Coherent photoproduction in incoherent interactions? A challenge for Good-Walker, and some thoughts on a fix

Spencer R. Klein, LBNL

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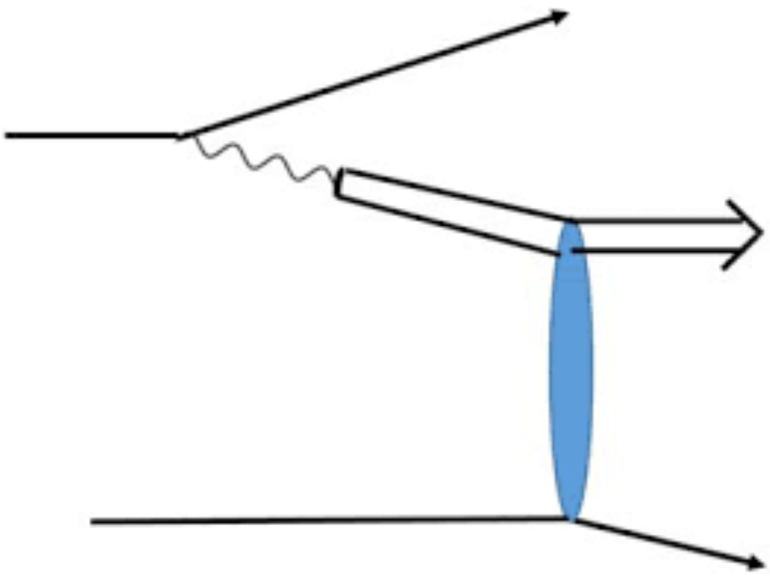
- The Good-Walker paradigm
- Two examples where it fails
- Why it fails
- An alternate approach
- A second issue with Good-Walker
- Future needs
- Conclusions



Based on SK, arXiv:2301.01408

Beyond gluon densities: to spatial distribution and fluctuations

- 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

$$\frac{d\sigma_{tot}}{dt} = \frac{1}{16\pi}\left\langle \left|A(K,\Omega)\right|^2 \right\rangle$$ Average cross-sections (Ω)

$$\frac{d\sigma_{coh}}{dt} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$ Average amplitudes (Ω)

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

Good and Walker, Phys. Rev. D120, 1857 (1960); Miettinen and Pumplin, Phys. Rev. D 18, 1696 (1978)

Transverse interaction profiles

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

$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi} \left|\langle A(K,\Omega)\rangle\right|^2$$

Average amplitudes (Ω)

  - $t = p_T^2 + p_z^2 \sim p_T^2$
- p_T and b are conjugate. $d\sigma/dp_T$ encodes information about the transverse locations of the interactions
  - Without shadowing, this is the shape of the nucleus
- 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

- Multiple serious caveats – range of integration/ windowing finding diffractive minima, subtracting out photon p_T etc.

Incoherent production and event-by-event fluctuations

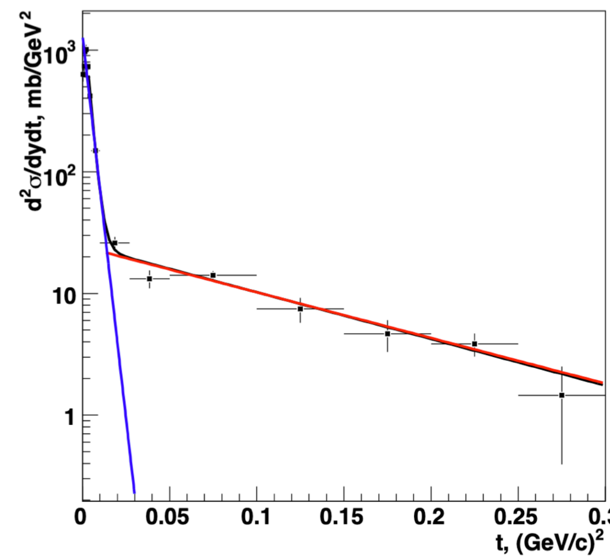
- The incoherent cross-section lets us measure the event-by-event fluctuations in the nuclear configuration, including the positions of individual nucleons, gluonic hot spots, etc.

