Hindawi
Advances in High Energy Physics
Volume 2022, Article ID 1456538, 12 pages
https://doi.org/10.1155/2022/1456538

Research Article

Study of Differential Scattering Cross-Section Using Yukawa Term of Medium-Modified Cornell Potential

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Received 18 July 2022; Revised 18 October 2022; Accepted 31 October 2022; Published 8 November 2022

Academic Editor: Theocharis Kosmas

In the present work, we have studied the differential scattering cross-section for ground states of charmonium and bottomonium in the frame work of the medium-modified form of quark-antiquark potential and Born approximation using the nonrelativistic quantum chromodynamics approach. To reach this end, quasiparticle (QP) Debye mass depending upon baryonic chemical potential (μ_b) and temperature has been employed, and hence the variation of differential scattering cross-section with baryonic chemical potential and temperature at fixed value of the scattering angle (θ=90^o) has been studied. The variation of differential scattering cross-section with scattering angle θ (in degree) at fixed temperature and baryonic chemical potential has also been studied. We have also studied the effect of impact parameter and transverse momentum on differential scattering cross-section at $\theta = 90^o$.

1. Introduction

Quantum chromodynamics (QCD) is one among the most important theories which well describes the strong interaction occurring at the subatomic level. Since the cross-section is an important key that paves a way of communication between the real world of the experiment and idealized theoretical models. In the high-energy physics, the term cross-section is used to specify the interaction of elementary particle quantitatively. Cross-section may also be thought of as the area within which the reaction among the elementary particle takes place. Theoretical predictions for the cross-section of the oppositely lepton pairs in pp collisions are accurate up to the next-to-leading order (NLO) and next-to-next-leading order (NNLO) in electroweak and perturbative quantum chromodynamics (PQCD) [1–4], respectively. Precise measurements of the differential cross-section at LHC for the Drel-Yan process (end up with conformal test for the standard model in the perturbative regime) is an important test for the standard model in the perturbative frame. ATLAS [5–7] and CMS [8–10] recently measured the single and double cross-section.

Inclusive quarkonia production in pp collisions is at $\sqrt{s}$ =5.02 TeV. Both the perturbative and nonperturbative fact of QCD can be studied easily in high-energy hadronic collision by considering the quarkonia production [11, 12]. The main consequence of scattering process in hadronic collision is to produce quarkonia. In such process, the momentum transfer should be two times the mass of heavy quark, and hence it can describe under perturbative calculations. But on the other hand, the binding energy of quarkonia comes under the nonperturbative process as it account for large distance scales and soft momentum scales. Various properties of the quark-gluon plasma (QGP) in nucleus-nucleus collision at different energy scales and that of cold matter nuclear effect appearing in AA collision could be investigated by the quarkonium production measurement [12, 13]. The quarkonium production can be described by various approaches. One of the most important countering problems in the QCD is to fully understand the production mechanism of the heavy quarkonia since after the discovery of J/ψ in 1973. According the colored singlet model, the quarkonium states are colorless, and they possesses the same J^{pc} quantum number [14–23].

Production of J/ψ and $\psi(2s)$ cross-section at high P_T was underestimated by the leading order (LO) calculation in colored singlet model by one order of magnitude [24], and this problem was overcome by considering the next-to-leading order (NLO) correction, but this result would not be still able to reduce the gap between color singlet model (CSM) and experimental measurements [25–27]. Thereafter the nonrelativistic QCD model came into existence, which includes both color singlet and color octet studies [28, 29], describing production cross-section at all P_T values but fails to explain the polarization [30–45]. Finally, studies [46–51] solved this countering problem via production of pairs of quarkonia, as the cross-section could be easily interpreted. This quarkonium pair production forbid the feed down of excited C-even states which are very crucial in the single quarkonia production. This typically makes the interpretation of polarization very difficult and hence to compare the data. The double parton process has a significant role for understanding the new physics, e.g, multijets and gave a pave for the transverse momenta of partons. Several new physics phenomenon have been studied by keeping in view of double parton process such as 4-jets by AFS [52], UA2 [53], CDF [54], and ATLAS [55] collaborations; $\gamma + 3$ jets by the CDF [56] and D_o [57, 58] collaborations; $W + 2jets$ [59] and $Y + Y$ [60] by CMS collaborations; $J/\psi + W$ [61], Z+open charm [62], and Y+open charm [63] by the LHC$_b$ collaborations. Quarkonia pairs are independently produced by different partonic interaction in the frame work of double parton process could by estimated by the formula [64–66].

In this present paper, we studied the differential scattering cross-section for the ground state of quarkonia (i.e, J/ψ and Y), in the presence of temperature, baryonic chemical potential (μ_b), and the scattering angle (θ). To carry out this, we use the Born approximation for calculating the scattering amplitude and differential scattering cross-section. For calculating the differential scattering cross-section, the potential we consider is the medium-modified form of Cornell potential (Here, we take only the Yukawa term and neglect the other terms of the potential). Differential scattering cross-section mainly define the probability of finding the particle in a certain area, and hence scattering angle θ plays a major role while studying the quarkonium production.

