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Neutron emission from the photon-induced reactions in UPC of heavy ions - impact of new ALICE data

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Abstract. We calculate the cross section for the production of a given number of neutrons in UPC of $^{208}Pb + ^{208}Pb$. A simple model which takes into account the fact that only a part of the energy is available in the thermalized phase, proposed recently, is discussed. The results of the model calculation are compared with recent neutron ZDC ALICE measurements. The role of multiple photon exchanges is discussed.

1 Introduction

There is a growing interest in ultraperipheral heavy ion collisions (UPCs) at RHIC and LHC. The processes that fulfill these categories can be divided into:
(a) photon-photon fusion (e.g. l^+l^-, M_1M_2, dijets or $\gamma\gamma$),
(b) photoproduction (e.g. production of vector mesons: ρ^0, ϕ, J/ψ).
UPCs considered usually have a simple final state in the measured midrapidity region. A very forward/backward region is typically not investiagted since it is quite challenging to measure. However, experimentally, one has Zero Degree Calorimeters (ZDC) that can be utilized. ALICE ZDCs can measure both: neutrons and protons. Any extra photon exchange leads to associated nucleus excitation. An excited nucleus may emit: neutrons, protons, alpha particles or photons. In principle, may even go to fission or fragmentation. The Lorentz boost causes that particles are emitted very forward/backward. In general, even Coulomb excitations alone (no midrapidity production) are possible and interesting. They lead to a damping of the beams at the LHC. Neutron emission happens very frequently and it can be easily measured with the help of ZDCs. Recently, the ALICE collaboration also measured protons [1]. Also simultaneous measurement of neutrons and protons is possible.

There exist a few models that treat excitation and deexcitation in photoproduction on nuclei. They were discussed in short in the presentation (for more details see [2]) and there is no place to present them here.

Recently, the ALICE collaboration performed a measurement of cross sections for a given number of neutrons in ZDCs [3]. A simplified physical picture of the process is illustrated in Fig. 1.

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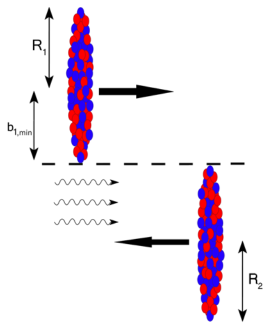

Figure 1. A sketch of excitation of a nucleus in UPC.

2 A sketch of formalism

Here, we only sketch a simple model which was presented recently in [2]. To calculate the cross sections for Coulomb excitation [2] we used the photon flux obtained using a realistic charge form factor

$$F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \cdot \sin(|\mathbf{q}|r) \cdot r dr \ .$$

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

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

for $E_{exc} < E_\gamma$, i.e. uniform population in excitation energy.

In our model the distribution of excitation energy of a nucleus caused by a photon with energy E_γ is

$$P(E_{exc}; E_\gamma) = c_1(E_\gamma)\delta\left(E_{exc} - E_\gamma\right) + c_2(E_\gamma)/E_\gamma \ . \tag{2}$$

The probabilistic interpretation requires:

$$c_1(E_\gamma) + c_2(E_\gamma) = 1 \ . \tag{3}$$

Overall, c_1 and c_2 may depend on the photon energy E_γ. As a trial function for further analysis, we propose

$$c_1(E_\gamma) = \exp\left(-E_\gamma/E_0\right) \ , \qquad c_2(E_\gamma) = 1 - \exp\left(-E_\gamma/E_0\right) \ . \tag{4}$$

The parameter E_0 was adjusted in [2] to the ALICE data.

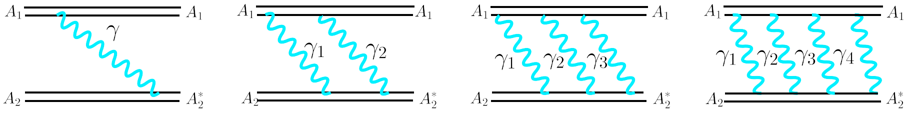

Figure 2. Excitation of the nucleus by exchange of 1, 2, 3, 4 photons.

In Fig. 2 we show diagrams of the exchange of 1, 2, 3, 4 photons which lead to the excitation of the nucleus. One photon exchange is the dominant mechanism, but multiple photon exchanges also play some role. In [2] we also discussed mechanisms of mutual excitations.

3 Results

In Fig. 3 we show the cross section for the $\gamma +^{208} Pb \rightarrow A^* + kn$ reaction, where k = 1,2,3,4,5 is the number of emitted neutrons. Different combinations of models were used [2]. The statistical model approach as implemented in the Monte Carlo code GEMINI++ [4] assuming $E_{exc} = E_\gamma$, gives a strength concentrated at some values growing systematically with k. The proposed in [2] the two-component model (TCM) generates, in addition, long tails extending towards larger E_γ. These tails seem to be consistent with old Saclay data [5].