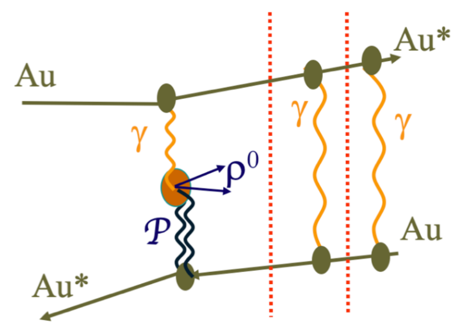
$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle \left| A(K,\Omega) \right|^2 \right\rangle - \left| \left\langle A(K,\Omega) \right\rangle \right|^2 \right)$$

- Probes the 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.

Examples of coherent photoproduction where Good-Walker predicts it should not occur

- Coherent: peak with p_T ~ < hbar/R_A
- AA -> A*A* V
  - Coherent photoproduction with nuclear excitation
- All published 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
  - Also possible with single photons, especially at larger p_T
- Good-Walker does not have an exception for mostly separable reactions

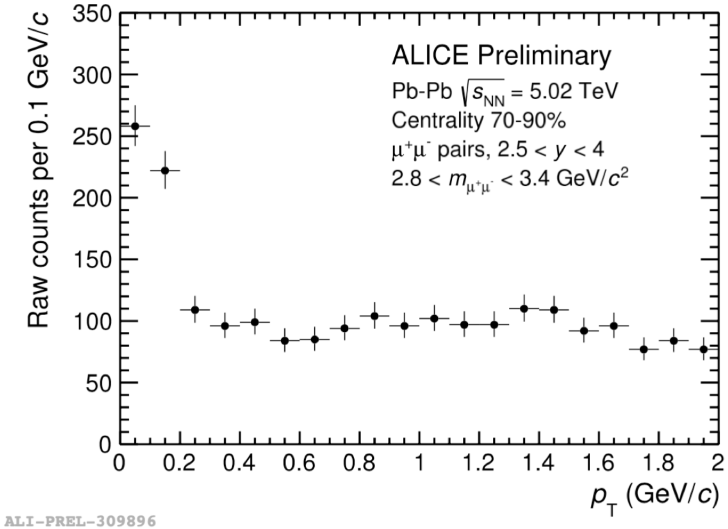




STAR, Phys. Rev C77, 034910 (2008)

Coherent photoproduction in peripheral collisions

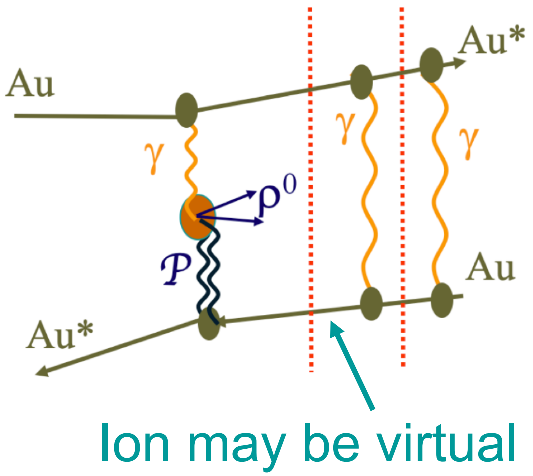
- Coherent J/ψ photoproduction in peripheral hadronic collisions
  - Peak at $p_T < \sim \text{hbar}/R_A$
- Seen by ALICE and STAR



L. Massacrier for ALICE, arXiv:1902.03637

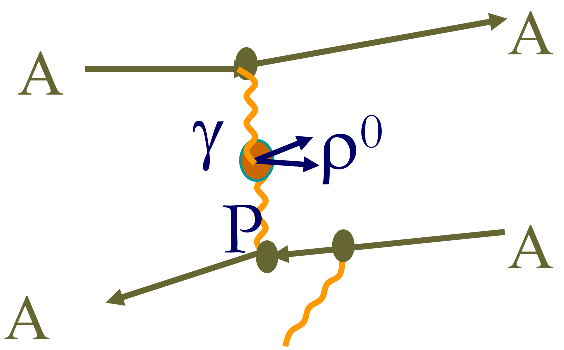
Why does Good-Walker fail here?

