IHJPAS. 35(4)2022

Ibn Al-Haitham Journal for Pure and Applied Sciences

Journal homepage: http://jih.uobaghdad.edu.iq/index.php/j/index

Theoretical Calculation of Photon Emission from Quark-Antiquark Annihilation Using QCD Theory

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Article history: Received 6 June 2022, Accepted 21 August 2022, Published in October 2022.

Doi: 10.30526/35.4.2879

Abstract

In this work, we calculate and analyze the photon emission from quark and anti-quark interaction during annihilation process using simple model depending on phenomenology of quantum chromodynamic theory (QCD). The parameters, which include the running strength coupling, temperature of the system and the critical temperature, carry information regarding photon emission and have a significant impact on the photons yield. The emission of photon from strange interaction with anti-strange is large sensitive to decreases or increases there running strength coupling. The photons emission increases with decreases running strength coupling and vice versa. We introduce the influence of critical temperature on the photon emission rate in order to facilitate its further applied in photon emission spectrum. Photon emission was increased with large critical temperature $T_c = 143\,\mathrm{MeV}$ comparing with photons emission at critical temperature $T_c = 126\,\mathrm{MeV}$. We analyze and discuss the sensitive of the emission of photon to photons energy $\mathrm{E}_\gamma = 1.5\,\mathrm{GeV}$ to $5\,\mathrm{GeV}$. It increases with decreased photons energy and vice versa. However, the photons emission increases with increases thermal energy of system T = 170 MeV to 270 Mev. It is implied that strength coupling, critical temperature and photons energy can be as important as thermal energy of system for emission of photon.

Key words: Photon emission, Quark-Antiquark, Annihilation, QCD Theory.

1.Introduction

The elementary particle is an important field of physics, it deals with the fundamental building block of matter and their interactions. It's part of the Standard Model, that's the most successful grand model of fundamental physics [1]. In the 1960s, a variety of strong interaction particles are observed in experiments on nucleons [2]. Latterly, both George Zweig and Murray Gell-Mann introduce and proposed independently the quark model to describe hadrons in 1964 [3]. It fundamentally classification hadrons into mesons and baryons. The mesons contain quark-antiquark while the baryons have three quark in bound states [4]. The standard model is the best model to describe the collision at higher energies for quarks interaction due to fundamental interactions by which it's influenced [5]. Recently, different theories are introduced to investigate and study the interaction of quark-gluon and the construction of the nature of nucleon structure [6]. The basic constituents of the nucleon are quarks and gluon. these quarks and gluons play a key role to produce nucleon mass. The spin of quarks fermion is 1/2 and has a spin equal to one [7]. The quark-gluon interaction matter has been observed and produced in relativistic heavy-ion collisions at the BNL collider. However, the complementary measurements at the CERN had been performed together with the development of the quantum kinetic theories [8]. Shortly after the quarks model, several models were developed to investigate the characteristic of hadrons in terms of the quarks mode. Greenberg introduces the color hypothesis that describes the quarks as fermions having three color degrees of freedom [9]. Recently, the structure of hadrons was understood from focused on the separated roles of gluons and quarks from theoretical and experimental work and integral properties; the quark and gluon spin and angular momentum[10]. Due to the color confinement, the quarks are bounded into the hadrons by a variety of configurations. The baryons are formed by three quarks in nucleons and mesons make by the pair of quark and antiquark, they observe in collision experiments [11]. Photons are produced in a variety of sources; prompt photons, thermal photons and photons are produced by hard interaction . There create experimentally in heavy-ion collisions [12]. The quark-antiquark state produces in the laboratory. It uses to investigate the transition in the nuclear matter in which quarks and gluons are confined in hadron [13]. In this paper, we present a theoretical calculation of photon rate that's emission from the annihilation of quark and antiquark using the QCD model.

