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

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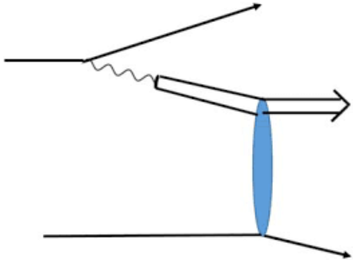
EICUG Theory WG: Meeting on Diffraction

- 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

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

Average cross-sections (Ω)

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

Average amplitudes (Ω)

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

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)

- Semi-classically, we can write $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Usually work with $t = p_T^2 + p_z^2 \sim p_T^2$
- Because of exponential $d\sigma/dp_T$ 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

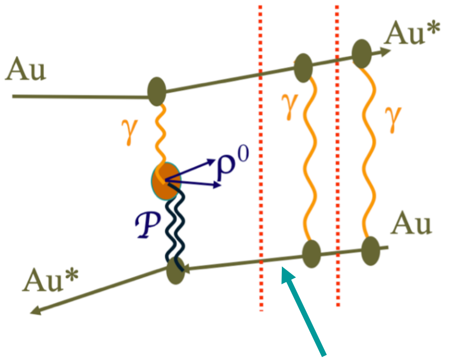
- The incoherent cross-section lets us measure the event-by-event fluctuations in the nuclear configuration, including the positions of individual nucleons, gluonic hot spots, etc.

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

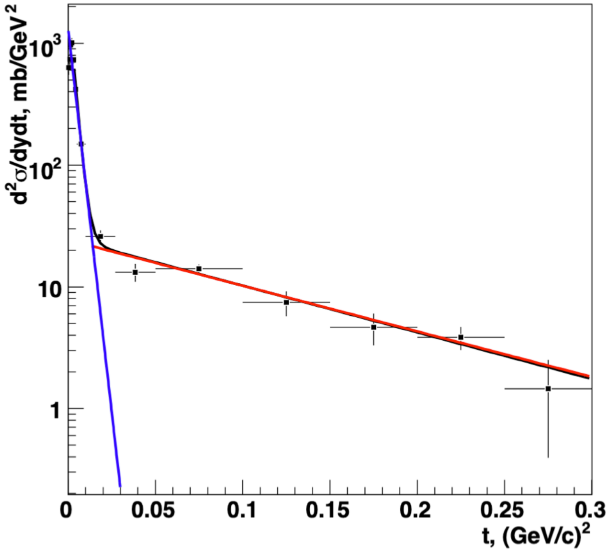
- Probes the deviations from the mean.
- The connection between t and impact parameter is weaker than with coherent production, but this can be used to test models.

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
- Can be 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



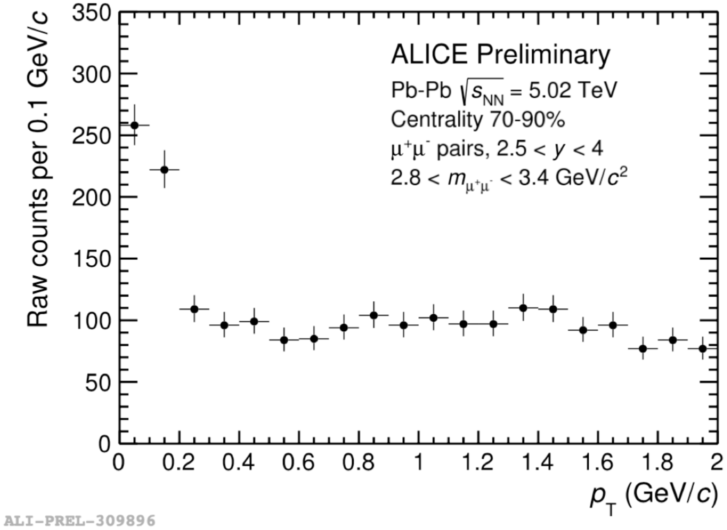
Ion may be virtual



STAR, Phys. Rev C77, 034910 (2008)

Coherent photoproduction in peripheral collisions

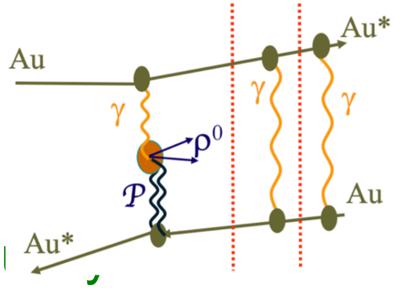
- Coherent J/ψ photoproduction in peripheral hadronic collisions
  - Peak at $p_T <\sim$ hbar/R_A
- Seen by ALICE and STAR



