Emission of neutrons and protons in photoproduction on nuclei in UPC at the LHC and EIC

Antoni Szczurek
Institute of Nuclear Physics PAN, Kraków, Poland

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in collaboration with P. Jucha, K. Mazurek and K. Pysz
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Synergies between the EIC and the LHC, September 22 - 24,09. 2025, Krakow, Poland

Introduction

- There is growing interest in ultraperipheral heavy ion collisions (LHC).
- The processes that fullfil these categories can be divided into:
  (a) photon-photon fusion (many examples: l^+l^-, $M_1 M_2$, dijets or $\gamma\gamma$)
  (b) photoproduction (examples: production of vector mesons: ρ^0, ϕ, J/ψ)
- UPCs have usually simple final state in the measured midrapidity region.
- Very forward/backward region is not always of unterest.
- However, experimentally we have ZDC callorimeters. They can measure neutrons and also protons.
- Any extra photon exchange may lead to associated nucleus excitation. Excited nucleus may emit: neutrons, protons, alpha particles or photons. May even go to fission.
- The Lorentz boost causes that those are emitted very

Introduction

- In general even Coulomb excitations alone (no midrapidity production) are possible. They lead to damping of the beams at the LHC.
- Neutron emission happens very frequently and it can be also easily measured.
- The ALICE collaboration measured cross section for a given number of neutrons ($n = 1, 2, 3,, 4, 5$) in ZDC.
- Recently the ALICE collaboration measured also protons.
- Also simultaneous measurement of neutrons and protons is possible.

Existing related approaches, programs

- RELDIS intranuclear cascade, not easily available
- DPMJET-III, dual parton model
- GEMINI++, Hauser-Feshbach formalism for nuclear cascade
- EMPIRE, traditional nuclear physics modelling, including equilibrium emission
- HIPSE, Heavy Ion Phase-Space Exploration, h+A, no photons!, preequilibrium model, for GANIL physics.
- STARlight (UPC), excitation in association with midrapidity emissions
  only 0n0n, 1n1n, Xn0n, XnXn categories
- BeAGLE (virtual photons), relevant for EIC
- GiBUU, BUU approach, can treat photons as projectiles
- Noon, parametrization of some fixed target data

Some basic formulae for Coulomb excitations in UPC

single photon exchanges

$$\sigma_{A_1 A_2 \xrightarrow{1\gamma} X_1 X_2 + kn} = \int\int dbd\omega \cdot 2\pi b \cdot e^{-m(b)} N(\omega, b)\sigma_{abs}(\omega) P_k(\omega)$$

$$m(b) = \int d\omega \cdot N(b, \omega)\sigma_{abs}(\omega)$$

multi photon exchanges

$$\sigma_{A_1 A_2 \xrightarrow{j\gamma} X_1 X_2 + kn} = \int d\omega_1 \ldots \int d\omega_j \int 2\pi b db \cdot \frac{e^{-m(b)}}{j!} \left(\prod_{i=1}^{j} N(\omega_i, b)\sigma_{abs}(\omega_i) \right) P_k(\Sigma_i^j(\omega_i))$$

Flux of photons

$$N(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2\beta^2}\frac{1}{\omega b^2} \times \left| \int d\chi\, \chi^2 \frac{F(\frac{\chi^2+u^2}{b^2})}{\chi^2+u^2} J_1(\chi) \right|^2 .$$

$$\chi = k_\perp b \qquad\qquad u = \frac{\omega b}{\gamma\beta}$$

$$F(\mathbf{q}^2) = 1 \qquad \text{– point-like model}$$

$$F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|}\int \rho(r)\cdot \sin(|\mathbf{q}|r)\cdot r dr \qquad \text{– realistic model}$$

Some details

- consider emitting (1) and absorbing (2) nucleus
  photon flux is associated with emitting nucleus, absorption cross section is associated with absorbing nucleus.
- distinguish $\vec{b}$, $\vec{b}_1$, $\vec{b}_2$
  In general are "independent", integrations: $d^2b\, d^2b_1$.
- from geometry:
  $b > 2R_A$ (UPC), $b_1 > R_A$ (UPC)
- equilibrium emission from Hauser-Feshbach theory:
- property of equilibrated nucleus:
  $E_{exc} < E_{\gamma/A_2}$
  spin: $S \approx 0$ (may be too approximate for large E_{γ/A_2})

Flux of photons

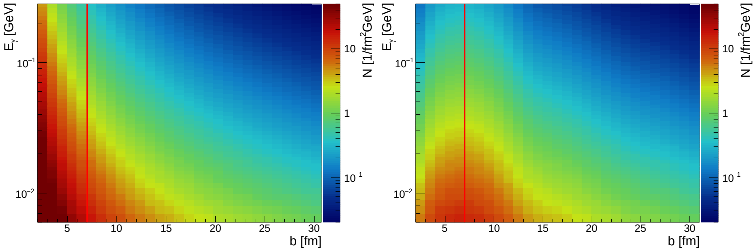
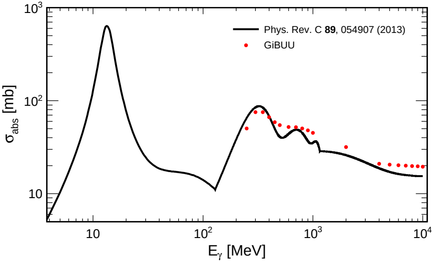


Figure: Point-like (left) versus realistic (right) photon flux.

Absorption cross section



Physics changes gradually with energy:

GDR, quasi deuteron, nucleon resonances, partonic reactions.

Probability of emission of a given number of neutrons

P_k is inclusive quantity !

k is number of neutrons, there can be any other particle in the accepted event.