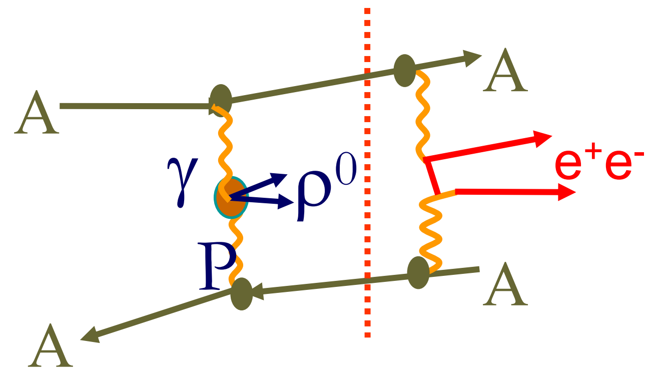
- Good-Walker assumes that the incident probe is a single photon (or other particle)
  - An interacting ion or electron can emit more than one photon
    - We cannot tell how many photons participate in the reaction
    - Ions are more likely to radiate photons than electrons, but this is a question of degree
      - Two-photon exchange effects have been observed in form-factor measurements in eA collisions at Jefferson Lab
- We cannot tell if another particle(s) is present in the interaction
- What about the reaction factorization?
  - Intermediate ions may be (slightly) virtual
  - Factorization is imperfect



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(pair) ~ >1 for b>= 2 R_A
    - Lepton p_T peaked at ~ 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!





Time scales

- The target may be involved in multiple subprocesses at once
- Different time scales ~~ hbar/energy scale
- Two cases
  - For UPC VM + XnXn excitation
    - Excitation time scale hbar/E_{exc} >> VM production hbar/M_V
  - Photoproduction in peripheral collisions
    - Time scales are similar or hadronic reaction is faster
    - If hadronic interactions occurs first, $W_{\gamma p}$ will be lower, reducing the cross-section. Any calculation should consider both time orderings.
    - Testable with better calculations and more accurate data
- Calculations that separate these time scales might be able to explain VM production with Coulomb excitation, but would not solve the problem for peripheral collisions.

An alternate, semi-classical approach

- Sum reactions where the target is indistinguishable
- $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Assume A_i are identical
  - For kb < hbar exp(ikb) ~ 1, and the amplitudes add coherently
    - $d\sigma/dt\,|_{t=0} \sim N^2$
  - For kb > hbar exp(ikb) the exponential has a random phase
    - $d\sigma/dt\,|_{t=0} \sim N$
- This naturally predicts coherent and incoherent regimes
  - Could add multiple interactions (ala Glauber) to include shadowing
  - Could include nucleon excitation regime by introducing partons
- Does not follow the target after the interaction
  - Insensitive to nuclear breakup
- Could accommodate gradual loss of coherence

Another issue with Good-Walker: incoherent emission in lead vs. gold

- In GW, the incoherent photoproduction cross-section depends on nuclear fluctuations
  - The density profiles for lead and gold are similar
    - Woods-Saxon distributions
  - Gluon shadowing should be similar
  - In GW, incoherent cross-sections should be similar
- Their shell-model structure is very different. This quantizes the energy transfer for low-|t| excitations, so may lead to rather different low-|t| incoherent production
- Different wave function bases: nucleon positions, etc. or shell model orbitals

Neutron emission in gold and lead

Lead-208

^{208}Pb	207.976627	Daltons
^{207}Pb	206.975872	Daltons
Neutron	1.00867108	Daltons
$^{207}Pb+n$	207.984543	Daltons
ΔE	-0.0079160	Daltons
ΔE	-7.38	MeV
P(single N)	118	MeV/c

