Relativistic heavy ion collider as a photon factory: from GDR excitations to vector meson production

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Abstract

A variety of phenomena, which reveal itself in distant collisions of ultrarelativistic nuclei is discussed. One or both nuclei may be disintegrated in a single collision event by the long-range electromagnetic forces due to the impact of the Lorentz-boosted Coulomb fields of collision partners. The process is considered in the framework of the Weizsäcker-Williams method and simulated by the RELDIS code, which takes into account all possible channels of nuclear disintegration, including multiple neutron and proton emission and meson production. Mutual electromagnetic dissociation of nuclei in peripheral collisions can best be studied at RHIC and LHC. The contributions of next-to-leading-order processes with multiple photon absorption of equivalent photons by collision partners are considered in detail. As demonstrated, the rates of the correlated forward-backward $2n$ and $3n$ emission are very sensitive to the presence of double and triple excitations of Giant Resonances in colliding nuclei. A practical application consists in the possibility of beam luminosity monitoring in colliders via the registration of the correlated $1n$ and $2n$ emission in mutual electromagnetic dissociation.

1 Introduction

The colliders of ultrarelativistic nuclei, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and the future Large Hadron Collider (LHC) at CERN, were designed for the primary aim to provide conditions for creating and detecting quark-gluon plasma. The conditions to create such an unexplored state of matter are expected to be fulfilled in central hadronic collisions of heavy nuclei like Au and Pb.

However, new phenomena in heavy ion collisions are anticipated also beyond the domain of impact parameter $b \leq R_1 + R_2$, where hadronic interactions of
nuclei with the nuclear radii $R_1$ and $R_2$ are confined. Due to the long-range electromagnetic interaction, ultraperipheral collisions of nuclei with $b \geq R_1 + R_2$ can be also considered. According to the Weizsäcker-Williams method [1, 2], the Lorentz-contracted Coulomb fields of moving charges can be represented as intense sources of equivalent virtual photons with a wide energy spectrum. Depending on virtual photon energy, the absorption of photons leads to a variety of photonuclear reactions with emission of nucleons, nuclear fragments and mesons [3]. This is commonly termed as electromagnetic dissociation (ED) of nuclei. Low-energy few-MeV photons are the most frequent in the spectrum, and the excitation of Giant Resonances (GR) in nuclei, in particular, Giant Dipole Resonance (GDR) followed by neutron emission is the most probable channel of electromagnetic dissociation.

1.1 Mutual electromagnetic dissociation of heavy ions in colliders

Since the first pioneering studies of the electromagnetic dissociation [4, 5], the process has gained a wide-spread interpretation as disintegration of one of the collision partners in ultraperipheral collisions of heavy ions without direct overlap of their nuclear densities. This consideration is fully justified in fixed target experiments, where the electromagnetic dissociation of either projectile or target nuclei is detected. Very recent experiments [6, 7] can be mentioned as examples of projectile and target dissociation measurements, respectively.

Both at the RHIC and LHC colliders, the single electromagnetic dissociation cross section by far exceeds the geometrical hadronic cross section due to the direct nuclear overlap, as shown by calculations [1, 2, 8, 9]. As a result, electromagnetic dissociation and $e^+e^-$-pair production followed by electron capture will reduce the beam lifetime in the colliders [8].

The consideration of single electromagnetic dissociation should be extended further, since both of the colliding nuclei may be disintegrated in a single event by their Coulomb fields. In this case mutual electromagnetic dissociation takes place [9]. This process can best be studied in heavy-ion colliders, in contrast to fixed target experiments, and has a practical application. It makes possible to monitor collider luminosity via the registration of correlated forward-backward neutrons produced in mutual electromagnetic dissociation.

