Nuclear $\gamma$-radiation as a Signature of Ultra Peripheral Ion Collisions at LHC energies

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Abstract

We study the peripheral ion collisions at LHC energies in which a nucleus is excited to the discrete state and then emits $\gamma$-rays. Large nuclear Lorenz factor allows to observe the high energy photons up to a few ten GeV and in the region of angles of a few hundred micro-radians around the beam direction. These photons can be used for tagging the events with particle production in the central rapidity region in the ultra-peripheral collisions. For that it is necessary to have an electromagnetic detector in front of the zero degree calorimeter in the LHC experiments.

Introduction

There are several reviews devoted to the coherent $\gamma\gamma$ and $\gamma g$ interactions in the very peripheral collisions at relativistic ion collides ([1],[2],[3]). The advantage of relativistic heavy ion colliders is that the effective photon luminosity for two-photon physics is of orders of magnitude higher than the one at available the $e^+e^-$ machines. There are many suggestions to use the electromagnetic interactions of nuclei to study production of meson resonances, Higgs boson, Radion scalar or exotic mesons. These interactions allow also to study fermion, vector meson or boson pair production, as well as to investigate a few new physic regions (see list in [3]). The $\gamma g$ interactions will open a new page of nuclear physics such as a study of nuclear gluon distribution. It is also important for a knowledge of the details of medium effects in nuclear matter at the formation of quark-gluon plasma [4]. These effects may be studied by photo-production of heavy quarks in virtual photon-gluon interactions ([5],[6],[4]).

For these investigations it is necessary to select the processes with large impact parameters $b$ of colliding nuclei, $b > (R_1 + R_2)$, to exclude background from strong interactions. Note, that some processes, like $\gamma\gamma$-fusion...
to Higgs boson or Radion scalar, are free from any problems caused by strong interactions of the initial state [7]. Therefore we need an efficient trigger to distinguish $\gamma\gamma$ and $\gamma g$ interactions from others. G.Baur et al. [8] suggested to measure the intact nuclei after the interaction. Evidently this is impossible in the LHC experiments since the nuclei fly into the beam pipe.

It is interesting to consider a $\gamma$ rays emitted by the relativistic nuclei at LHC energies. Such kind of process was used for the possible explanation of the high energy ($E_\gamma \geq 10^{12}$ eV) cosmic photon spectrum [9].

It was suggested to measure a nuclear $\gamma$ radiation after the excitation of discrete nuclear level in our work [10]. These secondary photons have the energy of a few GeV and the narrow angular distribution near the beam direction due to a large Lorentz boost. The angular width is enough to register them in the electromagnetic zero-degree detectors of the future LHC experiments CMS or ALICE. A nucleus saves its $Z$ and $A$ in this process. So we have a clear electromagnetic interaction of nuclei at any impact parameter. The nuclear $\gamma$ radiation may be used as “event-by-event” criteria for such kind of collisions.

We have considered [10] only the process $A + A \rightarrow A^* + A + e^+e^-, A^* \rightarrow A + \gamma'$, where a nucleus is excited by electron (positron) $e^\pm + A \rightarrow e^\pm' + A^*$. Now we calculate the production process of some system $X_f$ in $\gamma\gamma$ fusion with simultaneous excitation of discrete nuclear level.

In this work we consider the processes

$$16^O + 16^O \rightarrow 16^O + 16^O (2^+, 6.92 \text{ MeV}) + X_f, 16^O \rightarrow 16^O + \gamma,$$

$$208^Pb + 208^Pb \rightarrow 208^Pb + 208^Pb (3^-, 2.62 \text{ MeV}) + X_f, 208^Pb \rightarrow 208^Pb + \gamma,$$

where the $16^O$ and $208^Pb$ were taken since they are the lightest and heaviest ions in the ion list of the LHC program. The trigger requirements will include a signal in the central rapidity region of particles from $X_f$ decay, a signal of photons in the electromagnetic detector in front of the zero degree calorimeter and a veto signal of neutrons in ZDC. We suggest to use the veto signal of neutrons in order to avoid the processes with the nuclear decay into nucleon fragments.