Gold-197

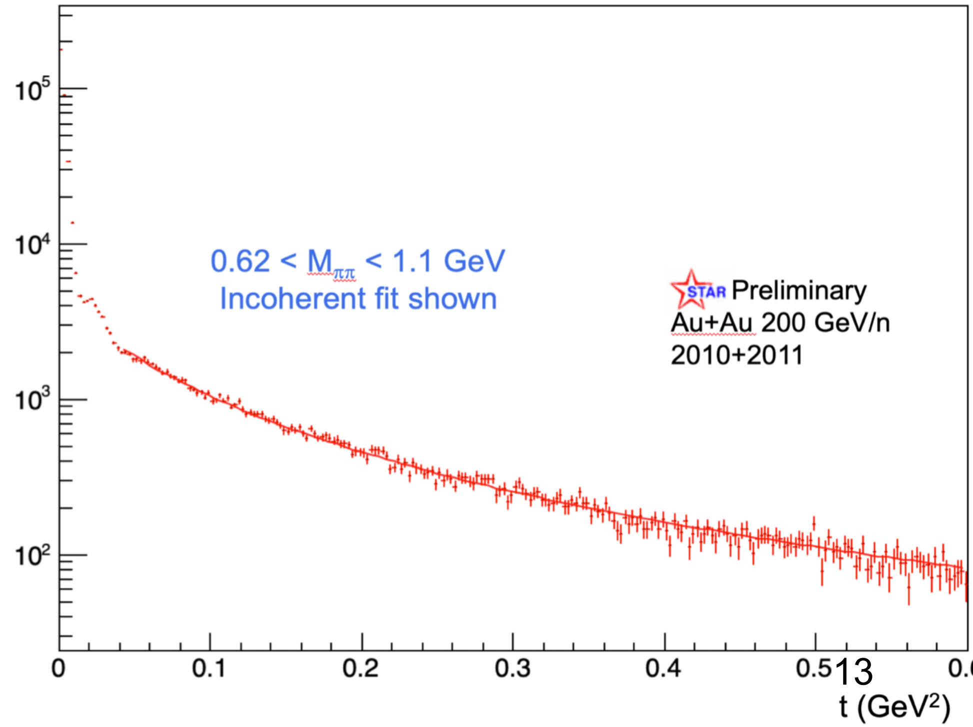
^{197}Au	196.966569	Daltons
^{196}Au	195.96657	Daltons
Neutron	1.00867108	Daltons
$^{196}Au+n$	196.975241	Daltons
ΔE	-0.00867238	Daltons
ΔE	-8.07	MeV
P(single N)	122	MeV/c

Both reactions are **endothermic**. There is a threshold for single neutron emission. As expected for stable nuclei. The energy thresholds are similar.

Proton emission thresholds are ~ similar for the two nuclei

Kinematics of nucleon emission

- The simplest model is that the photon strikes a single nucleon, ejecting it from the nucleus.
  - $p^2=E/2m$; If it takes E> 5-8 MeV to break up then nucleus, minimum initial nucleon momentum ~ 100 MeV/c
- This model is supported by STAR data. At larger |t|, $d\sigma/dt$ for coherent dipion production is consistent with a dipole form factor used for protons (but inconsistent with an exponential)
- The VM recoils against it
  - $p_{T, VM}$ >~ 100 MeV/c
  - At lower momenta, incoherent photoproduction must involve excited states decaying by photon emission



SK for STAR, arXiv:2107.10447

Nuclear excitation in the shell model regime

- At lower energies, excitation is determined by the shell model. Nuclei are excited to specific states, which decay by emitting one or more photons.
  - E> ~ 5 MeV – statistical model for photon emission
  - E < ~ 5 MeV – de-excitation by γ transitions between states
- Lead’s lowest excited state is at 2.6 MeV
  - Doubly magic
- Gold has an excited state at 77 keV
  - Lifetimes ~ 1.92 ns, so photonic deexcitations are invisible in RHIC/LHC/EIC detectors
- Very different energy levels, so expect different behavior at small |t| -> in GW, this is equivalent to predicting very different event-by-event fluctuations

Implications

- GW and the semi-classical model make similar predictions for coherent photoproduction for targets that remain in the ground state.
- For targets that are excited, in the semi-classical model, coherent prediction remains even when GW predicts it should disappear.
  - The semi-classical model correctly predicts this.
- Incoherent production has very different origins in the two models
  - GW – nuclear fluctuations (no dynamical origin)
  - Semi-classical – depends on momentum transfer, and distinguishability of the struck target.
- If we cannot see all target excitations, GW will mis-classify some reactions, and so mis-estimate the degree of nuclear fluctuations.
  - How can such soft (so with long time scales) reactions affect what happens at much higher energy scales?

