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

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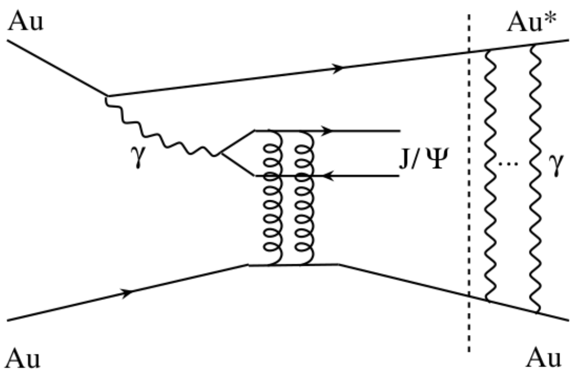
- Motivation
- Formalism
- Implementation
- Few results

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



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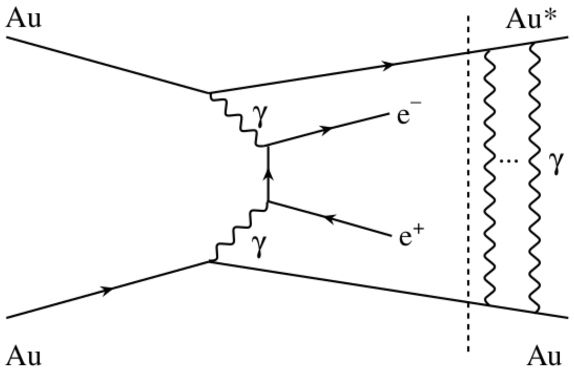
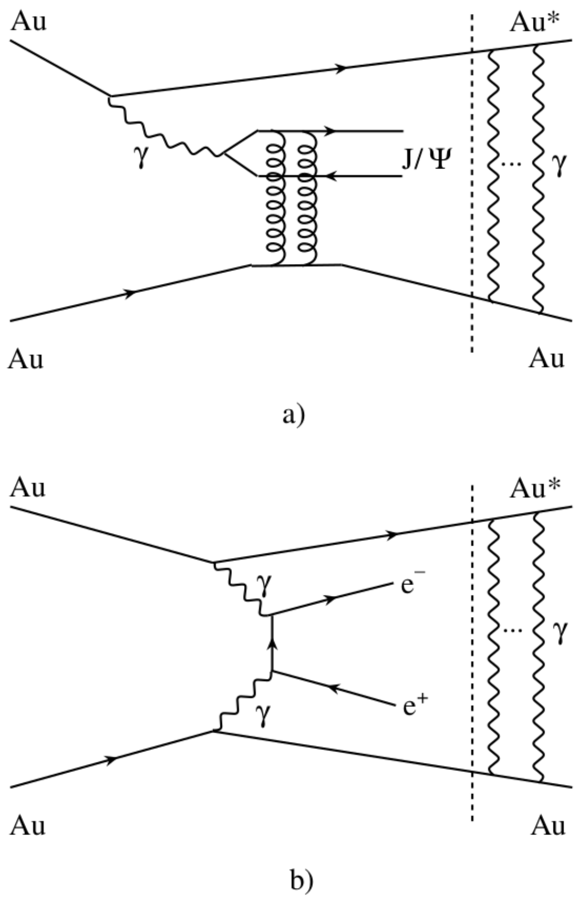


b)

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

$$\sigma(AA \to PA'_i A'_j) \propto \int d^2\vec{b} P_P(b) P_{ij}(b) \exp(-P_H(b))$$

- 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:

$$k = \frac{1}{2} M_V \exp(\pm y)$$

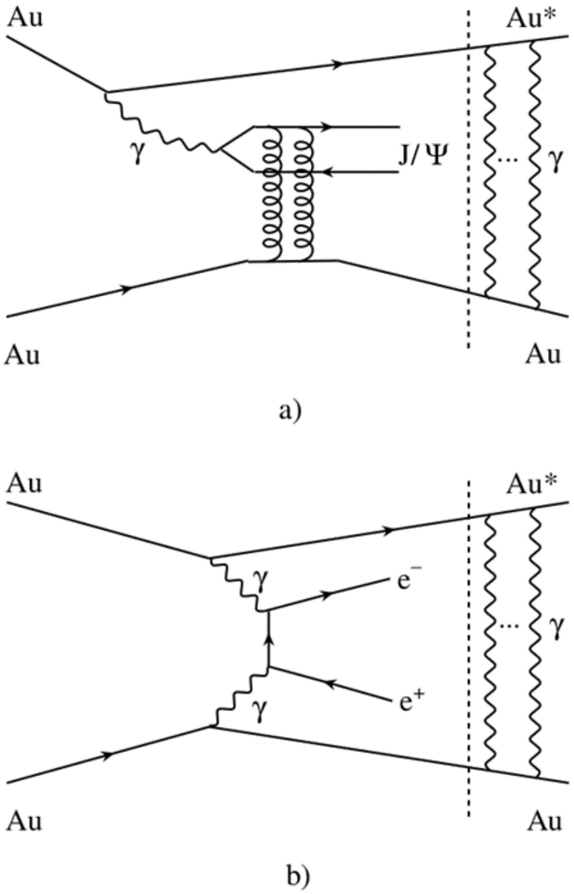


Photo-production cross section

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

$$P_P(b) = \int dk \frac{d^3n(b,k)}{dk d^2\vec{b}} \sigma_{\gamma A \to PA}(k)$$

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

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

- If we combine the formulas we get:

$$\sigma(AA \to PA_i' A_j') \propto \int d^2\vec{b} \int dk \frac{d^3n(b,k)}{dk d^2\vec{b}} \sigma_{\gamma A \to PA}(k) P_{ij}(b) \exp(-P_H(b))$$

Photo-production with nuclear break-up

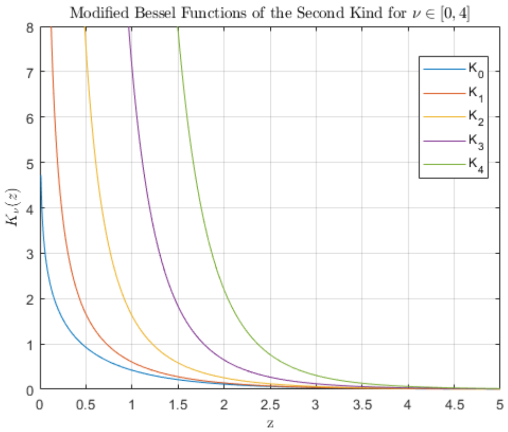
- For a single event the photon energy k is fixed and we can get rid of the integral over k:

$$\sigma(AA \to PA_i'A_j')\big|_{k=\mathrm{const}} \propto \int d^2\vec{b}\,\frac{d^3n(b,k)}{dk\,d^2\vec{b}} P_{ij}(b) \exp(-P_H(b))$$

