Geometry of ultraperipheral nuclear collisions

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Keywords: ions, ultraperipheral, interaction, resonance, LHC

Abstract

It is advocated that geometry of the interaction region of two heavy nuclei colliding at large impact parameters is important for the relative role of light-by-light scattering and QCD-initiated processes. Exclusive production of resonances is possible by dense electromagnetic fields in the interior space between the nuclei. The cross section of these processes is evaluated and some examples are considered. It is speculated that the exclusive production of $\rho^0$-mesons by two-photon processes forbidden by the Landau-Yang rule may become allowed within strong magnetic fields.

1 Introduction

Geometry of the internal structure of hadrons and their interaction regions is of utmost importance for understanding the outcome of these interactions. Since Yukawa times, the effective size of hadrons is considered being of the order of 1 fm=$10^{-13}$ cm i.e. close to the inverse pion mass. This scale is characteristic for the QCD potential and for simplified bag-models. More tiny details about the hadron structure were recently found [1, 2, 3, 4].

High energy interactions of heavy ions open a new avenue for studies of hadron properties. Central collisions are claimed to produce a new deconfined state of QCD-matter named the quark-gluon plasma. In their turn, ultraperipheral collisions provide access to strong electromagnetic fields created within the space between the colliding ions. Exclusive production of hadronic resonances via light-by-light scattering can become compatible with QCD sources [5]. The geometrical factor plays an important role there. Exclusive production of $\rho^0$-mesons asks for special attention because it can happen not only due to the direct transition of a single photon to $\rho^0$ in the QCD-field of a nucleus but also via two-photon collisions in a strong magnetic field. The analogy to creation of two photons by a single one considered in astrophysics [6, 7, 8] is useful there.
2 Exclusive production of resonances in ultraperipheral collisions

By definition, collisions of two heavy ions are called ultraperipheral if the shortest distance between the trajectories of their centers (the impact parameter \( b \)) exceeds noticeably the sum of their radii \( 2R_A \) (\( \approx 14 \) fm for Pb-Pb collisions). Unfortunately, the impact parameter can not be directly measured in experiment. One has to select ultraperipheral events according to special signatures left by products of the collision. For example, low multiplicities of final states favor this choice. In particular, exclusive production of resonances separated by large rapidity gaps from the colliding ions is a clear indication on ultraperipheral collisions. This process is considered as a good candidate for studying various geometrical and dynamical aspects of heavy ion interactions.

At large impact parameters the direct short-range interaction of hadronic constituents (quarks, gluons) of ions occupies small space volume. The long-range electromagnetic forces have a chance to dominate because the electromagnetic fields between two high energy ions are extremely dense. Each ion is surrounded by a widely spread cloud of virtual photons. The nuclei emit the photons coherently. The effective perturbation parameter associated with photon exchange is not \( \alpha = 1/137 \) but becomes equal \( Z\alpha(\approx 0.6 \) for Pb ions). The incoherent "inelastic" emission is a factor \( Z^{-1} \) smaller at large charge of the heavy ion \( Z \).

The coherent photon flux emitted by a heavy ion has been evaluated a long time ago [9]. The equivalent photon approximation has been used. Coherent emission constitutes the dominant contribution to the photon PDF at the starting scale of photon virtuality. Impact parameters larger than 19 fm are necessary for its formation in Pb-Pb collisions at LHC energies (see Fig. 4 in [5]). Thus the ions must be at least 5 fm apart to form the dense electromagnetic field. These collisions are really ultraperipheral.

The flux is dominated by photons carrying small fractions of the nucleon energy \( x \). It may be written [10] as

\[
\frac{dn}{dx} = \frac{2Z^2\alpha}{\pi x} \ln \frac{1}{4R_A x m},
\]

where the Pb-radius is \( R_A = 7 \) fm and \( m \) is a nucleon mass.

