



Physics of Ultra-Peripheral Collisions at RHIC and LHC

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Abstract. The electron-positron pair production by strong electromagnetic fields is one of the most fascinating processes of relativistic quantum mechanics. In heavy ion collisions, there are two dominant processes that restrict the luminosity of the ion beams. One of them is bound-free electron-positron pair production (BFPP). Antihydrogen atoms are the examples of BFPP mechanism. The other process is giant dipole resonance (GDR). In this work, we compared the cross section results that we calculated in lowest QED order for RHIC and LHC energies for bound-free pair production and anti-hydrogen production.

Keywords: Bound-free electron-positron pair production, antihydrogen production, Monte Carlo calculations.

1. INTRODUCTION

The creation of electron-positron pairs from the vacuum by strong electromagnetic fields is a fundamental and one of the most fascinating processes of relativistic quantum mechanics. Fields sufficiently strong to induce pair creation can be produced, for example, in collisions of bare ions. The process has been studied intensively both in theory and experiment since the 1980s. In peripheral relativistic heavy-ion collisions electromagnetic fields are very strong and interact with each other for a very short time. In these strong fields, probabilities of various electromagnetic processes such as free pair production, bound-free pair production and excitation are large and increase with the Lorentz factor γ . Measurement of cross sections and other relevant distributions are very important for understanding the strong field effect.

In ultra-relativistic heavy ion collisions, there are two dominant processes that restrict the luminosity of the ion beams. One of them is bound-free electron-positron pair production (BFPP) which occurs with the capture of the electron after the free electron-positron pair production and the positron moves freely. This process may lead to a change in the charge and mass of the ions and cause the ion to fall out of the beam. The calculation of the electron capture process is important for the lifetime of the beam.

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The other process that restricts the luminosity of the ion beams is giant dipole resonance (GDR). 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. The excited ions decay by emission of one or more neutrons.

2. MATERIAL and METHODS

2.1 Free pair creation in relativistic heavy-ion collisions

The fully ionized heavy ions collide with energies of 100 GeV and 3400 GeV per nucleon, in their center of mass frames at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC), respectively. Lorentz contracted strong electromagnetic fields are formed around the ions. In the two-photon mechanism for coherent lepton pair production, virtual photon compose the electromagnetic field of the moving ions. These virtual photons may produce an electron-positron pairs in collisions of the photons from the ion coming from the opposite beam [1-3].

$$Z_1 + Z_2 \rightarrow Z_1 + Z_2 + e^- e^+, \quad (1)$$

where $Z_{1,2}$ represents the heavy ions.

While calculating the free electron-positron pair production cross section with the peripheral collision of relativistic heavy ions, the semiclassical coupling of electrons to the electromagnetic field is given by the Lagrangian density,

$$L_{int}(x) = -\bar{\Psi}(x)\gamma_\mu\Psi(x)A^\mu(x). \quad (2)$$

In the Lagrangian density the term $\Psi(x)$ represents the wave function of free electron, γ_μ represents the four vector of the Dirac matrices and it depends on the field variables via the classical four-potential A^μ [4].

For the calculation of free electron-positron pair production, we use plane wave functions for the free electron and positron, respectively.

$$\Psi_k^{(+)} = e^{i\vec{k}\cdot\vec{r}} u_{\sigma_k}^{(+)}, \quad (3.a)$$

$$\Psi_q^{(-)} = e^{-iq\cdot\vec{r}} u_{\sigma_q}^{(-)}. \quad (3.b)$$

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Most of the calculations show that the cross section of free pair production agree with the following equation:

$$\sigma_{free\ pair} \approx Z_1^2 Z_2^2 \ln(\gamma)^3, \quad (4)$$

where Z_1 and Z_2 are the charge numbers of the target and projectile nuclei. Our calculation results for free electron-positron pair production agree with the above equation. The free pair production cross section is proportional to the energy and the square of the charges of the colliding nuclei [5,6].

2.2 Bound-free pair production in relativistic heavy-ion collisions

The bound-free electron-positron pair production has an important role at modern colliders such as RHIC or LHC, because it may restrict the luminosity of the ion beams that will be available. In the bound-free pair production, the electron is captured by one of the colliding ions

$$Z_1 + Z_2 \rightarrow (Z_1 + e^-)_{1s_{1/2}, \dots} + Z_2 + e^+, \quad (5)$$

and leads to the loss of the (one-electron) ion from the beam. BFPP has also an importance to lead to a separate beam of one-electron ions that strikes the beam pipe about 140 m away from the interaction point.

In lowest QED order, BFPP mechanism is described by the two Feynman diagrams, the (so-called) *direct* and *crossed* terms. These terms represent the leading contributions to the BFPP as appropriate especially for the high collision energies available at the RHIC and LHC facilities.