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

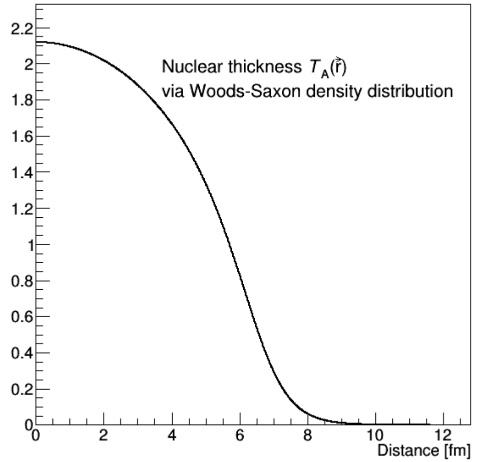
$$P(AA \to A_i'A_j')\big|_{k=\mathrm{const}} = \frac{\int d^2\vec{b}\frac{d^3n(b,k)}{dk\,d^2\vec{b}} \exp(-P_H(b))P_{ij}(b)}{\int d^2\vec{b}\frac{d^3n(b,k)}{dk\,d^2\vec{b}} \exp(-P_H(b))}$$

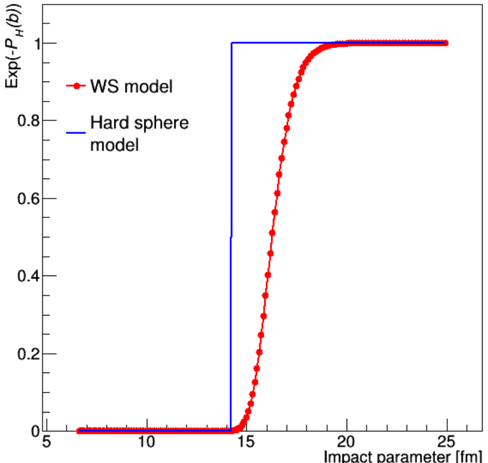
- The mass and rapidity of the photo-produced object restricts the impact-parameter phase space via fast decrease of the Bessel function for x > 1



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

$$P_{ij}(b) = P_i(b) \times P_j(b)$$

- 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:

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

- Probability to have at least one neutrons than is:

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

- where $P^1_{\mathrm{Xn}}(b)$ 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

- $P^1_{\mathrm{Xn}}(b)$ is the mean number of the Coulomb excitations of the nucleus to any state which emits one or more neutrons

$$P^1_{\mathrm{Xn}}(b) = \int dk \frac{d^3n(b,k)}{dk d^2 b} \sigma_{\gamma A \to A' + \mathrm{Xn}}(k)$$

- where $\sigma_{\gamma A \to A' + \mathrm{Xn}}(k)$ 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:

$$P^1_{\mathrm{Nn}}(b) = \int dk \frac{d^3n(b,k)}{dk d^2 b} \sigma_{\gamma A \to A' + \mathrm{Nn}}(k)$$

- such that: $P^1_{\mathrm{Xn}}(b) = \sum_{N=1}^{\infty} P^1_{\mathrm{Nn}}(b)$

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

$$
\begin{aligned}
P_1(b) &= P^1_{1\mathrm{n}}(b) \times \exp(-P^1_{\mathrm{Xn}}(b)), \\
P_2(b) &= [P^1_{2\mathrm{n}}(b) + \frac{(P^1_{1\mathrm{n}}(b))^2}{2!}] \times \exp(-P^1_{\mathrm{Xn}}(b)), \\
P_3(b) &= [P^1_{3\mathrm{n}}(b) + 2P^1_{2\mathrm{n}}(b)P^1_{1\mathrm{n}}(b) + \frac{(P^1_{1\mathrm{n}}(b))^3}{3!}] \times \exp(-P^1_{\mathrm{Xn}}(b))
\end{aligned}
$$

- Fulfills the unitarity condition: $\sum_{N=1}^{\infty} P_{\mathrm{Nn}}(b) = P_{\mathrm{Xn}}(b)$

Photo-nuclear cross section

$$P^1_{\mathrm{Nn}}(b) = \int dk \frac{d^3n(b,k)}{dk d^2 b} \sigma_{\gamma A \to A' + \mathrm{Nn}}(k)$$

- 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

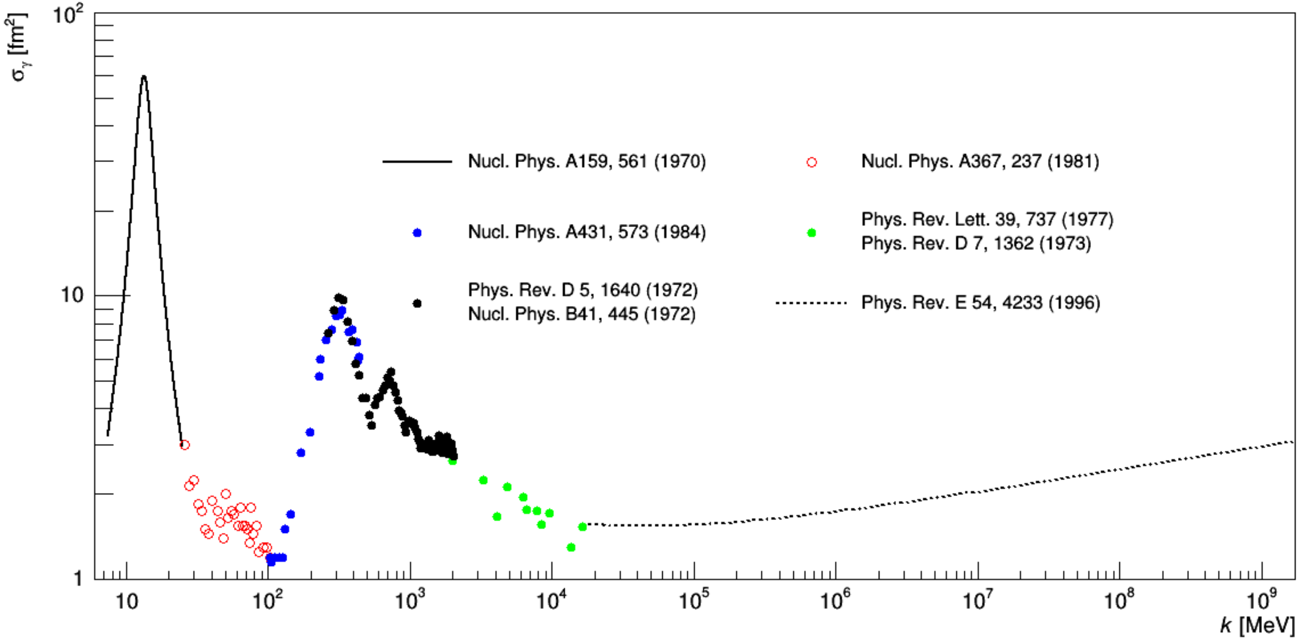
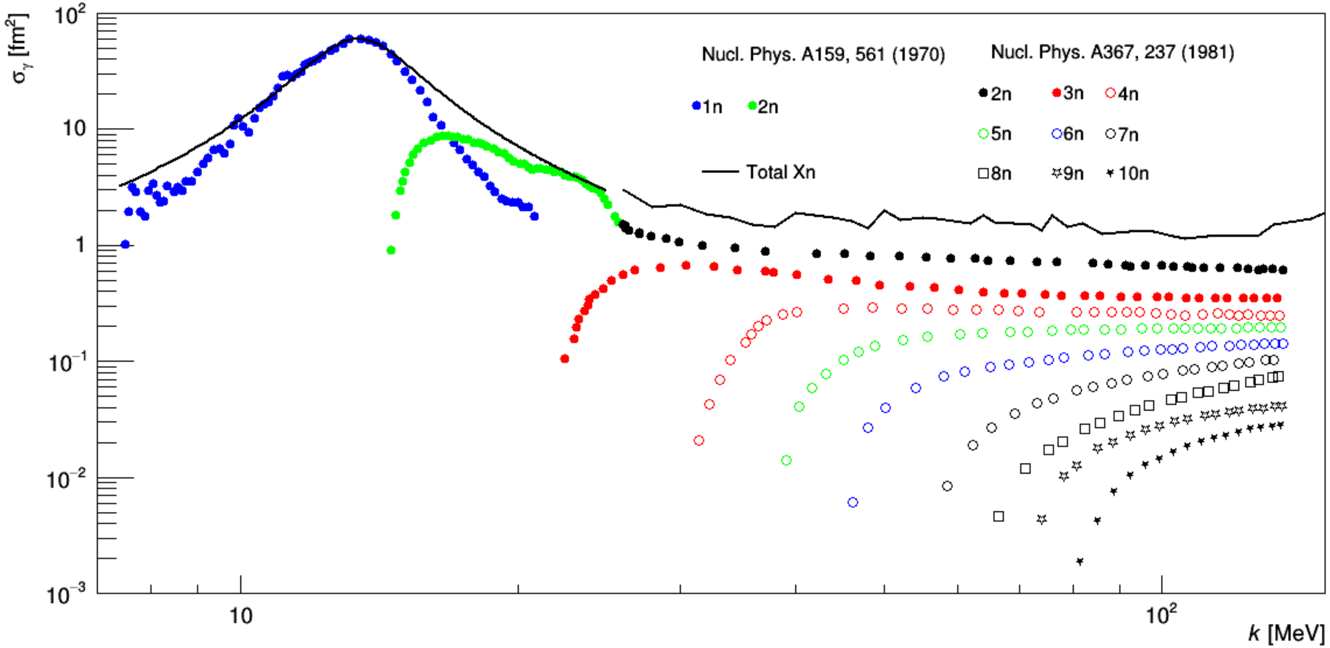


