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# Electromagnetic interactions of heavy ions at small impact parameters and lepton pair productions

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**Abstract.** In peripheral collisions, the strong electromagnetic fields are produced since the fully stripped heavy ions moves at ultra-relativistic velocities. Lepton pairs, especially the electron-positron pairs are the result of this collisions. At the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), virtual photons produce many particles such as electron-positron pairs, heavy lepton (muons and tauons) pairs, magnetic monopoles, W-pairs, b-quark pairs and possibly the Higgs. At small impact parameters, the colliding nuclei make peripheral collisions, photon fluxes are very large and these are responsible for the multiple photonuclear interactions. Free pair productions, bound free pair productions, and nuclear Coulomb excitations are important examples of such interactions, and these processes play important roles in the beam luminosity at RHIC and LHC. Here we obtained bound free electron-positron pair production with nuclear breakup for heavy ion collisions at RHIC and LHC.

## Introduction

Several years ago, it was suggested that ultra-relativistic heavy ion collisions provide very large fluxes of coherent photons. These photons can be real or virtual and these photons are the source for the electromagnetic production of various particles. These particles can be electron and heavy lepton (muons and tauons) pairs, magnetic monopoles, W-pairs, b-quark pairs and possibly the Higgs. Most of this particles occur at colliding beams of heavy nuclei at energies per nucleon in the range 3-$10^4$ GeV, corresponding to the experiments at AGS, CERN, RHIC facility and LHC facility [1].

There is many questions about on the electromagnetic and electroweak interactions in strongly dynamical hadronic systems. For example, the dilepton production and $J/\psi$ suppression can be a diagnostic of the formation of the quark-gluon plasma. If we know the electromagnetic pair production processes in detail, we can separete it from the hadronic processes. We know that coherent production of electron-positron pair is proportional to the $Z^4$ where Z is the charge of the colliding ions. Therefore the strong field of the colliding ions can help us to calculate the other processes such as W bosons and the Higgs particles [1].

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In peripheral collisions of the ions, it is known that a large number of lepton pairs can be produced owing to the Lorentz contracted high electromagnetic fields that occur in course of the collisions. In ultrarelativistic heavy ion colliders, such as RHIC and LHC, there are two dominant processes that restrict the luminosity of the ion beams: bound free electron-positron pair production (BFPP) and giant dipole resonance (GDR). In both processes, each ion is acted on by the Lorentz contracted electromagnetic field of the other ion. In the BFPP, an electron is captured by one of the colliding ions and leads to the loss of the ion from the beam. This leads to a change in the charge of the ion and causes the ion to fall out of the beam. In the GDR, the Coulomb force dissociates the nucleus where the protons and neutrons oscillate against each other. Then the neutrons fall out of the beam and these neutrons are detected in the forward zero degree calorimeter. Each of these processes causes the limitation of the beam lifetime for the collisions of Au+Au at RHIC or Pb+Pb at LHC [2].

The other intereting processes is the production of antihydrogen from the collisions of anti-proton and heavy nucleus. Anti-hydrogen in flight was first detected at CERN Low Energy Antiproton Ring (LEAR) using the process

$$\overline{p} + Z \rightarrow \overline{H} + e^{-} + Z \tag{1}$$

here, $Z = 54$ (Xe). This process is first suggested by Munger *et al.*[3] and they also calculated the cross section with equivalent photon approximation (EPA). It s a similar pair production mechanism with electron capture process. The calculations were done in high energy limit however the applicability of the EPA to this problem is questionable since the anti-hydrogen production were done in low energy region [4].

The Weizsacker-Williams method were used mostly for the calculation of the cross section of all these particles. The handicap of this method is, the photons must be “on-shell” , however in heavy ion collisions this condition is not always realized. Generally, the virtual photons carry a transverse momentum which is not taken into consideration in the Weizsacker-Williams method [5].

Heavy ion collisons are used to calculate the lepton pair production cross section as a model. This model can also be applied to the W-pair and Higgs production, where the electromagnetic potentials are taken as classical. In this method, the electromagnetic fields that are arose in interaction Lagrangian replaced by their classical term. With this way, the coherent pair production mechanism can be used as the excitations of quantum fields using perturbation theory. For the two photon process, the analytical integrals for the calculation of the cross section can be obtained in momentum space and this analytical integrals can be calculated by Monte Carlo Method [5].