The manuscript organized in the following manner. In the Section II, we provide an outline for the quark-antiquark potential. Section III deals with the Debye mass depending upon temperature and baryonic chemical potential. Section IV deals with formulation of differential scattering cross-section using nonrelativistic limit of quantum field theory. In Section V, we briefly discussed about the result and conclusions of this present work.

2. Medium-Modified Form of Cornell Potential

Since from [67], it has been seen that there is also nonperturbative calculations at deconfinement temperature instead of the perturbative and ideal gas behavior according to thermodynamical studies of the QCD. Following [67], one cannot drops the string tension arising between the quark-antiquark pairs above the critical temperature T_c. Medium modification to the quark-antiquark potential provides a reliable way to study the fate of the quarkonia. Here, the quark-antiquark potential has been corrected which embodied the medium effect [68]. In [69, 70], the authors assume that the string is melting, keeping in view that there is phase transition from the hadron matter to the quark-gluon plasma. Accordingly, the potential has been modified to study the deconfined state of matter. Also, at vanishing baryon density, there is cross-over rather than a phase transition. These indications come from the lattice studies. Bound state solutions of both relativistic and nonrelativistic wave have attracted more intention from the last decades.

The energy of these bound states is negative due to the fact that the energy of the quark-gluon plasma is less than the potential energy [71]. Schrodinger equation accounts for the nonrelativistic wave, whereas for the relativistic wave Klein-Gordan and Dirac equation are of utmost important [72–79]. There are various potentials that have been used to study the quarkonia bound states like Hulthen, Poschl Teller, Eckart, and Coulomb potential, and these are studied using special techniques AEIM, SUSYQM, and NU methods [80–90]. In the present work, we preferred to work with the Cornell potential which has both Coulombic as well as string part [91, 92], and here, we take only the Coulombic part of the said potential. This is because of the fact that the mass of quarkonia $m_Q \geq \lambda_{QCD}$, small velocity of the bound states pushes to understand these phenomenon in terms of nonrelativistic potential model.

In case of finite temperature QCD, we employ the ansatz that the medium modification enter in the Fourier transform of heavy quark potential V(k) as [93].

$$\tilde{V}(k) = \frac{V(k)}{\varepsilon(k)}, \tag{1}$$

where $\varepsilon(k)$ is dielectric permittivity which is obtained from the static limit of the longitudinal part of the gluon self-energy.

$$\varepsilon(k) = \left(1 + \frac{\pi_L(0, k, T)}{k^2}\right) \equiv \left(1 + \frac{m_D^2(T, \mu_b)}{k^2}\right). \tag{2}$$

V(k) is the Fourier transform of the Cornell potential given as

$$V(k) = -\sqrt{\frac{2}{\pi}}\frac{\alpha}{k^2} - \frac{4\sigma}{\sqrt{2\pi}k^4}. \tag{3}$$

Substituting the value of Equations (2) and (3) in Equation (1), and solving using inverse Fourier transform, we get the medium-modified potential depending upon 'r'

[94–98].

$$V(r,T,\mu_b) = \left(\frac{2\sigma}{m_D^2(T,\mu_b)} - \alpha\right)\frac{\exp\left(-m_D(T,\mu_b)r\right)}{r} - \frac{2\sigma}{m_D^2(T,\mu_b)r} + \frac{2\sigma}{m_D(T,\mu_b)} - \alpha m_D(T,\mu_b). \tag{4}$$

3. The Debye Mass with Baryonic-Chemical Potential from a Quasiparticle Picture of Hot QCD

In studies of the quantum mechanical properties of the quarkonia, Debye mass has played a significant role. Generalization of the Debye mass has been made from the quantum electrodynamics (QED) to QCD because of the non-Abelian nature of the QCD. In QCD, the Debye mass obtained is gauge invariant and nonperturbative, whereas the temperature dependent leading order Debye mass is perturbative and is known from a long time ago [99, 100]. The Debye mass can also be defined as the pole static quark propagator [101] instead of limit $p \longrightarrow 0$ in the gluon self-energy. Authors in [101, 102] also calculated Debye mass for the NLO in QCD using Polyakov loop correlator matching with HTL result.

Several studies have been devoted to include all the interaction present in the hot QCD equation of states (EoS) in terms of the quasipartons. Some of them include effective mass models, effective mass models with Polyakov loop, PNJL, NJL model, and effective fugacity model [103–107].

To understand the nonideal behavior of the quark-gluon plasma near the cross-over region, quasiparticle model has played eminent role. The interacting system of massless quarks and gluons is considered as the massive system in quasiparticle (QP) model [107]. In our present calculation, we use the quasiparticle model to study the quarkonia properties. All the interaction effects could be related to the $Z_{q,g}$ term in the distribution function of the quasipartons.

In our calculation, we use the Debye mass m_D for full QCD case which is

$$m_D^2(T) = g^2(T)T^2\left[\left(\frac{N_c}{3}\times\frac{6PolyLog[2,z_g]}{\pi^2}\right) + \left(\frac{\widehat{N}_f}{6}\times\frac{-12PolyLog[2,-z_q]}{\pi^2}\right)\right], \tag{5}$$

$$\widehat{N}_f = \left(N_f + \frac{3}{\pi^2}\sum\frac{\mu_q^2}{T^2}\right), \tag{6}$$

and we also know that, the quark chemical potential is equal to

$$\mu_q = \frac{\mu_b}{3}, \tag{7}$$

where (μ_q) defined the quark chemical potential and (μ_b) is baryonic chemical potential. Introducing the value of $\widehat{N}_f$ in the Equation (5), we get the full expression of quasiparticle Debye mass in terms of temperature and baryonic chemical potential.

