PRODUCTION OF NEUTRONS AND PROTONS FROM NUCLEI EXCITED IN UPC*

Paweł Jucha [a], Katarzyna Mazurek [a]
Mariola Kłusek-Gawenda [a], Antoni Szczurek [a,b]

[a]Institute of Nuclear Physics Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland
[b]Institute of Physics, Faculty of Exact and Technical Sciences
University of Rzeszów, Pigonia 1, 35-310 Rzeszów, Poland

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The strong electromagnetic field induced by a nucleus moving with relativistic velocity in ultraperipheral collisions is a source of the quasireal photons, which can be absorbed by the partner nucleus and excite it. This leads to the evaporation of particles such as neutrons, protons, and alpha particles. In our recent work, we applied the Equivalent Photon Approximation to calculate the cross sections for evaporation of given multiplicities of particles. We tested different statistical nuclear models, such as GEMINI++ and HIPSE, to define the probability functions. We also suggested a new, phenomenological approach for the estimation of excitation energy called the Two Component Model. The results were compared with recent ALICE data obtained with the neutron and proton Zero Degree Calorimeters.

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1. Introduction

The ultraperipheral collisions of relativistic heavy ions allow us to observe the electromagnetic (EM) processes such as the fusion of photons and photon-induced Coulomb excitation of the nucleus. The excited nucleus emits photons, neutrons and protons. This effect was discussed in the context of the beam lifetime at LHC [1]. The emitted particles have a high boost in the z-direction. The development of Zero Degree Calorimeters (ZDC) allows for the measurement of these particles [2, 3].

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In this paper, some details of the phenomenological approach used to describe particle emission from EM-excited nuclei are discussed. To calculate the cross section for particle emission, we use a hybrid model, where photon production is estimated in the Equivalent Photon Approximation (EPA), and the excitation energy of the nucleus comes from HIPSE [4] or Two Component Model (TCM). The de-excitation is done with GEMINI++ [5] statistical code. The results of our model [6] are presented and compared with data collected by the ALICE experiment in recent years.

2. Calculations

The Equivalent Photon Approximation formalism assumes that the longitudinal component of the electromagnetic field vanishes if the source of that field has a relativistic velocity. This assumption allows us to describe the electromagnetic fields as the photon flux

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

Above, ω is the photon energy and b is the transverse distance of photons from the emitting nucleus. In this paper, ω and E_γ are used alternatively. The electromagnetic form factor of the nucleus $F(\frac{\chi^2+u^2}{b^2})$ depends on $u = \frac{\omega b}{\gamma_{\mathrm{CM}}\beta}$, $\gamma_{\mathrm{CM}} = \frac{1+\beta^2}{1-\beta^2}$, and $\chi = k_\perp b$. The form factor is calculated as a Fourier transform of the nucleus charge density. In general, the nucleus may absorb more than one photon. Here, we present results for absorption up to four photons. Figure 1 shows the scheme of multiphoton absorption.

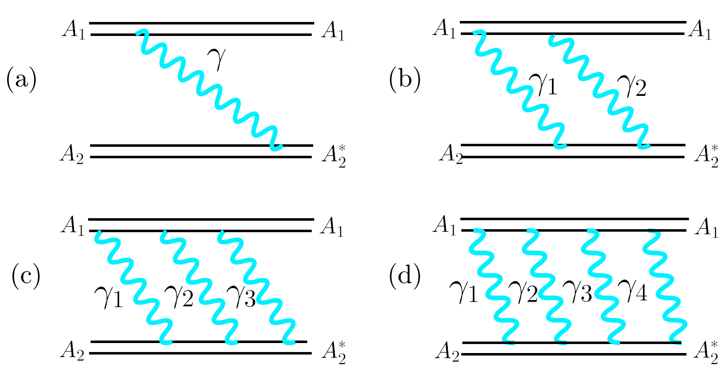

Fig. 1. Photon absorption by the single nucleus (A_2). In panel (a) one-photon absorption (LO), (b) two-photon absorption (NLO), (c) three-photon absorption (NLO_2), and (d) four-photon absorption (NLO_3) [6].

