A generator of forward neutrons for ultra-peripheral collisions: $n^0_{On}$

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- Motivation
- Formalism
- Implementation
- Few results
Motivation
UPC and nuclear break-up

- Relativistic heavy ions are accompanied by high photon fluxes due to their large electric charge and the strongly Lorentz contracted electric fields.
- At impact parameters large enough so that no hadronic interactions occur, the photonuclear interactions can be seen: these are Ultra-Peripheral Collisions (UPCs)
- Because of the high photon flux, the UPC events have a high probability to be accompanied by additional photon exchanges that excite one or both of the ions
UPC and nuclear break-up

- Experimentally, requiring mutual Coulomb excitation along with VM production may lead to a trigger with a higher purity, allowing more events to be collected than for the VM state by itself.
- Neutron-differential studies are considered as a promising tool to decouple low-x and high-x contributions in vector meson photo-production.
- STAR and CMS used requirement on forward neutrons in their UPC triggers.
- ALICE measured event fractions of various break-up scenarios.
Formalism
Photo-production with nuclear break-up

• Assuming that the sub-reactions are independent, the cross section to produce a vector meson (or probability of any other photo-production process) accompanied by a dissociation is

\[ \sigma(AA \rightarrow PA_i'A_j') \propto \int d^2\vec{b} P_P(b) P_{ij}(b) \exp(-P_H(b)) \]

• There are 3 independent probabilities in the formula
  ▫ The probability of the hard photoproduction process \( P_P(b) \)
  ▫ The probability of nuclear break-up with emission of i and j neutrons from the first and second nucleus, respectively \( P_{ij}(b) \)
  ▫ We expect the break-up probabilities to be independent \( P_{ij}(b) = P_i(b) \times P_j(b) \)
  ▫ The probability of a hadronic interaction \( P_H(b) \)
Photo-production cross section

- A photon from the field of one nucleus fluctuates to a quark-antiquark pair and scatters elastically from the other nucleus, emerging as a vector meson.
- The cross section is sensitive to the vector meson-nucleon interaction cross section.
- The photon energy $k$ is related to the final state object rapidity:

$$k = \frac{1}{2} M_V \exp(\pm y)$$
Photo-production cross section

- The probability for photo-production of vector meson or any other object:

\[ P_P(b) = \int dk \frac{d^3n(b,k)}{dkd^2b} \sigma_{\gamma\rightarrow PA}(k) \]

- The photon flux from a relativistic heavy nucleus is given by the Weizsaecker-Williams approach:

\[ \frac{d^3n(b,k)}{dkd^2b} = \frac{Z^2 \alpha}{\pi^2 \gamma^2} k \left[ K_1^2\left(\frac{k}{\gamma}\right) + \frac{1}{\gamma^2} K_0^2\left(\frac{k}{\gamma}\right) \right] \]

- If we combine the formulas we get:

\[ \sigma(AA \rightarrow PA_i'A'_j) \propto \int d^2b \int dk \frac{d^3n(b,k)}{dkd^2b} \sigma_{\gamma\rightarrow PA}(k) P_{ij}(b) \exp(-P_H(b)) \]
Photo-production with nuclear break-up

• For a single event the photon energy $k$ is fixed and we can get rid of the integral over $k$:

$$\sigma(AA \rightarrow PA_i' A_j') \bigg|_{k=\text{const}} \propto \int d^2b \frac{d^3n(b,k)}{dkd^2b} P_{ij}(b) \exp(-P_H(b))$$

• And we can define a probability of the breakup in the event:

$$P(AA \rightarrow A_i' A_j') \bigg|_{k=\text{const}} = \frac{\int d^2b \frac{d^3n(b,k)}{dkd^2b} \exp(-P_H(b)) P_{ij}(b)}{\int d^2b \frac{d^3n(b,k)}{dkd^2b} \exp(-P_H(b))}$$

• The mass and rapidity of the photo-produced object restricts the impact-parameter phase space via fast decrease of the Bessel function for $x > 1$
Hadronic interaction probability

- The collision is UPC, thus the hadronic interactions must be excluded
- The factor $\exp(-P_H(b))$ ensures that the reaction is unaccompanied by hadronic interactions
- In this work we only consider the Coulomb break-up of the nucleus
- For a hard sphere nucleus model, the hadronic interaction probability is 1 for $b < 2R$ and is zero otherwise
- More precisely one can calculating the probability of one or more hadronic interactions as a function of impact parameter
Coulomb excitation of the nucleus

Let $P_{Xn}$ be the probability of nuclear break-up of one nucleus to a state with any number ($X$) of neutrons ($n$). Under the assumption of a Poisson distribution, the probability of having exactly $L$ neutrons is:

$$P_{Ln}(b) = \frac{(P_{Xn}^1(b))^L \times \exp(-P_{Xn}^1(b))}{L!}$$

Probability to have at least one neutrons than is:

$$P_{Xn}(b) = 1 - \exp(-P_{Xn}^1(b))$$

where $P_{Xn}^1(b)$ is the mean number of the Coulomb excitations of the nucleus to any state which emits one or more neutrons.
Coulomb excitation of the nucleus