Photo-nuclear cross section

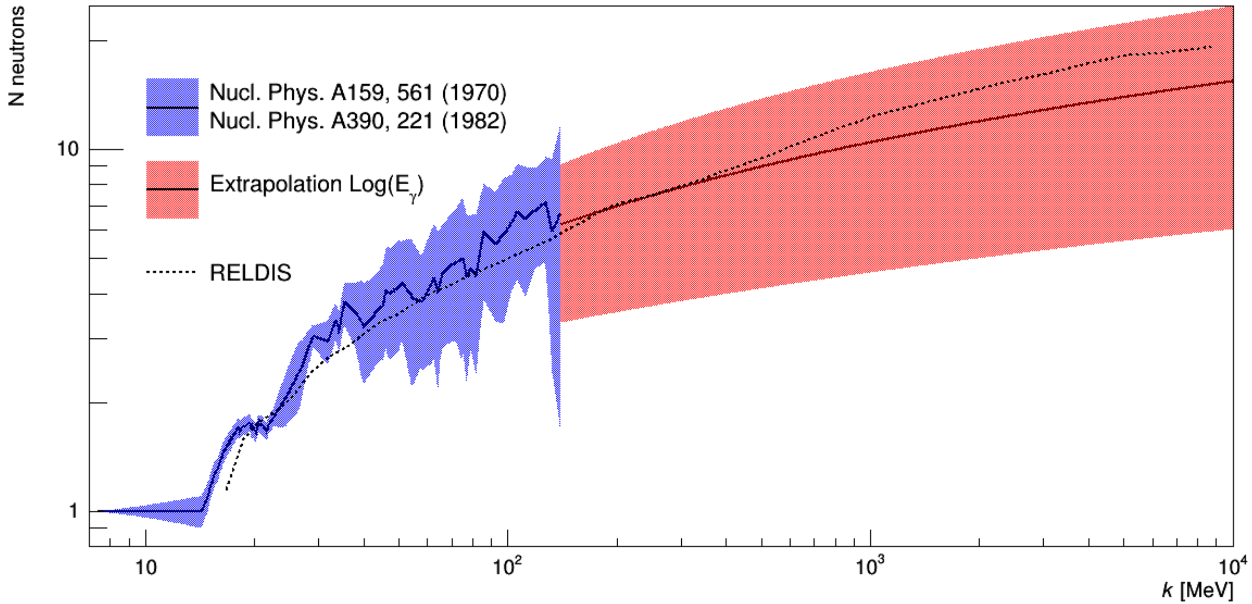
$$P^1_{\mathrm{Nn}}(b) = \int dk \frac{d^3n(b,k)}{dk d^2 b} \sigma_{\gamma A \to A' + \mathrm{Nn}}(k)$$

