Quantum mechanics in coherent photoproduction: the limits of coherence, and multiple vector mesons

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Presented at UPC2023, Dec. 10-15, Playa del Carmen, Mexico

- Good-Walker paradigm
- Where GW fails
- An alternative to GW
- Beyond the Pomeron:
  - Coherence with Reggeons?
- Multiple Vector Meson emission
Coherent and Incoherent Photoproduction: a quantum view

- The Good-Walker formalism links coherent and incoherent production to the average nuclear configuration and event-by-event fluctuations respectively.
  - Configuration = position of nucleons, gluonic hot spots etc.
- Coherent: Nucleus remains in ground state, so sum the amplitudes, then square -> average over different configurations.
- Incoherent = Total – coherent; total: square, then sum cross-sections for different configurations.

\[
\frac{d\sigma_{\text{tot}}}{dt} = \frac{1}{16\pi} \left\langle |A(K, \Omega)|^2 \right\rangle
\]

Average cross-sections ($\Omega$)

\[
\frac{d\sigma_{\text{coh}}}{dt} = \frac{1}{16\pi} \left| \left\langle A(K, \Omega) \right\rangle \right|^2
\]

Average amplitudes ($\Omega$)

\[
\frac{d\sigma_{\text{inc}}}{dt} = \frac{1}{16\pi} \left( \left\langle |A(K, \Omega)|^2 \right\rangle - \left| \left\langle A(K, \Omega) \right\rangle \right|^2 \right)
\]

Incoherent is difference

Transverse interaction profiles

- The coherent cross-section gives us access to the transverse spatial distribution of individual targets within the nucleus

\[
\frac{d\sigma_{\text{coh}}}{dt} = \frac{1}{16\pi} \left| \langle A(K, \Omega) \rangle \right|^2
\]

- \( t = p_T^2 + p_z^2 \sim p_T^2 \)

- \( p_T \) and \( b \) are conjugate. \( d\sigma/dp_T \) encodes information about the transverse locations of the interactions

- The two-dimensional Fourier transform of \( d\sigma/dt \) gives \( F(b) \), the transverse distribution of targets

\[
F(b) \propto \frac{1}{2\pi} \int_0^{\infty} dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}
\]

- *flips sign after each diffractive minimum

- Without shadowing, this is the shape of the nucleus

- Multiple serious caveats – range of integration/ windowing finding diffractive minima, subtracting out photon \( p_T \) etc.
Incoherent production and event-by-event fluctuations

- The incoherent cross-section accesses event-by-event fluctuations in the nuclear configuration, including the positions of individual nucleons, gluonic hot spots, etc.

\[
\frac{d\sigma_{inc}}{dt} = \frac{1}{16\pi} \left( \left| \langle A(K, \Omega) \rangle \right|^2 - \left| \langle A(K, \Omega) \rangle \right|^2 \right)
\]

- Deviations from the mean.
- The connection between \( t \) and impact parameter is weaker than for coherent production, but this can be used to test models.
Coherent photoproduction where Good-Walker predicts it should not occur

- Coherent: peak with $p_T \sim < \hbar/R_A$
- $AA \rightarrow A^*A^* V$
  - Coherent photoproduction with nuclear excitation
- Most older STAR UPC analyses REQUIRE mutual Coulomb excitation in trigger
- ALICE also sees coherent photoproduction in events containing neutrons
- Explained by diagram with independent photon emission
  - Factorization!
  - But also possible with single photons, especially at larger $p_T$
- Good-Walker does not have an exception for mostly separable reactions

SK, Phys. Rev. C 107, 055203 (2023)
Coherent photoproduction in peripheral collisions

- Coherent J/ψ photoproduction in peripheral hadronic collisions
  - Peak at $p_T < \sim \hbar/R_A$
- J/ψ photoproduction and hadronic interactions have similar time scales
- Seen by ALICE and STAR
- How large is the target region?
  - All nucleons?
  - Just spectators?

