Atomic Collisions and free Lepton Pair Production

Cite as: AIP Conference Proceedings **796**, 334 (2005); https://doi.org/10.1063/1.2130191
Published Online: 03 November 2005

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Atomic Collisions and free Lepton Pair Production

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Abstract. In this work, we have calculated the total cross sections of electron-positron pair production for the collisions of fully stripped gold ions for various energies. We have also compared our calculation with other methods.

Keywords: Lepton pair production, Coulomb corrections
PACS: 25.75.-q, 34.90.+q, 12.20.Ds

INTRODUCTION

Particle production via electromagnetic processes in peripheral collisions of relativistic heavy ions has been studied recently both experimentally and theoretically, because it is important at colliding beam accelerators. As an example, fully stripped heavy ions provided by relativistic Heavy-Ion collider (RHIC) and Large Hadron collider (LHC) will collide at 100 GeV and 3400 GeV per nucleon at the center of mass energies respectively. Main goal of these experiments are to create a so-called quark-gluon plasma and to study the physics associated with it. It is expected that ultra-relativistic heavy-ions can provide this form of matter in the central, or near-central collisions. In these central collisions, thermodynamic conditions may become sufficient to deconfine the constituent quarks and gluons of baryons and mesons into a short-lived plasma state. Lepton pairs, especially electron and muon-pair production, from hadronic interactions can help us to monitor the formation and decay of the quark-gluon plasma phase of matter. In these collisions, lepton-hadron final state interactions are generally small, therefore leptons may carry direct informations on the space-time region of their creation.

When heavy ions collide at relativistic velocities, the Lorentz-contracted electromagnetic fields in the space-time region near the collision are sufficiently intense to produce large numbers of electron-positron pairs, muon pairs, vector bosons, weak bosons (Z_0, W^+, W^-) or possibly the yet-unconfirmed Higgs bosons. These collisions are fundamentally different from those involving single charged projectiles because the strength of the coupling constant $Z\alpha$, where Z is the charge and α is the fine structure constant, can be large. Lepton pair production in these systems depends on energy and charge of the colliding nuclei. Although the first order perturbative calculation gives reliable answer for the low charge and energy, these calculations give some unphysical results for the higher charge and energies.

Due to the strong, long range electromagnetic forces between heavy-ions, which are

CP796 Low Energy Antiproton Physics-LEAP '05
edited by Dieter Grzonka, Rafał Czyżykiewicz, Walter Oelert, Tomasz Rożek, and Peter Winter

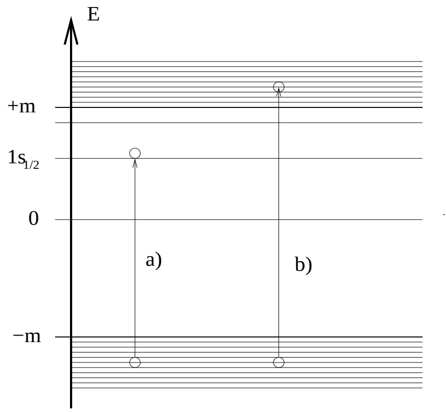

FIGURE 1. (a) bound-electron-free positron pair production and (b) free pair production

peripheral in nature, single/multiple-lepton pair production from the electromagnetic fields of the heavy-ions is a major contribution to the physical background and several authors suggested that these lepton pairs may mask the leptonic signals coming from the quark-gluon plasma phase via the Drell-Yan process. There are also two dominant electromagnetic processes that can lead to beam depletion at RHIC. The electron capture process following pair production during heavy-ion collisions and the Coulomb dissociation of the heavy-ions, following the electromagnetic excitation of the giant dipole resonance are the dominant modes of beam loss mechanism at RHIC. This collider will provide ultra-relativistic fully stripped heavy-ion beams, and the above electromagnetic processes cannot be ignored in detector or accelerator design.

