Feasibility of thermal photon measurements in heavy ion collisions at NICA energies

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Abstract. Thermal photons serve as valuable probes of the hot and dense medium produced in heavy ion collisions. The effective thermal photon temperature measured at RHIC and LHC energies far exceeds the temperature predicted for the phase space transition into the deconfined state of quarks and gluons, known as quark-gluon plasma (QGP). Direct photon measurements in heavy ion collisions at the future NICA collider may help to estimate the effective temperature of the produced medium at lower energies and trace the transition from QGP to the hadron gas state. In this contribution, we present feasibility studies on the thermal photon measurements in AuAu collisions using the photon conversion method in the MPD experiment at NICA.

1. Introduction

According to lattice quantum chromodynamics (QCD) calculations, the QCD matter should undergo a transition into a deconfined state of quarks and gluons, so-called quark-gluon plasma (QGP), at a temperature of about 170 MeV [1]. The study of a phase transition of hadronic matter to QGP in a laboratory environment is one of the main research activities in high-energy physics performed with heavy ion collisions at modern accelerators. Experiments at RHIC and LHC colliders have collected a wealth of experimental data on the properties of QCD matter in the QCD phase diagram region corresponding to high temperatures and low baryon chemical potential [2], while the region of intermediate temperatures and high baryon chemical potential remains unexplored. The NICA collider (JINR, Russia) and the FAIR particle accelerator facility (GSI, Germany) are being constructed to study the QCD phase diagram in this region [3,4].

Among various observables studied in heavy ion collisions, photons provide the most direct access to the temperature of the medium created in heavy-ion collisions. Since photons interact only electromagnetically, the mean free path of photons is large compared to the size of the colliding system therefore photons leave the interaction area unaltered immediately after their production. Photons are emitted during the entire space-time evolution of the collision, starting from primary parton-parton interactions in the initial state up to hadronic decays after freeze-out, and are characterized by different energy distributions depending on their source. In particular, the measurement of photon spectra at low momenta, so called thermal photons,
allows one to access the effective temperature of the thermalized expanding medium produced in heavy-ion collisions [2].

Experimental studies of photons created before the final chemical freeze-out of the system (direct photons) are however challenging because the observed photon spectra are dominated by photons from hadronic decays, mainly from $\pi^0$ and $\eta$ mesons. One of the useful observables traditionally explored in the studies of direct photon production is an excess photon ratio $R_\gamma = \gamma_{\text{incl}}/\gamma_{\text{hadr}}$, where $\gamma_{\text{incl}}$ is the inclusive yield of photons while $\gamma_{\text{hadr}}$ is the yield of photons from decays of final state hadrons [2]. Then the yield of direct photons $\gamma_{\text{dir}}$ can be calculated from $R_\gamma$ as follows: $\gamma_{\text{dir}} = (1 - 1/R_\gamma) \gamma_{\text{incl}}$. Thus the excess of $R_\gamma$ ratio over unity serves as experimental evidence of direct photons in the observed photon spectra. The yield of decay photons $\gamma_{\text{hadr}}$ can be estimated using measured spectra of hadrons such as $\pi^0$ and $\eta$ mesons. In the region of small transverse momentum, the value of $R_\gamma$ is typically close to unity since decay photons constitute about 90% of the inclusive spectrum [5]. Systematic uncertainties are mainly defined by the accuracy of separating the spectrum of decay photons from the inclusive spectrum, therefore precise measurements of neutral mesons are critical for thermal photon studies.

Two fundamentally different methods are usually used to measure photons. The first one is based on electromagnetic calorimetry where the energy of the photon and its direction are measured directly. The electromagnetic calorimetry is efficient in the region of relatively high $p_T > 2$ GeV/c where one can also utilize hardware trigger capabilities. The electromagnetic calorimeter resolution worsens with decreasing photon energy. In addition, photon identification may be difficult due to contamination from misidentified hadrons. The second method is based on the photon conversion in the detector material where photons are reconstructed via the measurement of electron-positron pairs in a tracking system. This method is usually preferable in the low transverse momentum region, $p_T < 2$ GeV/c, where a tracking system provides better resolution than an electromagnetic calorimeter. One of the disadvantages of the conversion method is the requirement of a large data sample since tracking systems are designed with low material budget and the photon conversion probability is relatively small.

MPD experiment is aimed to study properties of the nuclear matter under extreme conditions at the NICA collider [3]. The MPD detector is a $4\pi$ spectrometer designed to measure hadrons, electrons and photons in a dense environment of heavy ion collisions. The detector will consist of a central barrel spectrometer and a set of forward detectors. Charged particles will be measured by a time-projection chamber TPC located in a homogeneous magnetic field of 0.5T. Particle identification will be carried out by measuring energy loss of charged particles in the TPC, using the time of flight information from a time-of-flight system TOF and using an electromagnetic calorimeter ECAL. The centrality and reaction plane will be measured by forward FHCal and FFD detectors. Photons will be measured using both photon conversion method in the region of small $p_T$ and calorimetry at relatively high photon $p_T$.