See talks by N. Brize (ALICE) & K. Shen (STAR)
L. Massacrier for ALICE, arXiv:1902.03637
W. Zha et al., PRC97, 044910 (2018)
Other possible sub-reactions

- Bremsstrahlung from the ion
  - $1/k$ photon energy spectrum
    ✦ Logarithmically divergent

- Pair production
  - Electron mass keeps cross-section finite, but large
    ✦ 200,000 barns for Pb-Pb at the LHC
    ✦ $P(\text{pair}) \sim >1$ for $b \geq 2 R_A$
    ✦ Lepton $p_T$ peaked at $\sim$ few $m_e$
    ✦ Leptons are at large rapidity
  - Most of these pairs are invisible

- There are many ways to have additional, unseen particles

- Small kinematic changes, but breaks exclusivity of reactions
  - Good-Walker requires exclusive reactions!
Another issue with Good-Walker

- Nuclear excitation is endothermic: energy transfer to the nucleus
- Nucleon emission requires $E_T = 5-7$ MeV for lead/gold
  - If the reaction proceeds by single particle excitation (as expected), $p_{\text{struck-nucleon}} > \sqrt{2} m E_T \sim 100$ MeV/c
- Most of the coherent region. Incoherent cross-sections should change when crossing this threshold
- Lowest excitation energy for lead: 2.6 MeV
  - If a single nucleon is struck, $p_T > 70$ MeV
- Lowest excitation energy for gold: 77 MeV
  - If a single nucleon is struck, $p_T > 12$ MeV
- Incoherent interactions are impossible at lower energy/$p_T$ transfer
- In contrast, in GW, high-energy incoherent photoproduction depend on low-x partonic structure of the target, which should be very similar for lead and gold.
  - This difference should be testable.
An alternate, semi-classical approach

- Sum reactions where the target is indistinguishable
- \( \sigma_{\text{coherent}} = |\sum_i A_i k \exp(ikb)|^2 \)
  - Usually assume \( A_i \) are identical
  - For \( kb < hbar \exp(ikb) \sim 1 \), and the amplitudes add coherently
    - \( \frac{d\sigma}{dt} \big|_{t=0} \sim N^2 \)
  - For \( kb > hbar \exp(ikb) \) the exponential has a random phase
    - \( \frac{d\sigma}{dt} \big|_{t=0} \sim N \)

- This naturally predicts a transition between coherent and incoherent regimes as \( k \) rises
  - Could add multiple interactions (ala Glauber) to include shadowing
  - Could include nucleon excitation regime by summing over partons rather than nucleons

- Does not follow the target after the interaction
  - Insensitive to nuclear breakup

- Can accommodate gradual loss of coherence
Tests of semi-classical vs. Good-Walker

- Coherent photoproduction with nuclear excitation
- Coherent photoproduction in peripheral heavy-ion collisions
- Coherent photoproduction in Reggeon exchange
  - Reactions involving exchange of quantum numbers
  - $\gamma + A \rightarrow a_2^+(1320) + (A-1)$
    - Changes a proton into a neutron
    - Is this coherent over all protons in a target?
- Compare $d\sigma/dt$ for incoherent photoproduction in lead and gold
  - Including photoproduction accompanied by photons from nuclear excitation.
    - Possible at Jefferson Lab by adding a germanium detector to an existing spectrometer
      - For lighter (than the $J/\psi$) mesons
$a_2^+(1320)$ photoproduction in pA UPCs

- Charged Reggeon exchange $\gamma p \rightarrow a_2(1230)^+ n$
  - Parameters based on fixed-target data
  - Limited data
    
    $$\sigma_{\gamma p \rightarrow a_2^+(1320)n}(W) \approx 5.42(W^2 - m_p)^{-0.82} - 5.80\exp(-0.070(W^2 - m_n^2)^2),$$
  - $\sigma$ peaks at few*threshold
    - Favors low photon energy
  - UPC signal peaks at large $y$
  - $\sigma = 170$ $\mu$b (pAu@RHIC)/560 $\mu$b (pPb@LHC)
    - Large signals
  - $Br(\pi^+\pi^-\pi^+) \sim 70\%$
  - Visible in STAR forward detector and/or LHCb & ALICE FoCal

$a_2^+(1320)$ and $a_2^+(1320)$ photoproduction on ion targets

- $\gamma p \rightarrow a_2(1230)^+n$ probes protons in target
- $\gamma n \rightarrow a_2(1230)^-p$ probes neutrons in target
- Coherent photoproduction of both can compare proton and neutron radii of heavy nuclei in a single experiment, with small systematics
Studies of exotica

- The ability to study Reggeon exchange reactions greatly expands the range of accessible final states
  - Exotica, including c cbar and lighter particles
  - Many conventional mesons
- Meson-photon couplings probe the nature of these exotica
  - Couplings depend on nature (glueball, tetraquark, meson molecule etc.) and spin of the final state
- Heavier (ccbar) mesons have smaller <y> than lighter states