In addition, the experimental studies of the mutual electromagnetic dissociation of heavy nuclei in colliders can provide valuable information on double and triple excitations of Giant Resonances in heavy nuclei. Such exotic collective excitations of nuclear matter are difficult to study in fixed target experiments, since the contributions of double and triple excitations are at the level of $\sim 1\%$ and $\sim 0.01\%$, respectively [10].
2 Calculation of electromagnetic dissociation cross sections

According to the Weizsäcker-Williams method [1, 2], the impact of the Lorentz-boosted Coulomb field of the nucleus $A_1$ is treated as the absorption of equivalent photons by the nucleus $A_2$.

In the rest frame of this nucleus the spectrum of photons from the collision partner $A_1$ at impact parameter $b$ is expressed as:

$$N_{Z_1}(E_1, b) = \frac{\alpha Z_1^2}{\pi^2} \frac{x^2}{\beta^2 E_1 b^2} \left( K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right).$$

Here $\alpha$ is the fine structure constant, $x = E_1 b / (\gamma \beta \hbar c)$ is an argument of the modified Bessel functions of zero and first orders, $K_0$ and $K_1$, $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor of the moving charge $Z_1$ in the rest frame of $A_2$. If the Lorentz factor of each heavy-ion beam is $\gamma_{\text{beam}}$ in the laboratory system, then $\gamma = 2 \gamma_{\text{beam}}^2 - 1$ for the case of collider. For example, at LHC the Coulomb fields of ions are extremely Lorentz-contracted, $\gamma \sim 1.7 \times 10^7$.

The mean number of photons absorbed by the nucleus $A_2$ in the collision at impact parameter $b$ is defined by:

$$m_{A_2}(b) = \int_{E_{\text{min}}}^{E_{\text{max}}} N_{Z_1}(E_1, b) \sigma_{A_2}(E_1) dE_1,$$

where the appropriate total photoabsorption cross section $\sigma_{A_2}(E_1)$ is used. For $E_{\text{min}}$, one usually takes the neutron emission threshold, while the upper limit of integration is $E_{\text{max}} \approx \gamma / R_{1:2}$. The calculation results for $m(b)$ are shown in Fig. 1 for 100 + 100 A GeV AuAu collisions at RHIC and for 2.75 + 2.75 A TeV PbPb collisions at LHC. The range of integration in Eq. (2) extends well above the GR region, which gives the main contribution. However, the inverse-square dependence $m(b) \sim 1/b^2$ mentioned in Ref. [2] still can be used to approximate the results shown in Fig. 1. The lower limit of impact parameter $b_c$ in electromagnetic interactions is approximately given by the sum of nuclear radii, $b_c \approx R_1 + R_2$. Despite the fact that nuclei are relatively transparent for photons, the mean number of photons absorbed in close electromagnetic collisions ($b \sim b_c$) is not small, $m(b) \sim 1$, at RHIC and LHC. This is due to the fact that the flux of equivalent photons is quite high due to the extreme Lorentz contraction of Coulomb fields and high $Z$ of colliding nuclei.

2.1 Single dissociation

Assuming the Poisson distribution for the number of absorbed photons, the total single dissociation cross section for the nucleus $A_2$ due to the exchange of
one photon is given by:

$$\sigma_{s}^{ED}(\text{LO}) = 2\pi \int_{b_{c}}^{\infty} b db P_{s}(b) = 2\pi \int_{b_{c}}^{\infty} b db m_{A_{2}}(b) e^{-m_{A_{2}}(b)},$$  \hspace{1cm} (3)

for the leading order (LO) process. Here the probability of single LO dissociation

$$P_{s}(b)$$ at given impact parameter $$b$$ is introduced. Consequently, for the next-to-leading order (NLO) process with two exchanged photons (NLO$_{2}$):

$$\sigma_{s}^{ED}(\text{NLO}_{2}) = 2\pi \int_{b_{c}}^{\infty} b db \frac{m_{A_{2}}^{2}(b)}{2} e^{-m_{A_{2}}(b)}.$$

### 2.2 Leading order process of mutual dissociation

Following the assumption that the primary and secondary photon exchanges in the LO process of mutual dissociation shown in Fig. 2 may be considered
Figure 2: Mutual electromagnetic excitation of relativistic nuclei: leading order (LO) contribution, next-to-leading-order contribution with single and double photon exchange processes (NLO\(_{12}\)) and next-to-leading-order contribution with two double photon exchange processes (NLO\(_{22}\)). Open and closed circles denote elastic and inelastic vertices, respectively.