The formalism of the considered process is presented in the section 1. The nuclear form factors are calculated in the section 2. The angular and energy distributions of secondary photons are in the section 3. The cross sections of $\eta_c(2.979 \text{ GeV})$ production are presented in the part 6 with and without nuclear excitation. The section 6 is our conclusion.
1 Formulae of nuclear excitation cross-section and photon luminosity in peripheral interactions

Let us consider the peripheral ion collision

\[ A_1 + A_2 \rightarrow A_1^*(\lambda^P, E_0) + A_2 + X_f, \]  

where \( X_f \) is the produced system in \( \gamma^*\gamma^* \) fusion and \( A_1^* \) is an excited nucleus in a discrete nuclear level with spin-parity \( \lambda^P \) and energy \( E_0 \) (see Fig.1). Here the nucleus \( A_1 \) and \( A_2 \) have equal mass \( A \) and charge \( Z \), the only nucleus \( A_1 \) is excited. We suppose that the particles of \( X_f \) decay can be registered in the central rapidity region. The nuclear \( \gamma' \) radiation \( (A_1^* \rightarrow A_1 + \gamma') \) will be measured in the forward detectors such as ZDC.

![Diagram of the process](image)

Figure 1: Diagram of the process \( A_1 + A_2 \rightarrow A_1^*(\lambda^P, E_0) + A_2 + X_f \), \( A_1^* \rightarrow A_1 + \gamma \).

We use the quantum mechanical plane wave formalism ([11], [3]) and the derivation of the equivalent photon approximation. It allows us to introduce the elastic and inelastic nuclear form factors for the process (1). We take the formulae (19) and (21) in [3]:

\[ d\sigma_{A_1A_2\rightarrow A_1'A_2X_f} = \int \frac{dw_1}{w_1} \int \frac{dw_2}{w_2} n_1(w_1)n_2(w_2)d\sigma_{\gamma\gamma\rightarrow X_f}(w_1, w_2), \]  

\[ n_i(w_i) = \frac{\alpha}{\pi^2} \int d^2q_{i\perp} \int dv_i \frac{1}{(q_i^2)^2} \left[ 2 \frac{w_i^2m_i^2}{P_i^2} W_{i,1} + q_i^2 W_{i,2} \right], \]

where \( W_{i,1} \) and \( W_{i,2} \) are the Lorentz scalar functions. All kinematic variables are the same as in [3].

For “elastic” photon process \( A_1A_2 \rightarrow A_1A_2X_f \) we have

\[ W_1 = 0, \quad W_2(\nu, q^2) = Z^2F_{el}^2(-q^2)\delta(\nu + q^2/2m) \]
\[ n(w) = \frac{Z^2 \alpha}{\pi^2} \int d^2q_\perp \frac{q_\perp^2}{(q_\perp^2)^2} F_{el}^2(-q_\perp^2), \] (5)

where \( F_{el}(q) \) is the nuclear form-factor with \( F_{el}(0) = 1 \).

For the excitation of nucleus to a discrete state with a spin \( \lambda \) and an energy \( E_0 \) (“inelastic” photon process \( A_1 A_2 \rightarrow A_1^* (\lambda^P, E_0) A_2 X_f \))

\[
\begin{align*}
W_{1,2}(\nu, q^2) &= \hat{W}_{1,2}(q^2) \delta(\nu - E_0), \\
-q^2 &= \frac{w^2}{\gamma^2} + 2 \frac{wE_0}{\gamma} + \frac{E_0^2}{\gamma^2} + q_\perp^2 = q_L^2(w) + q_\perp^2, \\
\hat{W}_1 &= 2\pi[|T^e|^2 + |T^m|^2], \\
\hat{W}_2 &= 2\pi \frac{q^4}{(E_0^2 - q^2)^2} \left[ 2|M^e|^2 - \frac{E_0^2 - q^2}{q^2} (|T^e|^2 + |T^m|^2) \right].
\end{align*}
\] (6)

See notations again in \[3\].

We neglect the transverse electric \( T^e \) and transverse magnetic \( T^m \) matrix elements comparing with the Coulomb one \( M^e = M_\lambda \) for \( 0^+ \rightarrow \lambda^P \) nuclear transitions. Then for the inelastic photon process with a nuclear discrete state excitation we get

\[
n_1^{(\lambda)}(w) = \frac{4\alpha}{\pi} \int d^2q_\perp \frac{q_\perp^2}{(E_0^2 - q^2)^2}|M_\lambda(q)|^2, \] (7)

where \( M_\lambda(q) \) is the inelastic nuclear form-factor.