It can be formally defined as:

$$P_k(E_\gamma) = \frac{\sigma(\gamma A \rightarrow knA'; E_\gamma)}{\sigma^{tot}_{\gamma A}(E_\gamma)} \quad (1)$$

can be calculated in a model.

The probabilities fullfil the condition:

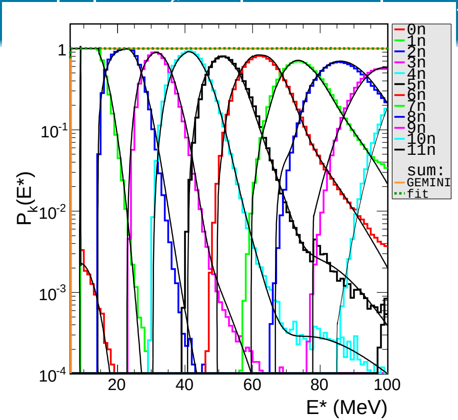
$$\Sigma_k P_k(E_\gamma) = 1, \quad (2)$$

for any energy.

Can be easily calculated in the Hauser-Feshbach approach.

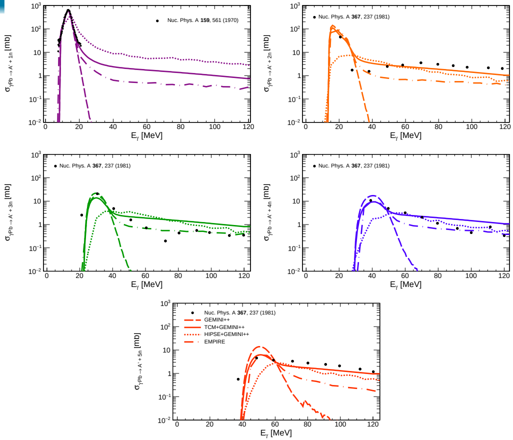
(see next slide from analyzing events from GEMINI++)

Probability of … f neutrons



M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek,
"Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions",
Phys. Rev. **C89** (2014) 054907.

Nucleus de-excitation channels from γA processes



those are from "low" energy reactions, Lepretre et al.
Long tails at high photon energies for a given k

Two-component model

In our previous approach (Klusek-Gawenda et al.), we implicitly assumed

$$P(E_{exc}; E_\gamma) \propto \delta\left(E_{exc} - E_\gamma\right) \ , \tag{3}$$

where δ is the Dirac delta function. Above $P(E_{exc}; E_\gamma)$ can be interpreted as a probability of populating equilibrated compound nucleus with a given excitation energy E_{exc} in a process initiated by the photon with energy E_γ. It must be constructed to fulfill the following probabilistic relation:

$$\int_0^{E_\gamma} P(E_{exc}; E_\gamma)\, dE_{exc} = 1 \ . \tag{4}$$

Two-component model

In order to better understand the situation, we consider a simple model in which different excitation energies $E_{exc} < E_\gamma$ (for the equillibrated nucleus) can be populated. We started with the somewhat academic step-like function:

$$P(E_{exc}; E_\gamma) = \mathrm{const}(E_{exc}) = 1/E_\gamma \tag{5}$$

for $E_{exc} < E_\gamma$, i.e. uniform population in excitation energy. Another option is to take the simple sinus-like function:

$$P(E_{exc}; E_\gamma) = \frac{\pi}{2E_\gamma} \sin\left(\pi E_{exc}/E_\gamma\right) \tag{6}$$

for $E_{exc} < E_\gamma$.

Two-component model

In general, the bigger number of neutrons, the larger the fraction of energy carried by neutrons.

$$P(E_{exc}; E_\gamma) = c_1(E_\gamma)\delta\left(E_{exc} - E_\gamma\right) + c_2(E_\gamma)/E_\gamma \ . \tag{7}$$

The probabilistic interpretation requires:

$$c_1(E_\gamma) + c_2(E_\gamma) = 1 \ . \tag{8}$$

In general, c_1 and c_2 may (should) depend on photon energy E_γ. As a trial function for further analysis, we propose

$$c_1(E_\gamma) = \exp\left(-E_\gamma/E_0\right) \ , \tag{9}$$
$$c_2(E_\gamma) = 1 - \exp\left(-E_\gamma/E_0\right) \ . \tag{10}$$

The parameter E_0 can be adjusted to the ALICE data. We suggest $E_0 \approx 50$ MeV to start with.

Two-component model

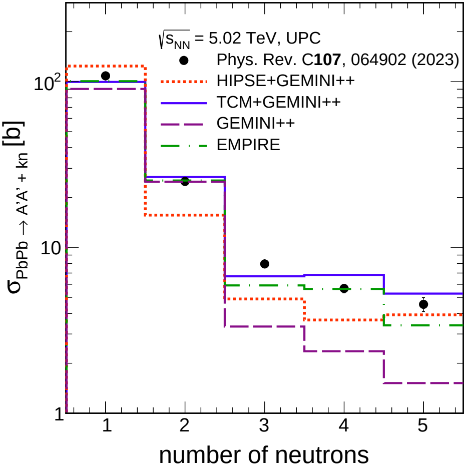
The full TCM formula for the probability of emitting a specified number of neutrons for a given photon energy is calculated by:

$$P_k(E_\gamma) = \sum_{E_{exc}}^{E_\gamma} (1 - \exp(-E_\gamma/E_0)) \frac{1}{E_\gamma} \frac{N_k(E_{exc})}{N_{ev}} \Delta E_{exc} + \exp(-E_\gamma/E_0) \frac{N_k(E_\gamma)}{N_{ev}}. \tag{11}$$

Here, the $N_k(E)$ is a number of events with k emitted neutrons for a given E_γ or an excitation energy, and N_{ev} is a total number of events for a given energy. Both numbers are obtained from GEMINI++ event generator. The ΔE_{exc} is a chosen interval of excitation energy in a discrete sum in (11). This is purely technical parameter to simplify the calculations.