Next steps

- We need to develop the GW formalism to properly account for more complicated reactions.
  - Coherent production should degrade gracefully in the presence of additional reactions.
  - This probably requires a higher order, or field theoretical formulation
- Precise measurements of coherent photoproduction in peripheral collisions would shed light on the gradual loss of coherence
  - What is the slope of $d\sigma/dt$?
    - How large is the coherent region?
  - How does $d\sigma/dt$ depend on the reaction plane?
    - The spectator region is not spherical
  - How does the cross-section change with centrality?
    - Time ordering, size of coherent region, J/ψ survival

Conclusions

- The Good-Walker approach connects coherent photoproduction with the transverse distribution of targets, and incoherent photoproduction with target fluctuations.
- Coherent VM photoproduction is seen in two regimes where GW says it should occur. A semi-classical calculation can explain this data.
- GW expects a single incident photon, whereas UPCs and eA collisions may involve multiple photons.
- There are many ways for VM photoproduction to produce unseen particles, complicating the separation into coherent and incoherent interactions, further confusing the picture.
    - The GW formalism needs to be extended to account for more complicated reactions with additional particles.

Backup

Incoherent final states

- Neutron emission is assumed dominant
- Proton emission is also possible, but subdominant because the nuclear surface is mostly neutrons
- Photon emission
  - Calculations assume momentum transfer to a single nucleon, followed by an intranuclear cascade
    - Microscopic model, many uncertainties
    - What is the region of validity
  - Strikman *et al.:* in LHC PbPb UPCs, ~7% of incoherent J/ψ come w/o neutrons
  - BeAGLE Monte Carlo: fraction of incoherent photoproduction depends on t
    - ~~2% at large t, larger at small t

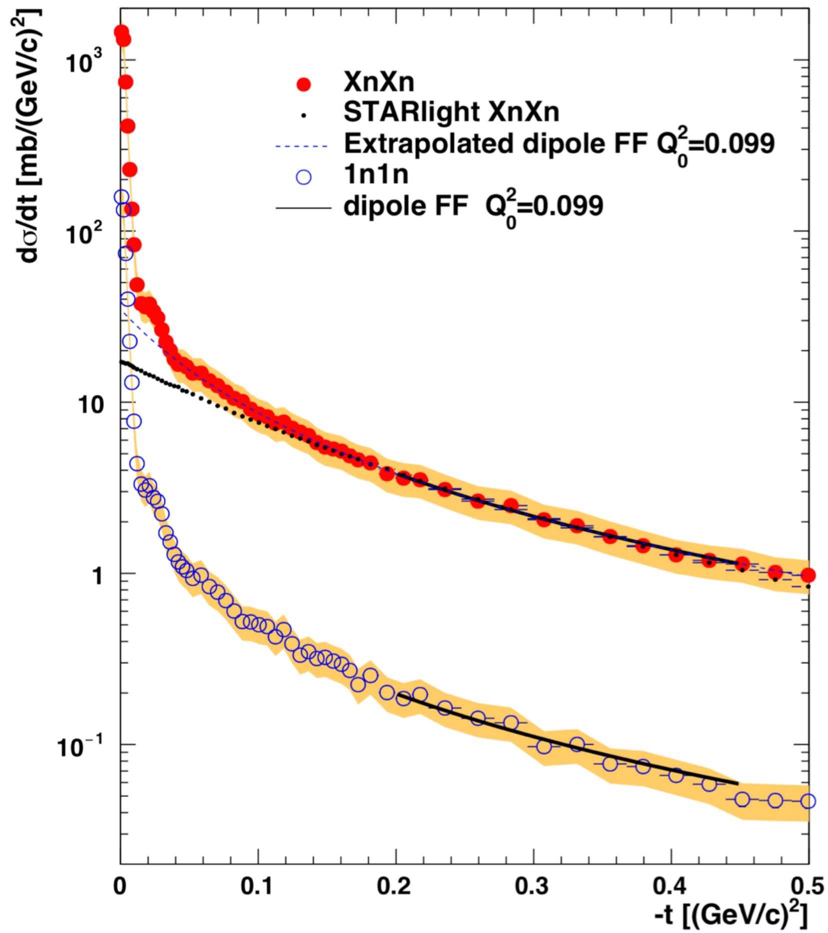
Strikman et al: Phys.Lett.**B 626**, 72 (2005)
BEAGLE, https://wiki.bnl.gov/conferences/images/4/47/ERD17_EICRD-2019-06.pdf