In the electron capture process, after the lepton pair creation, electron is captured by one of the colliding ions and positron becomes free that is described by the plane waves [7,8,9]

$$\Psi_q^{(+)} = N_+ [e^{i\vec{q}\cdot\vec{r}} \mathbf{u}_{\sigma_q}^{(+)}]. \quad (6)$$

In a semirelativistic approximation, these electron states are often represented by [10,11]

$$\psi^{(-)}(\vec{r}) = \left(1 - \frac{i}{2m} \vec{\alpha} \cdot \vec{\nabla}\right) u \frac{1}{\sqrt{\pi}} \left(\frac{Z}{a_H}\right)^{3/2} e^{-Zr/a_H}, \quad (7)$$

of the hydrogen like ion, and where u represents the spinor part of the captured electron and $a_H = 1/e^2$ the Bohr radius of atomic hydrogen.

Using these wave-functions that are described above for leptons, the total cross section can be written as

$$\sigma_{BFPP} = \frac{|N_+|^2}{4\beta^2} \frac{1}{\pi} \left(\frac{Z}{a_H}\right)^3 \sum_{\sigma_q} \int \frac{d^3q d^2p_{\perp}}{(2\pi)^5} \left(\mathbf{A}^{(+)}(q: \vec{p}_{\perp}) + \mathbf{A}^{(-)}(q: \vec{q}_{\perp} - \vec{p}_{\perp})\right)^2 \quad (8)$$

where the functions $\mathbf{A}^{(+)}(q: \vec{p}_{\perp})$ and $\mathbf{A}^{(-)}(q: \vec{q}_{\perp} - \vec{p}_{\perp})$ consist scalar part of the fields as associated with ions a and b and transition amplitudes.

The above equation agrees with

$$\sigma_{BFPP} \approx (Z\alpha)^8 \ln(\gamma), \quad (9)$$

and the BFPP cross section is different from free pair production with a factor Z^4 [12].

2.3 Relativistic antihydrogen production by pair production with positron capture

Antihydrogen atoms are the examples of BFPP mechanism. They are the simplest bound state of antimatter. In this mechanism, antiproton will pass near of the Coulomb field of the nucleus with charge Z and then electron–positron pair will be created. Then, the positron can be captured by the antiproton, as a result, antihydrogen can be created. The electron will move freely,

$$\bar{p} + Z \rightarrow \bar{H} + Z + e^{-}. \quad (10)$$

Antihydrogen atoms have been produced and observed for the first time in the LEAR (Low Energy Antiproton Ring) at CERN in 1995 that the Xenon ($Z = 54$) has been used as a nucleus in this experiment [13–16].

We calculated the cross section of the \overline{H} production by using the same method that we described above [17]. In our calculations, we use semi-classical approximation and we assume that the antiproton goes on a straight way. We described free electron by Sommerfeld–Maue wave function,

$$\Psi_k^{(-)} = N_+[e^{i\vec{k}\cdot\vec{r}}\mathbf{u}_{\sigma_k}^{(-)}]. \quad (11)$$

After the lepton production has occurred, we described captured positron by Darwin wave-function,

$$\psi^{(+)}(\vec{r}) = \left(1 + \frac{i}{2m}\vec{\alpha}\cdot\vec{\nabla}\right)u\frac{1}{\sqrt{\pi}}\left(\frac{Z}{a_H}\right)^{3/2}e^{-Zr/a_H}. \quad (12)$$

For the second order perturbation calculation, we wrote the direct Feynman diagram as:

$$\sigma_{anti-hyd.} = \frac{|N_+|^2}{4\beta^2}\frac{1}{\pi}\left(\frac{Z}{a_H}\right)^3\sum_{\sigma_k}\int\frac{d^3kd^2p_{\perp}}{(2\pi)^5}\left(\mathbf{B}^{(+)}(k:\vec{p}_{\perp})+\mathbf{B}^{(-)}(k:\vec{k}_{\perp}-\vec{p}_{\perp})\right)^2 \quad (13)$$

where the functions $\mathbf{B}^{(+)}(k:\vec{p}_{\perp})$ and $\mathbf{B}^{(-)}(k:\vec{k}_{\perp}-\vec{p}_{\perp})$ consist scalar part of the fields as associated with ions a and b and transition amplitudes. The cross section for the antihydrogen production in collisions of two heavy ions can be written down after taking the amplitudes for the direct and crossed terms [18].

3. RESULTS and DISCUSSION

Calculations in Table 1 display the total production cross sections of free-free electron-positron pairs, bound-free electron-positron pairs and the \overline{H} production.

Table-1 Free pair production, bound-free pair production and antihydrogen production cross sections results for RHIC and LHC collider facilities.

	$\sigma_{free\ pair} (kb)$	$\sigma_{BFPP} (b)$	$\sigma_{anti-hyd.} (mb)$
RHIC	$(Au + Au)$ 34	$(Au + Au)$ 94,5	$(Au + \bar{p})$ 15,3
LHC	$(Pb + Pb)$ 212	$(Pb + Pb)$ 202	$(Pb + \bar{p})$ 31,1

While the free-pair production cross section includes an eight-dimensional integral, the BFPP and \bar{H} production cross sections eventually depend only on five-dimensional integrals. To calculate these cross sections, Monte Carlo techniques are used [12,18].