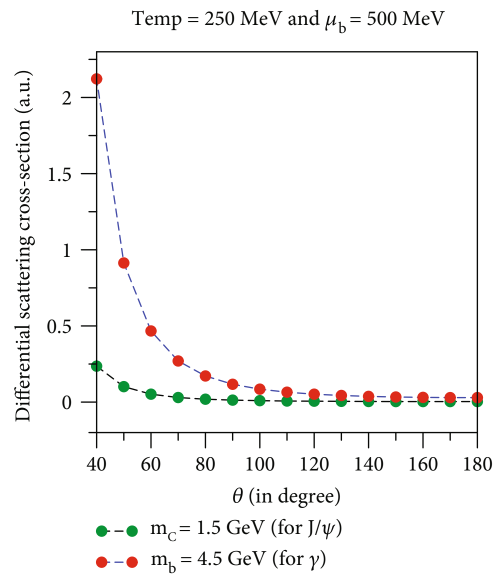

FIGURE 1: The variation of differential scattering cross-section as a function of theta after considering the values of charmonium and bottomonium masses at constant temperature and μ_b.

$$m_D^2(T,\mu_b) = T^2\left\{\left[\frac{N_c}{3}Q_g^2\right] + \left[\frac{N_f}{6} + \frac{1}{2\pi^2}\left(\frac{\mu_b^2}{9T^2}\right)\right]Q_q^2\right\}. \tag{8}$$

Here, $g(T)$ is the QCD running coupling constant, $N_c = 3$ is the number of color, and N_f is the number of flavor. The function $PolyLog[2,z]$ having form, $PolyLog[2,z] = \sum_{k=1}^{\infty}(z^k/k^2)$ and z_g is the quasi-gluon effective fugacity and z_q is quasi-quark effective fugacity.

$$f_{g,q} = \frac{z_{g,q}\exp(-\beta p)}{\left(1 \pm z_{g,q}\exp(-\beta p)\right)}. \tag{9}$$

These distribution functions are isotropic in nature. These fugacities have been introduced the all interaction effects present within the baryonic chemical potential. Both z_g and z_q have a very complicated temperature dependence and asymptotically reach to the ideal value unity [108]. The temperature dependence z_g and z_q fit well to the form given below,

$$z_{g,q} = a_{q,g}\exp\left(-\frac{b_{g,q}}{x^2} - \frac{c_{g,q}}{x^4} - \frac{d_{g,q}}{x^6}\right). \tag{10}$$

Here, $x = T/T_c$ and a, b, c, and d are fitting parameters, for both EOS1 and EOS2. Here, EoS1 is the $O(g^5)$ hot QCD and EoS2 is the $O(g^6\ln(1/g))$ hot QCD EoS in the quasiparticle description [94, 106], respectively. Where Q_g

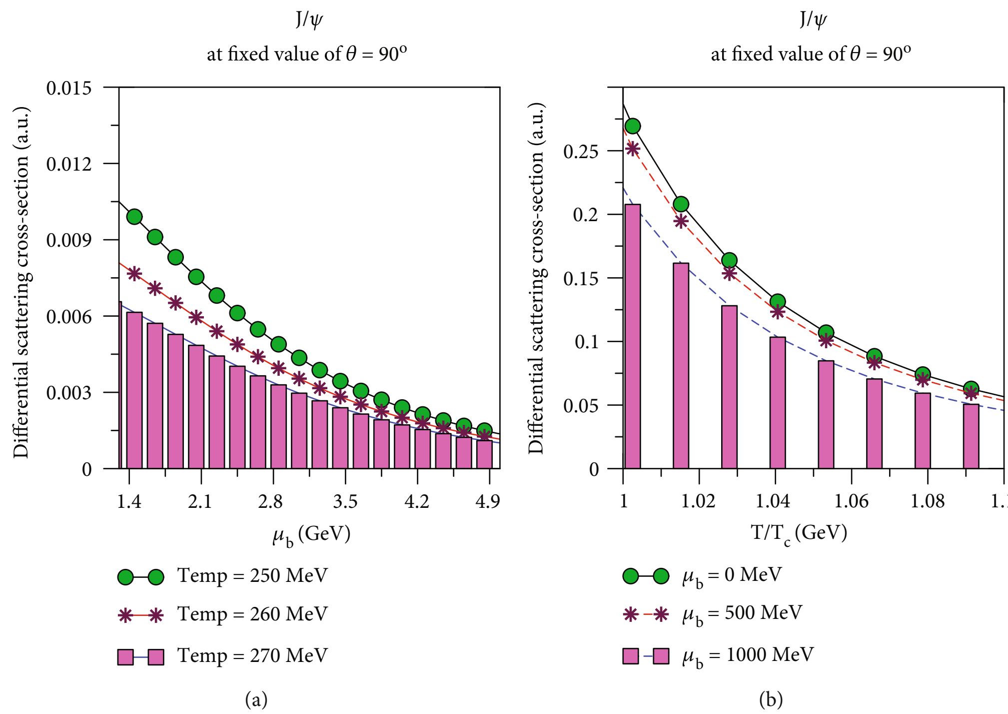

Figure 2: The variation of J/ψ differential scattering cross-section as a function of μ_b at different values of temperature (a) and as a function of T/T_c at different values of baryonic chemical potential (b).