2.Theory

The rate of photons emission from annihilation reaction of quark anti quarks is[3].

$$R_{ph} = \frac{4{N_s}^2}{(2\pi)^6} F_q\left(p_\gamma\right)(\frac{e_q}{e})^2 \int \sigma_a(s)\sqrt{s(s-4m^2)}\, ds. \frac{1}{4E_\gamma}\int_{\frac{s}{4E_\gamma}}^{\infty} F_{\bar{q}}\left(p_{\bar{q}}\right)[1+F_g\left(p_{\bar{q}}\right)dE_{\bar{q}} \int_0^{2\pi} d\phi \ldots(1)$$

Where N_s, e_q and e are number of spins, charges and electric charge of quarks $\sigma_a(s)$ is cross section, $F_q\left(p_\gamma\right)$ and $F_{\bar{g}}\left(p_{\bar{q}}\right)$ are Juttner distribution of quark and gluon, $E_{\bar{q}}$ and E_γ are quark and photons energy, $ds, d\phi$ and $dE_{\bar{q}}$ are element of momentum, solid angle and quarks energies. The Juttner function of quark distribution relative to fugacity of anti-quarkλ_q is [14].

$$\mathrm{F}_{\bar{q}}\left(E_{\bar{q}}\right) = \lambda_{\bar{q}}(e^{\frac{E_{\bar{q}}}{T}}+1)^{-1} \qquad (2)$$

And the distribution of gluon $\mathrm{F}_B(\mathrm{E})$ relative tofugacity of gluon λ_g is [15].

$$F_g(E_g) = \lambda_g (e^{E_g/T} - 1)^{-1} \qquad (3)$$

Inserting Eqs.(2) and (3) in Eq.(1) and integral over $E_{\bar{q}} \geq \frac{s}{4E_\gamma}$ to obtaine[16].

$$R_{ph} = \frac{4{N_s}^2}{(2\pi)^6} F_q(p_\gamma) (\frac{e_q}{e})^2 . \frac{1}{4E_\gamma} [\int_{\frac{s}{4E_\gamma}}^{\infty} \left[\lambda_{\bar{q}} (e^{\frac{E_{\bar{q}}}{T}} + 1)^{-1} + \lambda_{\bar{q}} \lambda_g (e^{\frac{E_{\bar{q}}}{T}} + 1)^{-1} (e^{E_g/T} - 1)^{-1}\right] dE_{\bar{q}} \int_0^{2\pi} d\phi \int \sigma_a(s) \sqrt{s(s-4m^2)}\, ds \ldots (4)$$

The solution of the first and second integral in Eq.(4) for $E_{\bar{q}} \cong E_g$is

$$R_{ph} = \frac{4{N_s}^2}{(2\pi)^6} F_q(p_\gamma) (\frac{e_q}{e})^2 . \int [T \lambda_{\bar{q}} \sum_{n=1}^{\infty} \frac{(-1)^{n+1} \left(e^{\frac{-s}{4E_\gamma T}}\right)^n}{n} + T \lambda_{\bar{q}} \lambda_g \sum_{n=1}^{\infty} \frac{e^{\frac{-(2n+1)s}{4E_\gamma T}}}{2n+1}] \sigma_a(s) \sqrt{s(s-4m^2)}\, ds \qquad (5)$$

The final term in Eq.(5) is [17].

$$\sqrt{s(s-4m^2)}\, \sigma(s) = 4\pi \alpha_0 \alpha_s m^2 [\ln\left(\frac{s}{m^2}\right) - 1] \qquad (6)$$

The Eq.(5) together Eq.(6) for S > $4m^2$ leads to

$$R_{ph} = \frac{4{N_s}^2}{(2\pi)^6} F_q(p_\gamma) (\frac{e_q}{e})^2 . 4\pi \alpha_0 \alpha_s m^2 T \lambda_{\bar{q}} \int [\sum_{n=1}^{\infty} \frac{(-1)^{n+1} \left(e^{\frac{-s}{4E_\gamma T}}\right)^n}{n} + \lambda_g \sum_{n=1}^{\infty} \frac{e^{\frac{-(2n+1)s}{4E_\gamma T}}}{2n+1}] \ln[\left(\frac{s}{m^2}\right) - 1] ds \qquad (7)$$