The photons in the flux fluctuate to quark-antiquark pairs. They may form \( \rho^0 \)-meson when the transverse separation of the pair becomes of the
hadronic size. Then the $\rho^0$-meson may elastically scatter on a nucleus. The strong short-range QCD-forces get involved. Namely they initiate the diffractive structure of $p_t$-distributions of mesons with its characteristic maxima and minima if the black disk model of ions is used as done in Ref. [10]. This process is semiperipheral because the target nucleus has to participate in the interaction with $\rho$. The transverse momentum spread of initial photons (integrated over in Eq. (1)) is less than 70 MeV and can not influence the diffractive minima because they are placed at larger transverse momenta. However, the incoherent and nucleon-break up processes may spoil the diffraction pattern as shown in Fig. 7 of [10]. Some other effects which may smooth out the diffraction picture are also discussed in [10].

Indeed, it would be fascinating to observe the well pronounced diffraction in nuclear collisions at LHC energies. Up to now, a very smooth behavior of the $p_t$-distribution of exclusively produced $\rho$-mesons with slight twists in place of strong diffraction minima predicted by Monte Carlo calculations was observed by STAR Collaboration (see Fig. 2 in [11], also [12]). Moreover, no distinct diffractive structure is observed nowadays in the data for elastic scattering of hadrons [13, 14]. Instead, the two exponentially (in $p_t^2$) decreasing regions with different exponents and some dip between them are seen. The dip is prescribed to the vanishing imaginary part of the elastic scattering amplitude.

The ultraperipheral processes are those with purely electromagnetic interactions of fields between the colliding nuclei. Further background to the one-photon mechanism of $\rho^0$-production considered in Ref. [10] may come from them. No diffraction pattern of $p_t$ distributions is expected to arise in such processes. Recently, elastic scattering of two photons from proton clouds was observed by ATLAS and CMS Collaborations at LHC [15, 16] even for proton-proton collisions at 13 TeV. The electromagnetic fields in ultraperipheral collisions of heavy ions are almost eight orders of magnitude stronger than those for $pp$-collisions being enhanced by the $Z^4$-factor. The photon flux (1) becomes very dense ($dn/dx \approx 300$) for extremely small effective values of $x \sim 3 \cdot 10^{-4}$ typical for resonance production at LHC energy (per nucleon) $\sqrt{s_{nn}} = 2.76$ TeV [10]. The density of fields is larger at higher energies because $x = m_R/\sqrt{s_{nn}}$ is inverse proportional to $\sqrt{s_{nn}}$ for a given resonance $R$. The hadronic resonances may be copiously created in purely photon interactions as advocated in many papers (see, e.g., [9, 5] and references therein). Geometry of ultraperipheral collisions with the large space (more than 5 fm) between the colliding ions and $Z$-factors ascribed to both
ions favor these reactions. To compare, strong interactions of hadronic constituents are limited by distances of the order of 1 fm.

One can consider the two- and multi-photon processes. Those with the even(odd) number of participating photons may produce para(ortho)-states of resonances. The $p_t$ distribution of produced resonances should be rather smooth because no diffraction gets involved in these processes.

As an example, let us consider a particular channel of production of a resonance $R$ by the two-photon interactions in the ultraperipheral collisions of Pb-ions at high energies. The exclusive cross section can be written as

$$\sigma_{AA}(R) = \int dx_1 dx_2 \frac{dn}{dx_1} \frac{dn}{dx_2} \sigma_{\gamma\gamma}(R), \quad (2)$$

where $dn/dx_i$ are given by Eq. (1) and (see Ref. [9])

$$\sigma_{\gamma\gamma}(R) = \frac{8\pi^2 \Gamma_{tot}(R)}{m_R} Br(R \rightarrow \gamma\gamma) Br_d(R) \delta(x_1 x_2 s_{nn} - m_R^2). \quad (3)$$

Here $m_R$ is the mass of $R$, $\Gamma_{tot}(R)$ its total width and $Br_d(R)$ denotes the branching ratio to a considered channel of its decay. The $\delta$-function approximation is used for resonances with small widths compared to their masses.