and Q_q are the effective charges given by

$$Q_g^2 = g^2(T)\frac{6\text{PolyLog}[2, z_g]}{\pi^2}, \tag{11}$$

$$Q_q^2 = g^2(T)\frac{-12\text{PolyLog}[2,-z_q]}{\pi^2}. \tag{12}$$

In our present analysis, the temperature and baryonic chemical potential dependent quasiparticle Debye mass, m_D^{QP} in full QCD with $N_f = 3$ have been employed to study the differential scattering cross-section of the ground states of quarkonia.

4. Formulation of Differential Scattering Cross-Section Using Nonrelativistic Limit of Quantum Field Theory (QFT)

In the nonrelativistic limit, the QFT equation for the S-matrix is reduced to the Lippmann-Schwinger equation for the scattering amplitude. The Lippmann-Schwinger equation is equivalent to the Schrodinger equation. In nonrelativistic quantum mechanics, the first order Born approximation of the elastic scattering amplitude is given by the Fourier transform of the potential. Correspondingly, the potential is given as inverse Fourier transform of the scattering amplitude.

In classical scattering theory, the essential countering problem is as follows: (a) to measure the impact parameter and (b) to calculate the scattering angle. But in the quantum scattering theory, the solution to the Schrodinger equation paves a good way to understand the scattering process for the proper wave function. Here, quantum description of scattering of nonrelativistic particles of mass m_1 and m_2 has been considered. For simplicity, we consider the case of elastic scattering. The interacting potential between particles is supposed to be time independent, and obviously time independent Schrodinger equation with the wave function has been used to obtaine the scattering amplitude formula, for the calculation of differential scattering cross-section.

$$\left[-\frac{\hbar^2}{2m_1}\nabla_1^2 - \frac{\hbar^2}{2m_2}\nabla_2^2 + V\left(\vec{r}_1, \vec{r}_2\right)\right]\psi\left(\vec{r}_1, \vec{r}_2\right) = E_T\psi\left(\vec{r}_1, \vec{r}_2\right), \tag{13}$$

where E_T is the total energy of the system, and this body problem can be reduced into a one-body problem, and then the Schrodinger equation will be

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V\left(\vec{r}\right)\right]\psi\left(\vec{r}\right) = E_T\psi\left(\vec{r}\right). \tag{14}$$

Now, we have to find wave function by solving Equation (14). And this is obtained by complex calculations using green function as following:

$$\psi\left(\vec{r}\right) = \Phi_{inc}\left(\vec{r}\right) - \frac{\mu}{2\pi\hbar^2}\int \frac{e^{ik\left|\vec{r}-\vec{r}'\right|}}{\left|\vec{r}-\vec{r}'\right|} V\left(\vec{r}'\right)\psi\left(\vec{r}'\right)d^3r', \tag{15}$$

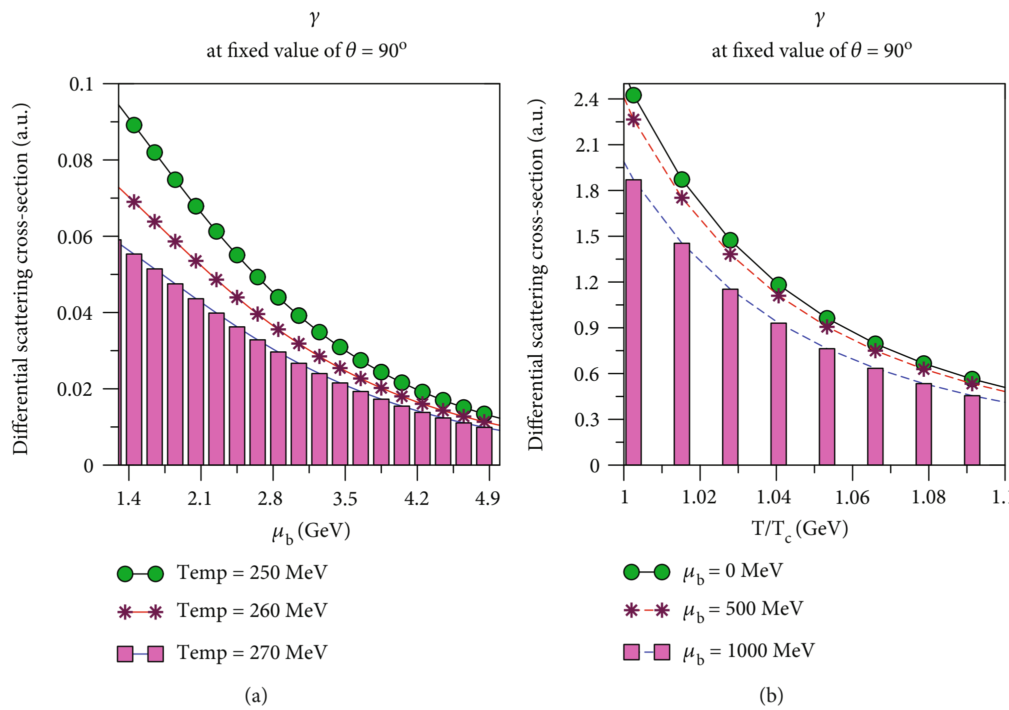

FIGURE 3: The variation of Y differential scattering cross-section as a function of μ_b at different values of temperature (a) and as a function of T/T_c at different values of baryonic chemical potential (b).