The solution integral in Eq.(7) with assume $s = 4m^2$z in and $m^2 \ll E_\gamma T$is.

$$R_{ph} = \frac{4{N_s}^2}{(2\pi)^6} \frac{F_q(p_\gamma)}{4E_\gamma} \left(\frac{e_q}{e}\right)^2 . 4\pi \alpha_0 \alpha_s m^2 T \lambda_{\bar{q}} \, [\lambda_{\bar{q}} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} (\frac{E_\gamma T}{n m^2}) \left[\ln\left(\frac{4E_\gamma T}{m^2}\right) - C - \ln n - 1\right] + \lambda_{\bar{q}} \lambda_g \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{2n+1} \frac{E_\gamma T}{(2n+1)m^2} \left[\ln\left(\frac{4E_\gamma T}{m^2}\right) - C - \ln(2n+1) - 1\right] \qquad (8)$$

The series in Eq.(8)reduce to [18]..

$$\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{(2n+1)^2} = \left(1 - \frac{1}{2^2}\right) \zeta(2) \sim \frac{\pi^2}{6} \qquad (9)$$

And

$$\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} = \frac{\pi^2}{6} \qquad (10)$$

Then the rate in Eq.(8) together Eq.(2), Eq.(9) and Eq.(10) with $N_s = 2$ and $\lambda_g \sim 1$to become.

$$R_{ph} = \frac{\alpha_0 \alpha_s}{3(2\pi)^2} \left(\frac{e_q}{e}\right)^2 T^2 \frac{\lambda_{\bar{q}} \lambda_q}{e^{\frac{E_\gamma}{T}} + 1} [\left[\ln\left(\frac{4E_\gamma T}{m^2}\right) - C + 1 + \ln n + \ln(2n+1)\right] \, (11)$$

Where α_0 is electrodynamic constant $\alpha_0 = (137)^{-1}$, α_s is QCD strength constant, and m is the finite quark mass $m = gT = \sqrt{4\pi\alpha_s}T$ [19] with $\frac{1}{e^{\frac{E_\gamma}{T}}+1} \approx e^{\frac{-E_\gamma}{T}}$ for $E_\gamma \gg T$ and $C_{ph} = C - 1 - lnn - ln(2n+1)$ the Eq.(11) reduce to

$$R_{ph} = \frac{\alpha_0\alpha_s}{3(2\pi)^2}\left(\frac{e_q}{e}\right)^2 T^2\lambda_{\bar{q}}\lambda_q e^{\frac{-E_\gamma}{T}}\left[\ln\left(\frac{4E_\gamma T}{m^2}\right) - C_{ph}\right] \qquad (12)$$

The running strength constant is given by [12].

$$\alpha_s = \frac{6\pi}{(33-2n_f)ln\frac{8T}{T_c}} \qquad (13)$$

The critical temperature is [21].

$$T_c = \left(\frac{90B}{\pi^2 n_{gq}}\right)^{\frac{1}{4}} \qquad (14)$$

Where B is the Bag constant with bag model and $n_{gq} = n_g + \frac{7}{8}\ (n_q + n_{\bar{q}})$ is the number of gluons n_g and quarks n_q and anti quarks $n_{\bar{q}}$ degrees of freedom.

3. Results

In order to evaluate the emission of photon coefficient from the interaction strange with anti-strange quarks, we calculate the running strength coupling with the critical temperature, flavor number and quarks electric charge. Firstly, the flavor number estimates using summation flavors $\sum n_f = 8$ in $s\bar{s}\longrightarrow\gamma g$ system. The critical temperatures for system is calculated using Eq.(14) by take the Bag constant $B^{1/4} = 230\ \ and$ 260 MeV [21] and inserts the spin $n_s = 2$ and color number $n_c = 8$ for gluon and takes $n_s = 2, n_c = 3\ and\ n_f = 8$ for quarks, results are $T_c = 126MeV$ to $143MeV$. The running strength coupling is evaluated using Eq.(13) as a function of the critical temperature, favor number and thermal energy of system. We insert the thermal energy T=170,190,210,230,250 and 270 MeV, the flavor number $n_f = 8$ and the critical temperature $T_c = 126\ to 143\ MeV$ in Eq.(13) to be results running strength coupling are shown in **Table (1)** and **Table (2)** at $T_c = 126$ to $143\ MeV$ alternatively