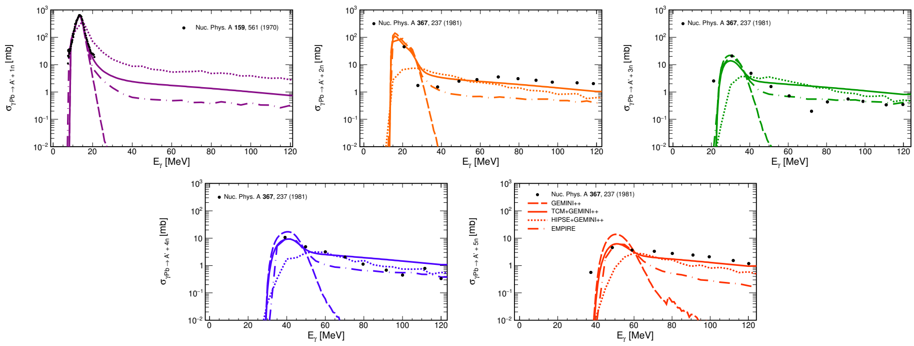

Figure 3. The cross section for the $\gamma +^{208} Pb \rightarrow A^* + kn$. We show results of different approaches together with experimental data from [5].

The cross section for a given number of neutrons for different upper limit on maximal photon energy is shown in Fig. 4 (a). Both low and high energies give significant contributions. We see that the larger neutron multiplicity the larger photon energies must be included in the calculation.

In [2] we discussed and estimated the role of multiple photon exchanges. They change the cross section at the level of 10 %. In Fig. 4 (b) we summarize our result. Here, the cross section for different neutron multiplicities is displayed. One can see that the TCM much

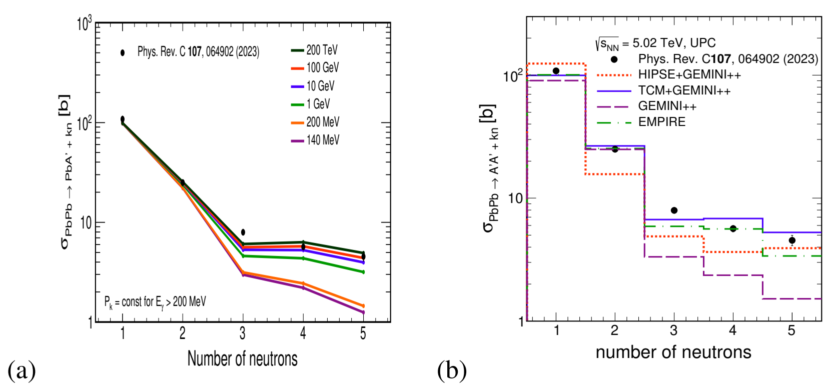

Figure 4. (a) Cross section for emission of k neutrons for different upper limit for photon energy. (b) The cross section for a given number of neutrons in ZDC from the approach presented in [2] compared to the ALICE experimental data [3].

better reproduces higher multiplicities compared to the pure GEMINI++ with $E_{exc} = E_\gamma$ assumption.

Table 1. Total cross section in barn at $\sqrt{s_{NN}} = 5.02$ TeV for charged particle emission.

	1p1n	1p2n	1p3n	1pXn	1dXn	1αXn
GEMINI++	0	0	0	19.56	6.91	30.66
TCM+GEMINI++	0.66	0.92	0.72	16.72	11.42	15.47
HIPSE+GEMINI++	9.86	0.82	0.93	28.48	64.02	42.38
EMPIRE	2.43	2.81	0.23	7.06	2.65	0.28
ALICE experiment	1.05	1.35	1.58	40.4	-	-

Very recently, the ALICE collaboration released new results using also so-called proton ZDCs [1]. In Table 1 we present cross sections for a proton registered in a proton ZDC with a given number of neutrons in a neutron ZDC. Shown are the results obtained from different models. The agreement with the ALICE data [1] is not satisfactory. More microscopic models/approaches will be investigated by us in the near future.

4 Conclusions

The following conclusions relevant to future studies were drawn from our recent analysis. In order to understand neutron and proton emissions by the nucleus excited in UPCs one has to understand well:

- Photon-induced intranuclear cascade in a broad range of photon energies. Preequilibrium emissions seem to be very important ingredient.
- The latter leads to initial conditions for equilibrium emission (GEMINI++ in our case).
- Multipole photon exchanges give extra contributions of the order of 10 % for a number of neutrons $k = 3, 4, 5$ (see [2]).

In the work presented at the QM2025, we discussed only neutron emission, and no activity in the main detector. Very recently (after QM2025), we have presented predictions for light-by-light scattering associated with neutron activity in ZDCs [6].

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