where $\psi(\vec{r})$ is the wave function after scattering. To find scattering amplitude, we will apply asymptotic limit on Equation (15) and will compare this wave function to the wave function in asymptotic limit that is discussed below for asymptotic limit is

$$\psi(r,\theta) \cong A\left\{e^{ikz} + f(\theta,\Phi)\frac{e^{ikr}}{r}\right\}. \tag{16}$$

The wave function in asymptotic limit after scattering will contain an unscattered plane wave plus a scattered spherical wave. We consider $A = 1$ because it does not contribute in $d\sigma/d\pi$.

$$k\left|\vec{r} - \vec{r}\,'\right| = kr - \vec{k}\,\vec{r}\,', \tag{17}$$

$$\frac{1}{\left|\vec{r} - \vec{r}\,'\right|} = \frac{1}{r}, \tag{18}$$

$$\psi\left(\vec{r}\right) = \Phi_{inc}\left(\vec{r}\right) - \frac{\mu}{2\pi\hbar^2}\int \frac{e^{i\left(kr-\vec{k}\,\vec{r}\,'\right)}}{r} V\left(\vec{r}\,'\right)\psi\left(\vec{r}\,'\right)d^3r', \tag{19}$$

$$\psi\left(\vec{r}\right) = \Phi_{inc}\left(\vec{r}\right) - \frac{\mu}{2\pi\hbar^2}\frac{e^{ikr}}{r}\int e^{-ikr'} V\left(\vec{r}\,'\right)\psi\left(\vec{r}\,'\right)d^3r'. \tag{20}$$

Now, compare it with

$$\psi\left(\vec{r}\right) = \Phi_{inc}\left(\vec{r}\right) + f(\theta,\Phi). \tag{21}$$

So, scattering amplitude is

$$f(\theta,\Phi) = -\frac{\mu}{2\pi\hbar^2}\int e^{-i\vec{k}\,\vec{r}\,'} V\left(\vec{r}\,'\right)\psi\left(\vec{r}\,'\right)d^3r'. \tag{22}$$

Now, using first order Born approximation, then the above expression is

$$f(\theta,\Phi) = -\frac{\mu}{2\pi\hbar^2}\int e^{i\vec{q}\,\vec{r}\,'} V\left(\vec{r}\,'\right)d^3r'. \tag{23}$$

Now, we consider the spherically symmetric potential,

$$f(\theta,\Phi) = -\frac{\mu}{2\pi\hbar^2}\int e^{i\vec{q}\,\vec{r}\,'} V(r) r^2 \sin\theta dr d\theta d\Phi. \tag{24}$$

This is the modified form of Born approximation mainly not necessarily at low energy. But the simplest form of spherical symmetry amplitude after complete solution we get,

$$f(\theta,\Phi) \cong -\frac{2m_{Q\bar{Q}}}{q\hbar^2}\int_0^\infty rV(r)\sin qr dr. \tag{25}$$

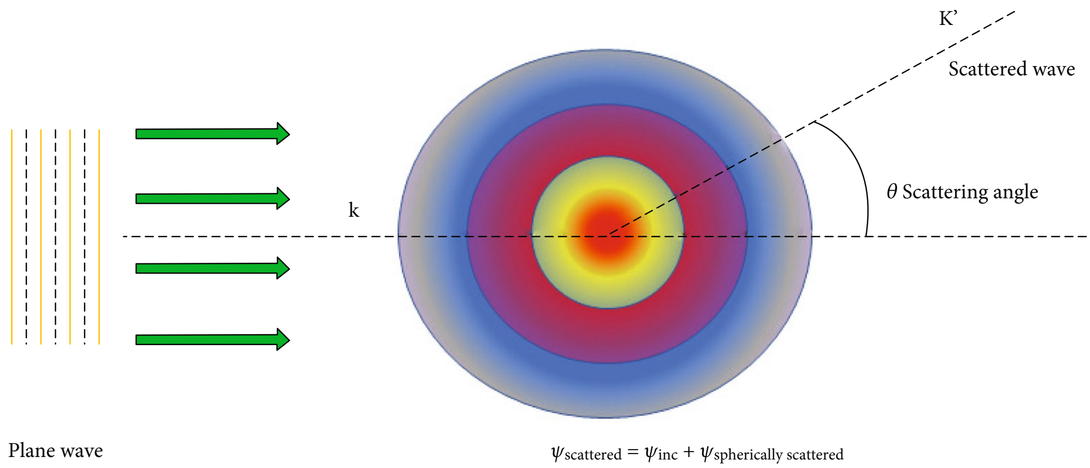

FIGURE 4: This figure shows the interaction of scattered wave and plane wave with the potential V(r).