Table 1. The running strength coupling at T_c = 126, 143 Mev for strange S quark interaction with anti-strange$\bar{s}$.

$T(MeV)$	The running strength coupling α_s	The running strength coupling α_s
170	0.46608	0.49227
190	0.44526	0.46910
210	0.42806	0.45005
230	0.41353	0.43402
250	0.40106	0.42030
270	0.39020	0.40839

Furthermore, The tuned values of electric charge of system estimates using summation $\sum\left(\frac{e_q}{e}\right)^2$ charge of strange quark $e_s = -{}^1/_3$ e and charge of anti-strange $e_{\bar{s}} = +{}^1/_3$ e to results

$^{1}/_{9}$. The emission of photons yields to the strange quark interaction with anti-strange calculates using Eq.(12) by substituting the running strength coupling from **Tables (1)**, the photon energy $E_{\gamma}\ = 1.5,2,2.5,3,3.5,4\ ,4.5\ and\ 5\ GeV$ from experimental data [21],critical temperature Tc = 126 MeV to 143 MeV with taken fugacity of strange and anti-strange quarks are λ_{q}= 0.06, $\lambda_{\bar{q}}$ = 0.06 and annihilation parameter is $C_{ph}\ =\ 1.415$ [22]. The results are tabulated in tables (2) and (3) for $T_{c}\ = 126\ MeV\ to\ 143\ MeV$.

Table 3. The emission of photon rate production at $T_{c}\ = 143\ MeV$ with λ_{q}= 0.06, $\lambda_{\bar{q}}$ = 0.06 for strange S quark interaction with anti-strange $\bar{s}$

	$R_{ph}(\frac{1}{GeV^2 fm^4})$					
	T=170 MeV	T=190 MeV	T=210 MeV	T=230 MeV	T=250 MeV	1T=270 MeV
$E_{\gamma}\ (GeV)$	$\alpha_s = 0.46608$	$\alpha_s = 0.44526$	$\alpha_s = 0.42806$	$\alpha_s = 0.41353$	$\alpha_s = 0.40106$	$\alpha_s = 0.39020$
1.5	3.72618E-14	9.32084E-14	1.87523E-13	3.1486E-13	4.46265E-13	5.21399E-13
2	3.45285E-15	1.28228E-14	3.69096E-14	8.77242E-14	1.79666E-13	3.26636E-13
2.5	2.43157E-16	1.26413E-15	4.81635E-15	1.45568E-14	3.68356E-14	8.10662E-14
3	1.54642E-17	1.11044E-16	5.5137E-16	2.08115E-15	6.36962E-15	1.65446E-14
3.5	9.33739E-19	9.21246E-18	5.92707E-17	2.77615E-16	1.02045E-15	3.10373E-15
4	5.46644E-20	7.39102E-19	6.14427E-18	3.56054E-17	1.56675E-16	5.56063E-16
4.5	3.13611E-21	5.80217E-20	6.22265E-19	4.45391E-18	2.34206E-17	9.68163E-17
5	1.77389E-22	4.48661E-21	6.2015E-20	5.47698E-19	3.43802E-18	1.65349E-17

The emission of photon production was plotted in in **Figure (1)** at $T_{c}\ = 126MeV$ and **Figure (2)** at $T_{c}\ = 143\ MeV$ as a function of the photons energy $E_{\gamma}\ (GeV)$for strange S quark interaction with anti-strange $\bar{s}$ at fugacity $\lambda_{q}\ = 0.06$ and $\lambda_{\bar{q}}$= 0.06 .