- 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



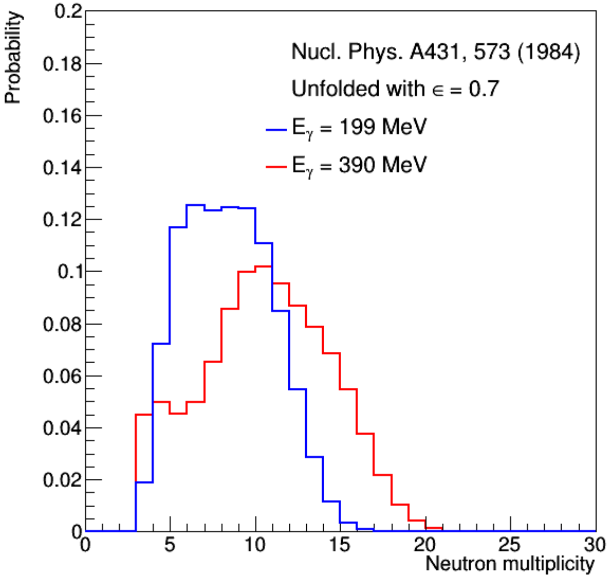
Neutron multiplicity

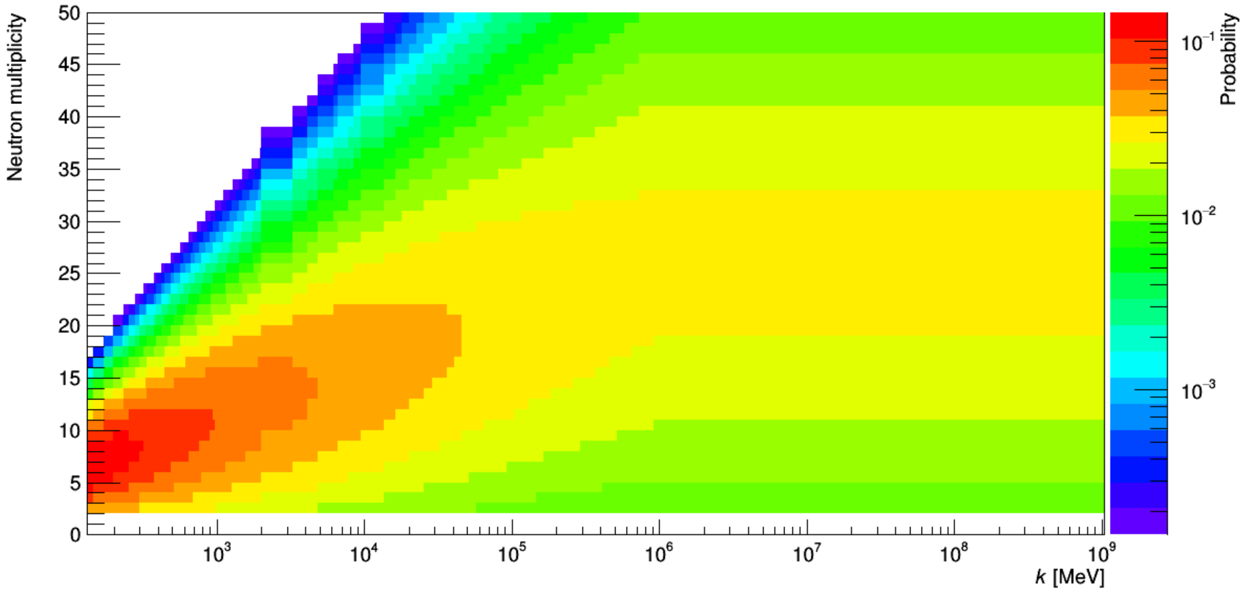
- Saclay used the partial cross sections to extract the average and the dispersion of the number of neutrons as a function of the incident energy
- Fitted to a logarithm and extrapolated to higher energies
- Comparison with RELDIS model in rather good agreement



Neutron multiplicity

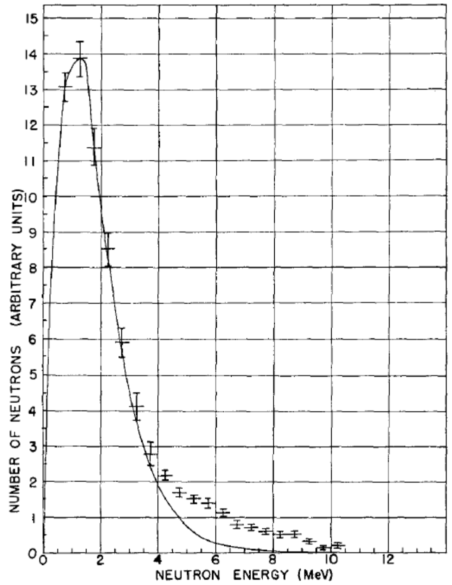
- The branching ratios to each partial cross section are computed from the fit by extrapolating the arithmetic average and dispersion, and using a Gaussian approximation for the shape





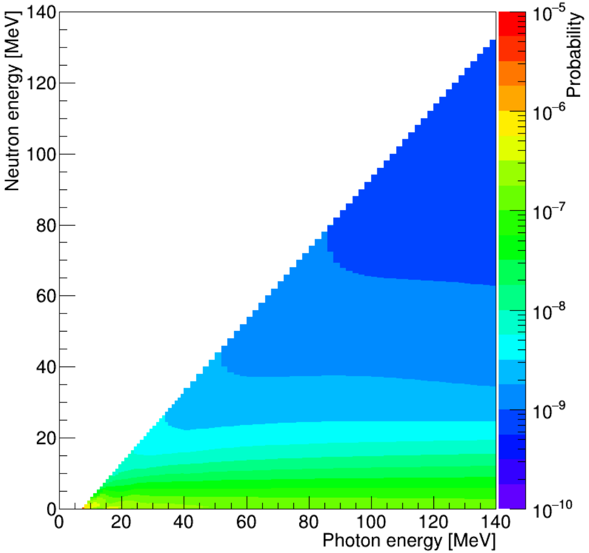
Neutron energy

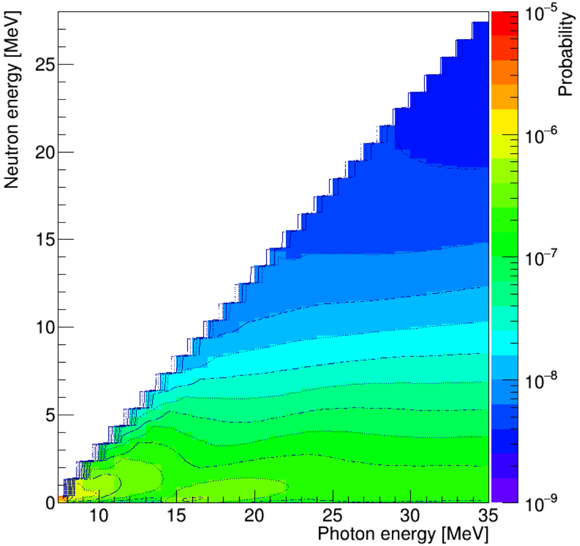
- Very few measurement exist for the spectra of secondary particles from mono-energetic source of photons
- Nevertheless one may have confidence in the accuracy of the evaluated spectra in case when the agreement between calculated and measured channel cross section (γ, n) (γ, 2n) is good
- This is because the energy dependence strongly influences the relative population of various product nuclides when multi-particle production is possible



Neutron energy

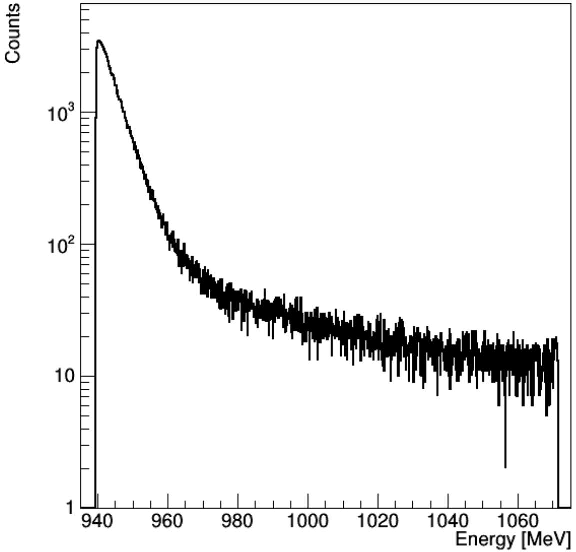
- The emission spectra of the secondary particles was part of the “Photonuclear Data for Applications” project by International Atomic Energy Agency
- Tables are available in Evaluated Nuclear Data File (ENDF) format https://www-nds.iaea.org/exfor/endf.htm