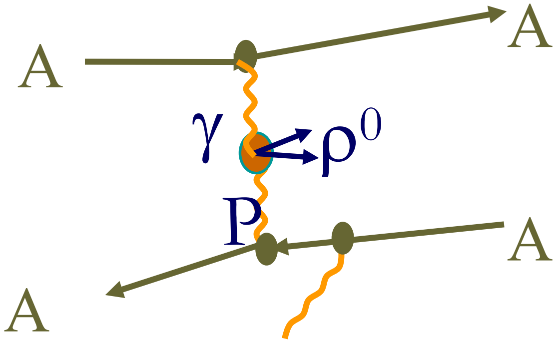
L. Massacrier for ALICE, arXiv:1902.03637

Why does Good-Walker fail here?

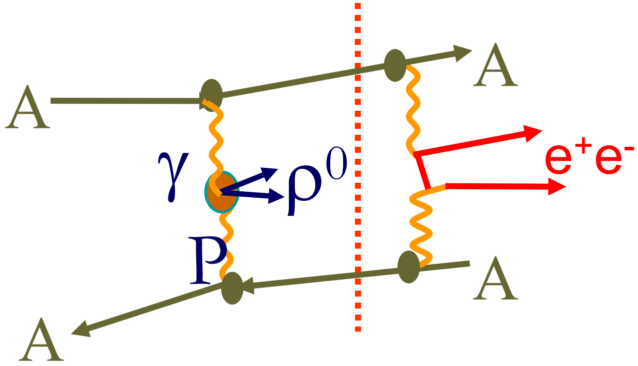
- Good-Walker assumes that the incident probe is a single photon (or other particle)
  - An interacting ion or electron can emit more than one photon
    - We cannot tell how many photons participate in the reaction
    - Ions are more likely to radiate photons than electrons, but this is a question 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?
  - GW only applies for stable particles
    - $\pi^+\pi^-$nn + nuclear remnants
    - Pions and neutrons are not stable, but they us ore decaying
  - 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
- Little change to overall kinematics, but Good-Walker requires exclusive reactions!

Gradual failures and time scales?

- The target may be involved in multiple subprocesses at once
  - Different time scales ~~ hbar/energy scale
- For UPC VM + XnXn excitation
  - Excitation time scale hbar/E_{exc} >> VM production hbar/M_V
- Not true for photoproduction in peripheral collisions
  - Time scales are similar
  - If hadronic interactions occurs first, the photoproduction center-of-mass energy will be lower, reducing the cross-section. A better calculation should consider both time orderings.
  - Testable with better calculations and more accurate data
- A better calculation might predict a gradual loss of coherent production with increasing other activity, rather than the abrupt disappearance seen in GW
  - A mechanism whereby lower-energy interactions can gradually disrupt coherence at higher energy scales

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 returns 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 should depend on nuclear fluctuations, including nucleon positions and low-x gluonic hotspots
  - The density profiles for lead and gold are similar
    - Woods-Saxon distributions
  - Their gluon shadowing should be similar
  - They should have similar incoherent cross-sections
- But, 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

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

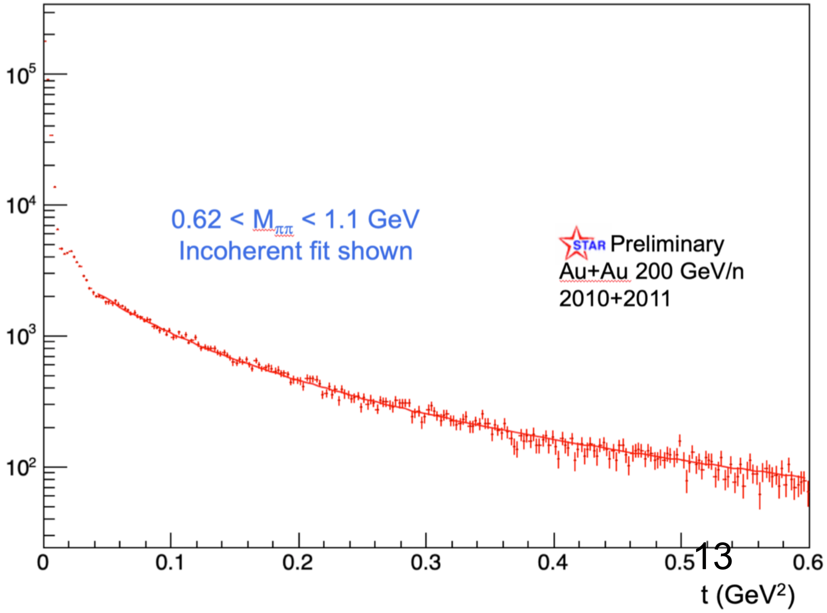
^{197}Au	196.966569	Daltons
^{196}Au	195.96657	Daltons
Neutron	1.00867108	Daltons
^{196}Au+n	196.975241	Daltons
ΔE	-0.00867238	Daltons
ΔE	-8.07	MeV
P(single N)	122	MeV/c