History of multiple vector meson production

- Klein & Nystrand (1999) explained via factorization:
  - $\sigma = \int d^2b \ P_1(b)P_2(b)$...
  - Data on VM + mutual Coulomb excitation show factorization works

- A series of papers by Mariola Klusek-Gawenda et al. calculated cross-sections and kinematics
  $$\sigma (AA \rightarrow AA\rho^0\rho^0) = \int \hat{\sigma} \ (\gamma\gamma \rightarrow \rho^0\rho^0; W_{\gamma\gamma}) \ S_{ab}^2 (b) \ N(\omega_1, b_1)N(\omega_2, b_2) \times d^2b_1d^2b_2d\omega_1d\omega_2 ,$$

- Other papers showed used similar approaches
  - $\sigma(\rho^0\rho^0) \sim 20\%$ of $\sigma(\pi^+\pi^- \pi^+\pi^-)$, so current non-observation not problematic

Interference in meson production

- Interference has been seen in single-meson production.
- Destructive interference
  - \( \sigma \sim |A_1 - A_2 e^{i k \cdot b}|^2 \) for pp, AuAu…
    - \( A_1, A_2 \) are functions of photon energy
      - When \( y \neq 0 \) then \( A_1 \neq A_2 \)
      - \( \sigma \) drop as \( p_T \rightarrow 0 \)
    - \( \sigma \sim |A_1 + A_2 e^{i k \cdot b}|^2 \) for pbarp

- Angular modulation of \( d\sigma/dt \) since pair \( p_T \) follows \( b \) and \( \pi^\pm p_T \) depends on VM polarization
  - Allows a quality fit to \( d\sigma/dt \), with the reasonable nuclear radii & skin thicknesses

Talks by A. Riffero (ALICE) & K. Wang (STAR)
SK & J. Nystrand, PRL 84, 2330 (2000); STAR PRL 102, 112301 (2009); H. Xing et al., JHEP 10, 064 (2020); STAR Sci. Adv. 9, 1 eabq3903 (2023) etc.
Notation

- $p$ – vector meson momentum
- $q$ – photon momentum
- $k$ – Pomeron momentum
- $A_{1,i}$ and $A_{2,l}$ – $A_1$ and $A_2$ are the two ions; the sums over indices $i$ and $l$ run over the individual nucleons in the ion
  - This could alternately be an integral over nuclear density, with similar results
- The nucleons have impact parameters $\vec{b}_i$ and $\vec{b}_l$. These vectors are taken from the center-of-mass of the system. For the two nuclei, $\vec{b}_1$ and $\vec{b}_2$ are the vectors from the center of the nuclei to the system COM.
  - So $\vec{b}_1 = -\vec{b}_2$
Double mesons - nonidentical (e. g. $\rho\phi$)

Either meson can come from either nucleus -> 4 diagrams

$$P(b) = \left| \sum_i A_{1,i}(b, p_j^i) e^{i\vec{k}_1 \cdot \vec{b}_i} \sum_{\ell} A_{1,\ell} e^{i\vec{k}_2 \cdot \vec{b}_\ell} ight|^2$$

- $$\sum_i A_{1,i}(b, p_j^i) e^{i\vec{k}_1 \cdot \vec{b}_i} \sum_{\ell} A_{2,\ell} e^{i\vec{k}_2 \cdot \vec{b}_\ell}$$
- $$\sum_i A_{2,i}(b, p_j^i) e^{i\vec{k}_1 \cdot \vec{b}_i} \sum_{\ell} A_{1,\ell} e^{i\vec{k}_2 \cdot \vec{b}_\ell}$$
- $$\sum_i A_{2,i}(b, p_j^i) e^{i\vec{k}_1 \cdot \vec{b}_i} \sum_{\ell} A_{2,\ell} e^{i\vec{k}_2 \cdot \vec{b}_\ell}$$

- Sum over individual nucleons; could also integrate density
  - Gives 2nd momentum scale: $\hbar/R_A$ (in addition to $\hbar/b$)
  - Vectors $\vec{b}$ are from center of mass

- Signs come from negative parity of vector mesons

- $A_{1,i}$, $A_{2,\ell}$ are production amplitudes on individual nucleons
  - Slightly photon-energy dependent