• $P_{Xn}^1(b)$ is the mean number of the Coulomb excitations of the nucleus to any state which emits one or more neutrons

\[
P_{Xn}^1(b) = \int dk \frac{d^3n(b, k)}{dkd^2b} \sigma_{\gamma A \to A' + Xn}(k)
\]

• where $\sigma_{\gamma A \to A' + Xn}(k)$ is an photo-nuclear cross section determined mainly by data

• In a similar way mean number of the Coulomb excitations of the nucleus to a state with N neutrons is:

\[
P_{Nn}^1(b) = \int dk \frac{d^3n(b, k)}{dkd^2b} \sigma_{\gamma A \to A' + Nn}(k)
\]

• such that: $P_{Xn}^1(b) = \sum_{N=1}^{\infty} P_{Nn}^1(b)$
Coulomb excitation of the nucleus

- Two neutron states can be produced either by direct two neutron emission or by two emissions of one neutron;
- Contributions to the three neutron states are from three one neutron emissions, one emission of three neutrons, or emissions of one and two neutrons

\[
P_1(b) = P_{1n}^1(b) \times \exp(-P_{Xn}^1(b)),
\]

\[
P_2(b) = [P_{2n}^1(b) + \frac{(P_{1n}^1(b))^2}{2!}] \times \exp(-P_{Xn}^1(b)),
\]

\[
P_3(b) = [P_{3n}^1(b) + 2P_{2n}^1(b)P_{1n}^1(b) + \frac{(P_{1n}^1(b))^3}{3!}] \times \exp(-P_{Xn}^1(b))
\]

- Fulfills the unitarity condition:

\[
\sum_{N=1}^{\infty} P_{Nn}(b) = P_{Xn}(b)
\]
Photo-nuclear cross section

- Giant dipole resonance (GDR) peak via Lorentz line fit (Breit-Wigner)
- Black points via scaling of proton/neutron cross sections
- Regge model parametrization for high energies

\[
P_{\text{NN}}^1(b) = \int dk \frac{d^3n(b,k)}{dkd^2b} \sigma_{\gamma A' \to A + Nn}(k)
\]
The GDR excitations produce mainly final states with one or two neutrons and were investigated in detail by various experiments.

The partial cross sections, up to 10 neutrons and up to 140 MeV measured at Saclay
Neutron multiplicity

- Saclay used the partial cross sections to extract the average and the dispersion of the number of neutrons as a function of the incident energy.
- Fitted to a logarithm and extrapolated to higher energies.
- Comparison with RELDIS model in rather good agreement.
Neutron multiplicity

- The branching ratios to each partial cross section are computed from the fit by extrapolating the arithmetic average and dispersion, and using a Gaussian approximation for the shape.
Neutron energy

• Very few measurement exist for the spectra of secondary particles from mono-energetic source of photons

• Nevertheless one may have confidence in the accuracy of the evaluated spectra in case when the agreement between calculated and measured channel cross section $(\gamma, n) (\gamma, 2n)$ is good

• This is because the energy dependence strongly influences the relative population of various product nuclides when multi-particle production is possible
Neutron energy

• The emission spectra of the secondary particles was part of the “Photonuclear Data for Applications” project by International Atomic Energy Agency

• Tables are available in Evaluated Nuclear Data File (ENDF) format [https://www-nds.iaea.org/exfor/endf.htm](https://www-nds.iaea.org/exfor/endf.htm)
Particle generation

- Neutron is generated in the rest frame with energy generated using the ENDF table and isotropic angular distribution.
- Then it is boosted by the $\beta$ of the beam either to positive or negative direction.
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Implementation
Code notes

- Whole generator is rather small ROOT based utility
  - Class ~1000 lines + two macros and ENDF
  - Inherited from TObject
  - Using TF1, TH1D, TH2D, TGraph, TClonesArray, TTree, etc...
- To run you need an input = the k distribution
  - Invariant mass and rapidity distribution you just predicted for a current photo-production process since you are a skilled phenomenologist
  - You can run together with STARlight
  - Generator can produce flat neutron multiplicity distribution and run standalone like that
  - Interface mode = do it in other custom way within a framework you use at your experiment

https://github.com/mbroz84/noon
Code notes

• **Output:**
  - It can produce a TTree with TParticles
  - You can import the TClonesArray with TParticles to your framework after every event

• **Units to communicate with outside world are GeV**
  - The input mass should be in GeV
  - Output TParticle momenta are in GeV

• **Works for $^{208}$Pb only for the time being**
  - Near future: $^{197}$Au, $^{129}$Xe, $^{238}$U

• **Only coherent photon-pomeron process**
  - Near future: Two Photon process
  - Medium term: Incoherent process
Example of possible applications

- Can use theory predictions as a function of rapidity for the cross section of the coherent photonuclear production of a vector meson, together with the mass distribution of the vector meson to produce neutron multiplicities in a selected rapidity range.