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
- The vector meson recoils against this, so the minimum vector meson momentum is ~ 100 MeV/c
  - At lower momenta, incoherent photoproduction must involve excited states with photon emission
- STAR data supports the single-nucleon picture. At larger |t|, $d\sigma/dt$ for coherent dipion production is consistent with a dipole form factor,
  - Used for protons.
  - Inconsistent with an exponential



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?

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.

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 soft reactions.
  - It is unfortunately not so clear how to do this.
- Precise measurements of coherent photoproduction in peripheral collisions may 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.
- We observe coherent VM photoproduction in two regimes where GW says it should not be present. 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 should be extended to account for more complicated reactions involving additional particles. Coherent production might gradually disappear in the presence of soft particles, rather than the current abrupt disappearance.

Backup

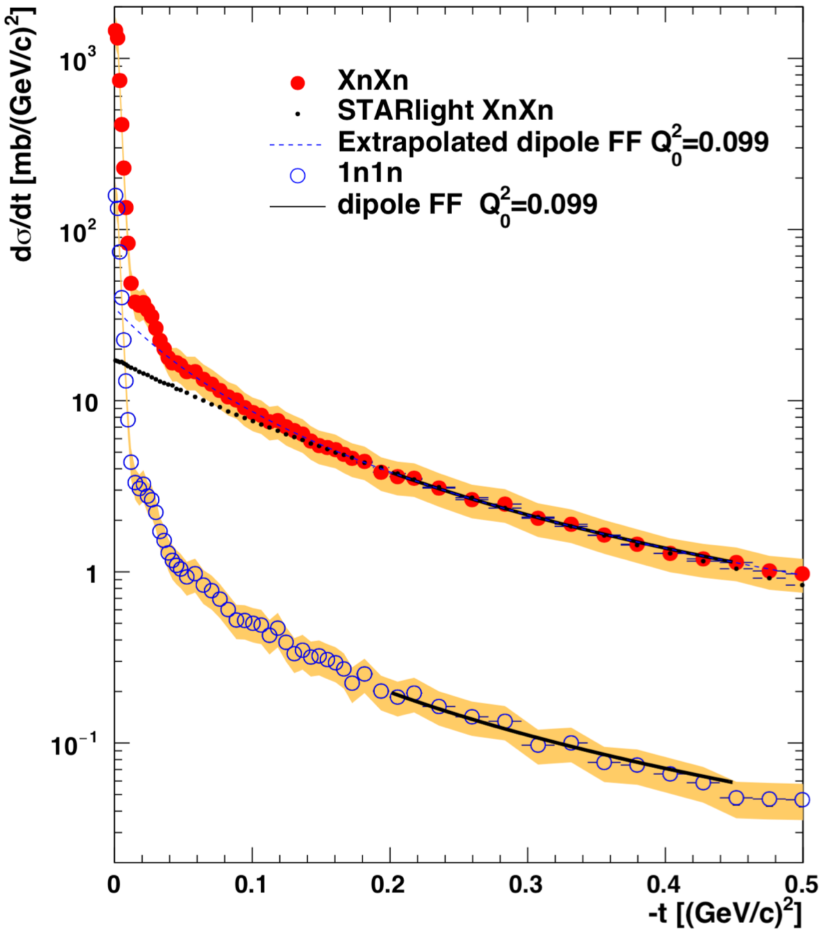
Incoherent final states

- 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

Incoherent recoil

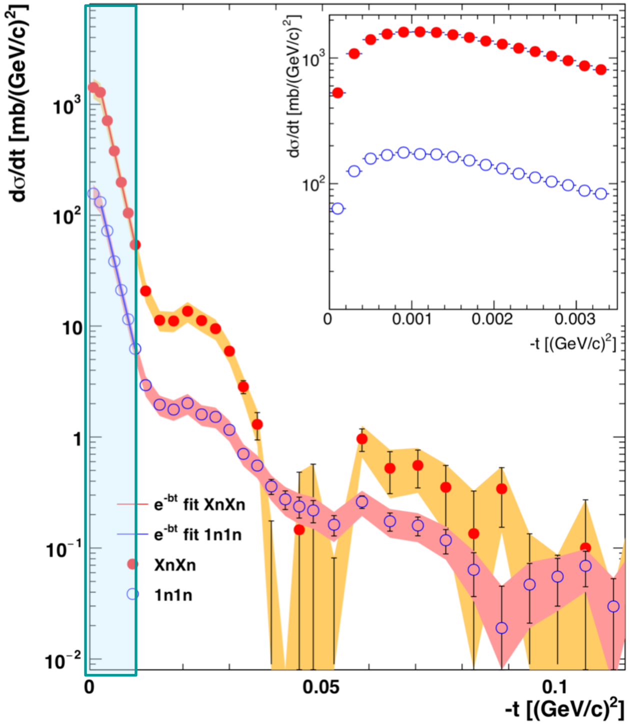
- UPC data, from ALICE and others is well fit by the assumption that, in incoherent photoproduction, a single nucleon recoils.
  - Implicit in STARlight
  - Clearly seen for $|t|>\sim 0.1$ GeV^2
- $d\sigma/dt$ well fit by dipole form factor.
  - Exponential does not fit the data.
- Slope is consistent 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

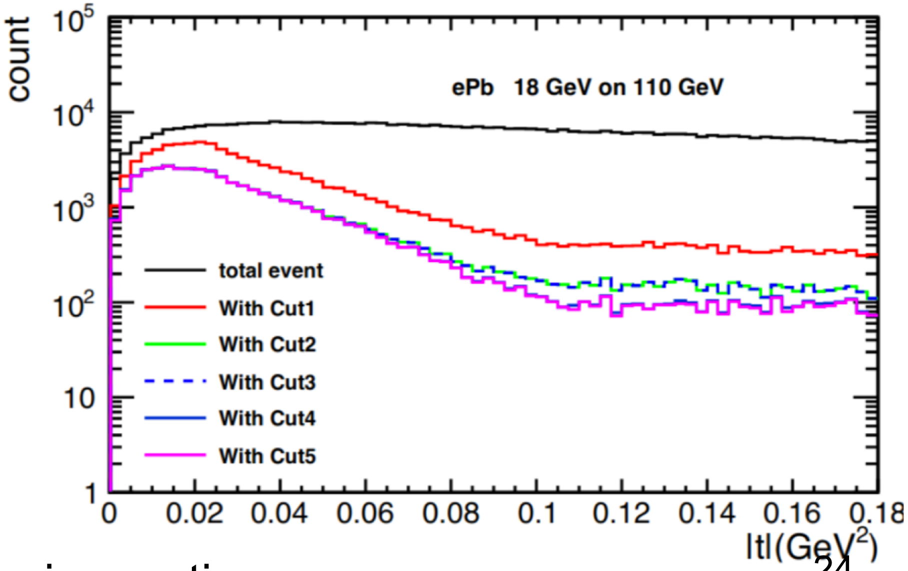
^{197}Au	196.966569	Daltons
^{196}Pt	195.964952	Daltons
Proton	1.00727647	Daltons
^{196}Pt+p	178.984701	Daltons
ΔE	-0.0056592	Daltons
ΔE	-5.27	MeV
P(single N)	99	MeV/c