The equivalent photon number (7) can be represented as the function of \( q_\perp \) for inelastic photon emission:

\[
\frac{dN_1^{(\lambda)}}{dq_\perp^2}(w_1, q_\perp) = \frac{4\alpha}{\pi} \frac{q_\perp^2}{(E_0^2 - q^2)^2}|M_\lambda(-q^2)|^2 = \]

\[
= \frac{4\alpha}{\pi} \frac{q_\perp}{(E_0^2 - q^2)} M_\lambda(-q^2) e^{i\varphi_\perp} \]

where \( q_\perp e^{i\varphi_\perp} = q_\perp^2 \) (see \[12\]).

Let us do the inverse transformation to the impact parameter \( b \) presentation

\[
f(\vec{b}) = \frac{1}{2\pi} \int d^2q_\perp e^{-i\vec{q}_\perp \cdot \vec{b}} f(q_\perp). \] (9)

For the function under the module in equation (8) we get

\[
f(\vec{b}) = \frac{1}{2\pi} \int d^2q_\perp \frac{q_\perp}{(E_0^2 - q^2)} M_\lambda(-q^2) e^{i\varphi_\perp} \cdot e^{-i\vec{q}_\perp \cdot \vec{b}} = \]

\[
i \int dq_\perp \frac{q_\perp}{(E_0^2 - q^2)} M_\lambda(-q^2) \cdot J_1(q_\perp b) = \]

\[
i \int du \frac{u^2}{u^2 + (E_0^2 + q_\perp^2) b^2} M_\lambda \left( -\frac{x^2 + u^2}{b^2} \right) J_1(u). \] (10)
If we take $M_{el}$ instead of the inelastic $M_\lambda$ as

$$ |M_{el}(-q^2)|^2 = \frac{Z^2}{4\pi} F_{el}^2(-q^2) $$

we get a well-known formula for elastic photon process (see (4) in [12]) where $F_{el}(0) = 1$:

$$ N_{el}^2(w, b) = \frac{Z^2\alpha}{\pi^2} \frac{1}{b^2} \int du \frac{u^2}{x^2 + u^2} J_1(u) F_{el}[-(x^2 + u^2)/b^2]^2, $$

(12)

for a point charge, $F_{el}(q) \equiv 1$, we readily obtain

$$ N_{el}^2(w, b) = \frac{Z^2\alpha}{\pi^2} \frac{1}{b^2} x^2 K_1^2(x), $$

(13)

in agreement with [3] at very large $\gamma_A$.

We write the form factors of elastic and inelastic nuclear process in the same forms:

$$ F_0^2(q) = \frac{1}{4\pi e^2 Z^2} F_{el}^2(q) $$

(14)

$$ F_0^2(q) = \left|4\pi \frac{1}{q} \int \sin(qr) \rho_0(r) r dr\right|^2 \rightarrow 1, $$

(15)

$$ F_\lambda^2(q) = (2\lambda + 1) \left|4\pi \int j_\lambda(qr) \rho_\lambda(r, Z) r^2 dr\right|^2 \rightarrow $$

(16)

$$ \rightarrow \frac{(4\pi)^2 B(E\lambda)}{e^2 Z^2[(2\lambda + 1)!!]^2} q^2 \lambda, $$

(17)

where $\rho_\lambda(r, Z)$ is an nuclear transition density and $B(E_0\lambda)$ is the reduced transition probability.

Then for the matrix elements $M_\lambda$ we get in the limit $q \rightarrow 0$

$$ |M_{el}(-q^2)|^2 = \left(\frac{Z^2}{4\pi}\right) F_{el}^2(q) \bigg|_{q \rightarrow 0} \rightarrow \frac{Z^2}{4\pi} $$

(18)

$$ |M_\lambda(-q^2)|^2 = \left(\frac{Z^2}{4\pi}\right) F_\lambda^2(q) \bigg|_{q \rightarrow 0} \rightarrow \frac{Z^2}{4\pi} \frac{(4\pi)^2 B(E_0\lambda)}{e^2 Z^2[(2\lambda + 1)!!]^2} q^2 \lambda. $$

(19)

