The PHENIX experiment has been carried out at RHIC to investigate the properties of the QGP. Di-electron yields in p+p and Au+Au collisions have been measured. An enhancement over a hadronic cocktail calculation is clearly seen for Au+Au collisions while the result in p+p collisions are in agreement with the hadronic cocktail calculation. This enhancement concentrates in \( p_T < 1.0 \text{ GeV}/c \). The fraction of the virtual direct photon component to the di-electron distribution is obtained from a shape analysis using the di-electron distributions for \( 1.0 < p_T < 5.0 \text{ GeV}/c \) and \( m_{ee} < 300 \text{ MeV}/c^2 \). Finally, the real direct photon spectra in p+p and Au+Au collisions for \( 1.0 < p_T < 5.0 \text{ GeV}/c \) are obtained from the virtual direct photon fraction. An excess above a binary-scaled p+p result is observed in Au+Au collisions, and the inverse slope of a fitting function to the Au+Au result is \( 221 \pm 23 \pm 18 \text{ MeV} \). If this excess comes from thermal photons, the inverse slope is related to an initial temperature of a created matter.

1 Introduction

The Quark Gluon Plasma (QGP) is a de-confined phase of quarks and gluons. The lattice QCD predicts a phase transition from a hadronic phase to the QGP at a critical temperature and energy density of higher than \( 150 \sim 200 \text{ MeV} \) and \( 1 \text{ GeV}/fm^3 \). The study of the QGP is very important because it is of relevance to the history of the early universe where the QGP is believed to have existed.

A possible experimental approach to investigate the properties of the QGP is heavy ion collisions. A lot of very exciting results such as the large energy loss of light quarks, gluons \(^1\) and heavy quarks \(^2\) and the strong elliptic flow of light \(^3\) and charmed \(^2\) hadrons have been reported from \( \sqrt{s_{NN}} = 200 \text{ GeV} \) Au+Au collisions at Relativistic Heavy Ion Collider (RHIC). These experimental facts indicate that the created matter is a high-density and rapid-thermalized medium.
Di-leptons and direct photons are one of the most important probes to study the QGP and measured in the PHENIX experiment. They are emitted from a thermally equilibrated medium, and penetrate the strongly interacting matter. Therefore they can carry the thermodynamic information of the created matter directly. This paper focuses on di-electron production in the low mass region below 1 GeV/$c^2$ and covers the following two topics. The first topic is the measurement of the di-electron yield in the low-mass low-$p_T$ region. There an enhancement could be possibly due to thermal $q\bar{q}$ and $\pi\pi$ annihilations. The second one is the measurement of the direct photon yield with the virtual photon method. Thermal photons are considered to be the primary contributor in the $p_T$ range of $1.0 < p_T < 5.0$ GeV/$c$ at RHIC energy $^{4}$. The $e^+e^-$ pairs from virtual photon decays are one of the possible sources of the di-electron continuum in the low mass region.

2 Low-mass Low-$p_T$ Di-electron Continuum

The $e^+e^-$ pair yield was measured in $p+p$ and $Au+Au$ collisions at PHENIX and hadron decay components were estimated by a hadronic cocktail calculation which was tuned to the individually measured yields for both $p+p$ and $Au+Au$ collisions. The left and right panels in Fig. 1 show the invariant mass spectra in $p+p$ and $Au+Au$ collisions compared to the hadronic cocktail calculation for each. The symbols and lines indicate the real data and the cocktail calculations, respectively. While the real data is in excellent agreement with the cocktail in $p+p$ collisions, a large enhancement over the cocktail is clearly seen in the mass range between $150 \sim 750$ MeV/$c^2$. The ratio of the integrated yield in $150 \sim 750$ MeV/$c^2$ between the real and the cocktail is $3.4\pm0.2$(stat)$\pm1.3$(sys)$\pm0.7$(model). This enhancement concentrates at the $p_T$ region below 1 GeV/$c$ and may come from thermal $q\bar{q}$ and $\pi\pi$ annihilations.