Work in progress!
Forward production of light mesons

- $\sigma(\gamma A \rightarrow \rho/\phi A)$ varies slightly with photon energy
- Photon flux scales as $1/k$
- At large $|y|$ photons come predominantly from one nucleus
- The first two diagrams dominate at large $+y$ and $-y$ respectively.
  - No interference, for one direction:
    $$P(b) = \left| \sum_i A_{1,i}(b, \vec{p}_1) e^{i \vec{k}_1 \cdot \vec{b}_i} \sum_i \bar{A}_{1,i}(b, \vec{p}_2) e^{i \vec{k}_2 \cdot \vec{b}_l} \right|^2$$
  - Same ion – $p_T$ scale for coherence is $\hbar/R_A$
    - As with single ions

Here

Dominant

\[\text{STAR: Au+Au } |S_{NN}|=200 \text{ GeV}\]

Data: $|\phi| < \pi/24$
- Model II, $\phi=0$
- Woods-Saxon, $R=7.90 \text{ fm}, a=0.54 \text{ fm}$
Mid-rapidity production of non-identical double mesons (e. g. $\rho\phi$)

- All four diagrams contribute

$$P(b) = \left| \sum_i A_{1,i}(b, \vec{p}_j) e^{i k_1 \cdot \vec{b}_i} \sum_l A_{1,l} e^{i k_2 \cdot \vec{b}_l} ight|^2$$

- Consider limit identical nuclei, $y=0$, $p_{T1}=p_{T2}=0$
  - Production disappears.
  - Some similarities to the single-ion case, but more complex patterns. Coherent enhancement for $p_T<hbar/R_A$, & destructive interference for $p_T<hbar/<b>.$
Mid-rapidity production of non-identical double mesons (e.g. $\rho\phi$)

- All four diagrams contribute
- 2 like-target terms are similar
  - Need a propagator $\exp[i(k_1-k_2)b]$ to go from one to the other by swapping targets
    - $k_1-k_2$ because the $\vec{b}$ go in opposite directions
  - All terms have momentum scale $\hbar/b$
- 2 opposite-target terms:
  - $-\exp[i(k_1b_1+k_2b_2)] - \exp[i(k_1b_2+k_2b_1)]$
  - $=-\exp[i((k_1-k_2)b_1)] - \exp[-i((k_1-k_2)b_1)]$
  - $=-2 \cos((k_1-k_2)b_1)$
    - Coherent enhancement with $k_1,k_2$ large as long as $k_1-k_2$ is small

$$P(b) = \left| \Sigma_i A_{1,i}(b, \vec{p}_j^*) e^{i\vec{k}_1 \cdot \vec{b}_i} \Sigma_l A_{1,l} e^{i\vec{k}_2 \cdot \vec{b}_l} - \Sigma_i A_{1,i}(b, \vec{p}_j^*) e^{i\vec{k}_1 \cdot \vec{b}_i} \Sigma_l A_{2,l} e^{i\vec{k}_2 \cdot \vec{b}_l} - \Sigma_i A_{2,i}(b, \vec{p}_j^*) e^{i\vec{k}_1 \cdot \vec{b}_i} \Sigma_l A_{1,l} e^{i\vec{k}_2 \cdot \vec{b}_l} + \Sigma_i A_{2,i}(b, \vec{p}_j^*) e^{i\vec{k}_1 \cdot \vec{b}_i} \Sigma_l A_{2,l} e^{i\vec{k}_2 \cdot \vec{b}_l} \right|^2$$

Full combination
Still to come
Identical (indistinguishable) mesons

- Two possibilities
  - Photon 1 -> Meson 1 and Photon 2 -> Meson 2
  - Photon 1 -> Meson 2 and Photon 2 -> Meson 1
    - Identical routes to the same final state
Identical (indistinguishable) mesons at forward rapidity

- Two diagrams contribute.
  \[ P(b) \sim |2N^2A_i^2 \exp[i(k_1+k_2)b]|^2 \]
  - Depends on sum of Pomeron \( k_T \)

- Coherent enhancement when \( k_1 b < \hbar \)

- Longitudinal coherence also required
  - \( k_{z1} + k_{z2} < \hbar/R_A \)
  - Coherence condition tightens compared to single mesons

- If coherence conditions are satisfied, the cross-section is twice the non-identical meson case.
  - Superradiance

Here, for simplicity:
Neglect longitudinal coherence
More than 2 forward mesons

- For M mesons, there are M! diagrams

- Production probability scales as

\[ P_M(b) = M! N^{M*M} A_i^{M*M} = M! [P_1(b)]^M \]

  - For large M, M! increases faster than \([P_1(b)]^M\)
  - For PbPb at the LHC, \(P_r(b=2R_A) \sim 0.03\)