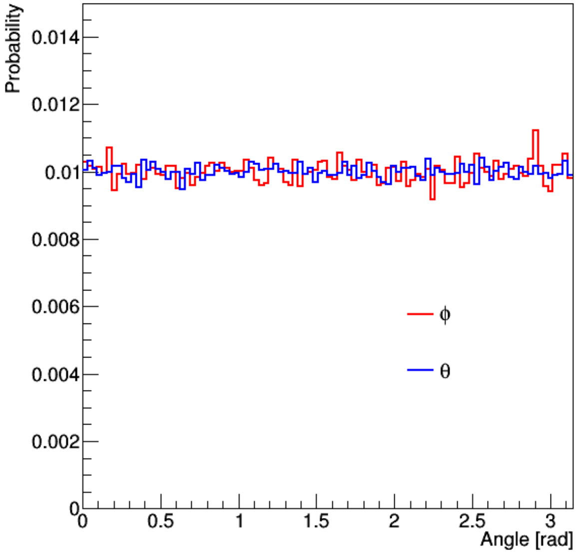




Particle generation

- Neutron is generated in the rest frame with energy generated using the ENDF table and isotropic angular distribution
- Then it is boosted by the β of the beam either to positive or negative direction





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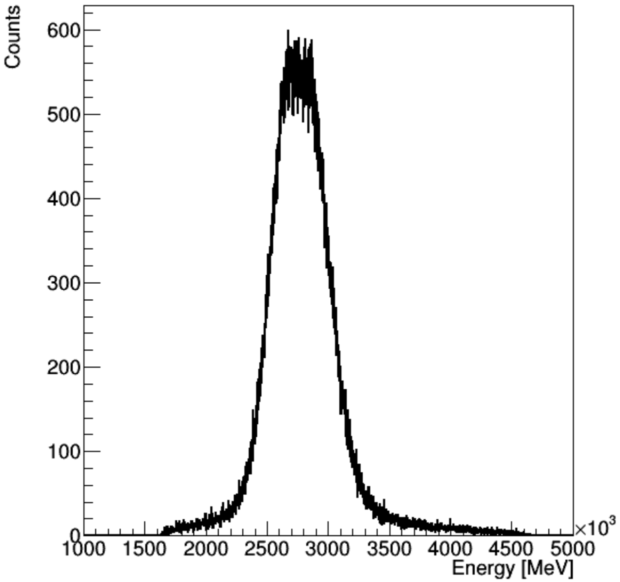
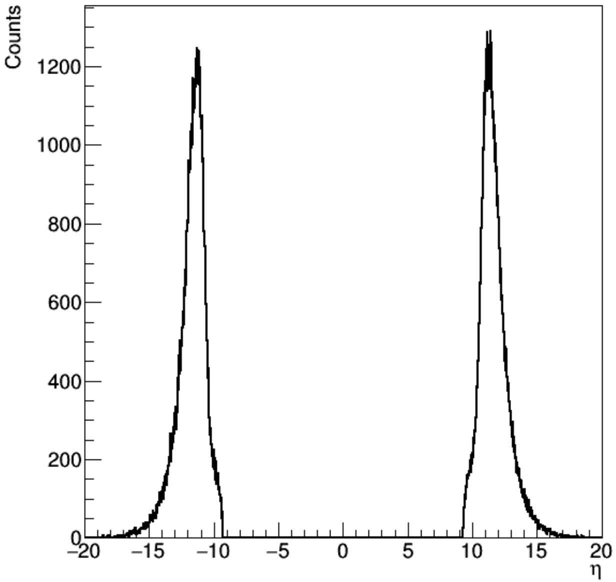




Implementation

Code notes

https://github.com/mbroz84/noon

- 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

Code notes

https://github.com/mbroz84/noon

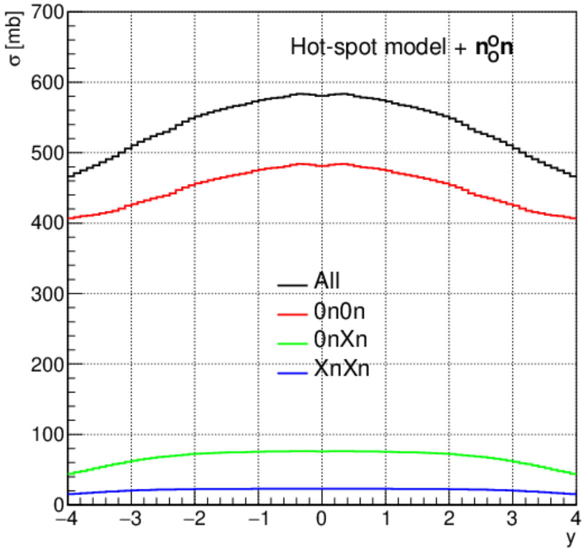
- Output:
  - It can produce a TTree with TParticles
  - You can import the TClonesArray with TParticles to your framework after every event
- Units to communicate with outside world are GeV
  - The input mass should be in GeV
  - Output TParticle momenta are in GeV
- Works for ^{208}Pb only for the time being
  - Near future: ^{197}Au, ^{129}Xe, ^{238}U
- Only coherent photon-pomeron process
  - Near future: Two Photon process
  - Medium term: Incoherent process

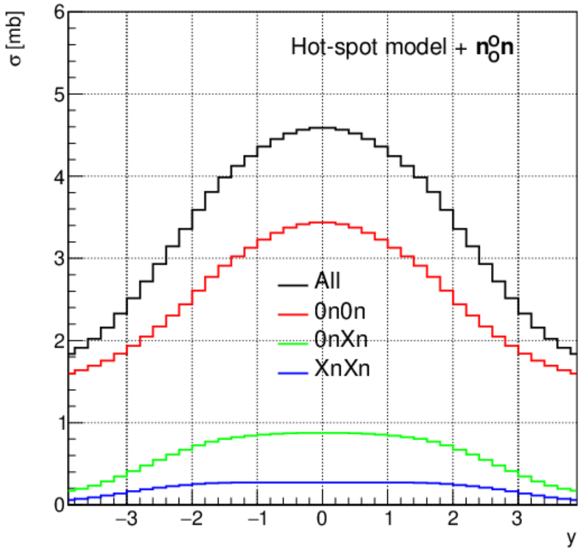
Example of possible applications

- 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.