The quasi-real photon is absorbed by the nucleus via different mechanisms, which depend on the photon energy. This observation is important because the excitation energy in UPC may vary together with the photon energy. In our first approach presented in [7], we tested the statistical GEMINI++ model [5], and we assumed $E_\gamma = E_{\mathrm{exc}}$. This assumption seems correct for 1- and 2-neutron emission, where the photon energy is relatively small and the Giant Dipole Resonance mechanism is dominant. However, for photons energy larger than 20 MeV, the Quasi Deutron mechanisms play an important role. We propose a phenomenological approach, called TCM, to describe the difference in energies. We correct the probability function of k-particle (neutrons or protons) emission from the nucleus as follows:

$$P_k\left(E_\gamma\right) = \exp\left(-\frac{E_\gamma}{E_0}\right)\delta\left(E_{\mathrm{exc}} - E_\gamma\right) + \left[1 - \exp\left(-\frac{E_\gamma}{E_0}\right)\right]\frac{1}{E_\gamma}\,, \qquad (2)$$

with one free parameter E_0. We tested different E_0 parameters in a range between 30 MeV and 70 MeV, in plots (Figs. 2, 3) marked by gray area. The final parameter used in our further calculation is 50 MeV. Figure 2 (a) shows the dependence of excitation energy on photon energy with different models. We also tested the HIPSE model, which simulates the behavior of an excited nucleus before reaching the thermal equilibrium.

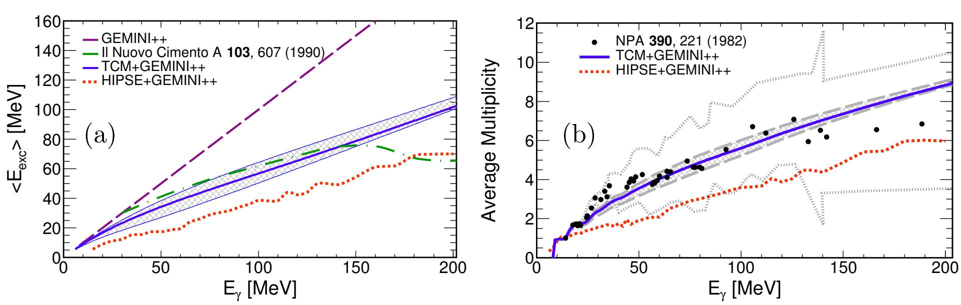

Fig. 2. (a) The excitation energy as a function of photon energy. The purple dashed line is from GEMINI++, the blue line depicts TCM+GEMINI++ with shadow area due to different values of E_0 from 30 to 70 MeV, and the red dotted line stands for HIPSE+GEMINI++. The green line is a result from [8]; (b) The mean neutron multiplicity: experimental [9] (black points), and estimated with TCM (blue) and HIPSE (red) models. The gray dotted lines show the experimental uncertainty [6].

The proposed modification of the probability function had a positive impact on the average multiplicity of produced neutrons, as shown in Fig. 2 (b). The cross sections for the emission of k neutrons have also improved. Figure 3 presents the cross sections obtained using different models and shows a comparison with experimental data from [10, 11].