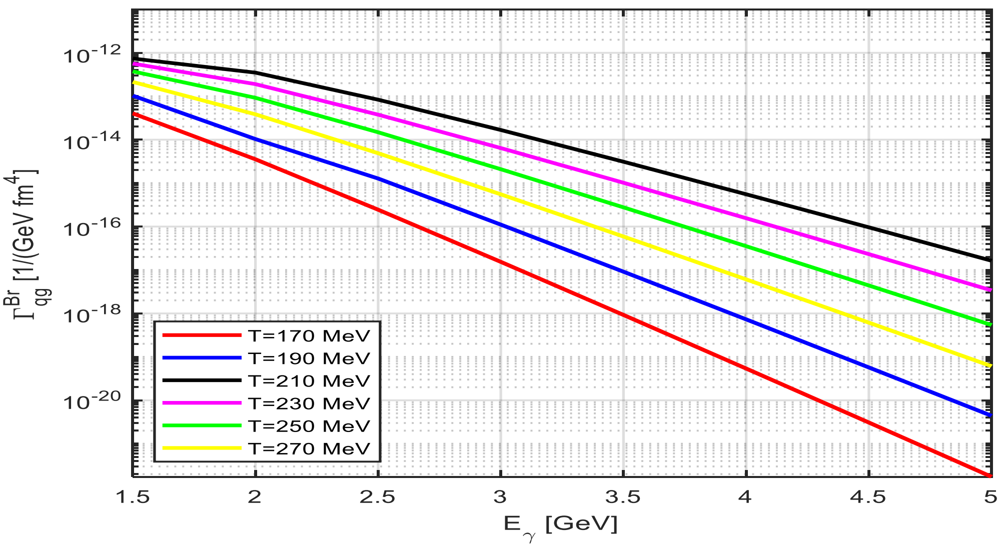

Figure 1. The emission of photon production R_{ph} foror strange S quark interaction with anti-strange $\bar{s}$ at $T_{c}\ = 126\ MeV$ and $\lambda_{q}\ = 0.06$ and $\lambda_{\bar{q}}$= 0.06 .