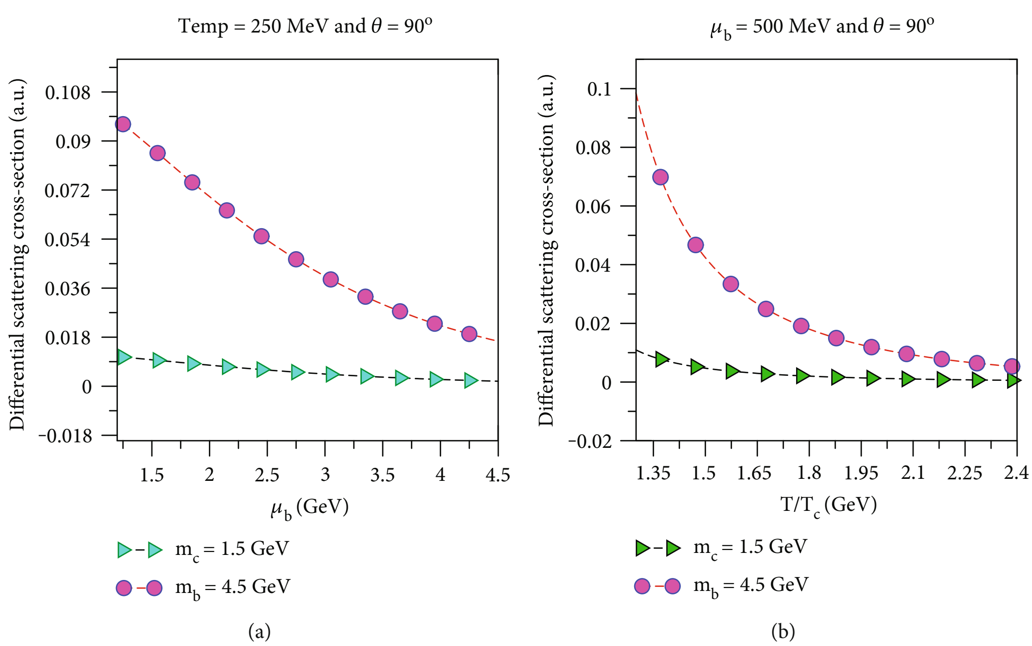

FIGURE 5: The variation of differential scattering cross-section as a function of μ_b at fixed values of temperature and theta (a) and as a function of T/T_c at fixed value of μ_b and theta (b) after considering the values of charmonium and bottomonium masses.

The angular dependence of f is carried by q,

$$q = 2k \sin \frac{\theta}{2}. \quad (26)$$

We consider the r-dependence of the medium-modified Cornell potential Equation (4) for the calculation of differential scattering cross-section, we consider only Yukawa term and neglect the constant term of the Equation (4) then we get,

$$V(r) = \left[\frac{2\sigma}{m_D^2} - \alpha\right] \frac{\exp(-m_D r)}{r} - \frac{2\sigma}{m_D^2 r}. \quad (27)$$

Now, we used Equation (25) (scattering amplitude formula) for the above potential Equation (27) to calculate the differential scattering cross-section, and hence the result of differential scattering cross-section is shown below,

$$\frac{d\sigma}{d\Omega} = |f(\theta, \mu_b)|^2 = \left[\frac{2\sigma}{m_D^2} - \alpha\right]^2 \left[\frac{m_q}{m_D^2 + (10 \sin(\theta/2))^2}\right]^2 + \left[\frac{2m_q\sigma}{m_D^2(10 \sin(\theta/2))^2}\right]^2. \quad (28)$$

We also calculate the differential scattering cross-section in terms of impact parameter and momentum transfer which is described below,