The integrals in Eq. (2) can be easily calculated so that

$$\sigma_{AA}(R) = \frac{64}{3} Z^4 \alpha^2 Br(R \rightarrow \gamma\gamma) Br_d(R) \frac{\Gamma_{tot}(R)}{m_R^2} \ln^3 \frac{\sqrt{s_{nn}}}{4 R A m m_R}. \quad (4)$$

The most fascinating feature of this result is the rather fast increase of the cross section with increasing energy as $\ln^3 s$. The growth of the flux density (1) is its main source. It overshoots the famous Froissart bound $\ln^2 s$ for increase of hadronic cross sections. The long-range electromagnetic forces admit such a possibility. Surely, Eq. (4) can be only valid at rather high energies $\sqrt{s_{nn}} \gg 4 R A m m_R \approx 200 m_R$.

The simplest example would be to estimate the cross section of exclusive production of $\pi^0$-mesons. In fact, this is the estimate of the lower bound for light-by-light scattering in ultraperipheral nuclear collisions. Other non-resonant quark loops would contribute as well beside the $\gamma\gamma$-state favored by $\pi^0$. Even though the $\pi^0$-lifetime is extremely short ($\Gamma_{tot} = 7.5 \cdot 10^{-6}$ MeV), its rather low mass ($m_{\pi^0} = 135$ MeV) and high branchings equal 1 save the situation. According to Eq. (4) one gets the values $\sigma_{AA}(R) =$
Another interesting process is the exclusive production of $\eta'$-mesons. It is especially attractive because it leads to the additional supply of $\rho^0$-mesons due to the decay $\eta' \rightarrow \rho^0 + \gamma$. The transverse momentum of $\rho^0$ from such decay may be as large as 170 MeV. The oscillations at $p_t \sim 120$ MeV predicted in Ref. [10] would be filled in if the corresponding cross section is large enough. It is estimated from Eq. (4) using the mass, width and branching ratios of $\eta'$-meson ($m_{\eta'} = 957.8$ MeV, $\Gamma_{tot} = 0.196$ MeV, $\text{Br}_{\gamma\gamma} = 0.0222$, $\text{Br}_{\rho\gamma} = 0.29$) from the Particle Data Group tables [17]. As expected, the contribution of this particular channel is rather low, about 0.8 mb at 2.76 TeV and 1.4 mb at 5.02 TeV compared to the values of hundreds millibarns predicted in Ref. [10] and measured by STAR Collaboration [11]. This is mainly due to the low total width of the resonance and small $2\gamma$-branching ratio of $\eta'$ i.e. low effectiveness of its production in photon-photon collisions. Contribution of the non-resonant background and other resonant parastates ($f^0$ etc) is expected to be similar and must be Monte-Carlo-computed with account of experimental requirements.

Actually, there could be other sources of $\rho^0$ production. Very intriguing would be the direct production of $\rho^0$-mesons (or other orthostates) by the two-photon collisions within the strong magnetic fields between the colliding ions. According to some estimates [18], the magnetic field can be as large as $eB \approx (10 - 15)m_e^2(\approx 10^{18}G)$. Therefore the photon-photon interactions in such fields can probably become more effective than the direct interaction with the target nucleus of the $\rho^0$-meson produced by a single exchanged photon, as considered in Ref. [10]. The impact of the strong magnetic field should be considered as the collective effect of the odd number of photons on a colliding pair of them. As such, it does not violate the Landau-Yang rule. Unfortunately, we have no methods to estimate the outcome besides considering some simplest loops of electrons or quarks immersed in this field. This process reminds the creation of two photons by a single one passing through the magnetic field considered in astrophysics [6, 7, 8]. Again, no diffraction patterns in $p_t$ distributions are expected for these background processes.

To conclude, the exclusive cross sections of resonance production in ultraperipheral nuclear collisions are rather low but measurable at LHC for some particular channels and become larger at higher energies. The detailed analysis of other possibilities (especially, of collective effects in the magnetic field) should be done to get final conclusions.
Acknowledgements

This work was supported by RFBR grant 18-02-40131 and by the RAN-CERN program.

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