Other caveats and concerns

- Breakup into A>1 fragments might also be possible.
- Strictly speaking, Good-Walker applies only for stable final states.
  - Miettinen and Pumplin, “Coherent Production on Nuclei Does Not Measure Total Cross-Sections for Unstable Particles,” Phys. Rev. Lett. 42, 204 (1979).
  - Caneschi and Schwimmer, “Diffractive Production on Nuclei and Total Cross-Sections of Unstable Particles, Nucl. Phys. B133, 408 (1978).
- It would be interesting to add a small calorimeter to ALICE to try to measure these low-energy photons from lead excitation. It is possible that the proposed calorimeter to test Low’s theorem might be suitable for this.

Incoherent recoil

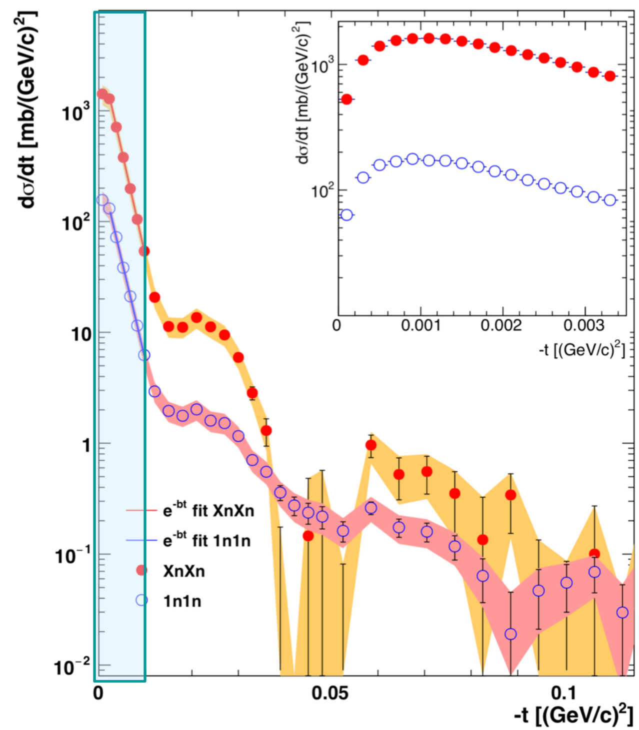
- UPC data, from ALICE and others is well fit by the assumption that, in incoherent photoproduction, a single nucleon recoils.
  - Implicit in STARlight
  - Clearly seen for $|t|>\sim 0.1$ GeV^2
- $d\sigma/dt$ well fit by dipole form factor.
  - Exponential does not fit the data.
- Slope is consistent with single nucleon recoil
- $|t|=p_T^2 + p_z^2$;
  - Well above threshold p_z is subdominant
    - $|t_{min}| = p_z^2$ is small
- Assume single nucleon recoil for the rest of the talk



STAR, Phys. Rev. **C96**, 054904 (2017)

Minimum energy for nucleon emission

- Nucleon emission from is endothermic.
  - The required energies are 7-8 MeV, except for proton emission from ^{197}Au, where threshold energy is 5.3 MeV.
- For a recoiling on-shell nucleon, this is
  - p ~ 100-120 MeV/c
  - $|t| > 0.01\ (GeV/c)^2$
    - Approaches first diffractive minimum
- Nucleon emission disallowed at lower energy transfer
- The small phase space should lead to a slowish turn-on above threshold.
- Implications for both the EIC and UPCs



Region where incoherent background subtraction is questionable

STAR, Phys. Rev. **C96**, 054904 (2017)

Minimum energy for proton emission

What is the minimum energy for a heavy nucleus to emit a proton?
Energy balance only (neglecting potential energy barriers)

Lead-208

^{208}Pb	207.976627	Daltons
^{207}Tl	206.975872	Daltons
Proton	1.00727647	Daltons
^{207}Tl+p	207.9846954	Daltons
ΔE	-0.00806846	Daltons
ΔE	-7.57	MeV
P(single N)	118	MeV/c