The neutron emission probability fulfill the following condition:

Final results



Photoabsorption in GiBUU approach

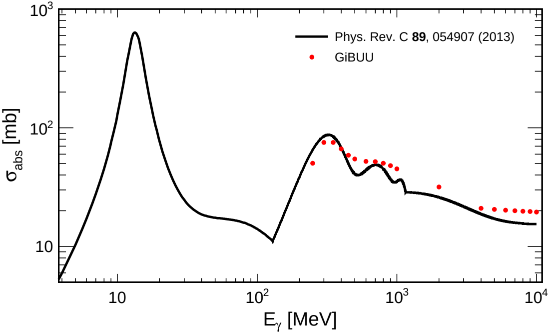


Figure: Photoabsorption cross section for γ+Pb reaction in energy range 10 MeV- 100 GeV compared with the total cross section obtained with the GiBUU model.

$\gamma +^{208} Pb$ in two models

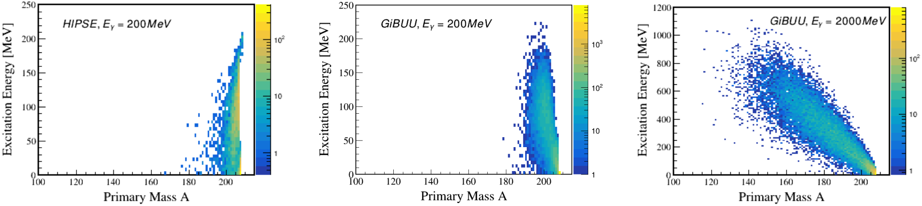


Figure: Distribution of the primary mass and its excitation energy predicted in the naively adopted HIPSE (E_γ=200 MeV - top), and GiBUU (E_γ=200 MeV - middle and E_γ=2000 MeV - bottom.)

Average excitation energy in γ+^{208}Pb

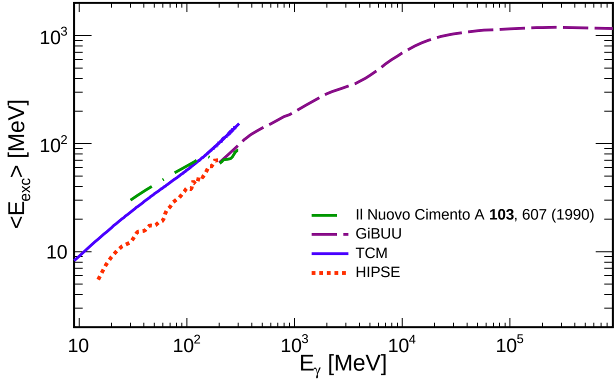


Figure: Average excitation energy as a function of energy of the photon in γ+^{208}Pb collisions in different models.

A-Z distributions, from preequilibrium

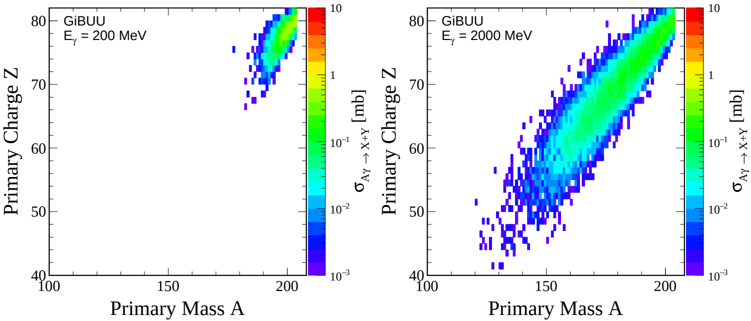


Figure: Cross section for production of primary fragments: GiBUU for collisions of 200 MeV and 2000 MeV photons in $\gamma + {}^{208}$Pb reaction.

A-Z distributions, after equilibrium

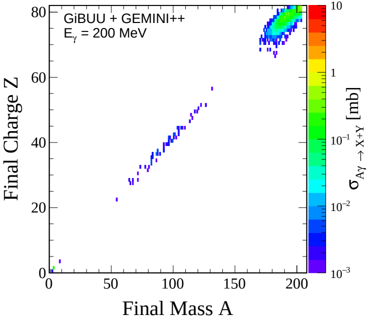


Figure: Cross section for production of final nuclei: GiBUU + GEMINI++ for 200 MeV and 2000 MeV photons in $\gamma + ^{208}$Pb reactions.

Neutron multiplicity

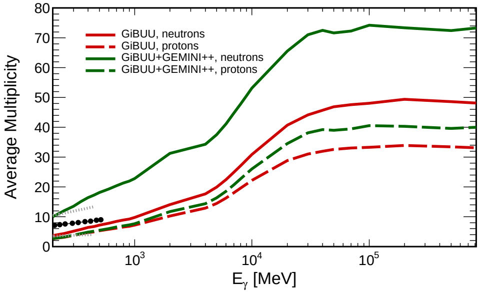


Figure: Average neutron multiplicity: pre-equilibrium obtained in GiBUU (red line), final results with GEMINI++ de-excitation code (green line). The extrapolation of experimental data (LEPRETRE1982, NooN) (black dots) and its dispersion (dotted lines) are shown. The full lines are for neutrons and the dashed ones are for protons.