In this contribution, we present feasibility studies on thermal photon measurements in AuAu collisions at $\sqrt{s_{NN}} = 4$ and 11 GeV using the photon conversion method in the MPD experiment at the NICA collider.

2. Reconstruction of neutral mesons and spectra of decay photons

Two most popular event generators UrQMD and PHSD, that were successfully used at CERN and GSI, were selected to study neutral meson production in AuAu collisions at two extreme NICA collider energies of $\sqrt{s_{NN}} = 4$ and 11 GeV [6,7]. Rapidity distributions of $\pi^0$ and $\eta$ mesons are shown in figure 1 for minimum bias AuAu collisions. Roughly 35 and 15 $\pi^0$ mesons are expected to be produced per event at midrapidity in AuAu collisions at $\sqrt{s_{NN}} = 11$ and 4 GeV respectively. The yields of $\eta$ mesons are expected to be almost ten times smaller than the yields of $\pi^0$ mesons. Predictions of UrQMD and PHSD event generators agree reasonably well
with each other except for the production of \( \eta \) mesons in AuAu collisions at \( \sqrt{s_{NN}} = 4 \) GeV where UrQMD event generator predicts almost two times larger yield compared to PHSD event generator.

![Rapidity distributions of \( \pi^0 \) (a) and \( \eta \) mesons (b) in minimum bias AuAu collisions at \( \sqrt{s_{NN}} = 4 \) and 11 GeV obtained with UrQMD and PHSD generators.](image)

Figure 1. Rapidity distributions of \( \pi^0 \) (a) and \( \eta \) mesons (b) in minimum bias AuAu collisions at \( \sqrt{s_{NN}} = 4 \) and 11 GeV obtained with UrQMD and PHSD generators.

Reconstruction of neutral mesons was studied in \( \pi^0 \rightarrow \gamma\gamma \) and \( \eta \rightarrow \gamma\gamma \) decay channels by combining pairs of photons reconstructed with the use of the photon conversion method \[6, 7\]. Collisions of gold nuclei at \( \sqrt{s_{NN}} = 4 \) and 11 GeV were generated with the UrQMD event generator. Transport of particles in the MPD detector material was simulated using Geant 3 package while the official framework of the MPD collaboration MpdRoot was used for Monte Carlo simulations of the MPD detector response, track reconstruction and pattern recognition. Simulations were performed for the Stage I of the MPD detector setup equipped with TPC, TOF, ECal and forward FFD and FHCal detectors. During the upcoming upgrade at Stage II, the MPD detector will be equipped with the inner tracking system (ITS). Additional material around the interaction point will increase the material budget and the photon conversion probability favoring the photon conversion method.

Photons were reconstructed by combining electron and positron candidates in \( e^+e^- \) pairs. The following requirements were applied to select electron candidates from all tracks reconstructed in the TPC: a pseudorapidity \( |\eta| < 1 \), more than 20 TPC hits, transverse momentum \( p_T > 50 \) MeV/c, \( dE/dx \) energy losses in the TPC and/or time-of-flight measurement in the TOF detector compatible with the electron hypothesis within \( 4\sigma \) \[6, 7\]. Additional requirements on the electron-positron pair were applied to reduce combinatorial background and maximize the signal significance: a small distance of closest approach of reconstructed electron-positron candidates, a small angle between the plane perpendicular to the magnetic field and the plane which is spanned by the momentum vectors of the \( e^+e^- \) pair (\( \theta_{\text{pair}} < 0.1 \) rad); a small angle between the reconstructed pair momentum and the direction to the vertex (\( \theta < \exp(-2.777 - 2.798 p_T^{\text{pair}}) + 0.0175 \)); a small invariant mass of the reconstructed \( e^+e^- \) pair (\( m_{\text{pair}} < 22.6 + 17.4 p_T^{\text{pair}} \)). The resulting photon reconstruction efficiency as a function of \( p_T \) at different selection steps is shown in figure 2 (a). The photon reconstruction efficiency increases with transverse momentum reaching maximum of about 1.8% at \( p_T \sim 1.2 \) GeV/c.

The low photon reconstruction efficiency makes it difficult to perform detailed \( p_T \) differential studies of the neutral meson production with UrQMD event generator alone. To overcome this difficulty, an embedding technique was used for further analysis \[6, 7\]: 500 \( \pi^0 \rightarrow \gamma\gamma \) and 500
\( \eta \rightarrow \gamma \gamma \) decays were generated with flat meson \( p_T \) and rapidity distributions and embedded in every UrQMD generated event. \( \pi^0 \) and \( \eta \) meson candidates were obtained by combining reconstructed photons into \( \gamma \gamma \) pairs and measuring invariant mass distributions in narrow pair transverse momentum intervals. In order to extract raw neutral meson yields, the obtained invariant mass distributions of the \( \gamma \gamma \) pairs for different \( p_T \) intervals were fitted with a Gaussian on top of a second-order polynomial function. The resulting neutral meson reconstruction efficiency roughly scales as a square of the photon reconstruction efficiency and is shown in figure 2 (b), as function of the neutral meson \( p_T \). The \( \pi^0 \) and \( \eta \) meson reconstruction efficiencies reach maximum of about \( 0.16 \times 10^{-3} \) and \( 0.11 \times 10^{-3} \) at 1.9 GeV/c respectively.