\[
\frac{\sigma_{AA\rightarrow V\Lambda}(y)}{dy} = \int d^2b \int d^3n(b, y) \sigma_{\gamma A\rightarrow VA}(y) + \int dk d^2b \sigma_{\gamma A\rightarrow VA}(-y)
\]
Example of possible applications

- Can run as an STARlight afterburner
- An interface to STARlight is provided through the ROOT class TStarlight, so that to each event one can add the neutrons produced by the generator
- It is then trivial to pass these neutrons (along with the particles produced by STARlight) through the detailed simulation of the experiments
Summary

- Neutrons from nuclear break-up which can pile-up a photo-production event are widely used on present HEP experiments for both, triggering and physics.
- STARlight and phenomenologists can predict the event fractions for various break-up scenarios, but no Monte Carlo generator producing the emission neutron was on the market up to now.
- We collected the available methods used to predict the break-up probability, expanded them using additional experimental data and nuclear modeling and made a Monte Carlo generator of the neutrons from nuclear break-up.
- Generator is a ROOT based tool which can run in several ways according to the user needs.
- Generator is public, available on [GitHub](https://github.com/).
Outlook

• An updated version of $n_0^O n$ will appear on GitHub soon

  ▫ Extended by $^{197}$Au, $^{129}$Xe and $^{238}$U nuclei
  ▫ Nuclear break-up in $\gamma \gamma$ interactions
  ▫ Framework for easy management of cross section datasets

• Coupling to STARlight within ALICE framework is being tested

• An extension by a model for forward neutrons in incoherent interactions is foreseen

• An extension to electron-Ion collision systems is being discussed
Backup
Neutron emission in UPC experiments

- ALICE studied the event multiplicities in various cases of neutron emission for $\rho^0$ and $\psi(2S)$
Neutron emission in UPC experiments

- STAR required signal compatible with at least one neutron in both neutron ZDCs in the trigger for $\rho^0$
- STAR $\rho^0$ cross sections are published for $1n1n$ and $XnXn$ emission cases
Neutron emission in UPC experiments

- CMS coherent $J/\psi$ cross section is measured for the case when the $J/\psi$ mesons are accompanied by at least one neutron on one side of the interaction point and no neutron activity on the other side ($X_{n0n}$)
- UPC trigger also selects the $X_{nXn}$, $1_{n0n}$, and $1_{n1n}$ break-up modes.
- In the end the cross section is scaled from $X_{n0n}$ to total
Photo-nuclear cross section

\[ \sigma_{\gamma A \rightarrow A' + X_n(k)} \]

**Table I.** Total hadronic cross sections per nucleon (in nb).

| \( E_\gamma \) (GeV) | \( \sigma_{\gamma A \rightarrow A' + X_n(k)} \) (nb) |
|-----------------|-----------------|
| 5.5             | 11.5            |
| 10              | 22.5            |
| 20              | 45.5            |
| 30              | 80.5            |

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**Figure:**

- **Energy vs. Cross Section Graph:**
  - Data points for different energies and cross sections are plotted.
  - Curve fits to the data are shown.

- **Graphs:**
  - Various cross section vs. energy plots for different elements.
  - Waveforms for different conditions are displayed.

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**Graphical Elements:**

- **Graphs:**
  - Energy vs. Cross Section
  - Photon Energy vs. Cross Section

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**References:**

- B. A. Tovey, J. G. Gilmore, *Advances in Nuclear Physics*, 1975, pp. 1-30.
- C. M. DeJong, *Fundamentals of Nuclear Physics*, 2010, pp. 45-75.
- D. L. Brown, *Quantum Nuclear Physics*, 2012, pp. 8-47.

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**Legend:**

- **Graphs:**
  - Different symbols and colors represent various experimental data sets.
Hadronic interaction probability

• In this work we only consider the Coulomb break-up of the nucleus.
• The factor $\exp(-P_H(b))$ ensures that the reaction is unaccompanied by hadronic interactions.
• The mean number of projectile nucleons that interact at least once we can write as:

$$P_H(b) = \int d^2\vec{r} T_A(\vec{r} - \vec{b})(1 - \exp(-\sigma_{NN} T_B(\vec{r})))$$

• here we use nuclear thickness function

$$T_A(\vec{r}) = \int dz \rho_A(\sqrt{\vec{r}^2 + z^2})$$

• and nuclear density for a nucleus A at distance s from its center is modeled with a Woods-Saxon distribution for symmetric nuclei

$$\rho_A(s) = \frac{\rho_0}{1 + \exp\left(\frac{s-R_{WS}}{d}\right)}$$
Nucleus break-up probabilities

![Graph showing probability vs. impact parameter for different nucleon break-up channels: Xn, 0n, 1n, 2n, 3n, 4n, and 5n. The graph indicates the probability decreases with increasing impact parameter.]
Normalization ratio

![Normalization ratio graph](image-url)