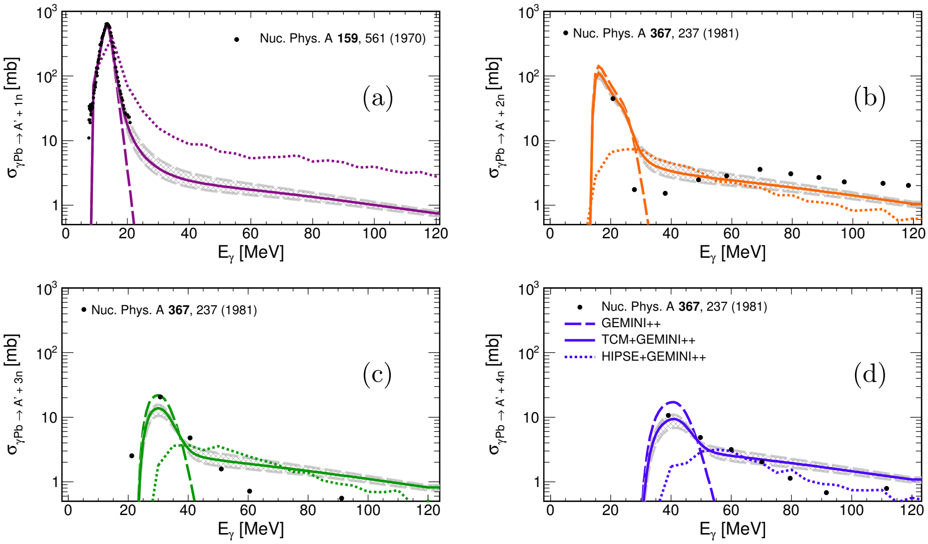

Fig. 3. The cross section for the $\gamma + {}^{208}\mathrm{Pb} \to kn + X$ reaction, where displayed are neutron multiplicities: $k = 1$ (a), $k = 2$ (b), $k = 3$ (c), and $k = 4$ (d). We compare the results of experimental data from Refs. [10, 11] (dots) with model calculations: pure GEMINI++ (dashed line), TCM+GEMINI++ (solid line), HIPSE+GEMINI++ (dotted line). The gray area shows the influence of the TCM E_0 parameter ($E_0 \in (30, 70)$ MeV) on the cross section.

To calculate the final cross section for the emission of particles, with the absorption of a given number of photons j, we combine the photon flux, photoabsorption cross section ($\sigma_{\mathrm{abs}}(\omega)$), and probability functions and integrate them over the photon energy and impact parameter

$$\sigma_{A_1 A_2 \xrightarrow{j\gamma} X_1 X_2 + kn} = \int \mathrm{d}\,\omega_1 \cdots \int \mathrm{d}\,\omega_j \int 2\pi b\, \mathrm{d}\, b\, \frac{\mathrm{e}^{-m(b)}}{j!} \tag{3}$$

$$\times \left(\prod_{i=1}^{j} N(\omega_i, b)\sigma_{\mathrm{abs}}(\omega_i) \right) P_k \left(\Sigma_i^j(\omega_i) \right) . \tag{4}$$

Here, the weight factor $\frac{\mathrm{e}^{-m(b)}}{j!}$ enables avoiding double counting. This factor depends on the mean number of absorbed photons calculated as

$$m(b) = \int \mathrm{d}\,\omega\, N(\omega, b)\sigma_{\mathrm{abs}}(\omega)\,. \tag{5}$$

In Fig. 4, the neutron emission cross section as a function of photon energy is displayed. We have also calculated the proton emission cross section, including the TCM+GEMINI++ model. The results are presented in Table 1.

One can see that the estimation of the neutron evaporation obtained in our models describes the experimental data. However, for the proton emission, further tests of our approach are necessary. In particular, the inclusive proton emission cross sections differ from the ALICE data by a factor of 2. Some preliminary results on proton emission are included in [12].