The effective photon number for inelastic process with nuclear transition $0 \rightarrow \lambda$ will be

$$ N_{1}^{(\lambda)}(w, b) = \frac{Z^2\alpha}{\pi^2} \frac{1}{b^2} \int_0^\infty du \frac{u^2}{x_{in}^2 + u^2} J_1(u) F_\lambda[-(x_{in}^2 + u^2)/b^2]^2, $$

(20)
as the generalization of (12). Here $x_{in}^2 = \left( E_0^2 + \frac{w^2}{\gamma_A^2} + 2 \frac{w E_0}{\gamma_A} + \frac{E_0^2}{\gamma_A^2} \right) b^2$.

We take the inelastic form-factor from inelastic electron scattering off nuclei. A good parameterization of inelastic form-factor is

$$F_\lambda^2(q) = 4\pi \beta_\lambda^2 j_\lambda^2(q R)e^{-q^2 g^2} \quad (21)$$

in the Helm’s model [13]. The squared transition radius is equal to $R_\lambda^2 = R^2 + (2\lambda + 3)g^2$, where $g$ is a size of a nuclear diffusion side.

The reduced transition probability in this case is equal to

$$B(E_0\lambda) = \frac{\beta_\lambda^2}{4\pi} Z^2 e^2 R^{2\lambda}. \quad (22)$$

So, the formulae for the process (1) are

$$d\sigma_{A_1 A_2 \rightarrow A_1^* A_2 X_f} = \int \frac{dw_1}{w_1} \int \frac{dw_2}{w_2} n_1^{(\lambda)}(w_1) n_2(w_2) d\sigma_{\gamma\gamma \rightarrow X_f}(w_1, w_2); \quad (23)$$

$$n_1^{(\lambda)}(w_1) = \frac{Z^2 \alpha}{\pi^2} \int d^2 q_\perp \frac{q_\perp^2}{(E_0^2 - q_{in}^2)^2} |F_\lambda(-q_{in}^2)|^2; \quad (24)$$

$$-q_{in}^2 = \frac{w^2}{\gamma_A^2} + 2 \frac{w E_0}{\gamma_A} + \frac{E_0^2}{\gamma_A^2} + q_\perp^2; \quad (25)$$

$$n_2(w_2) = \frac{Z^2 \alpha}{\pi^2} \int d^2 q_\perp \frac{q_\perp^2}{q_{el}^4} F_{el}(\frac{-q_{el}^2}{q_{el}^2}); \quad (26)$$

$$-q_{el}^2 = \left( \frac{w}{\gamma_A} \right)^2 + q_\perp^2. \quad (27)$$

The value $q_{in}^2$ is close to $q_{el}^2$ at a large $\gamma_A$ factor at LHC energies.

The effective two photon luminosity can be expressed as

$$L(\omega_1, \omega_2) = 2\pi \int_{R_1}^{\infty} b_1 db_1 \int_{R_2}^{\infty} b_2 db_2 \int_0^{2\pi} d\phi N_1^{(\lambda)}(\omega_1, b_1) N_{el}^{(\lambda)}(\omega_2, b_2) \Theta(B^2), \quad (28)$$

where $R_1$ and $R_2$ are the nuclear radii, $\Theta(B^2)$ is the step function and $B^2 = b_1^2 + b_2^2 - 2b_1 b_2 \cos \phi - (R_1 + R_2)^2 [3]$. Then the final cross-section is

$$\sigma_{A_1 A_2 \rightarrow A_1^* A_2 X_f} = \int \frac{d\omega_1}{\omega_1} \int \frac{d\omega_2}{\omega_2} L(\omega_1, \omega_2) \sigma_{\gamma\gamma \rightarrow X_f}(w_1, w_2) \quad (29)$$

### 2 Nuclear levels and form-factors

The elastic form factor of a light nucleus is

$$F_{el}(q^2) = \exp \left( -\frac{(q^2)}{6} \right) \quad (30)$$
with $\sqrt{\langle r^2 \rangle} = 2.73$ fm for the nucleus $^{16}$O. For a heavy nucleus we take a modified Fermi nuclear density [14]

$$\rho(r) = \rho_0 \left\{ \frac{1}{1 + \exp \frac{r-R}{g}} + \frac{1}{1 + \exp \frac{R-r}{g}} - 1 \right\}$$