Gold-197

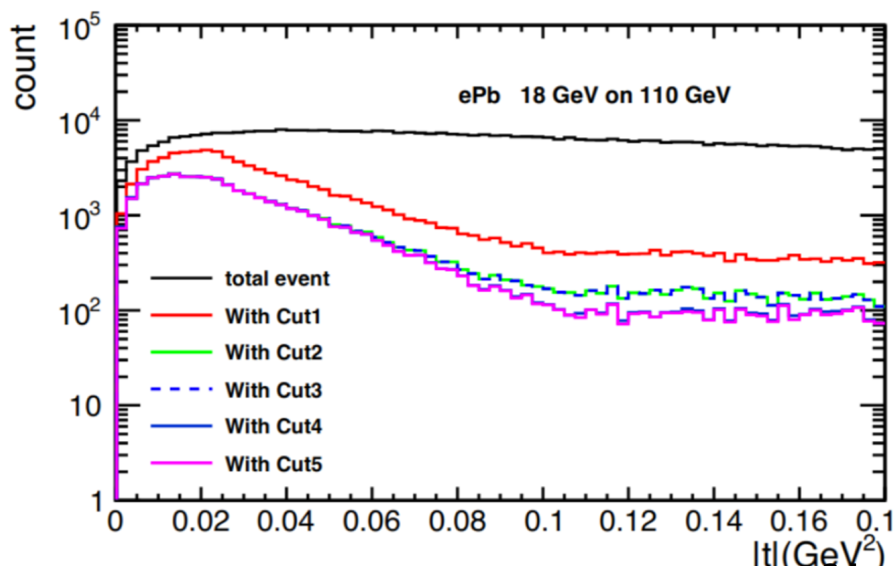
^{197}Au	196.966569	Daltons
^{196}Pt	195.964952	Daltons
Proton	1.00727647	Daltons
^{196}Pt+p	178.984701	Daltons
ΔE	-0.0056592	Daltons
ΔE	-5.27	MeV
P(single N)	99	MeV/c

These reactions are also endothermic, with a threshold for single proton emission. The required energy for gold-197 to emit protons is lower than the energy required to emit neutrons.

Breakup into heavier fragments might be possible.

Incoherent photoproduction without nucleons

- Strikman *et al.:* in LHC PbPb UPCs, ~7% of incoherent J/ψ come w/o neutrons
- BEAGLE simulations
  - nucleon-free fraction depends on |t|
    - Expected – nuclear breakup depends on available energy
  - Rejection < ~ 1/50 at large |t|
- Large theoretical uncertainties from intranuclear cascade models
- Nucleon-free modes radiate only ~ MeV photons
  - Only half are Lorentz boosted
  - Large uncertainties on # of photons, energies
  - We need to know these distributions!



Plot from Wan Chang presentation at Pavia meeting

^{208}Pb

- No low-lying nuclear states
- First state, 2.6 MeV, corresponds to p_T= 70 MeV
  - No accessible incoherent excitation for p_T < 70 MeV/c
    - Marginally accessible: 3 hbar angular momentum needed.