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	$^{208}_{82}\mathrm{Pb}_{126}$	0	0+		STABLE							
2	$^{208}_{82}\mathrm{Pb}_{126}$	2614.522 *10*	3-		16.7 ps *3*	1.67E-11			+1.9 *2*	-0.34 *15*		
3	$^{208}_{82}\mathrm{Pb}_{126}$	3197.711 *10*	5-		294 ps *15*	2.94E-10			+0.11 *4*		El. Trans. Prob. 0.0447 *30*	
4	$^{208}_{82}\mathrm{Pb}_{126}$	3475.078 *11*	4-		4 ps *3*	4E-12						
5	$^{208}_{82}\mathrm{Pb}_{126}$	3708.451 *12*	5- *2*								El. Trans. Prob. 0.0241 *18*	
6	$^{208}_{82}\mathrm{Pb}_{126}$	3919.966 *13*	6-		690 fs	6.9E-13						
7	$^{208}_{82}\mathrm{Pb}_{126}$	3946.578 *14*	4- *2*		430 fs	4.3E-13						
8	$^{208}_{82}\mathrm{Pb}_{126}$	3961.162 *13*	5- *3*								El. Trans. Prob. ≈ 0.0008	
9	$^{208}_{82}\mathrm{Pb}_{126}$	3995.438 *13*	4- *3*		690 fs	6.9E-13						
10	$^{208}_{82}\mathrm{Pb}_{126}$	4037.443 *14*	7-		690 fs	6.9E-13					El. Trans. Prob. ≈ 0.0010	
11	$^{208}_{82}\mathrm{Pb}_{126}$	4051.134 *13*	3- *2*		326 fs *+28-21*	3.26E-13						
12	$^{208}_{82}\mathrm{Pb}_{126}$	4085.52 *4*	2+		0.80 fs *4*	8E-16				-0.7 *3*		
13	$^{208}_{82}\mathrm{Pb}_{126}$	4125.347 *12*	5- *4*		490 fs	4.9E-13						
14	$^{208}_{82}\mathrm{Pb}_{126}$	4144 ? *5*	+									
15	$^{208}_{82}\mathrm{Pb}_{126}$	4180.414 *14*	5- *5*		319 fs *35*	3.19E-13						
16	$^{208}_{82}\mathrm{Pb}_{126}$	4206.277 *14*	6- *2*		690 fs	6.9E-13						
17	$^{208}_{82}\mathrm{Pb}_{126}$	4229.590 *17*	2-		333 fs *28*	3.33E-13						
18	$^{208}_{82}\mathrm{Pb}_{126}$	4254.795 *17*	3- *3*		97 fs *7*	9.7E-14						
19	$^{208}_{82}\mathrm{Pb}_{126}$	4261.871 *13*	4- *4*		520 fs	5.2E-13						

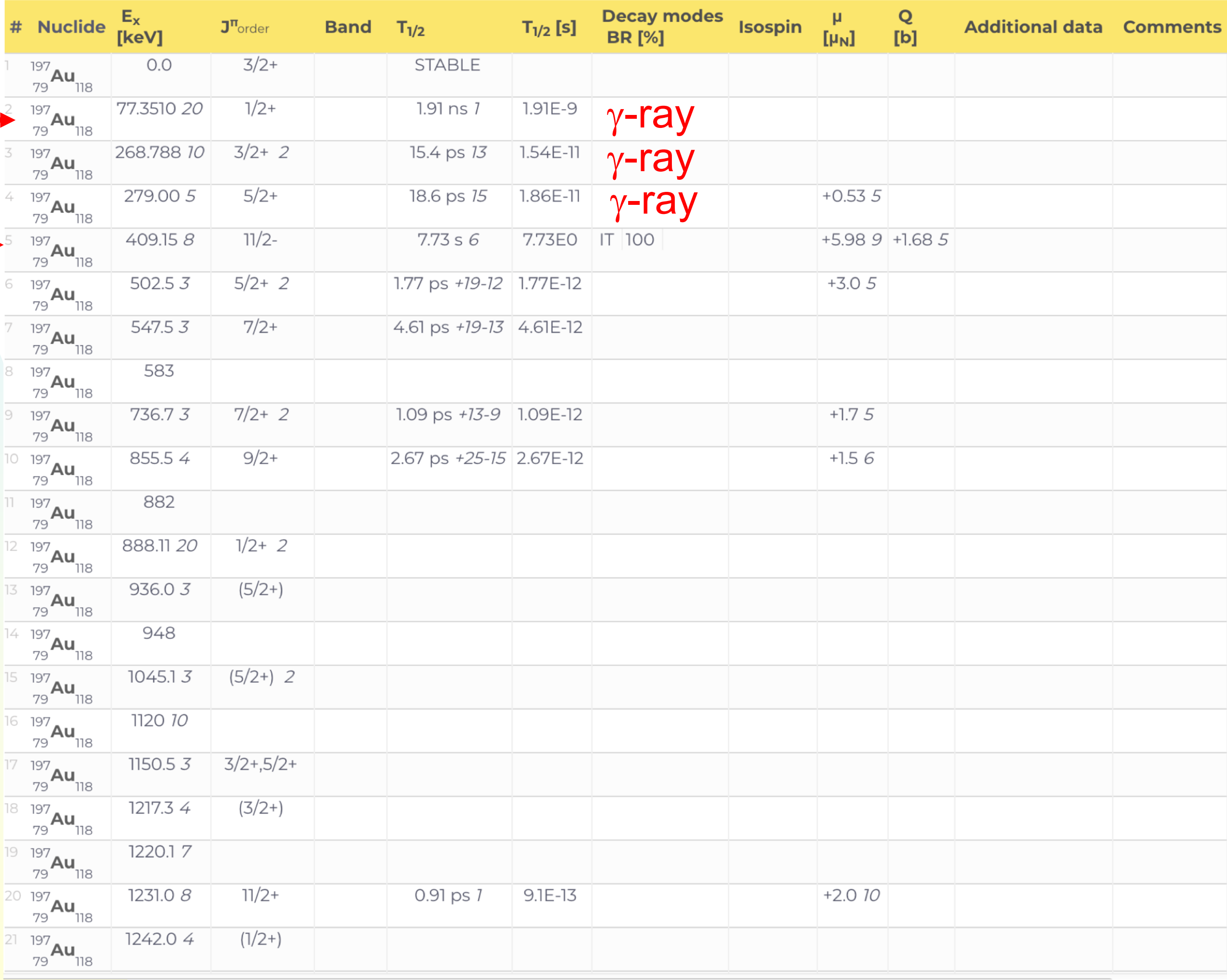
From https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