Multiplicities, GiBUU+GEM2

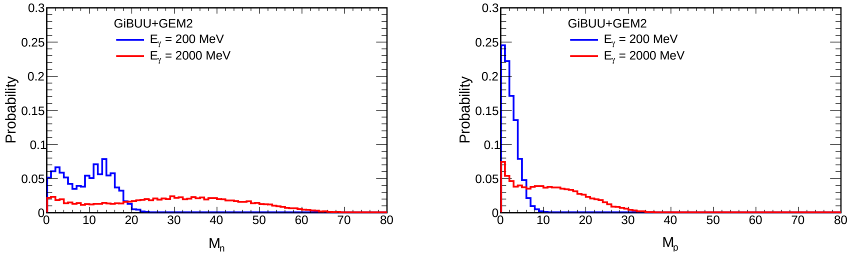


Figure: Neutron (a) and proton (b) multiplicities obtained with GiBUU+GEM2 for de-excitation of the initial nucleus at E_γ=200 (blue) and 2000 (red) MeV.

Neutron and proton multiplicities

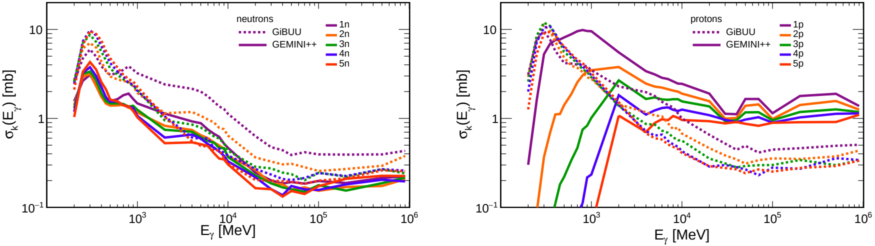


Figure: Neutron a) and proton (b) cross section for different multiplicities obtained with GiBUU + GEMINI++.

Neutron and proton multiplicities

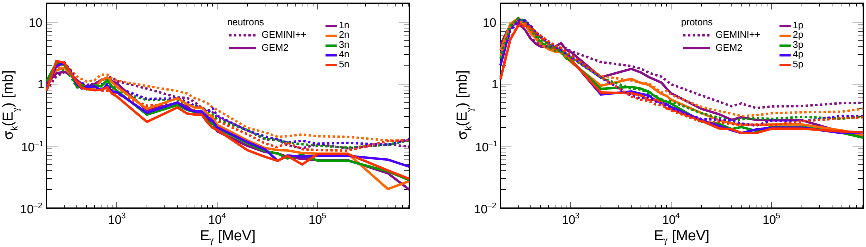


Figure: Comparison of the GEMINI++ (dashed lines) and GEM2 (solid lines) de-excitation models cross section for a given number of: a) neutrons, b) protons.

Neutron multiplicities from different approaches

Table: Total cross sections (in barn) for a fixed number of neutron in UPC for reaction of ^{208}Pb+^{208}Pb with $\sqrt{s_{NN}} = 5.02$ TeV. The integration is done only for energies $E_\gamma > 200$ MeV. The two-component model (TCM) with GEMINI++ and constant neutron probability equal to $P(E_\gamma = 200 \text{ MeV})$ (const.) are compared to the GiBUU with GEMINI++ and the GiBUU with GEM2 results. Here, only one photon exchange is taken into consideration.

	TCM	GiBUU+GEMINI++	GiBUU+GEM2
1n	2.294	1.308	1.160
2n	3.210	1.553	1.207
3n	2.513	1.160	1.155
4n	3.324	1.325	1.136
5n	2.940	1.156	1.079

Neutron multiplicities

E_γ	TGC	TGG2	TGG++	HGG++	EMPIRE	ALICE
$<$ 200	Two Comp. Mod.			HIPSE		
$>$ 200	const.	GiBUU				
1n	98.79	97.23	97.37	113.21	98.90	108.4$\pm$3.90
2n	25.31	22.90	23.24	14.34	23.39	25.0$\pm$1.30
3n	6.03	4.23	4.24	4.24	3.91	7.95$\pm$0.25
4n	6.32	3.51	3.69	3.41	2.28	5.65$\pm$0.33
5n	4.91	2.49	2.56	2.79	1.05	4.54$\pm$0.44

E_γ	TGC	TGG2	TGG++	HGG++	EMPIRE	ALICE
$<$ 200	Two Comp. Mod.			HIPSE		
$>$ 200	const.	GiBUU				
1p 2p 3p	6.59 0.44 0.01	13.18 3.71 2.35	12.54 6.63 3.40	5.25 4.74 4.60	2.36 0.01 0.01	40.4 ± 1.6 16.8 ± 3.7 6.8 ± 2.2
Pb Tl Hg Au	150.47 5.86 9.67 2.43	- - - -	128.21 0.75 1.21 0.29	130.7 7.24 4.92 4.25	129.51 0.001 0.0007 0.00001	157.5 ± 4.6 40.4 ± 1.6 16.8 ± 3.7 6.8 ± 2.2

Nuclear remnants in UPC

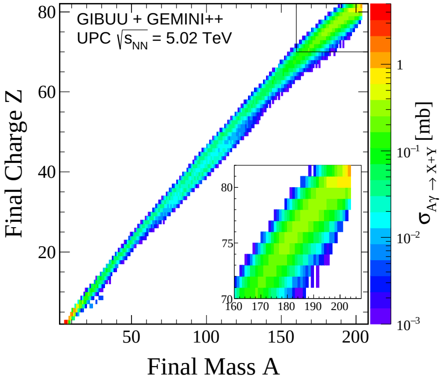


Figure: Cross section for production of nucleus remnants in $^{208}Pb+^{208}Pb$ UPC. The inset plot is the zoom on mass range A=(160-208).

General picture for $E_\gamma > 180$ MeV

Primary collision:
$\gamma + N \to N' + mesons$ process
Leads to (1p 1h) state. At higher energies particles (p or n) are emitted.
Secondary collisions:
The outgoing nucleon or mesons when passing nucleus may create (2p 2h), (3p 3h) etc.
Equilibrium emission:
The presence of vacancies means excitation of the nucleus. The excited nucleus tends to equilibration and may emit neutrons or protons. For ^{208}Pb the emission of neutrons dominates.
What is contribution of the different mechanisms to the production of neutrons or protons is to some extend an open question.
In GiBUU the secondary emission is very large.
We will discuss that it may not be so when comparing to ZDC data.