![Figure 2](image-url). Photon (a) and neutral meson (b) reconstruction efficiencies.

A one-year data sample of about \( 10^9 \) AuAu minimum bias events should allow for the measurement of \( \pi^0 \) spectra in fine \( p_T \) intervals in several centrality bins while \( \eta \) measurements would require much higher event statistics. An example of the expected efficiency-corrected spectrum of \( \pi^0 \) mesons in central AuAu collisions at \( \sqrt{s_{NN}} = 11 \) GeV is shown in figure 3 (a). The spectrum was approximated with the Tsallis, two-component model and Hagedorn functions. The fits were extrapolated down to zero transverse momentum and were used to calculate the spectra of photons from \( \pi^0 \) meson decays shown in figure 3 (b). Fits provide significantly different extrapolations at low pion \( p_T \) but these discrepancies do not result in significant differences of spectra of photons from \( \pi^0 \) meson decays.

3. Direct photons production

UrQMD and PHSD event generators do not include direct photon production mechanisms thus a data-driven method was developed to estimate spectra of direct photons in AuAu collisions at NICA energies. The method is based on the universal scaling of direct photon yields with the (pseudo)rapidity density of final state charged particles \( dN_{ch}/d\eta \) observed at RHIC and LHC energies \(^2\). PHENIX experiment found that the integrated yields of direct photons above \( p_T > 1 \) GeV/c scale as a power law \( (dN_{ch}/d\eta)^{1.25} \) in a wide range of centralities and collisions energies. This scaling works well for collisions with \( dN_{ch}/d\eta > 20 \) and is broken at lower multiplicities. The \( dN_{ch}/d\eta \) multiplicity densities for AuAu collisions at midrapidity at \( \sqrt{s_{NN}} = 4 \) and 11 GeV for different centralities were estimated using the UrQMD event generator and are shown in figure 4. Assuming the scaling still holds at NICA energies for multiplicities \( dN_{ch}/d\eta > 20 \), one can expect its validity for AuAu collisions in the range of (0 – 60)% centrality at \( \sqrt{s_{NN}} = 11 \) GeV and (0 – 40)% centrality at \( \sqrt{s_{NN}} = 4 \) GeV.
Figure 3. Efficiency-corrected pion spectrum expected in 200M central AuAu collisions at $\sqrt{s_{NN}} = 11$ GeV, fitted with Tsallis, two-component model and Hagedorn functions (a) and corresponding spectra of photons from $\pi^0$ meson decays (b).

Figure 4. Charged particle multiplicity density as function of centrality in AuAu collisions at $\sqrt{s_{NN}} = 4$ GeV and 11 GeV generated with UrQMD.

Transverse momentum spectra of direct photons can be also predicted assuming universal $p_T$ scaling observed by PHENIX in the region $p_T > 0.4$ GeV/$c$ \cite{2,11}. Differential direct photon yields in AuAu collisions at $\sqrt{s_{NN}} = 4$ and 11 GeV were calculated in the region of $p_T > 0.6$ GeV/$c$ assuming $d^3N/d^2p_Tdy = 2.755 \times 10^{-4} \cdot p_T^{-4.5} \times (dN_{ch}/d\eta)^{1.25}$ dependence as shown in figure 4(a). In the region of low $p_T < 0.6$ GeV/$c$, direct photon spectra were estimated assuming thermal spectrum $dN/dp_T \sim p_T \exp(-p_T/T_{\text{eff}})$ with conservative effective temperature $T_{\text{eff}} = 150$ MeV \cite{12}.

The obtained spectra were multiplied by the photon reconstruction efficiency and summed with expected yields of decay photons to get the inclusive photon spectra in AuAu collisions at $\sqrt{s_{NN}} = 11$ GeV. Excess photon ratio $R_\gamma$ was calculated as a ratio of inclusive photon spectrum to decay photon spectrum and is shown in figure 5(b). The performed study shows that $R_\gamma$ significantly exceeds unity starting from 1.03 for semi-central collisions and increases with $p_T$ exceeding 1.2 at 1.4 GeV similar to previous measurements at higher energies. Typical systematic uncertainties on $R_\gamma$ can be reduced to about 5% according to experience of other
experiments [2]. Thus the obtained $R_\gamma$ estimates justify the possibility to measure direct photon production with the MPD detector down to low transverse momentum.

![Figure 5. Inclusive photon spectra (a) and excess photon ratio $R_\gamma$ (b).](image)

4. Conclusions
In this contribution, we demonstrated that photons serve as valuable probes of the hot and dense medium produced in heavy ion collisions. The procedure of photon and neutral meson reconstruction with the photon conversion method was improved and successfully used to study the feasibility of thermal photon measurements. The possibility to measure thermal photon production spectra in AuAu collisions at $\sqrt{s_{NN}} = 11$ GeV with the MPD detector at NICA was shown.

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