ GeV/$c^2$
- $\sqrt{s_{NN}} = 200$ GeV
- Fit: $C(1 + A_{2\Delta \phi} \cos 2\Delta \phi + A_{4\Delta \phi} \cos 4\Delta \phi)$
- $\pm 1 \sigma$

$\cos 4\Delta \phi$ (First lab evidence for vacuum birefringence) observed at $> 6\sigma$ significance

- photons from intense EM fields ($B > 10^{14}$ T) are linearly polarized

January 13, 2021

Daniel Brandenbarger
Photo-nuclear process

STAR has studied $\gamma P \rightarrow \rho^0 \rightarrow \pi^+\pi^-$ (and direct $\pi^+\pi^-$ production) in the past.

**How can we use linearly polarized photons to study the nucleus?**

**Diffractive structure in $p_T^2 \approx -t$ distribution**

**Cross section vs. $p_T^2 \approx -t$ sensitive to the gluon density within nucleus**

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Measure $\Delta\phi$ observable in $\gamma P \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$

If the photons are linearly polarized in the transverse plane:

→ Expect a $\cos 2\Delta\phi$ modulation in the final state[1]

• Quantized spin is encoded into the orbital angular momentum of the $\pi^+ \pi^-$ pair

Polarization Interference Effect

• Nuclei “take-tURNS” emitting photon vs. Pomeron

• Polarization vector: aligned radially with the “emitting” source

• Well defined in the photon position eigenstates

Interference is sensitive to:
→ Nuclear Geometry (gluon distribution)
→ Impact Parameter
Results: $\langle \cos 2\Delta\phi \rangle$ vs. $P_\perp$

- Strong $\cos 2\Delta\phi$ modulation observed at pair $p_{\perp \pi\pi} < \sim 60$ MeV/c
- Interference structure visible → dip and peak in modulation at higher $p_{\perp \pi\pi}$
- STARLight[1] does not include polarization effect
- Qualitatively consistent with theoretical calculation including two-source interference effects[2]
- Like-sign pairs roughly illustrate the effect of the STAR acceptance.
- Acceptance effect is very small at low $p_{\perp \pi\pi}$ and grows to $\sim -10\%$ at $p_{\perp \pi\pi} = 200$ MeV/c

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Comparison between Au+Au and U+U Collisions

- Clear $\rho^0$ peak in both Au+Au and U+U UPC events.
- First measurement of diffractive coherent photonuclear production in U+U collisions.
- Select region around $\rho^0$ mass with roughly uniform acceptance.
Comparison between Au+Au and U+U Collisions

- Compare the \( \cos 2\Delta \phi \) modulation in ultra-peripheral events from Au+Au at \( \sqrt{s_{NN}} = 200 \) and U+U at \( \sqrt{s_{NN}} = 193 \) at low \( p_T \) where the modulation is strongest (\( p_T < 60 \text{ MeV/c} \))

Quantify the difference in strength for Au+Au vs. U+U via a fit:

\[
 f(\Delta \phi) = 1 + a \cos 2\Delta \phi
\]

Au+Au:
\[
a = 0.292 \pm 0.004 \text{ (stat.)} \pm 0.004 \text{ (syst.)}
\]

U+U:
\[
a = 0.237 \pm 0.006 \text{ (stat.)} \pm 0.004 \text{ (syst.)}
\]

Difference of 4.3\( \sigma \) (stat. & syst.):
- Interference effect is sensitive to the nuclear geometry / gluon distribution

\[
f(\Delta \phi) = 1 + a \cos(2\Delta \phi)
\]
cos 2\Delta\phi \ vs. \ p_T \ in \ U+U \ at \ \sqrt{s_{NN}} = 193 \ GeV

- Strong cos 2\Delta\phi modulation observed at p_T < ~60 MeV/c – similar to Au+Au
- U+U curve is fully corrected for STAR acceptance
- Systematic uncertainty shown in blue band
- Similar structure observed with respect to Au+Au
- Narrower main peak than Au+Au
- Broader second peak, large uncertainty
\( \cos 2\Delta \phi \) vs. \( p_T \) in U+U and Au+Au

- Strong \( \cos 2\Delta \phi \) modulation observed at \( p_T < \sim 60 \) MeV/c – similar to Au+Au
- U+U curve is fully corrected for STAR acceptance
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- Similar structure observed with respect to Au+Au
- Narrower main peak than Au+Au
- Au+Au: acceptance and background corrected with syst. uncert.
Quantitative Comparison: Au+Au and U+U

• Fit U+U curve with scaled Au+Au curve ($\alpha p_{\perp} \rightarrow p_{\perp}$)

• Robust best fit for $\alpha = 1.194 \pm 0.021$ (stat. and syst. uncert) $\rightarrow 9\sigma$ significant difference

• Consistent with ratio of long axes (U/Au) of $1.22 \pm 0.02$

STAR Preliminary

$\alpha = 1.194 \pm 0.021$

$\chi^2 = 11.49 / \text{ndf} = 16 = 0.72$

Fit range $p_T < 0.12 \text{ GeV/c}$

Theoretical Predictions for $\gamma \mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$

Predicted modulation shows structure vs. pair $p_\perp$

Structure in $\cos 2\Delta \phi$ signal is sensitive to:

$\rightarrow$ Nuclear Geometry / gluon distribution
  Nuclear skin depth (right)
$\rightarrow$ Impact parameter
  UPC (blue) vs. 70–90% central (red)

Summary

1. Observed \( (6.7\sigma) \cos 4\Delta\phi \) angular modulation in linear polarized \( \gamma \gamma \rightarrow e^+ e^- \) (Breit-Wheeler) process
   - First laboratory evidence for vacuum birefringence
   - Colliding photons are linearly polarized

2. First measurement of \( \Delta\phi \) modulations in \( \gamma \Pi^0 \rightarrow \rho^0 \rightarrow \pi^+ \pi^- \) process
   - Strong \( \cos 2\Delta\phi \) modulations due to photon polarization
     - Strong structure observed vs. pair \( p_T \)
   - Measurement in \( \text{Au+Au} \) and \( \text{U+U} \) collisions
     - Experimentally demonstrate sensitivity to gluon distribution within nucleus
   - Results are qualitatively consistent with theoretical predictions
     - Sensitive to nuclear geometry \( \rightarrow \) gluon density within nucleus
     - Sensitive to “double-slit” interference of photon polarization

- Looking forward to more theoretical developments