In Figure 1, we illustrated the pair production in which the electron is created in a bound state and pair production in which the electron is created in a continuum state. Previously, we have obtained the impact parameter dependence cross section of [1, 2, 3, 4] electron-positron pair production cross section by calculating the second order Feynman diagrams. Including the direct and exchange terms of Feynman diagrams, the total cross section can be written as

$$\sigma = \int d^2\rho \sum_{\sigma_k}\sum_{\sigma_q} \int \frac{d^3k}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3} \times |\langle \chi_k^+ | S_{direct} | \chi_q^- \rangle + \langle \chi_k^+ | S_{exchange} | \chi_q^- \rangle|^2 \tag{1}$$

where

$$\langle \chi_k^+ | S_{direct} | \chi_q^- \rangle = \frac{1}{4\beta^2} \int \frac{d^2 p_\perp}{(2\pi)^2} e^{i[\mathbf{p}_\perp - (\frac{\mathbf{k}_\perp + \mathbf{q}_\perp}{2})]\cdot\rho} \mathscr{A}^+(k,q;\mathbf{p}_\perp) \tag{2}$$

is the explicit form of the direct term and

$$\langle \chi_k^+ | S_{exchange} | \chi_q^- \rangle = \frac{1}{4\beta^2} \int \frac{d^2 p_\perp}{(2\pi)^2} e^{-i[\mathbf{p}_\perp - (\frac{\mathbf{k}_\perp + \mathbf{q}_\perp}{2})]\cdot\rho} \mathscr{A}^-(k,q;\mathbf{p}_\perp) \tag{3}$$

TABLE 1. Total pair production cross sections for Au + Au collisions. Methods A,B,C and D are the Monte Carlo Calculation, Born Approximation, Born Approximation with Coulomb Corrections and Racah Approximation, respectively.

	10 GeV	100 GeV	3400 GeV
Method A	4349	35148	193499
Method B	5298	42383	233329
Method C	3284	34035	206903
Method D	3622	34087	205073

is the exchange term.

We have calculated the electron-positron pair production cross section exactly by using the Monte Carlo method. In this calculation, we have not made any approximation and calculated the cross sections exactly. On the other hand, the authors in Ref. [5] made a small momentum approximation (small k and small transverse momentum $p_{\perp}$) and obtain an analytic expressions. Although, most of the integration comes from the small momentum range, lowest order in transverse momentum is not adequate to obtain accurate Coulomb corrections and higher orders should be also included. This was first noticed by Tony Baltz [6], and in this work we were also convinced that small momentum approximation alone is not adequate to obtain correct Coulomb corrections.

In a recent paper [7], the Racah formula for the total electron-positron pair production cross section in perturbative theory [8] is given as

$$\sigma_R = \frac{(Z_A\alpha)^2(Z_B\alpha)^2}{\pi m^2}\left\{\frac{28}{27}\mathscr{L}^3 - \frac{178}{27}\mathscr{L}^2 + \frac{370+7\pi^2}{27}\mathscr{L} - \frac{116}{9} - \frac{13\pi^2}{54} + \frac{7}{9}1.202\right\} \tag{4}$$

where

$$\mathscr{L} = log2(2\gamma^2 - 1). \tag{5}$$

Here γ is the Lorentz factor. We have also compared our result with the Racah formula in Table 1.

In addition to this, Monte Carlo calculations and the Born approximation gives similar total cross sections and impact parameter dependence cross sections. However, Born approximation results are valid for the impact parameters only above the one electron Compton wavelength. We made an assumption that, since both results agree for the valid impact parameter region, they should also behave similarly for the small impact parameter region. We have applied our results that are obtained by computational calculations to the Born approximation and obtain well behaved impact parameter dependence cross section and probabilities. We have compared the total e^+e^- pair production cross sections for the calculations of Monte Carlo, Born with Coulomb corrections and the Racah formula. We have also tabulated the total cross sections obtained from these methods for the energies $\gamma = 10, 100$ and 3400 and for the $Au+Au$ collisions in Table 1. These calculations show that the agreement of Monte Carlo calculation, Born approximation with Coulomb correction and the Racah equation is very good especially for $\gamma \geq 20$.

Recent publications about peripheral relativistic heavy-ion collisions [9, 10, 11, 12, 13] show that the impact parameter dependence cross sections of lepton pair production are very important and detail knowledge of impact parameter dependence cross sections particularly for small impact parameters can help to understand many physical events in STAR experiments.

ACKNOWLEDGMENTS

This research is partially supported by the Istanbul Technical University.

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