The observation of the Higgs boson would give us a chance to explain the mass splittings in a unified theory of weak and electromagnetic interactions. It is thoght that, at relativistic heavy ion collisions, the coherent two photon mechanism can be applied to produce an intermediate- mass Higgs boson. At coherent pair production mechanism, the cross section behaves as the fourth power of the nuclear charge, relative to the corresponding mechanism at p-p colliders. The coherent pair production at heavy ion collisons provide that the two photon pair production mechanism occurs at distances of far away from the nucleus. Therefore the Higgs boson can be separated from the usual hadronic background. The Weizsacker-Williams method underestimate the coherent production cross sections since the nuclear form factors play important role in the calculation and the form factors are not well identified in this method [6].

First heavy ion collisions were done in Brookhaven National Laboratory (BNL) at the Relativistic Heavy Ion Collider (RHIC) in the mid of 2000 that gave an important contribution to the heavy ion physics. Before RHIC, these type of interactions has been observed only with cosmic rays. Many type of collisions have been studied in the laboratory and their first target was to study on central collisions. The main aim of these collisons at RHIC is to observe the quark-gluon plasma phase that is the signature of a new state of hadronic matter [7].

In this work, a physics of the peripheral collisions are taken into consideration at RHIC and LHC energy regimes. In the collisions, the protons in the nucleus are coherent and the electromagnetic fields that are surrounded by the ion is so strong and acts for a short time. As seen in figure 1, Fermi suggests that the time dependent electromagnetic field can be replaced with the radiation frequency of the field. And this photon spectrum is calculated by the "Weizsacker-Williams method" [7].

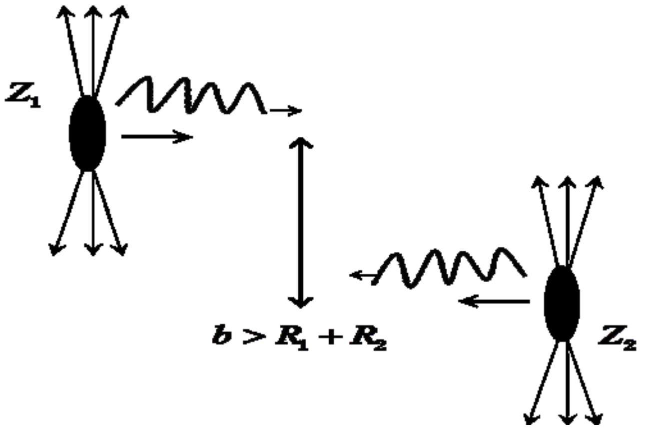

**Figure 1.** Fast nucleus Ze that surrounded by the strong electromagnetic field. The cloud of quasireal photons.

Photon-photon collisions can be observed in hadron-hadron collisions. Relativistic heavy ion collisions is a general method for two photon physics and suggested many years ago. Landau and Lifschitz in 1934 and Racah in 1937 had studied the electron-positron pair production in nucleus-nucleus collisons. After this calculations, many years later the Higgs boson pair production with photon-photon collision is also suggested. Therefore it is clear that strong field of the ultra-relativistic heavy ions at RHIC and LHC are the source of the production of some exotic particles [7].

**Formalism**

In this work, we calculate the cross section of BFPP with the GDR of the ions in lowest-order QED as shown in figure 2. We use the semiclassical approximation in the calculation and the Monte Carlo method to obtain the exact results in Ref. [2]. Bound-free pair production accompanied by giant dipole resonance can be represent as;

$$Z_1 + Z_2 \rightarrow (Z_1^* + e^-)_{1s_{1/2,\dots}} + Z_2^* + e^+ . \tag{2}$$

In the bound free pair production accompanied by giant dipole resonance, the electron is captured by one of the colliding ions that is nuclear excited which leads to the loss of the (one-electron) excited ion from the beam. In our calculations, Monte Carlo techniques were used, and the integrands were tested on about 10 million randomly chosen "positions" to ensure sufficient convergence of our theoretical results. The total numerical error in the computations is estimated to be less than or approximately 5%. And then we calculate the impact parameter dependence cross section of BFPP accompanied by GDR.

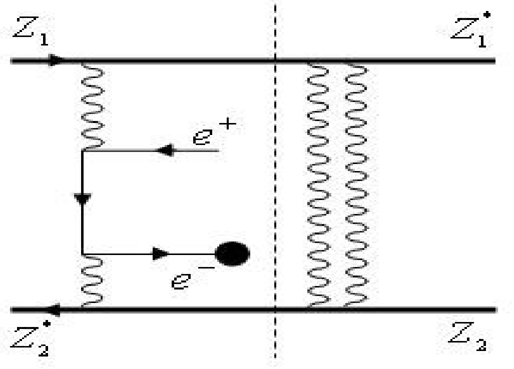

**Figure 2.** Dominant Feynman diagram for two photon reactions BFPP accompanied by GDR in a relativistic heavy ion collision.