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	$^{197}_{79}\mathrm{Au}_{118}$	0.0	3/2+		STABLE							
2	$^{197}_{79}\mathrm{Au}_{118}$	77.3510 *20*	1/2+		1.91 ns *1*	1.91E-9	γ-ray					
3	$^{197}_{79}\mathrm{Au}_{118}$	268.788 *10*	3/2+ *2*		15.4 ps *13*	1.54E-11	γ-ray					
4	$^{197}_{79}\mathrm{Au}_{118}$	279.00 *5*	5/2+		18.6 ps *15*	1.86E-11	γ-ray		+0.53 *5*			
5	$^{197}_{79}\mathrm{Au}_{118}$	409.15 *8*	11/2-		7.73 s *6*	7.73E0	IT 100		+5.98 *9*	+1.68 *5*		
6	$^{197}_{79}\mathrm{Au}_{118}$	502.5 *3*	5/2+ *2*		1.77 ps *+19-12*	1.77E-12			+3.0 *5*			
7	$^{197}_{79}\mathrm{Au}_{118}$	547.5 *3*	7/2+		4.61 ps *+19-13*	4.61E-12						
8	$^{197}_{79}\mathrm{Au}_{118}$	583										
9	$^{197}_{79}\mathrm{Au}_{118}$	736.7 *3*	7/2+ *2*		1.09 ps *+13-9*	1.09E-12			+1.7 *5*			
10	$^{197}_{79}\mathrm{Au}_{118}$	855.5 *4*	9/2+		2.67 ps *+25-15*	2.67E-12			+1.5 *6*			
11	$^{197}_{79}\mathrm{Au}_{118}$	882										
12	$^{197}_{79}\mathrm{Au}_{118}$	888.11 *20*	1/2+ *2*									
13	$^{197}_{79}\mathrm{Au}_{118}$	936.0 *3*	(5/2+)									
14	$^{197}_{79}\mathrm{Au}_{118}$	948										
15	$^{197}_{79}\mathrm{Au}_{118}$	1045.1 *3*	(5/2+) *2*									
16	$^{197}_{79}\mathrm{Au}_{118}$	1120 *10*										
17	$^{197}_{79}\mathrm{Au}_{118}$	1150.5 *3*	3/2+,5/2+									
18	$^{197}_{79}\mathrm{Au}_{118}$	1217.3 *4*	(3/2+)									
19	$^{197}_{79}\mathrm{Au}_{118}$	1220.1 *7*										
20	$^{197}_{79}\mathrm{Au}_{118}$	1231.0 *8*	11/2+		0.91 ps *1*	9.1E-13			+2.0 *10*			
21	$^{197}_{79}\mathrm{Au}_{118}$	1242.0 *4*	(1/2+)									

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