Upper limit for $\sigma_{1p}(idea)$

The primary (unknown) cross section for single nucleon production cannot be bigger than (known) photon absorption cross section.

$$\sigma_{1p}(\omega) + \sigma_{1n}(\omega) < \sigma_{\gamma A}^{abs}(\omega) \tag{13}$$

for each photon energy.
$\gamma p \to p, n$ or $\gamma n \to n, p$ happen in almost 100 % (baryon number conservation). There is a small amount of hiperons.

Components of phooabsorption cross section

Our total photoabsorption cross section is a sum of four different components (Klusek-Gawenda, et al.):

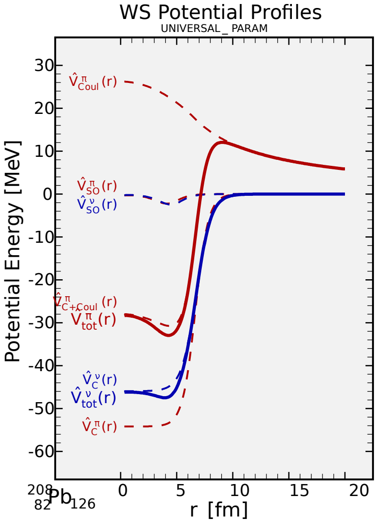
1) giant dipole resonance, $\sigma_{\gamma A}^{GDR}(\omega)$,
2) quasi deuteron mechanism, $\sigma_{\gamma A}^{QD}(\omega)$,
3) nucleon resonance region,[1] $\sigma_{\gamma A}^{res}(\omega)$,
4) partonic region, $\sigma_{\gamma A}^{part}(\omega)$,

$$\sigma_{\gamma A}(\omega) = \sigma_{\gamma A}^{GDR}(\omega) + \sigma_{\gamma A}^{QD}(\omega) + \sigma_{\gamma A}^{res}(\omega) + \sigma_{\gamma A}^{part}(\omega) \; , \tag{14}$$

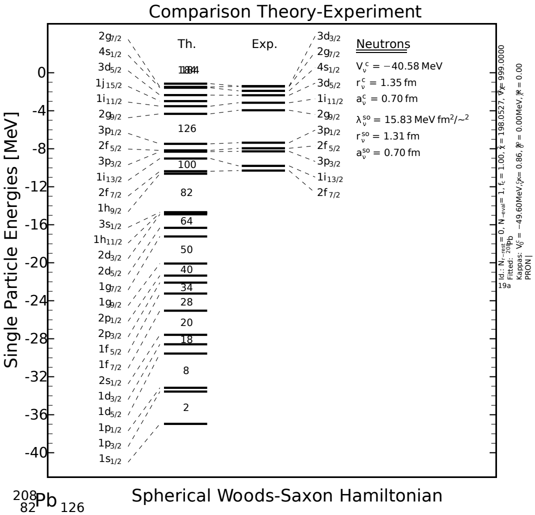
where ω is photon energy.
As will be discussed in the following, for lowest photon energies (GDR), practically no protons are emitted.

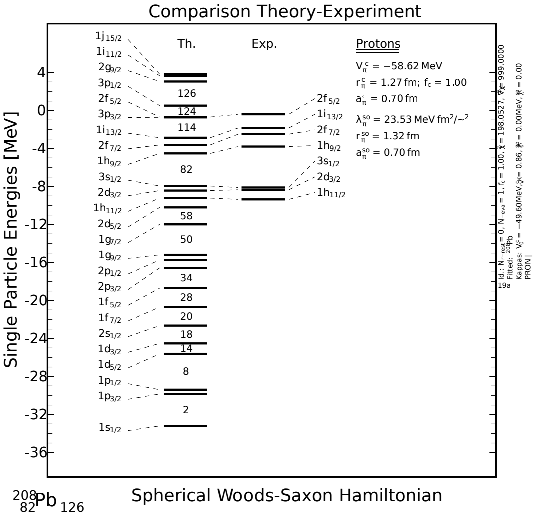
[1] The "resonance" region includes also non-resonance contributions.

Single particle potentials



Shell model states, neutrons




Comparison Theory-Experiment
Th.
Exp.
Protons
$V_\pi^c = -58.62$ MeV
$r_\pi^c = 1.27$ fm; $f_c = 1.00$
$a_\pi^c = 0.70$ fm
$\lambda_\pi^{so} = 23.53$ MeV fm$^2/\hbar^2$
$r_\pi^{so} = 1.32$ fm
$a_\pi^{so} = 0.70$ fm
Single Particle Energies [MeV]
4
0
-4
-8
-12
-16
-20
-24
-28
-32
-36
$1j_{15/2}$
$1i_{11/2}$
$2g_{9/2}$
$3p_{1/2}$
$2f_{5/2}$
$3p_{3/2}$
$1i_{13/2}$
$2f_{7/2}$
$1h_{9/2}$
$3s_{1/2}$
$2d_{3/2}$
$1h_{11/2}$
$2d_{5/2}$
$1g_{7/2}$
$1g_{9/2}$
$2p_{1/2}$
$2p_{3/2}$
$1f_{5/2}$
$1f_{7/2}$
$2s_{1/2}$
$1d_{3/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
126
124
114
82
58
50
34
28
20
18
14
8
2
$2f_{5/2}$
$1i_{13/2}$
$2f_{7/2}$
$1h_{9/2}$
$3s_{1/2}$
$2d_{3/2}$
$1h_{11/2}$
$^{208}_{82}Pb_{126}$
Spherical Woods-Saxon Hamiltonian