$$b = \frac{a}{2} \cot \frac{\theta}{2}. \quad (29)$$

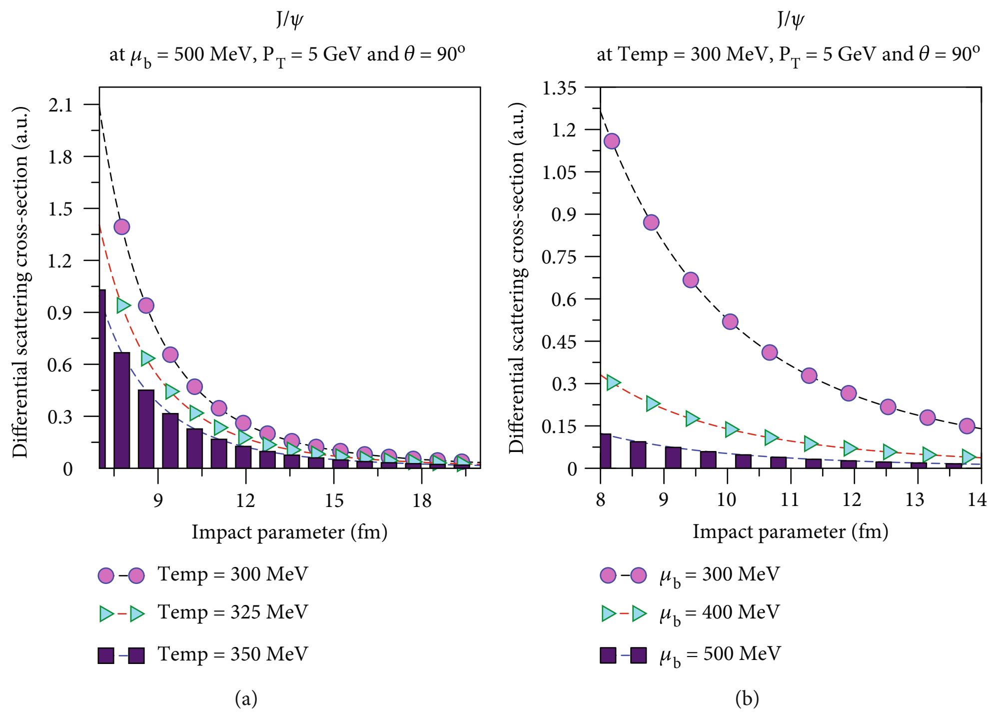

FIGURE 6: The variation of J/ψ differential scattering cross-section as a function of impact parameter at different values of temperature (a) and at different values of baryonic chemical potential (b).

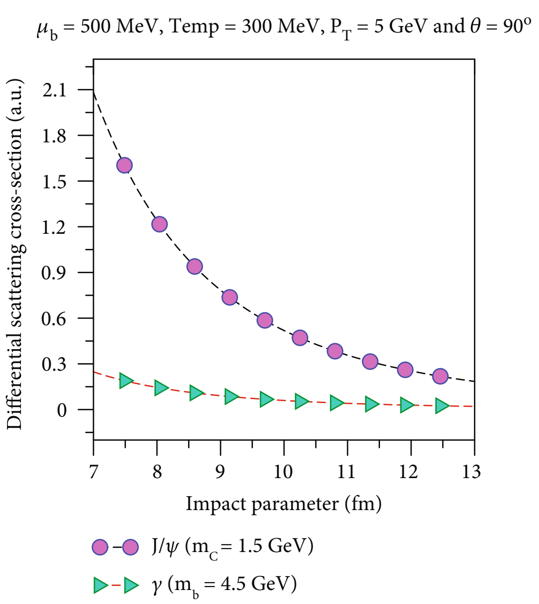

FIGURE 7: The variation of differential scattering cross-section as a function of impact parameter after considering the values of charmonium and bottomonium masses.

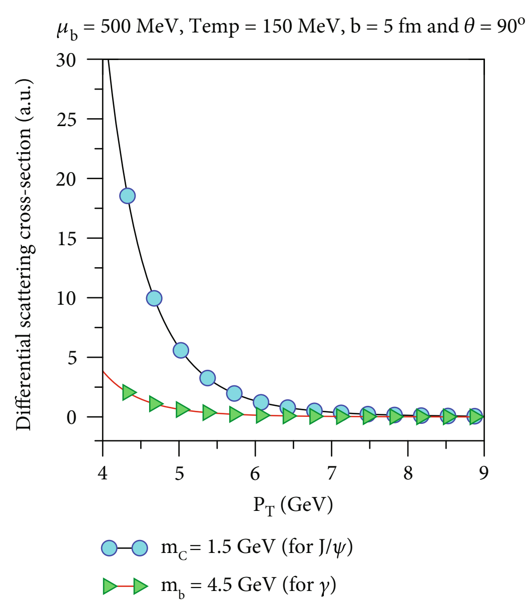

FIGURE 8: Variation of the differential scattering cross-section with the transverse momentum (P_T) at $\mu_b = 500$ MeV, θ=90^o, and impact parameter $b = 5$ fm and temperature $T = 150$ MeV.

After considering the semiclassical consideration, for H-atom like problem ($z_1 e = z_2 e \approx 1$), the value of a is

$$a = \frac{z_1 z_2 e^2}{m v^2}. \quad (30)$$

So, after considering the Equation (30), the Equation (29) is changed into the Equation (31), i.e,

$$\sin\frac{\theta}{2} = \frac{m_q \cos(\theta/2)}{2P_T^2 \sin(\theta/2)}. \quad (31)$$

Now, put the value of Equation (31) into the Equation (28), then the differential scattering cross-section is converted into the Equation (32) in terms of impact parameter and momentum transfer.

$$\frac{d\sigma}{d\Omega} = |f(\theta, \mu_b)|^2 = \left[\frac{2\sigma}{m_D^2} - \alpha\right]^2 \left\{\frac{m_q}{m_D^2 + \left[10m_q \cos\theta/2/2bP_T^2\right]^2}\right\}^2 + \left\{\frac{2m_q\sigma}{m_D^2\left[10m_q \cos(\theta/(2))/2bP_T^2\right]^2}\right\}^2. \tag{32}$$

5. Results and Conclusions

In the present paper, we have studied the differential scattering cross-section for quarkonium ground states, i.e, charmonium (J/ψ state) and bottomonium (Y state) using Nonrelativistic limit of quantum field theory (QFT). Figure 1 shows the variation of differential scattering cross-section as a function of theta for different masses of the quarkonia (for J/ψ = 1.5 GeV and for $Y = 4.5$ GeV). It has been seen from Figure 1 that the variation of differential scattering cross-section for Y is greater than that of J/ψ at $T = 250$ MeV and $\mu_b = 500$ MeV. It has been also observed that if the value of θ increases, the separation between the differential scattering cross-section of Y and J/ψ is decreased. This is because of the fact, with the increase in the values of θ, the probability of finding the particle (J/ψ and Y) decreases.