The cross sections for the BFPP can be expressed as

$$\sigma = \frac{|N_+|^2}{4\beta^2}\frac{1}{\pi}(\frac{Z}{a_H})^3 \sum_{\sigma_q}\int \frac{d^3q d^2 p_\perp}{(2\pi)^5}\left(\boldsymbol{A}^{(+)}(q:\vec{p}_\perp) + \boldsymbol{A}^{(-)}(q:\vec{q}_\perp - \vec{p}_\perp)\right)^2 \tag{3}$$

where

$$\boldsymbol{A}^{(+)}(q:\vec{p}_\perp) = F(-\vec{p}_\perp:\omega_1)F(\vec{p}_\perp - \vec{q}_\perp:\omega_2)\tau_q(\vec{p}_\perp:+\beta) \tag{4.a}$$

and

$$\boldsymbol{A}^{(-)}(q:\vec{q}_\perp - \vec{p}_\perp) = F(\vec{p}_\perp - \vec{q}_\perp:\omega_2)F(-\vec{p}_\perp:\omega_1)\tau_q(\vec{q}_\perp - \vec{p}_\perp:-\beta) \tag{4.b}$$

are some proper products of the transition amplitudes and scalar parts of the fields as associated with ions *a* and *b* [8].

We found an expression for the impact parameter dependence cross section of free-pair production in Ref. [9]. We used the same method to calculate the impact parameter dependence BFPP cross section. Finally, we reach the impact parameter dependence cross section as

$$P_{BFPP}(b) = \sigma_{BFPP}\frac{a}{2\pi(a^2+b^2)^{3/2}}. \tag{5}$$

In this article, we calculate bound free electron-positron pair production accompanied by GDR, and this process can be seen in figure 2. In addition to the lepton pairs, the nuclei also exchange some photons and this may break up the nuclei. After the GDR, if the nucleus emits only one neutron we show this as ($1n$) [2].

The probability of one Coulomb excitation is

$$P_{C(1n)}(b) = S / b^2 \tag{6}$$

where

$$S = \frac{2\alpha^2 Z^3 N}{A m_N \omega_{GDR}} \approx 5.45 \times 10^{-5} Z^3 N A^{-2/3} fm^2 \tag{7}$$

here $m_N$ is the nucleon mass and the neutron, proton, and mass numbers of the ions are $N$, $Z$, and $A$, respectively. The excitation probability is inversely proportional to the energy $\omega \approx 80 MeV A^{-1/3}$ of the GDR state [2].

The total cross section for BFPP with mutual nuclear excitation can be written as [2];

$$\sigma_{BFPP}^{GDR} = 2\pi \int_{b_{\min}}^{\infty} db\, b\, P_{BFPP}(b) P_{C(1n)}^2(b). \tag{8}$$

**Results and Discussions**

In Table 1, some values of tagged and untagged cross sections are calculated for RHIC and LHC energies for free pair production and bound free pair production. We calculated untagged bound free pair production cross sections and the results are 94.5 b for RHIC and 202 b for LHC collisions. Here we did not include the nuclear excitation processes and these values are shown in the first column in the table. When we include the nuclear excitation processes (mainly the GDR), the results are more than two orders of magnitude smaller than the untagged calculations.

**Table 1.**Integrated cross sections for Au + Au collisions at RHIC energies and for Pb + Pb collisions at LHC energies for free pair production and bound free pair production.

| | $\sigma$ (***barn***) | $\sigma^{1n1n}$ (***barn***) |
|---|---|---|
| Au+Au (RHIC-Free) | 34x10$^4$ | 1.63 |
| Pb+Pb (LHC-Free) | 2.1x10$^5$ | 10.2 |
| Au+Au (RHIC-BFPP) | 94.5 | 4.5x10$^{-3}$ |
| Pb+Pb (LHC-BFPP) | 202 | 9.7x10$^{-3}$ |

This calculations are done by using the Monte-Carlo techniques. Ten million random numbers are used for each variable and the estimated error is about five percent.

**Conclusions**

In this work, we obtained the cross sections of producing electron-positron pairs from the peripheral heavy ion collisions. We have also used the same method for the bound-free pair production processes. This calculations are well agree with the experimental results that were done at SPS and at STAR with some kinematical restrictions. We have also obtained the impact parameter dependence cross sections valid all impact parameters. By using this result, we calculated BFPP with GDR cross sections for $1n1n$ excitations. We have also obtained some results for the future experiments that may be done at LHC.

By using the same procedure and the same method, we can also obtain the cross sections of producing heavy lepton (muons and tauons) pairs, W-pairs, b-quark pairs and possibly the Higgs boson. We will show this calculations in our future works.

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