INPUT

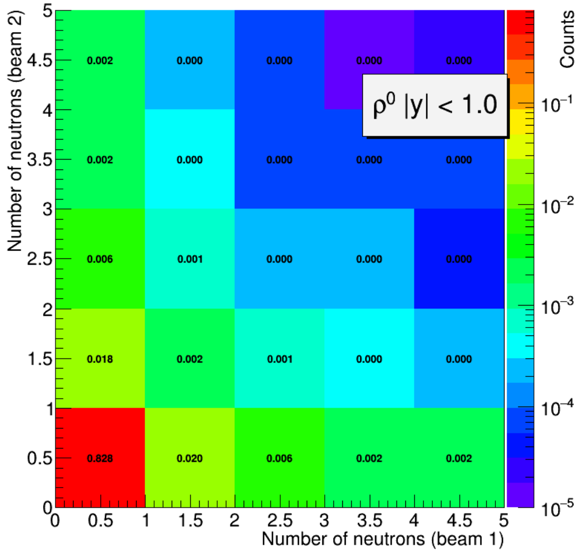
$$\frac{\sigma_{AA\to VAA}(y)}{dy} = \int d^2b \frac{d^3n(b,y)}{dkd^2b} \boxed{\sigma_{\gamma A\to VA}(y)} + \int dk \frac{d^3n(b,-y)}{dkd^2b} \sigma_{\gamma A\to VA}(-y)$$

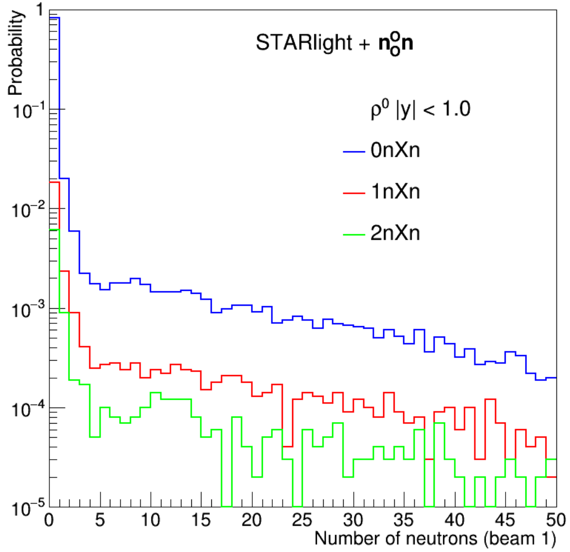




Example of possible applications

- 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

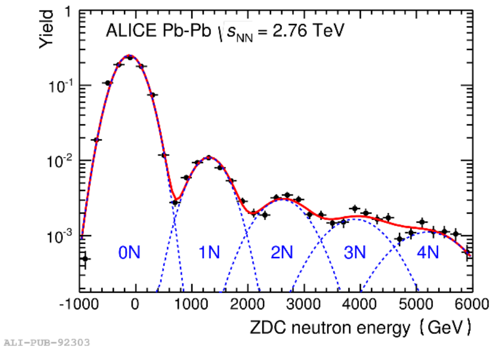
Outlook

- An updated version of n_0^0n will appear on GitHub soon
  - Extended by ^{197}Au, ^{129}Xe and ^{238}U nuclei
  - Nuclear break-up in γγ 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 ρ^0 and $\psi(2S)$

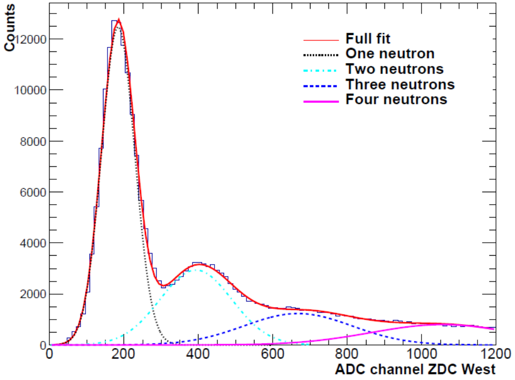


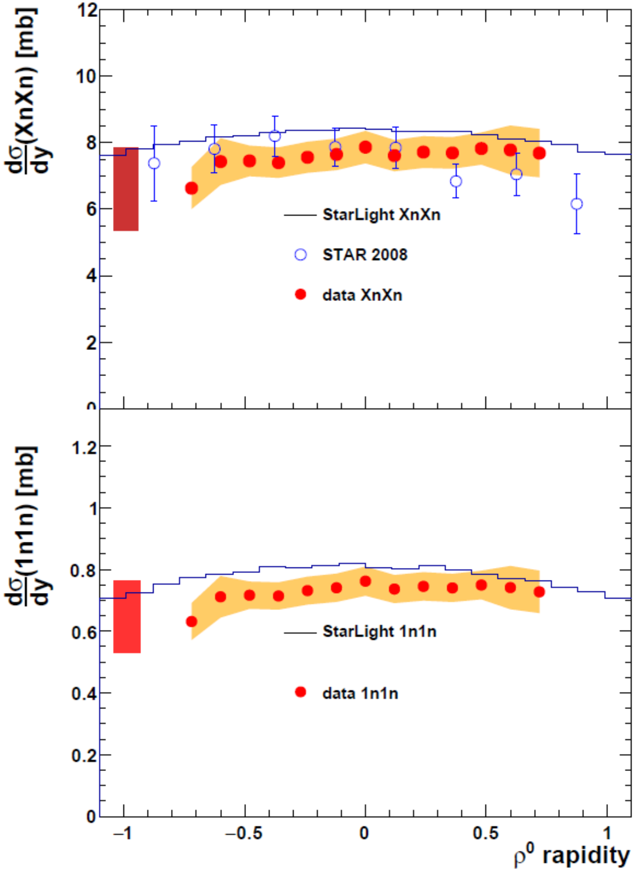
Selection	Number of events	Fraction	STARLIGHT	GDL
All events	7293	100 %		
0n0n	6175	$84.7\pm0.4(\text{stat.})^{+0.4}_{-1.9}(\text{syst.})$ %	79 %	80 %
Xn	1174	$16.1\pm0.4(\text{stat.})^{+2.2}_{-0.5}(\text{syst.})$ %	21 %	20 %
0nXn	958	$13.1\pm0.4(\text{stat.})^{+0.9}_{-0.3}(\text{syst.})$ %	16 %	15 %
XnXn	231	$3.2\pm0.2(\text{stat.})^{+0.4}_{-0.1}(\text{syst.})$ %	5.2 %	4.5 %

	Data	Fraction	STARLIGHT	RSZ
0n 0n	20	(71^{+9}_{-11})%	66%	70%
Xn	8	(29^{+11}_{-9})%	34%	30%
0n Xn	7	(25^{+11}_{-9})%	25%	23%
Xn Xn	1	(4^{+8}_{-3})%	9%	7%

Neutron emission in UPC experiments

- STAR required signal compatible with at least one neutron in both neutron ZDCs in the trigger for ρ°
- STAR ρ° cross sections are published for 1n1n and XnXn emission cases





Neutron emission in UPC experiments

- CMS coherent J/ψ cross section is measured for the case when the J/y mesons are accompanied by at least one neutron on one side of the interaction point and no neutron activity on the other side (Xn0n)
- UPC trigger also selects the XnXn, 1n0n, and 1n1n break-up modes.
- In the end the cross section is scaled from Xn0n to total