Independently (see details in Ref. [9]), one can write the cross section for the dissociation of nuclei \(A_1\) and \(A_2\) to channels \(i\) and \(j\), respectively, as:

\[
\sigma_{m}^{ED}(i \mid j) = 2\pi \int_{b_c}^{\infty} bdb P_{A_1}(b) P_{A_2}(b),
\]

In Eq. \(\text{[5]}\) the probability of dissociation of the nucleus \(A_2\) at impact parameter \(b\) via the channel \(i\) is defined as:

\[
P_{A_2}(b) = e^{-m_{A_2}(b)} \int_{E_{min}}^{E_{max}} dE_1 N_{Z_1}(E_1, b) \sigma_{A_2}(E_1) f_{A_2}(E_1, i).
\]

\(N_{Z_1}(E_1, b)\) is the spectrum of virtual photons from the collision partner \(A_1\) at impact parameter \(b\). \(\sigma_{A_2}(E_1)\) and \(f_{A_2}(E_1, i)\) are the total photoabsorption cross section and the branching ratio for the channel \(i\), respectively, for the absorption of a photon with energy \(E_1\) on the nucleus \(A_2\). Naturally, the expression for \(P_{A_1}(b)\) is obtained by exchange of subscripts.

The total cross section for the mutual electromagnetic dissociation due to the leading order process shown in Fig. \(\text{[2]}\) is given by:

\[
\sigma_{m}^{ED}(\text{LO}) = 2\pi \int_{b_c}^{\infty} bdb P_{m}(b) = 2\pi \int_{b_c}^{\infty} bdb m_{A}^2(b) e^{-2m_{A}(b)},
\]

\(\text{[7]}\)
Table 1: Total mutual electromagnetic dissociation cross sections for the leading order, next-to-leading order processes and for the sum of all contributions for Pb-Pb collisions at LHC.

| Cross section (barns) | 2.75+2.75 A TeV Pb-Pb at LHC |
|-----------------------|-------------------------------|
| $\sigma_{m}^{ED}\,(LO)$ | 3.92                          |
| $\sigma_{m}^{ED}\,(NLO_{12}) + \sigma_{m}^{ED}\,(NLO_{21})$ | 1.50                          |
| $\sigma_{m}^{ED}\,(NLO_{22})$ | 0.23                          |
| Triple excitations: NLO$_{TR}$ | 0.56                          |
| $\sigma_{m}^{ED}\,(tot)$ | 6.21                          |

where the mutual dissociation probability $P_{m}(b)$ at given impact parameter $b$ is introduced, and the case of equal masses and charges of collision partners is considered, $A_{1} = A_{2} = A$ and $Z_{1} = Z_{2} = Z$.

2.3 Next-to-leading-order processes

In addition to the leading order process of mutual dissociation, a set of next-to-leading order (NLO) processes with exchange of three or four photons should be considered. The total cross section for the process with three photons shown as NLO$_{12}$ in Fig. 2 is given by:

$$
\sigma_{m}^{ED}\,(NLO_{12}) = 2\pi \int_{b_{c}}^{\infty} bdb \frac{m_{A}^{3}(b)}{2} e^{-2m_{A}(b)}. \quad (8)
$$

A complementary process (NLO$_{21}$) with the excitation of the nucleus $A_{2}$ via double photon absorption is equally possible and has the same cross section.