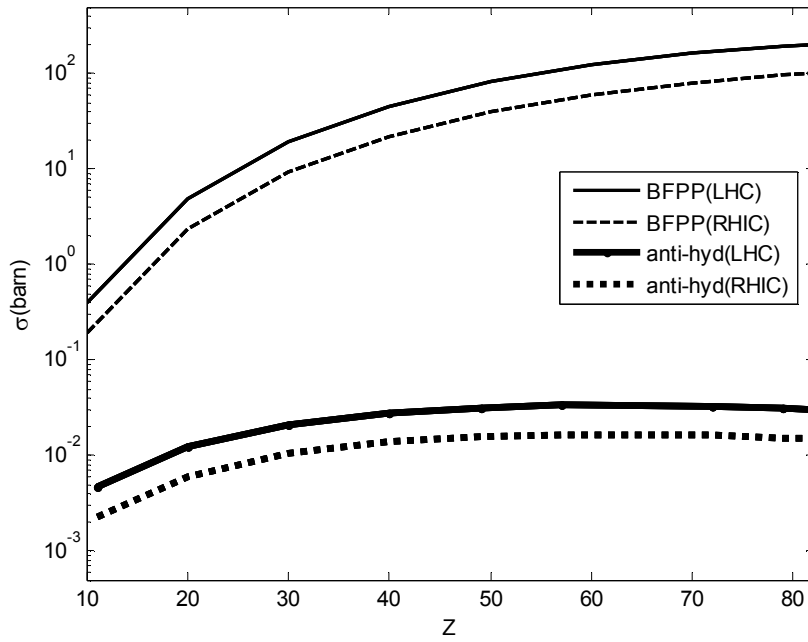


Fig.1 Bound-free pair production and antihydrogen cross sections for RHIC and LHC energy systems as functions of the nuclear charge Z .

Fig.1 displays the BFPP and anti-hydrogen production cross sections as function of the nuclear charge in order to understand the importance of these processes. Cross sections are shown for the two collision energies *RHIC* and *LHC*.

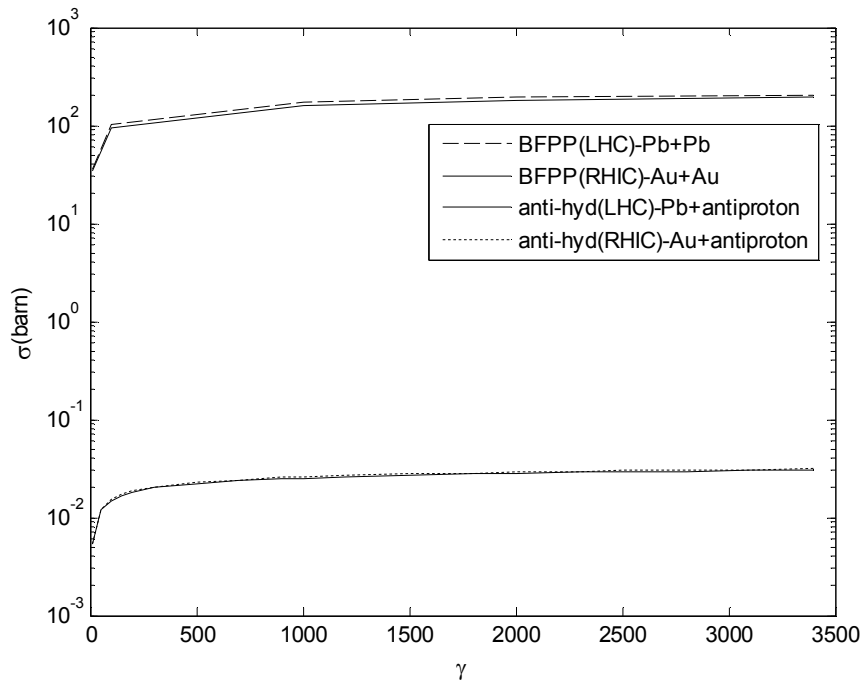


Fig.2 Bound-free pair production and antihydrogen cross sections for two different ions (*Au&Pb*) as functions of γ that the magnitude of it is going from 10 to 3400.

Fig.-2 displays the BFPP and anti-hydrogen production cross sections as functions of the Lorentz contraction factor γ .

While the cross sections for the production of free-pair scale approximately with $\approx (Z\alpha)^4 \ln^3(\gamma)$, the BFPP cross sections increase with $\approx (Z\alpha)^8 \ln(\gamma)$. In this scaling behavior, the reason for an extra factor Z^3 arises from the bound wave function, while another power in Z comes from the normalization constant for the positron wave function. The anti-hydrogen production cross sections includes Z^5 dependence for BFPP, and an extra Z factor comes from the square of the normalization constant [12,18]. In our future work, we are planning to do these cross section calculations for different lepton pairs.

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