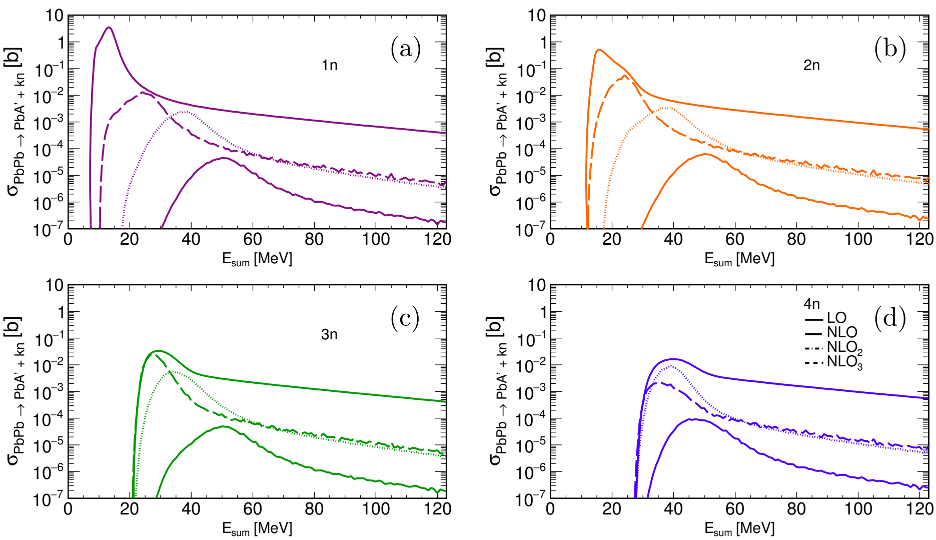

Fig. 4. Distribution in the sum of excitation energy for a given number of exchanged photons for fixed multiplicities: (a) 1 neutron, (b) 2 neutrons, (c) 3 neutrons, and (d) 4 neutrons.

Table 1. Total cross sections (in barn) for a charged particle emission in UPC ^{208}Pb+^{208}Pb with collision energy $\sqrt{s_{NN}} = 5.02$ TeV. The cross section for exclusive channels of $1p1n$, $1p2n$, and $1p3n$ and also inclusive channel $1pXn$ are compared with the ALICE data [2, 3].

	σ [b]							
Model	$1n$	$2n$	$3n$	$4n$	$1p1n$	$1p2n$	$1p3n$	$1pXn$
GEM.	90.37	24.91	3.33	2.36	0	0	0	19.56
TCM+GEM.	99.80	26.60	6.70	6.82	0.66	0.92	0.72	16.72
HIPSE+GEM.	124.1	15.68	4.88	3.65	9.86	0.82	0.93	28.48
ALICE exp.	108.4	25.0	7.95	5.65	1.05	1.35	1.58	40.4

3. Conclusion

To describe the cross section for the neutron emission from an excited nucleus in UPC collisions of lead ions, we have used the Equivalent Photon Approximation combined with low-energy nuclear physics models. The cross section for the emission of 3–4 neutrons cannot be explained by purely statistical evaporation, assuming that the full photon energy is transformed into internal energy of the nucleus. This motivated us to propose a phenomenological Two Component Model which takes into account the energy difference between the excitation energy of thermal equilibrium and the energy of the photon. We have also applied our TCM model to the proton emission and compared our results with the recent ALICE data.

REFERENCES

[1] A.J. Baltz, M.J. Rhoades-Brown, J. Weneser, *Phys. Rev. E* **54**, 4233 (1996).
[2] ALICE Collaboration (S. Acharya *et al.*), *Phys. Rev. C* **107**, 064902 (2023).
[3] ALICE Collaboration (S. Acharya *et al.*), *Phys. Rev. C* **111**, 054906 (2025).
[4] D. Lacroix, A. Van Lauwe, D. Durand, *Phys. Rev. C* **69**, 054604 (2004).
[5] R.J. Charity, *Phys. Rev. C* **82**, 014610 (2010).
[6] P. Jucha *et al.*, *Phys. Rev. C* **111**, 034901 (2025).
[7] M. Kłusek-Gawenda, M. Ciemala, W. Schäfer, A. Szczurek, *Phys. Rev. C* **89**, 054907 (2014).
[8] C. Guaraldo *et al.*, *Nuovo Cim. A* **103**, 607 (1990).
[9] A. Leprêtre *et al.*, *Nucl. Phys. A* **390**, 221 (1982).
[10] A. Veyssiere *et al.*, *Nucl. Phys. A* **159**, 561 (1970).
[11] A. Leprêtre *et al.*, *Nucl. Phys. A* **367**, 237 (1981).
[12] P. Jucha *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **18**, 2-A44 (2025).