Another next-to-leading order process of mutual dissociation is due to exchange of four photons (NLO$_{22}$ in Fig. 2), and its cross section can be written as:

$$
\sigma_{m}^{ED}\,(NLO_{22}) = 2\pi \int_{b_{c}}^{\infty} bdb \frac{m_{A}^{4}(b)}{4} e^{-2m_{A}(b)}. \quad (9)
$$

Calculations of $\sigma_{m}^{ED}\,(i\mid j)$, $\sigma_{m}^{ED}\,(LO)$, $\sigma_{m}^{ED}\,(NLO)$ were performed by the modified code RELDIS [9], which contains a special simulation mode for the mutual
electromagnetic dissociation process. As one can see from Tab. 1, the LO mechanism gives $\sim 63\%$ of the $\sigma_{ed}^{(tot)}$ at LHC energies. The sum of the NLO contributions to the total cross section gives additional $\sim 28\%$. Therefore, as expected at LHC, the remaining contribution of 0.56 b ($\sim 9\%$ of the total mutual ED cross section) is due to exotic triple nuclear excitations (NLO$_{TR}$) with three and more photons absorbed by at least one of the collision partners. This includes the following processes in our notation: NLO$_{23}$, NLO$_{32}$, NLO$_{33}$, and also NLO$_{34}$, NLO$_{43}$, NLO$_{44}$

3 Mutual dissociation as a filter to select close collisions and high-order excitations

Most mutual ED events take place in close collisions with small $b \geq b_c$, where the probability to absorb a virtual photon is large, and hence, two or more photons can be absorbed by each of the collision partners. This is demonstrated in Fig. 3 where the probabilities for single $P_s(b)$ and mutual $P_m(b)$ electromagnetic dissociation are shown as functions of impact parameter $b$ for each of the LO and NLO processes. The mutual dissociation probabilities $P_m(b)$ have much steeper decrease as $b$ increases compared to $P_s(b)$. In other words, detection of particles emitted in mutual dissociation can be used as a filter to select close collisions. The NLO contributions in mutual dissociation are noticeably enhanced compared to single dissociation, as shown in Fig. 3. The sum of NLO$_{12}$ and NLO$_{21}$ contributions approaches the LO contribution in the region of close collisions $b \sim b_c$. In this region the probability of triple excitations NLO$_{TR}$ is also found to be comparable with the LO contribution. However, all the NLO contributions have steeper decrease compared to the LO contribution, and the resulting NLO cross sections given in Tab. 4 are found to be lower compared to the LO cross sections.

As recently confirmed by calculations [11], mutual electromagnetic excitation of nuclei can be also used to tag production of vector mesons, $\rho^0, \omega, \phi$ and $J/\psi$ by virtual photons in collisions with smaller average $b$.

Double and triple excitations are expected to be frequent in mutual electromagnetic dissociation, $\sim 28\%$ and $\sim 9\%$, respectively, see Tab. 4. Therefore, the experimental studies of the mutual dissociation of heavy ions at LHC can provide valuable information on double and triple nuclear excitations in electromagnetic interactions. This is particularly important for the triple Giant Resonance excitations, since currently there are no experimental data on such extreme excitations and only first theoretical predictions for the positions and widths of such states were given recently [12].

4 Neutron emission in mutual dissociation

The numbers of forward neutrons emitted in the mutual ED process and registered by the Zero Degree Calorimeters [13] can be used to obtain information
on multiple excitations at LHC [14]. For example, if the decay channel of one of the collision partners in mutual dissociation is not exactly known, one can define inclusive mutual dissociation cross sections, $\sigma_m(1nX \mid D)$, $\sigma_m(2nX \mid D)$, $\sigma_m(3nX \mid D)$ for emission of one, two and three neutrons, respectively, by the other partner. In such notations $D$ denotes an arbitrary dissociation mode, while $X$ denote any particle, except neutron. In the case, when the numbers of neutrons are exactly known, one can define semi-inclusive mutual neutron emission cross sections $\sigma_m(1nX \mid 1nY)$, $\sigma_m(1nX \mid 2nY)$ and $\sigma_m(2nX \mid 2nY)$.