- Potentially, a vector meson laser

- Significant limitations
  - The accessible phase space drops as 1/M
  - Can only access a fraction of the energy in the photon fields
  - \(P_r(b=2R_A)\) is pretty small, even for U beams at fcc
  - Open question – superradiance/lasing requires independent emitters. Photons emission is independent, but with common phase

- Clear demonstration probably requires a forward detector
  - N=2 is clearly accessible, and N=3 should also be visible with effort
Identical particles at mid-rapidity

- 8 amplitude terms
  - 4 w/ emission from same nucleus
  - 4 w/ emission from opposite nuclei
- 2 distance scales
  - $\hbar/R_A$ for emission from same nucleus
  - $\hbar/b$ for emission from different nuclei
- First, consider $\hbar/R_A < k < \hbar/b$
- 4 paired opposite nuclei terms:
  - Similar enhancement as non-identical particles
  - Coherent enhancement with $k_1,k_2$ large as long as $k_1 - k_2$ is small

$$P(b) = \left| \sum_i A_{1,i}(b, \vec{p}_j) e^{ik_1 \cdot \vec{b}_i} \sum_l A_{1,l} e^{ik_2 \cdot \vec{b}_l} \\ - \sum_i A_{1,i}(b, \vec{p}_j) e^{ik_1 \cdot \vec{b}_i} \sum_l A_{2,l} e^{ik_2 \cdot \vec{b}_l} \\ - \sum_i A_{2,i}(b, \vec{p}_j) e^{ik_1 \cdot \vec{b}_i} \sum_l A_{1,l} e^{ik_2 \cdot \vec{b}_l} \\ + \sum_i A_{2,i}(b, \vec{p}_j) e^{ik_1 \cdot \vec{b}_i} \sum_l A_{2,l} e^{ik_2 \cdot \vec{b}_l} + \sum_i A_{1,i}(b, \vec{p}_j) e^{ik_2 \cdot \vec{b}_i} \sum_l A_{1,l} e^{ik_1 \cdot \vec{b}_l} \\ - \sum_i A_{1,i}(b, \vec{p}_j) e^{ik_2 \cdot \vec{b}_i} \sum_l A_{2,l} e^{ik_1 \cdot \vec{b}_l} \\ - \sum_i A_{2,i}(b, \vec{p}_j) e^{ik_2 \cdot \vec{b}_i} \sum_l A_{1,l} e^{ik_1 \cdot \vec{b}_l} \\ + \sum_i A_{2,i}(b, \vec{p}_j) e^{ik_1 \cdot \vec{b}_i} \sum_l A_{2,l} e^{ik_1 \cdot \vec{b}_l} \right|^2$$
Azimuthal asymmetries

- Multiple vector mesons are linearly polarized along the same axis
  - They should display azimuthal asymmetries
  - Sort-of like due to two-source interference, but with richer phenomenology
Going further – stimulated decays

- If we can produce $\rho^0$ (or other mesons) in the same state, then should be able to observe stimulated decays.
- Same state criteria for short-lived particles: coherence time $>$ particle lifetime
  - Momentum close enough together
- Stimulated decays should be visible in one of two ways
  - For particles with different decays (e.g. $J/\psi \rightarrow ee, \mu\mu$) by ‘tagging’ one one decay, should see an excess of the same state from the other $J/\psi$
  - For states like $\rho^0\rho^0$, should see angular correlations between the $\pi^+ \pi^+$ and $\pi^- \pi^-$
Conclusions

- Coherence is an interesting and subtle topic, with important consequences.
- The Good-Walker paradigm relates coherent and incoherent photoproduction to the average nuclear configuration and configuration fluctuations respectively. In Good-Walker coherence means that the target remains in the ground state. That disagrees with some experimental observations of coherent photoproduction.
- An alternate approach to coherence – adding amplitudes, so $\sigma_{\text{coherent}} = |\sum_i A_i k \exp(ikb)|^2$ – can explain data where Good-Walker fails.
- ‘Adding amplitudes’ allows some new coherent UPCs channels, including coherent photoproduction of charged mesons.
- UPC production of multiple vector mesons exhibits many interesting aspects of interference.
  - Superradiance for identical meson emission in the forward direction.
  - Interference when $k_1, k_2 > \hbar/b$, as long as $k_1 - k_2 < \hbar/b$. 
Conclusions (II)

BIG MATH NEWS: THEY FINALLY FIGURED OUT THE VALUE OF X.

\[ x = 4.1083 \]

Gracias!

xkcd.com