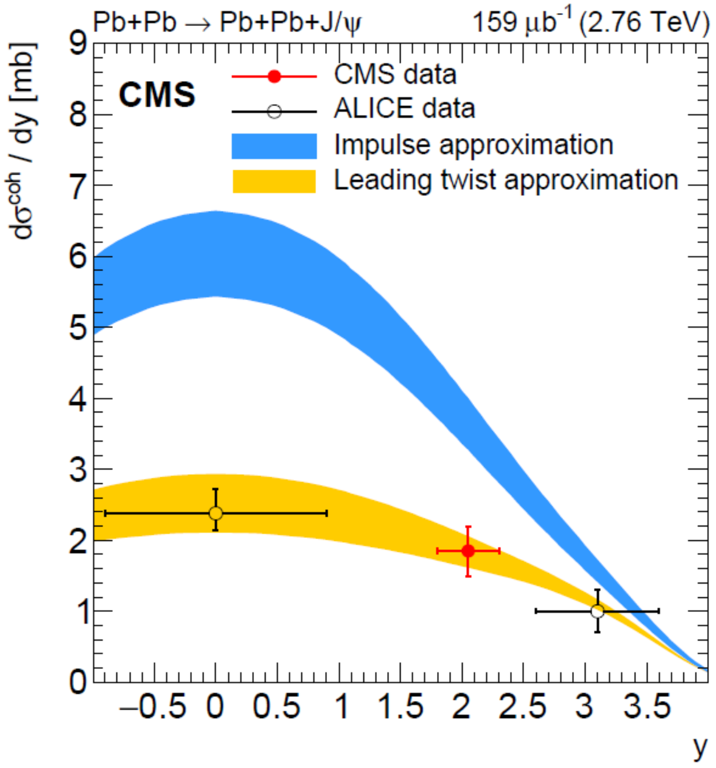
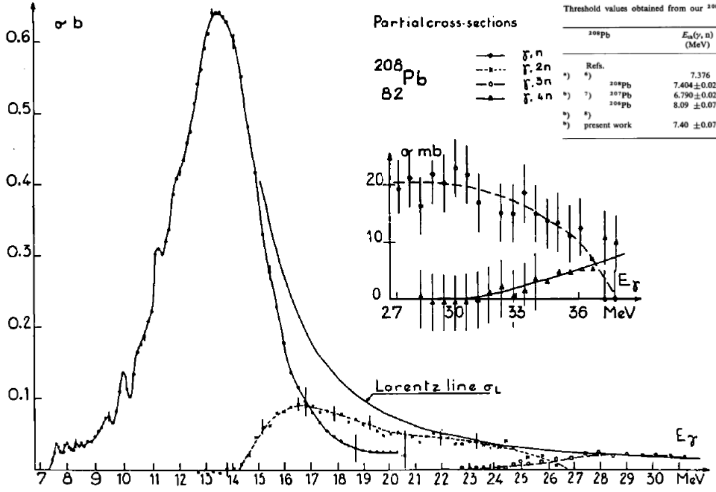


Photo-nuclear cross section $\sigma_{\gamma A \to A' + \mathrm{Xn}}(k)$

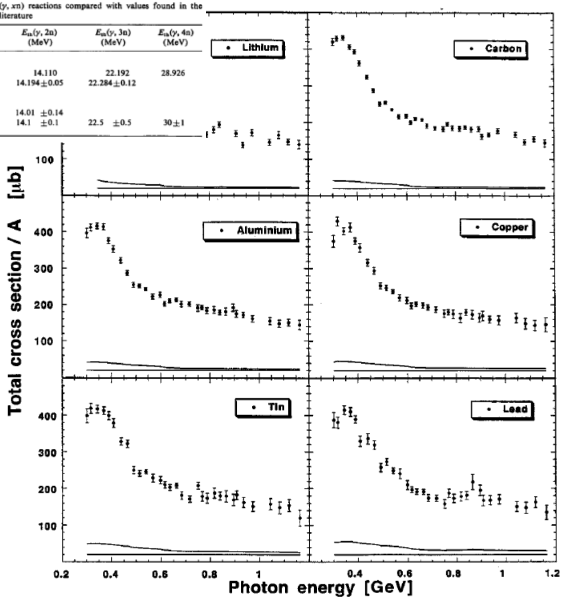
TABLE I. Total hadronic cross sections per nucleon (in μb).

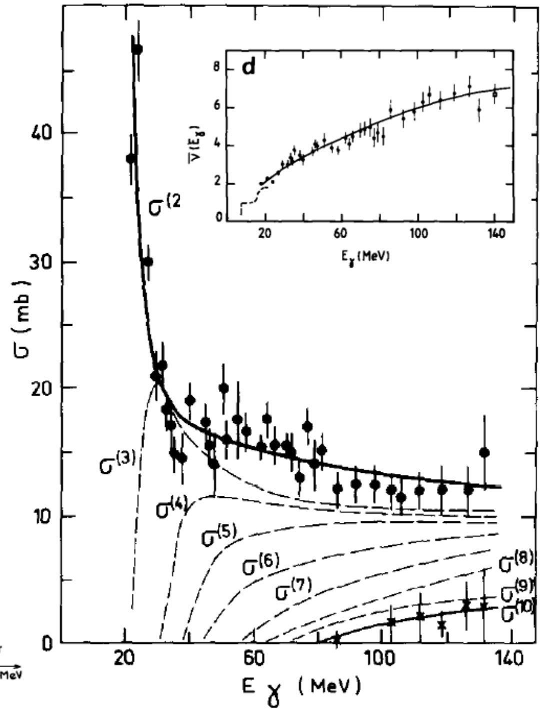
	k = 2.00 (GeV)	3.27 (GeV)	4.81 (GeV)	6.21 (GeV)	7.79 (GeV)	9.51 (GeV)
H	143.2 ± 2.7	126.8 ± 2.2	121.8 ± 2.2	115.9 ± 2.2	123.8 ± 2.4	114.1 ± 2.8
D	132.6 ± 2.5	119.8 ± 2.0	122.0 ± 2.2	112.3 ± 2.1	116.0 ± 4.4	107.8 ± 2.4
C	125.7 ± 5.8	116.6 ± 5.3	115.5 ± 5.5	103.9 ± 4.7	97.0 ± 4.6	91.7 ± 4.8
Al	118.3 ± 4.6	107.6 ± 3.6	106.4 ± 4.0	105.7 ± 4.1	104.0 ± 5.0	100.0 ± 6.1
Cu	124.1 ± 4.9	107.2 ± 3.8	102.5 ± 4.1	95.6 ± 4.1	94.9 ± 3.9	89.5 ± 4.4
Ag	120.5 ± 4.5	105.6 ± 3.9	102.9 ± 4.1	95.6 ± 3.9	88.5 ± 4.1	86.9 ± 4.4
Au	126.6 ± 5.4	108.0 ± 5.3	101.7 ± 4.9	94.2 ± 4.4	84.1 ± 4.1	82.7 ± 4.7
U	127.3 ± 6.6	103.3 ± 4.0	99.2 ± 4.2	96.0 ± 4.3	91.6 ± 4.2	79.9 ± 4.4



Threshold values obtained from our ^{208}Pb(γ, xn) reactions compared with values found in the literature