The cross sections for some specific channels of mutual dissociation at LHC predicted by the RELDIS model [9] are given in Tab. 2. As one can note, $\sigma_m^{ED}(1nX \mid 1nY)$ has a small NLO correction, $\sim 7\%$, while $\sigma_m^{ED}(3nX \mid D)$ becomes almost twice as large as its LO value if NLO correction is included. This is due to the fact that the NLO processes shown in Fig. 2 include nuclear excitation due to double photon absorption and, particularly, the double GDR excitation process. Since the average GDR energy for Pb is about 13–14 MeV, the double GDR excitation introduces, on average, 26–28 MeV excitation energy which is already above the $3n$ emission threshold.
Table 2: Mutual electromagnetic dissociation cross sections for Pb-Pb collisions at LHC. X and Y denote any particle, except neutron. D means any dissociation channel. Calculation results are given (a) for the leading order contribution only, (b) for the sum of leading order and next-to-leading-order contributions.

| Cross section (mb) | (a) LO | (b) LO+NLO+NLO_{21}+NLO_{22} |
|--------------------|--------|-------------------------------|
| \( \sigma_m^{ED}(1nX | 1nY) \) | 750 | 805 |
| \( \sigma_m^{ED}(1nX | D) \) | 1698 | 2107 |
| \( \sigma_m^{ED}(2nX | D) \) | 443 | 654 |
| \( \sigma_m^{ED}(3nX | D) \) | 241 | 465 |

Therefore, as a rule, 1n and 2n emission cross sections are less changed by taking into account NLO corrections than 3n cross sections. The measurements of the rates of forward 3n emission can be proposed to detect multiple GDR excitations in nuclei.

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**References**

[1] F. Krauss, M. Greiner and G. Soff, Prog. Part. Nucl. Phys. 39 (1997) 503.
[2] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky and Y. Kharlov, Phys. Rept. 364 (2002) 359.
[3] I. A. Pshenichnov, I. N. Mishustin, J. P. Bondorf, A. S. Botvina and A. S. Ilinov, Phys. Rev. C 60 (1999) 044901.
[4] H. H. Heckman and P. J. Lindstrom, Phys. Rev. Lett. 37, 56 (1976).
[5] D. L. Olson, B. L. Berman, D. E. Greiner, H. H. Heckman, P. J. Lindstrom, G. D. Westfall and H. J. Crawford, Phys. Rev. C 24, 1529 (1981).

[6] C. Scheidenberger, I. A. Pshenichnov, T. Aumann, S. Datz, K. Summerer, J. P. Bondorf, D. Boutin, H. Geissel, P. Grafstrom, H. Knudsen, H.F. Krause, B. Lomme, S. P. Moller, G. Munzenberg, R. H. Schuch, E. Uggerhoj, U. Uggerhoj, C. R. Vane, A. Ventura, Z. Z. Vilakazi, H. Weick, Phys. Rev. Lett. 88 (2002) 042301.

[7] J. C. Hill, A. Petridis, B. Fadem and F. K. Wohn, Nucl. Phys. A 661 (1999) 313.

[8] A. J. Baltz, M. J. Rhoades-Brown and J. Weneser, Phys. Rev. E 54 (1996) 4233.

[9] I. A. Pshenichnov, J. P. Bondorf, I. N. Mishustin, A. Ventura and S. Masetti, Phys. Rev. C 64 (2001) 024903.

[10] W. J. Llope and P. Braun-Munzinger, Phys. Rev. C 41 (1990) 2644.

[11] A. J. Baltz, S. R. Klein and J. Nystrand, Phys. Rev. Lett. 89 (2002) 012301.

[12] E. J. de Passos, M. S. Hussein, L. F. Canto and B. V. Carlson, arXiv:nucl-th/0108002

[13] C. Oppedisano, “Centrality measurement in the ALICE experiment with the Zero Degree Calorimeters”, ALICE Internal Note, ALICE-INT-2002-08.

[14] I. A. Pshenichnov, J. P. Bondorf, A. B. Kurepin, I.N. Mishustin, A. Ventura, “Electromagnetic dissociation of nuclei and collider luminosity monitoring in ALICE experiment at LHC”, ALICE Internal Note, ALICE-INT-2002-07.