1p emission

It is obvious that the cross section for $1p$ emission must be smaller than the photoabsorption cross section for any ω. Then the absolutely maximal estimation of the one-proton cross section in UPC can be approximated as:

$$\begin{aligned} max\{\sigma_{AA\to 1p}\} &= max\{\sigma^{QD}_{AA\to p}\} + max\{\sigma^{res}_{AA\to p}\} \\ &+ max\{\sigma^{part}_{AA\to p}\}\,, \end{aligned} \tag{15}$$

where cross sections for one-side $1p$ emission (forward or backward) in UPC can be obtained as

$$\begin{aligned} max\{\sigma^{QD}_{AA\to 1p}\} &\approx \int N(\omega,b)\sigma^{QD}_{\gamma A}(\omega)\ d^2bd\omega\ , \\ max\{\sigma^{res}_{AA\to 1p}\} &\approx \int N(\omega,b)\sigma^{res}_{\gamma A}(\omega)\ d^2bd\omega\ , \\ max\{\sigma^{part}_{AA\to 1p}\} &\approx \int N(\omega,b)\sigma^{part}_{\gamma A}(\omega)\ d^2bd\omega\ . \end{aligned} \tag{16}$$

Similar equation can be written for one neutron pre-equilibrium

1p emission

If we apply parametrizations of different γPb photoabsorption components in (15)

$$\begin{aligned} max\{\sigma^{QD}_{AA\to p}\} &= 12.62\ b, \\ max\{\sigma^{res}_{AA\to p}\} &= 39.31\ b, \\ max\{\sigma^{part}_{AA\to p}\} &= 34.29\ b. \end{aligned} \tag{17}$$

Adding maximal values for each component we get: $\max(\sigma_{AA\to 1p}) =$ 85 b which is only about two times bigger than the cross section measured by the ALICE collaboration.
The estimation above is an absolute upper limit. Not only protons but also neutrons can be produced in $\gamma + N$ collisions.

A simple Sum Rule

Not only protons but also neutrons can be produced in $\gamma + N$ collisions. Then for different reaction mechanisms (i) following simple sum rule must be fulfilled:

$$\sigma_{\gamma A}^{(i)}(\omega) > \quad Z\left(\sigma_{\gamma p\to pX}^{(i)}(\omega) + \sigma_{\gamma p\to nX}^{(i)}(\omega)\right) + N\left(\sigma_{\gamma n\to nX}^{(i)}(\omega) + \sigma_{\gamma n\to pX}^{(i)}(\omega)\right) \,, \tag{18}$$

where i numerates individual processes. Since for the different distinct mechanisms the relative production of protons and neutrons is approximately known one can set upper limit on $\sigma_{AA\to p}(i)$. This estimation includes production of nucleon resonances and their decay. The maximal value of the cross section can be therefore lowered. This requires more detailed analyses. We shall discuss all three contributions one by one.

Quasi deuteron mechanism

We start from quasi-deuteron contributions. We assume the simplest form:

$$\sigma^{QD}_{\gamma A\to 1p}(\omega) = C_p \times \sigma^{QD}_{\gamma A}(\omega) \quad (19)$$

and fit C_p to the existing data (Heidelberg bremsstrahlung). We find $C_p \approx 0.3$. Then $\sigma^{QD}_{AA\to 1p} \approx 3.5$ b, much less than the ALICE result.

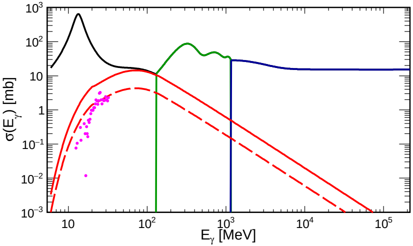


Figure: Cross section for $\gamma + {}^{208}\text{Pb} \to p$ and our simple fit result. The giant dipole resonance, quasi deuteron, nucleon resonances and partonic components are shown. The experimental points (Dahmen 1971).

Resonance region

Therefore we consider also the resonance region. A representative example of the reaction to be considered are:

$$\begin{aligned}
\gamma + p &\rightarrow \Delta^+ \rightarrow p\pi^0,\ P = |\langle \frac{3}{2}, \frac{1}{2} | \frac{1}{2}, \frac{1}{2}, 1, 0 \rangle|^2 = \frac{2}{3}\ , \\
\gamma + p &\rightarrow \Delta^+ \rightarrow n\pi^+,\ P = |\langle \frac{3}{2}, \frac{1}{2} | \frac{1}{2}, -\frac{1}{2}, 1, 1 \rangle|^2 = \frac{1}{3}\ , \\
\gamma + n &\rightarrow \Delta^0 \rightarrow n\pi^0,\ P = |\langle \frac{3}{2}, -\frac{1}{2} | \frac{1}{2}, -\frac{1}{2}, 1, 0 \rangle|^2 = \frac{2}{3}\ , \\
\gamma + n &\rightarrow \Delta^0 \rightarrow p\pi^-,\ P = |\langle \frac{3}{2}, -\frac{1}{2} | \frac{1}{2}, \frac{1}{2}, 1, -1 \rangle|^2 = \frac{1}{3}\ .
\end{aligned} \tag{20}$$

There are other nucleon resonances (not visible in γA collisions) and a few continuum contributions like:

$$\begin{aligned}
\gamma + p &\rightarrow \pi^0 + p, \\
\gamma + p &\rightarrow \pi^+ + n,
\end{aligned}$$

Resonance region

Another strongly populated final state is exclusive vector meson production V:

$$\begin{aligned} \gamma + p &\rightarrow V + p, \\ \gamma + n &\rightarrow V + n. \end{aligned} \qquad (22)$$

where $V = \rho^0, \omega, \phi, J/\psi$ [2]. The $\gamma N \rightarrow VN$ reactions can be successfully calculated either within Regge approach, within tensor-pomeron model or dipole model approach. However, the $\gamma N \rightarrow VN^*$ processes were not carefully studied within microscopic models, but they also lead to sizable production of protons or neutrons. The cross section for $\gamma + p \rightarrow \rho^0 + p$ only weakly depends on energy and is 100-200 μb. The corresponding contribution to $\gamma + A \rightarrow p$ is therefore about 0.8-1.6 mb, which constitutes sizable fraction of the $\gamma + A$ absorptive cross section. This inelastic cross section is of the same order of magnitude as $\gamma + A \rightarrow \rho^0 + A$.