(31)

$$= \rho_0 \frac{sh(R/g)}{ch(R/g) + ch(r/g)},$$

(32)

$$\rho_0 = \frac{3}{4\pi R^3} \left\{ 1 + \left( \frac{\pi g}{R} \right)^2 \right\}^{-1}$$

(33)

with the parameters for $^{208}$Pb are equal to $R = 6.69$ fm, $g = 0.545$ fm. Such form of density is close to the usual Fermi density at $g \ll R$

$$\rho_F(r) = \rho_0 \frac{1}{1 + \exp \frac{r-R}{g}}$$

(34)

and allows us to calculate analytically the elastic form factor

$$F_{el}(q) = \frac{4\pi^2 R g \rho_0}{q \ sh(\pi g q)} \left\{ \frac{\pi g}{R} \sin(qR) \ cth(\pi g q) - \cos(qR) \right\}.$$

(35)

There are a few discrete levels of $^{16}$O below $\alpha$, $p$ and $n$ thresholds $E_{th}(\alpha) = 7.16$ MeV, $E_{th}(p) = 7.16$ MeV, $E_{th}(n) = 7.16$ MeV [15]. The level $2^+$ at $E_0 = 6.92$ MeV is the strongest excited one in the electron scattering.

The parameters from the inelastic electron scattering fit on $^{16}$O with excitation of $2^+$ level ($E_0 = 6.92$ MeV) of $^{16}$O are [16]:

$$\beta_2 = 0.30, \ R = 2.98 \text{ fm}, \ g = 0.93 \text{ fm}.$$

They correspond to

$$B(E_02) = (36.1 \pm 3.4)e^2 \text{ fm}^4.$$

(36)

There are more than 70 discrete levels of $^{208}$Pb [17] below the neutron threshold $E_{th}(n) = 7.367$ MeV. About 30% of the levels decay to the first $3^-$ level of $^{208}$Pb at $E_0 = 2.615$ MeV. This level is well studied experimentally [18] and has a large excited cross-section.

The reduced transition probability from the fit of inelastic electron scattering on $^{208}$Pb with excitation of the $3^-$ level is [18]:

$$B(E_03) = (6.12 \ 10^5 \pm \ 2.2\%)e^2 \text{ fm}^6.$$

(37)
We calculate the parameter \( \beta_3 \), using this \( B(E_03) \), and take \( R \) and \( g \) from the density of the \( ^{208}\text{Pb} \) ground state:

\[
\beta_3 = 0.113, \quad R = 6.69 \text{ fm}, \quad g = 0.545 \text{ fm}.
\]

Note that there are many levels higher than \( E_0 = 2.615 \text{ MeV} \) which decay to the first level of \( ^{208}\text{Pb} \). This fact increases the event rate of the process (1), but we don’t know cross-section excitation of these levels.

The elastic form factor (30) of \( ^{16}\text{O} \) and inelastic form-factor \( ^{16}\text{O} \) \( (2^+, 6.92 \text{ MeV}) \) (21), corresponding to the electron scattering data, are shown in Fig.2. The same for a nucleus \( ^{208}\text{Pb} \) and the exited state \( ^{208}\text{Pb} \) \( (3^-, 2.64 \text{ MeV}) \) are shown in Fig.3.

![Figure 2: The elastic form-factor of \( ^{16}\text{O} \) (1) and the inelastic form-factor of \( ^{16}\text{O} \) \( (2^+, 6.92 \text{ MeV}) \) (2) from the electron scattering.](image)

The squared inelastic form-factor is less than the elastic form-factor by more then two orders at small \( q < q_0 \) \( (q_0 = 1 \text{ fm}^{-1} \text{ for } ^{16}\text{O} \text{ and } q_0 = 0.6 \text{ fm}^{-1} \text{ for } ^{208}\text{Pb}) \). In the region of \( q \approx q_0 \) they are comparable. The region of large \( q > q_0 \) will give contribution for the small impact parameter \( b \). We are able to calculate the photon luminosity (28) for all regions of \( b \) to get the maximum electromagnetic cross-section of process we are interested in. Then it should be possible to compare with experimental data in the condition of clear selection of such process by the photon signal and the veto neutron or proton signal in ZDC.
3 Angular and energy distributions of secondary nuclear photons

We suppose that the nucleus $A_1^*$ in the process (I) is unpolarized. Just now we don’t know the relative excitation probability of $|\lambda\mu >$ state of $A_1^*$, where $\mu$ is a projection of spin $\lambda$. This assumption needs the study in future. So we use a formula (27) in our work [10] for the angular distribution of secondary photons, which is valid for isotropic photon distribution in the rest system of $A_1^*$.