^{208}Pb			$E_{th}(\gamma, n)$ (MeV)	$E_{th}(\gamma, 2n)$ (MeV)	$E_{th}(\gamma, 3n)$ (MeV)	$E_{th}(\gamma, 4n)$ (MeV)
	Refs.					
a)	6)		7.376	14.110	22.192	28.926
		^{208}Pb	7.404 ± 0.028	14.194 ± 0.05	22.284 ± 0.12	
b)	7)	^{207}Pb	6.790 ± 0.023			
		^{206}Pb	8.09 ± 0.07			
b)	8)			14.01 ± 0.14		
b)	present work		7.40 ± 0.07	14.1 ± 0.1	22.5 ± 0.5	30 ± 1





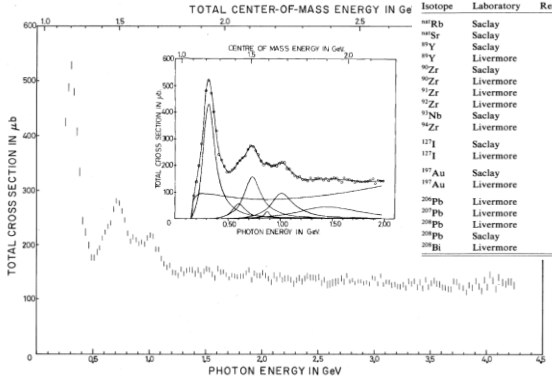
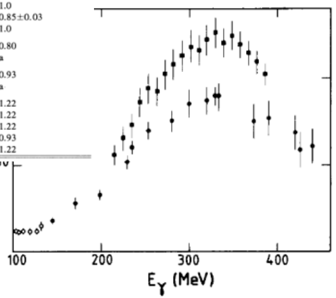
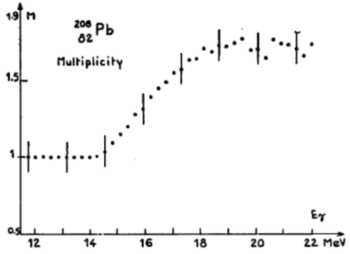


TABLE VI. Recommended normalization factors.

Isotope	Laboratory	Reference	Normalization factor
^{nat}Rb	Saclay	9	0.85±0.03
^{nat}Sr	Saclay	9	0.85±0.03
^{89}Y	Saclay	9	0.82
^{89}Y	Livermore	8	1.0
^{90}Zr	Saclay	9	0.88
^{90}Zr	Livermore	8	1.0
^{91}Zr	Livermore	8	1.0
^{92}Zr	Livermore	8	1.0
^{93}Nb	Saclay	9	0.85±0.03
^{94}Zr	Livermore	8	1.0
^{127}I	Saclay	10	0.80
^{127}I	Livermore	2	a
^{197}Au	Saclay	12	0.93
^{197}Au	Livermore	13	a
^{206}Pb	Livermore	11	1.22
^{207}Pb	Livermore	11	1.22
^{208}Pb	Livermore	11	1.22
^{208}Pb	Saclay	12	0.93
^{208}Bi	Livermore	11	1.22



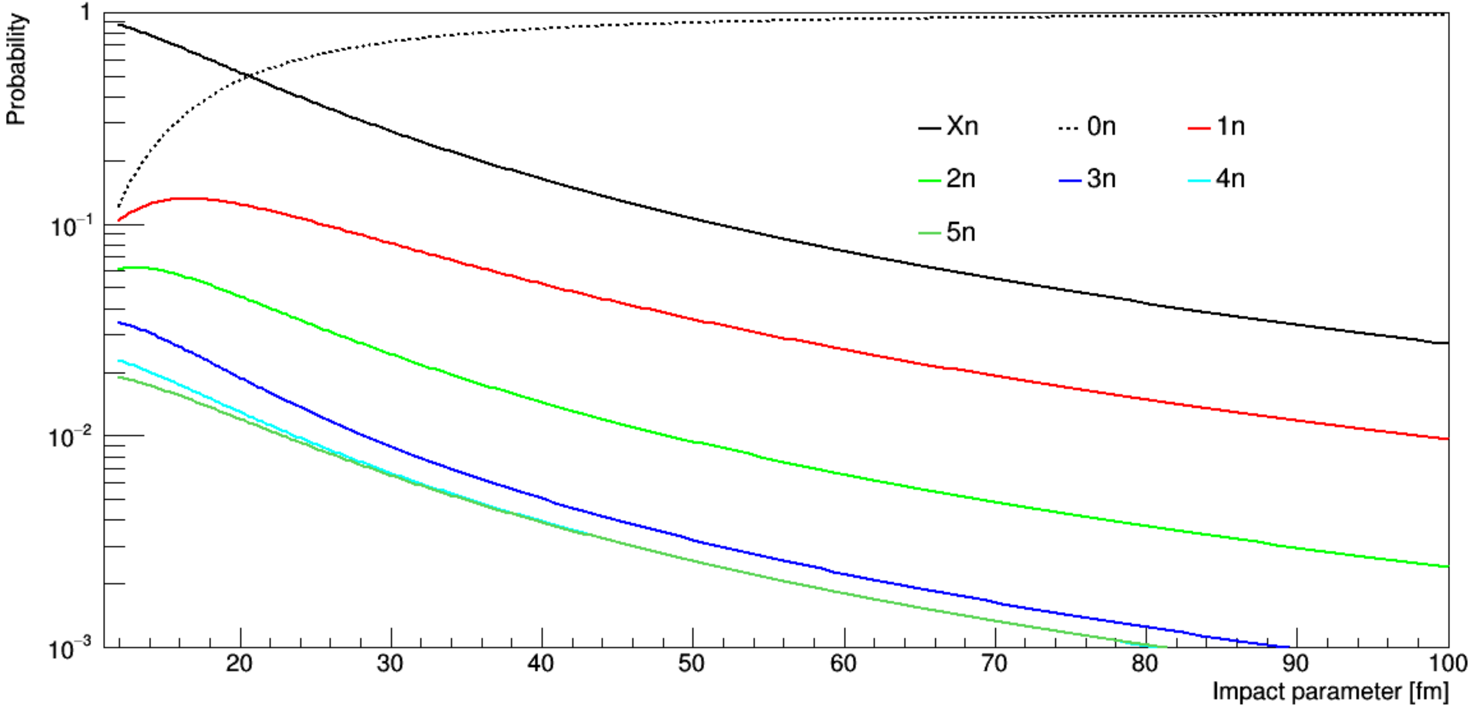


Hadronic interaction probability

- 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: $$P_H(b) = \int d^2\vec{r}T_\mathrm{A}(\vec{r}-\vec{b})(1-\exp(-\sigma_\mathrm{NN}T_\mathrm{B}(\vec{r})))$$
- here we use nuclear thickness function $T_\mathrm{A}(\vec{r}) = \int dz\rho_A(\sqrt{|\vec{r}|^2+z^2})$
- and nuclear density for a nucleus A at distance s from its center is modeled with a Woods-Saxon distribution for symmetric nuclei

$$\rho_A(s) = \frac{\rho_0}{1+\exp(\frac{s-R_\mathrm{WS}}{d})}$$

Nucleus break-up probabilities



Normalization ratio