Figures 2 and 3 show that the variation of differential scattering cross-section as a function of μ_b (a) at different values of temperature and as a function of temperature (b) at different values of μ_b at fixed value of $\theta = 90^o$ for the J/ψ and for Y, respectively. It has been seen that the differential scattering cross-section as a function of μ_b and temperature is decreases exponentially. If we increase the values of temperature (b), then variation of differential scattering cross-section is also decreased. With the increase in the values of baryonic chemical potential μ_b (b), the variation of differential scattering cross-section is decreased but the effect of μ_b is smaller as compared to the temperature which can be seen from of Figures 2(b) and 3(b), respectively.

Figure 4 shows the interaction of plane wave with the potential V(r), after interaction, the plane wave scattered spherically. The interacting potential between particles is considered as time independent potential given in Equation (27), and here, we use time independent Schrodinger equation to calculate the differential scattering cross-section expression which is given in Equation (28).

Whereas, Figure 5 shows the variation of differential scattering cross-section as a function of baryonic chemical potential at fixed value of $\theta = 90^o$ and temperature ($T = 250$ MeV) (a) and (b) as a function of T/T_c for the fixed value of μ_b and θ (i.e., $\mu_b = 500$ MeV and $\theta = 90^o$) and for mass $m_{J/\psi} = 1.5$ GeV and $m_Y = 4.5$ GeV, respectively. It has been clearly seen from Figure 5 that the variation of differential scattering cross-section of Y is greater than in comparison to J/ψ because mass of Y is greater than as compared to J/ψ.

Figure 6 shows the variation of differential scattering cross-section for the fixed value of transverse momentum $P_T = 5$ GeV and $\theta = 90^o$ as a function of impact parameter at different values of temperature and fixed baryonic chemical potential $\mu_b = 500$ MeV (a) and at different values of the baryonic chemical potential and fixed temperature $T = 300$ MeV (b). Also, differential cross-section of the quarkonium production is decreased with impact parameter. In the case of impact parameter, the variation of differential scattering cross-section is also decreased with the increase of temperature and baryonic chemical potential.

Figure 7 shows the variation of differential scattering cross-section for the fixed values of the temperature ($T = 300$ MeV), baryonic chemical potential ($\mu_b = 500$ MeV), transverse momentum ($P_T = 5$ GeV), and $\theta = 90^o$ with impact parameter for charmonium ($m_{J/\psi} = 1.5$ GeV) and bottomonium ($m_Y = 4.5$ GeV) masses. It has been clearly seen from Figure 4, that the variation of differential scattering cross-section of J/ψ is greater than in comparison to Y with respect to impact parameter.

Finally, Figure 8 shows how the differential scattering cross-section varies with the transverse momentum at $\mu_b = 500$ MeV, $\theta = 90^o$, $b = 5$ fm, and $T = 150$ MeV. It has been also observed that there is strong decrease in the differential cross-section with the transverse momentum for higher masses, and same behavior of deferential scattering cross-section is observed like impact parameter.

Usually, the scales one encounters are P_T, m_Q, $m_Q\lambda$, and $m_Q\lambda^2$, where P_T, m_Q, and λ are the transverse momentum, heavy quark mass, and heavy quark-antiquark pair relative velocity in the quarkonium rest frame (λ^2 is 0.1 for bottomonium and 0.3 for charmonium). For moderate and high transverse momentum, $P_T \| 2m_Q$ is the established and most successful theory that describes quarkonium production and decays in nonrelativistic QCD [34, 38], and this theory is very useful for showing the accurate description of this kind of purpose.

In recent years, different phenomenological approaches have been proposed to describe the modification of the production cross-section of moderate and high transverse momentum quarkonia. Theoretical guidance on the relative significance of the various nuclear effects in the currently accessible transverse momentum range can be very useful.

Finally, we have concluded that the probability of finding the particle (charmonium $m_{J/\psi} = 1.5$ GeV and bottomonium $m_Y = 4.5$ GeV) depends upon the scattering angle (θ^o), temperature (T/T_c), and baryonic chemical potential μ_b. Although the baryonic chemical potential shows small effect in comparison to the temperature. Moreover, differential scattering cross-section shows the strong decrease with increase in the impact parameter as well as in the transverse momentum. This work might be helpful in understanding the process of quarkonia production under different parameters such as temperature, and baryonic chemical potential. It is also useful to investigate the scattering rates of quarkonia. It would also provide a large amount of information regarding the internal structure of the colliding particles.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

One of the authors, VKA acknowledges the Science and Engineering Research Board (SERB) Project No. EEQ/2018/000181, New Delhi for providing the financial support. We record our sincere gratitude to the people of India for their generous support for the research in basic sciences.

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