If we know the cross-section of reaction (I) calculated by the equation (29) then the angular and energy distribution of photons are equal to:

$$\frac{d\sigma_{A^*}}{d\theta_\gamma} = \sigma_{A_1A_2\rightarrow A_1^*A_2X} \cdot \frac{2\gamma_A^2 \sin \theta_\gamma}{(1 + \gamma_{A_1^*}^2 \tan^2 \theta_\gamma)^2 \cdot \cos^3 \theta_\gamma}. \quad (38)$$

The photon energy $E_\gamma$ and polar angle $\theta_\gamma$ in laboratory system are defined as:

$$E_\gamma = \gamma_{A_1^*} E_0 (1 + \cos \theta'_\gamma) = 2\gamma_{A_1^*} E_0 / (1 + \gamma_{A_1^*}^2 \tan^2 \theta_\gamma), \quad (39)$$

$$\tan \theta_\gamma = \frac{1}{\gamma_{A_1^*}} \frac{\sin \theta'_\gamma}{1 + \cos \theta'_\gamma}, \quad (40)$$

where $\theta'_\gamma$ and $\theta_\gamma$ are polar angles of nuclear photon in the rest nuclear system and in the laboratory system with an axis $\vec{z}|\vec{p}_{A^*}$. Photon energy $E_\gamma$ dependence on $\theta_\gamma$ are shown in Fig.4.
Our calculations with the help of TPHIC event generator [19] show that a deflection of the direction \( \vec{p}_{A^*} \) from \( \vec{p}_{beam} \) at LHC energies in the reaction (1) is very small at large \( \gamma_A \), \( \langle \Delta \theta \rangle \simeq 0.5 \mu \text{rad} \).

![Figure 4: Nuclear photon energy as function of its polar angle in the laboratory system at LHC energies for two nuclei: \( ^{16}\text{O} \) \( (2^+ \to 0^+, 6.92 \text{ MeV}) \) (1) and \( ^{208}\text{Pb} \) \( (3^- \to 0^+, 2.615 \text{ MeV}) \) (2). ZDC marks a region of Zero Degree Calorimeter in CMS.](image)

In the experiments CMS and ALICE, which are planned at LHC (CERN), the Zero Degree Calorimeter ([20], [21]) were suggested for the registration of nuclear neurons after interaction of two ions. We demonstrate a schematic figure of ZDC (CMS) at a distance \( L = 140 \text{ m} \) in the plane transverse to the beam direction in Fig.5. The CMS group plans to include also the electromagnetic calorimeter in front of ZDC.

As an example we demonstrate the angular distributions (38) in arbitrary units and energy dependence (39) on the \((x, y)\) coordinates of ZDC (CMS) for two nuclei \(^{16}\text{O}\) and \(^{208}\text{Pb}\) in Fig.6. The direction of the nucleus \( A_i^* \) coincides here the beam direction. A point \((x, y) = (0, 0)\) is a center of the ZDC plane.
Figure 5: Transverse ZDC plane. The points are the simulated hits of neutrons (left) and photons (right) from a work ([21]).

4 Cross-section of the process with the nuclear $\gamma$ radiation

We demonstrate our results on example of the $\eta_c(2.979)$ resonance production. The previous results ([3]) used old values of its widths and a point nuclear charge. Now we take resonance parameters from a new Particle Date Group ([22]) $\Gamma_{\eta_c \rightarrow \gamma\gamma} = 4.8$ keV and the realistic charge distribution. The calculations was made with the help of TPHIC event generator [19]. We use a well known formula [2] of a narrow resonance cross-section

$$
\sigma_{\gamma\gamma \rightarrow X}(w_1, w_2) = 8\pi^2(2\lambda_X + 1)\Gamma_{X \rightarrow \gamma\gamma}\delta(W^2 - M_X^2)/M_X
$$