[2] The p/n proportions there are different than for Δ resonances discussed above.

Resonance region

Our estimation here has advantage that it exhausts by construction the absorption cross section for processes on individual nucleons. For the sake of simplicity, assuming that the Δ resonances are representative for the whole "resonance" region, we write:

$$\sigma^{res}_{AA\to 1p} \approx \left(\frac{2}{3}\frac{Z}{A} + \frac{1}{3}\frac{N}{A}\right)\sigma^{res}_{AA} ,$$
$$\sigma^{res}_{AA\to 1n} \approx \left(\frac{1}{3}\frac{Z}{A} + \frac{2}{3}\frac{N}{A}\right)\sigma^{res}_{AA} . \tag{23}$$

We can see that even including the quasi-deuteron and resonance regions we are not able to understand the ALICE result for one proton emission.

Decomposition of the partonic component

Therefore we consider also the highest energy, “partonic”, component. The production of protons or neutrons is subjected to the mechanism of nucleon remnant fragmentation (see e.g. LEPTO). The HERA data on leading neutron and proton production in $\gamma^* p$ collisions showed that we did not fully understand the underlying physics before the HERA results. New mechanisms were proposed in 1990 (Holtmann, Szczurek, Nikolaev) Combining the conventional at that time and “new” mechanisms requires a hybrid approach for fixed target experiments (Szczurek et al.). Since in the current paper we are interested just in proton and neutron production, we should used here such a hybrid model.

Decomposition of the partonic component

We have to consider first elementary γp or γn cross sections. The partonic cross section on proton can be decomposed into a sum of three components, named for brevity diffractive, Sullivan and hadronization:

$$\begin{aligned} \sigma_{\gamma p \to p} &= \sigma^{diff}_{\gamma p \to p} + \sigma^{Sull.}_{\gamma p \to p} + \sigma^{hadr}_{\gamma p \to p} \,, \\ \sigma_{\gamma p \to n} &= \sigma^{diff}_{\gamma p \to n} + \sigma^{Sull.}_{\gamma p \to n} + \sigma^{hadr}_{\gamma p \to n} \,. \end{aligned} \tag{24}$$

In an analogous way for production for scattering on neutron:

$$\begin{aligned} \sigma_{\gamma n \to p} &= \sigma^{diff}_{\gamma n \to p} + \sigma^{Sull.}_{\gamma n \to p} + \sigma^{hadr}_{\gamma n \to p} \,, \\ \sigma_{\gamma n \to n} &= \sigma^{diff}_{\gamma n \to n} + \sigma^{Sull.}_{\gamma n \to n} + \sigma^{hadr}_{\gamma n \to n} \,. \end{aligned} \tag{25}$$

Diffractive component

The diffractive components can be estimated as:

$$\sigma^{diff}_{\gamma p \to p} \approx 0.1\ \sigma_{\gamma p \to p}\ ,$$
$$\sigma^{diff}_{\gamma n \to n} \approx 0.1\ \sigma_{\gamma n \to n}\ . \qquad (26)$$

This means:

$$\sigma^{diff}_{AA \to p} \approx \frac{Z}{A}\sigma^{part}_{AA}\ ,$$
$$\sigma^{diff}_{AA \to n} \approx \frac{N}{A}\sigma^{part}_{AA}\ . \qquad (27)$$

The remaining diffractive components for $p \to n$ and $n \to p$ are small and can be ignored in our simple estimation. For the so-called Sullivan processes [3] one has

$$\sigma^{Sull.}_{\gamma p \to p} = \sigma^{Sull.}_{\gamma n \to n} = 0.35\ \frac{1}{3}\sigma_{\gamma p \to p}\ ,$$
$$\sigma^{Sull.}_{\gamma p \to n} = \sigma^{Sull.}_{\gamma n \to p} = 0.35\ \frac{2}{3}\sigma_{\gamma p \to p}\ . \qquad (28)$$

Sullivan processes

Combining the results for UPC

$$\begin{aligned} \sigma^{Sull}_{AA\to p} &\approx \left(\frac{Z}{A}0.35\frac{2}{3}+\frac{N}{A}0.35\frac{1}{3}\right)\sigma^{part}_{AA} \;, \\ \sigma^{Sull}_{AA\to n} &\approx \left(\frac{Z}{A}0.35\frac{1}{3}+\frac{N}{A}0.35\frac{2}{3}\right)\sigma^{part}_{AA} \;. \end{aligned} \tag{29}$$

Hadronization component, summary

Assuming only light u, d quarks and antiquarks in p and n and $u(x) \propto d(x)$ (SU(2) symmetry of quark distributions) we get

$$\begin{aligned} \sigma_{\gamma n}^{hadr} &= \frac{2}{3}\sigma_{\gamma p}^{hadr} \quad , \\ \sigma_{\gamma n}^{hadr} &= \sigma_{\gamma p}^{hadr} \end{aligned} \qquad (30)$$

for valence and sea dominance, respectively. The contributions with $1p$ or $1n$ from that component is estimated as

$$\begin{aligned} \sigma_{\gamma p \to p}^{hadr} &= 0.7\ \sigma_{\gamma p}^{hadr} \ , \\ \sigma_{\gamma p \to n}^{hadr} &= 0.3\ \sigma_{\gamma p}^{hadr} \ , \\ \sigma_{\gamma n \to n}^{hadr} &= 0.7\ \sigma_{\gamma n}^{hadr} \ , \\ \sigma_{\gamma n \to p}^{hadr} &= 0.3\ \sigma_{\gamma n}^{hadr} \ . \end{aligned} \qquad (31)$$