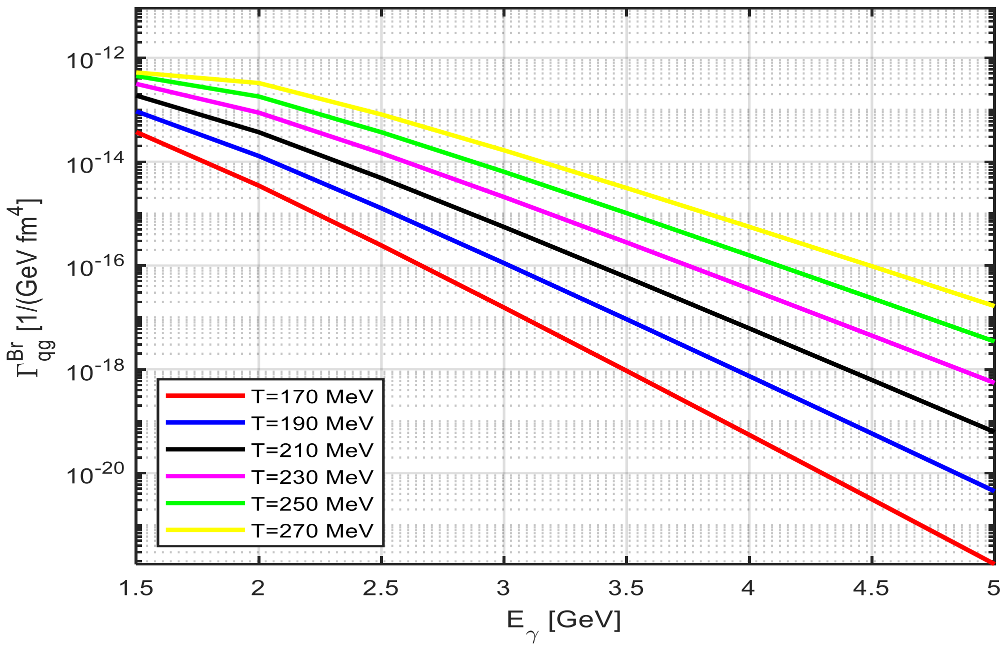

Figure 2. The emission of photon production R_{ph} foror strange S quark interaction with anti-strange $\bar{s}$ at $T_c = 143\ MeV$ and $\lambda_q = 0.06$ and $\lambda_{\bar{q}}$=0.06 .

4.Discussion

To understand the mechanism of emission of photons yields, we analytically calculate the running strength coupling, critical temperature,thermal energy and energy of photon. The running strength coupling as function to flavour number, critical temperature and thermal energy of system forint reaction of strange quark and anti-strange quarkat annihilation process. **Table (1)** show that running strength coupling increases with decrease of thermal energy from 170 to 270 MeV of system. Also, the running strength coupling increases with increase critical temperature from $T_c = 126$ to 143 MeV**.** Emission of photon was increase with decreasing running strength coupling and vice versa. The emission of photon relative to photon energy are done in **Figure (1)** and figure (2). The emission of photon is maximum $R_{ph} = 5.21399 \times 10^{-13} \frac{1}{GeV^2 fm^4}$ at critical temperature $T_c = 126\ MeV$ with $E_\gamma = 1.5\ GeV$ and T = 270 MeV and running strength coupling $\alpha_s = 0.39020$ while reach minimum $R_{ph} = 1.77389 \times 10^{-22} \frac{1}{GeV^2 fm^4}$ critical temperature $T_c = 126\ MeV$ with $E_\gamma = 5\ GeV$ and $\alpha_s = 0.46608$ for low thermal energy T=170Mev. However, the emission of photon reachs maximum $R_{ph} = 2.87147 \times 10^{-13}$ at critical temperature$T_c = 143\ MeV$. With $E_\gamma = 1.5\ GeV$and $\alpha_s = 0.40839$ and T = 270 MeV comparing to minimum $R_{ph} = 1.80895 \times 10^{-22}\ T_c = 143\ MeV$. With $E_\gamma = 5\ GeV$and $\alpha_s = 0.49227$ for low thermal energy T=170 Mev. **Figures (1) and (2)** show the emission of photon yield as function of photon energy, it increases with decreases energy of photons and, the emission of photons have maximum for photon energy less than 2 GeV. Thus, emission of photon yields increase with increases thermal energy, and dramatically decrease the running strength coupling of interaction strange quark with anti-strange quark with larger critical are more strongly enhanced Generally, the emission of photon in **Figure (1)** and **Table (3)** larger than in **Figure (1)** and **Table(2)** because that photons are increased with increased critical temperature 143MeV. We can extract the emission of photon increases with increasing thermal energy it has maximum at T = 270 MeV by comparing both **Tables (2)** and **(3).** However, the probability of the emission of photon affected by running strength coupling, critical temperature, thermal energy and photons energy and reach maximum at critical temperature T_C = 143 MeV and temperature T = 270 MeV of system.

5. Conclusion

In conclusion, the emission of photon from strange quark interaction with anti-strange for annihilation processes depending on running strength coupling, critical temperature, thermal energy and photon energy. Therefore, one may demonstrated the emission of photon production be affected forcedly by running strength coupling, thermal and critical temperature. It is decreased with increasing the running strength coupling and decreased critical temperature and thermal energy of system for strange -anti strange annihilation process with flavor number $n_f = 8$. The photons yield results are implied affected by photon energy. It each top emission for photon energy less than 2 GeV. We explore that emission of photon is a unique feature and occurs at minimum running strength coupling and large thermal temperature and critical temperature. In conclusion, the emission of photon is produced forcedly at less strength coupling and large temperature T = 270 MeV with critical temperature T_C = 143MeV and photon energy less 2 GeV.

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