where $W^2 = 4w_1w_2$, $\lambda_X$ and $M_X$ is a spin and a mass of the resonance. The LHC luminosity and our results according to (29) and (28) are in Tab. 1 for the process $\Pi$ with $A_{\text{final}} = A_1$ or $A_1^*$. Our results from a Tab. 1 shows that though the cross-section of the process $\Pi$ for the nucleus $^{208}$Pb is larger than that for $^{16}$O, the event rate is smaller because of the lower LHC luminosity for $^{208}$Pb. The cross section with a nuclear excitation is less by three orders of magnitude than that without the excitation since the intensity of excitation is not large and the inelastic form factor is less than the elastic form factor (see Fig.2 and Fig.3). Therefore for the accepted LHC luminosities it is possible to use the secondary photons as a signature of the clear electromagnetic nuclear process only for the production $X_f$ with rather large cross-section $\sigma_{\gamma\gamma \rightarrow X}$. The light ions are more preferable than the heavy ions to detect the nuclear $\gamma$ radiation.
Figure 6: The photon angular distributions (upper raw) and the energy dependence (lower raw) for $^{16}\text{O}^*(2^+, 6.92 \text{ MeV})$ (left coulomb) and $^{208}\text{Pb}^*(3^-, 2.62 \text{ MeV})$ (right coulomb) radiation decay in the laboratory system on the ZDC plane ($x, y$) at the distance 140 m from point interaction. $x$, cm is a horizontal and $y$, cm is a vertical axis. Photon energy interval in ZDC region is $19 \div 48 \text{ GeV}$ for $^{16}\text{O}^*(2^+)$ and $7 \div 14 \text{ GeV}$ for $^{208}\text{Pb}^*(3^-)$.
Table 1: Cross-section of $\eta_c$ production by $\gamma\gamma$ fusion

| $A_{\text{final}}$ | $L$ (cm$^{-2}$ s$^{-1}$) | $L$ (pb$^{-1}$) | $\sigma$ (µb) | event/10$^6$ s |
|-------------------|--------------------------|----------------|--------------|----------------|
| $^{208}\text{Pb}_{82}$ | 4.2·10$^{26}$ | 0.013 | 356 | 147000 |
| $^{16}\text{O}_{8}$ | 1.4·10$^{31}$ | 441.5 | 73 | 1020000 |
| $^{208}\text{Pb}_{82}$ | 4.2·10$^{26}$ | 0.013 | 296 | 122000 |
| $^{208}\text{Pb}_{82}$ (3$^-$) | 4.2·10$^{26}$ | 0.013 | 129 | 53 |
| $^{16}\text{O}_{8}$ | 1.4·10$^{31}$ | 441.5 | 66 | 926000 |
| $^{16}\text{O}_{8}$ (2$^+$) | 1.4·10$^{31}$ | 441.5 | 0.201 | 2810 |

5 Conclusion

In the work we suggest a new signature of the peripheral ion collisions.

The formalism of the process (1) is developed in the frame of the equivalent photon approximation. New point is an introduction of the inelastic nuclear form factor. It allows to consider the excitation of discrete nuclear levels and their following $\gamma$ radiation decay. It is shown that the energy of this secondary photons are in GeV region due to a large Lorentz boost at LHC energies. The angular distribution of the photons has a peculiar form as a function of polar angle in the beam direction. The most photons hit the region of ZDC in CMS and ALICE experiments in the region of angles of a few hundred micro-radians.

So the nuclear $\gamma$ radiation is a good signature of the clear peripheral ion collisions at LHC energies when $A$ and $Z$ of beam ion are conserved. The trigger requirements will include a signal in the central rapidity region of particles from $X_f$ decay, a signal of photons in the electromagnetic detector in front of the zero degree calorimeter and a veto signal of neutrons in ZDC. We suggest to use the veto signal of neutron in order to avoid the processes with nuclear decay into nucleon fragments. The nuclear $\gamma$ radiation can be used for tagging the events with particle production in the central rapidity region in the ultra-peripheral collisions.

The light nuclei are more preferable comparing with heavy ions since they have higher beam luminosity at LHC. The cross-sections of the process with the nuclear excitation is three orders of magnitude smaller than one without excitation. The accepted nuclear luminosities enable to use this signature for the large cross section of $X_f$ system production.

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