3 Low $p_T$ Direct Photon

In general, any source of real photons can emit virtual photons which convert to low mass $e^+e^-$ pairs. A direct photon production process such as $q+g \rightarrow g+\gamma$ has an associated process that produces low mass $e^+e^-$ pairs, i.e. $q+g \rightarrow g+\gamma^* \rightarrow q+e^+e^-$. The relationship between the photon production and the associated $e^+e^-$ pair production can be written by the Kroll-Wada formula, Eq. 1 $^5$.

$$
\frac{d^2n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi m_{ee}} \sqrt{1 - \frac{4m_{ee}^2}{m_{ee}^2}} \left(1 + \frac{2m_{ee}^2}{m_{ee}^2}\right) Sdn_\gamma,
$$

Figure 1: Invariant mass spectrum for $p+p$ (left) and $Au+Au$ (right) collisions compared to the hadronic cocktail calculations.
where $\alpha$ is the fine structure constant, $m_\text{e}$ and $m_\text{ee}$ are the masses of the electron and the $e^+e^-$ pair, respectively, and $S$ is a process dependent factor. An important point in this measurement is as follows. In the case of hadrons such as $\pi^0$ and $\eta$ Dalitz decays, the $S$ is given by $S = |F(m_\text{ee}^2)|^2 \left(1 - \frac{m_\text{ee}^2}{M_\text{hadron}^2}\right)^3$, where $|F(m_\text{ee}^2)|M_\text{hadron}$ is the form factor and the parent hadron mass. The $S$ is obviously zero for $m_\text{ee} > M_\text{hadron}$. On the other hand, the $S$ goes to 1 for $m_\text{ee} \leq p_T$ in the case of the virtual direct photons. Therefore it is possible to separate the virtual direct photon component in a mass spectrum from the hadron decay components in a proper region which satisfies the described condition.

Figure 2: The left and center panels show the invariant mass spectra in p+p and Au+Au collisions for several $p_T$ bins compared to the cocktail calculations. The right panel shows the mass spectrum in Au+Au collisions for $1.0 < p_T < 1.5$ GeV/c together with a fit result by Eq. 2.

An enhancement of the $e^+e^-$ pair yield for Au+Au collisions is clearly visible in the $p_T$ region above 1 GeV/c and the mass region of $100 < m_\text{ee} < 300$ MeV/c$^2$ shown as the center panel in Fig. 2. We would like to emphasize that a small excess over the cocktail is also observed for p+p collisions in the higher $p_T$ region shown as the left panel in Fig. 2.

The virtual direct photon measurement is applicable in this region. The following function is fitted to the data in order to determine the fraction of the virtual direct photon component in the mass spectrum.

$$f(m_\text{ee}) = (1 - r) \cdot f_{\text{cocktail}}(m_\text{ee}) + r \cdot f_{\text{direct}}(m_\text{ee}),$$

where $f_{\text{cocktail}}$ is the mass distribution from the hadronic cocktail calculation and $f_{\text{direct}}$ is that from the virtual direct photon decays given by Eq. 1 with $S = 1$ and $r$ is the virtual direct photon fraction. Assuming that this excess comes from virtual direct photons, the fit to the result for Au+Au collisions in $1.0 < p_T < 1.5$ GeV/c gives $\chi^2/\text{NDF} = 13.8/10$. On the other hand, assuming that this excess comes from $\eta$, i.e. $f_\eta(m_\text{ee})$ is used in place of $f_{\text{direct}}(m_\text{ee})$, the fit gives $\chi^2/\text{NDF} = 21.1/10$. Therefore the assumption that this excess comes from virtual direct photons is favorable.

Figure 3 shows the obtained fraction of the virtual direct photon component as a function of $p_T$ in p+p and Au+Au collisions. The symbols show the result and the lines are the expectations from next-to-leading-order perturbative QCD (NLO pQCD) calculations with different theoretical scales. A clear excess above the NLO pQCD calculation is seen in Au+Au collisions while the result in p+p collisions is consistent with the NLO pQCD calculation.

Finally, the real direct photon yield is obtained by multiplying an inclusive photon yield to the virtual direct photon fraction. Figure 4 shows the direct photon spectra in p+p and Au+Au collisions. This is the first time that the direct photon production in p+p collisions has been measured in $1.0 < p_T < 4.0$ GeV/c. The result in p+p collisions are well described by a modified
Figure 3: The obtained fraction of the virtual direct photon component as a function of $p_T$ in $p+p$ (left) and $Au+Au$ (right) collisions.

Figure 4: The direct photon spectra in $p+p$ and $Au+Au$ collisions as a function of $p_T$.

power law function as shown by the dashed curve. The result in $Au+Au$ collisions are above the $p+p$ fit curve scaled by the number of collisions for $p_T < 2.5$ GeV/$c$. It indicates that the direct photon yield in the low $p_T$ region is larger than the binary-scaled cross section in $p+p$ collisions. Fitting an exponential plus the binary-scaled $p+p$ fit curve to the $Au+Au$ central result results in the inverse slope of $221 \pm 23 \pm 18$ MeV. If the direct photon in $Au+Au$ collisions are of thermal origin, the inverse slope is related to the initial temperature of the created matter.

References