#	Nuclide	E_x [keV]	J^{π}_{order}	Band	$T_{1/2}$	$T_{1/2}$ [s]	Decay modes BR [%]	Isospin	μ [μ_N]	Q [b]	Additional data	Comments
1	$^{208}_{82}Pb_{126}$	0	0+		STABLE							
2	$^{208}_{82}Pb_{126}$	2614.522 10	3-		16.7 ps 3	1.67E-11			+1.9 2	-0.34 15		
3	$^{208}_{82}Pb_{126}$	3197.711 10	5-		294 ps 15	2.94E-10			+0.11 4		El. Trans. Prob. 0.0447 30	
4	$^{208}_{82}Pb_{126}$	3475.078 11	4-		4 ps 3	4E-12						
5	$^{208}_{82}Pb_{126}$	3708.451 12	5- 2								El. Trans. Prob. 0.0241 18	
6	$^{208}_{82}Pb_{126}$	3919.966 13	6-		690 fs	6.9E-13						
7	$^{208}_{82}Pb_{126}$	3946.578 14	4- 2		430 fs	4.3E-13						
8	$^{208}_{82}Pb_{126}$	3961.162 13	5- 3								El. Trans. Prob. ≈ 0.0008	
9	$^{208}_{82}Pb_{126}$	3995.438 13	4- 3		690 fs	6.9E-13						
10	$^{208}_{82}Pb_{126}$	4037.443 14	7-		690 fs	6.9E-13					El. Trans. Prob. ≈ 0.0010	
11	$^{208}_{82}Pb_{126}$	4051.134 13	3- 2		326 fs +28-21	3.26E-13						
12	$^{208}_{82}Pb_{126}$	4085.52 4	2+		0.80 fs 4	8E-16				-0.7 3		
13	$^{208}_{82}Pb_{126}$	4125.347 12	5- 4		490 fs	4.9E-13						
14	$^{208}_{82}Pb_{126}$	4144 ? 5	+									
15	$^{208}_{82}Pb_{126}$	4180.414 14	5- 5		319 fs 35	3.19E-13						
16	$^{208}_{82}Pb_{126}$	4206.277 14	6- 2		690 fs	6.9E-13						
17	$^{208}_{82}Pb_{126}$	4229.590 17	2-		333 fs 28	3.33E-13						
18	$^{208}_{82}Pb_{126}$	4254.795 17	3- 3		97 fs 7	9.7E-14						
19	$^{208}_{82}Pb_{126}$	[illegible]	[illegible]		[illegible]	[illegible]						

From https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Nuclear structure of ^{197}Au

- Many excited states below 1 MeV

$T_{1/2}$= 1.92 ns
$\gamma\beta c\tau$ = 118 m

7.3 s half-life
(Inaccessible due to L)

#	Nuclide	E_x [keV]	J^{π} order	Band	$T_{1/2}$	$T_{1/2}$ [s]	Decay modes BR [%]	Isospin	μ [μ_N]	Q [b]	Additional data	Comments
1	$^{197}_{79}Au_{118}$	0.0	3/2+		STABLE							
2	$^{197}_{79}Au_{118}$	77.3510 *20*	1/2+		1.91 ns *1*	1.91E-9	γ-ray					
3	$^{197}_{79}Au_{118}$	268.788 *10*	3/2+ *2*		15.4 ps *13*	1.54E-11	γ-ray					
4	$^{197}_{79}Au_{118}$	279.00 *5*	5/2+		18.6 ps *15*	1.86E-11	γ-ray		+0.53 *5*			
5	$^{197}_{79}Au_{118}$	409.15 *8*	11/2-		7.73 s *6*	7.73E0	IT 100		+5.98 *9*	+1.68 *5*		
6	$^{197}_{79}Au_{118}$	502.5 *3*	5/2+ *2*		1.77 ps *+19-12*	1.77E-12			+3.0 *5*			
7	$^{197}_{79}Au_{118}$	547.5 *3*	7/2+		4.61 ps *+19-13*	4.61E-12						
8	$^{197}_{79}Au_{118}$	583										
9	$^{197}_{79}Au_{118}$	736.7 *3*	7/2+ *2*		1.09 ps *+13-9*	1.09E-12			+1.7 *5*			
10	$^{197}_{79}Au_{118}$	855.5 *4*	9/2+		2.67 ps *+25-15*	2.67E-12			+1.5 *6*			
11	$^{197}_{79}Au_{118}$	882										
12	$^{197}_{79}Au_{118}$	888.11 *20*	1/2+ *2*									
13	$^{197}_{79}Au_{118}$	936.0 *3*	(5/2+)									
14	$^{197}_{79}Au_{118}$	948										
15	$^{197}_{79}Au_{118}$	1045.1 *3*	(5/2+) *2*									
16	$^{197}_{79}Au_{118}$	1120 *10*										
17	$^{197}_{79}Au_{118}$	1150.5 *3*	3/2+,5/2+									
18	$^{197}_{79}Au_{118}$	1217.3 *4*	(3/2+)									
19	$^{197}_{79}Au_{118}$	1220.1 *7*										
20	$^{197}_{79}Au_{118}$	1231.0 *8*	11/2+		0.91 ps *1*	9.1E-13			+2.0 *10*			
21	$^{197}_{79}Au_{118}$	1242.0 *4*	(1/2+)									

From https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html