Hadronization component

The hadronization component can be found by solving the set of Eq.(30) and

$$Z \cdot \sigma_{\gamma p}^{had} + N \cdot \sigma_{\gamma n}^{had} \approx \sigma_{\gamma A}^{had} \;, \tag{32}$$

where the hadronization component can be approximated as

$$\sigma_{\gamma A}^{hadr} \approx 0.55 \; \sigma_{\gamma A}^{part} \;. \tag{33}$$

No shadowing effects are included above. It would reduce somewhat our estimate.
Finally, we get for the hadronization component:

$$\begin{aligned} \sigma_{AA\to p}^{hadr} &= \left(\frac{Z}{A} 0.7 \cdot 0.55 + \frac{N}{A} 0.3 \cdot 0.55 \right) \sigma_{AA}^{part} \;, \\ \sigma_{AA\to n}^{hadr} &= \left(\frac{Z}{A} 0.3 \cdot 0.55 + \frac{N}{A} 0.7 \cdot 0.55 \right) \sigma_{AA}^{part} \;. \end{aligned} \tag{34}$$

Short summary of all regions

In our approach we assume that $p \to p$ and $p \to n$ transitions happened in 100 % and similarly for $n \to n$ and $n \to p$ transitions. At high energies one may expect a small energy dependent reduction (less than 5 %) due to hiperon production, which we neglect in the current estimation.

Finally, combining the different components, we get the following estimate:

$$\begin{aligned} \sigma_{AA \to 1p} &= 38\ b\ , \\ \sigma_{AA \to 1n} &= 44\ b\ . \end{aligned} \tag{35}$$

Different photon energy regions

Table: Maximal contributions of pre-equilibrium emission of p and n separately for different mechanisms (regions).

σ [b]	quasideuteron	nucl. resonances	partonic
proton	3.786	18.269	15.561
neutron	3.786	21.041	18.729

One can see that the biggest contributions come from the resonance and partonic regions. Not all models on the market include the partonic contributions. We note that it is impossible to describe the ALICE data for proton production without this high-energy component.

Protons from Hauser-Feshbach approach

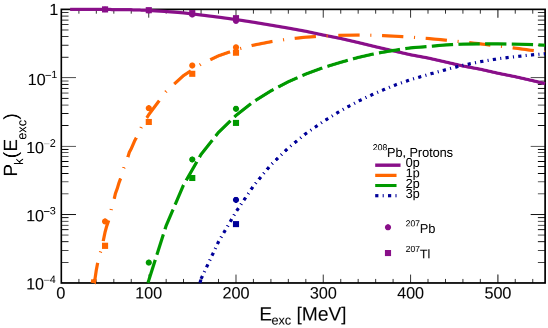


Figure: Probability of emission of 1p, 2p, 3p as a function of excitation energy calculated within GEMINI++ approach for ^{208}Pb (lines). The circles are for initial ^{207}Pb and squares for initial ^{207}Tl.

Short summary of neutron emission

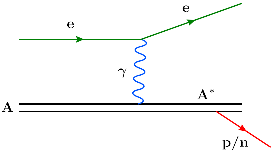
In order to understand neutron and proton emissions by the nucleus excited in UPC one has to understand well:

- Photon induced intranuclear cascade in a broad range of photon energy.
- Preequilibrium emissions is also very important.
- The latter lead to initial conditions for equilibrium emission (GEMINI++ in our case).
- Multipole photon exchanges give extra contributions of the order of 10 % for $n = 3, 4, 5$.

Preequilibrium, etc.

- ZDC results allow testing microscopic models of preequilibrium.
- No microscopic model can explain proton multiplicities.
- GiBUU microscopic model predicts many neutrons and protons in the preequilibrium phase.
- Proton ZDC measures huge cross section for one proton emission.
- We have estimated maximal cross sections for 1p and 1n emission from reactions on nucleus constituents (quasi-deuteron, nucleon resonances, reactions on partons in protons and neutrons).
- The cross section is very close to the 1p cross section measured by the ALICE collaboration
- Different reaction mechanisms participate. High-energy component seems very important !

Nucleon emission in e+A collisions at EIC



The cross section for p or n emission from the nucleus: (schematically)

$$\sigma(eA \to e'A^* \to p,n) = \int d\omega_e dQ^2 \frac{d^2N}{d\omega_e dQ^2} \sigma(\gamma^* A \to A^* \to p.n) \tag{36}$$

where the photon flux reads:

$$\frac{d^2N}{d\omega_e dQ^2} = \frac{\alpha_{em}}{\pi \omega_e Q^2} \left((1 - \frac{\omega_e}{E_e})(1 - \frac{Q^2_{min}}{Q^2}) + \frac{\omega_e^2}{2E_e^2} \right) . \tag{37}$$

Nucleon emission in e+A collisions at EIC

Above:

$$\begin{aligned} Q^2_{min} &= m_e^2\omega_e^2/[E_e(E_e-\omega_e)]\ , \\ Q^2_{max} &= 4E_e(E_e-\omega_e)\ . \end{aligned}$$

ω_e is energy in laboratory frame
$E_{exc} = \omega_A$ is photon energy with respect to the nucleus.
$\omega_A > \omega_e$

Two options to be studied:
(a) untagged case ($Q^2 \approx 0$, as for UPC) ;,
(b) tagged case ($Q^2 > 0$, new) ;.