Direct Photons in Nuclear Collisions at FAIR Energies

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Abstract

Using the extrapolation of existing data estimations of prompt photon production at FAIR energies have been made. At \( y = y_{c.m.} \) the rapidity density of prompt photons with \( p_t > 1.5 \text{ GeV/c} \) per central Au+Au event at 25 AGeV is estimated as \( \sim 10^{-4} \). With the planned beam intensity \( 10^9 \) per second and 1% interaction probability, for 10% of most central events one can expect the prompt photon rate \( \sim 10^2 \) photons per second.

Direct photons from the hadron scenario of ion collisions generated by the Hadron-String-Dynamics (HSD) transport approach with implemented meson scatterings \( \pi \rho \rightarrow \pi \gamma, \pi \pi \rightarrow \rho \gamma \) have been analyzed. Photons from short-living resonances (e.g. \( \omega \rightarrow \pi^0 \gamma \)) decaying during the dense phase of the collision should be considered as direct photons. They contribute significantly in the direct photon spectrum at \( p_t = 0.5 - 1 \text{ GeV/c} \). At the FAIR energy 25 AGeV in Au+Au central collisions the HSD generator predicts, as a lower estimate, \( \gamma_{\text{direct}}/\gamma_{\pi^0} \simeq 0.5\% \) in the region \( p_t = 0.5 - 1 \text{ GeV/c} \). At \( p_t = 1.5 - 2 \text{ GeV/c} \) \( \gamma_{\text{prompt}}/\gamma_{\pi^0} \simeq 2\% \).

Thermal direct photons have been evaluated with the Bjorken Hydro-Dynamics (BHD) model. The BHD spectra differ strongly from the HSD predictions. The direct photon spectrum is very sensitive to the initial temperature parameter \( T_0 \) of the model. The 10 MeV increase in the \( T_0 \) value leads to \( \sim 2 \) times higher photon yield.

PACS 24.10.Lx, 25.20.Lj, 25.75.-q

∗Talk at the session of Russian Academy of Sciences, ITEP, Moscow, 26 - 30 November 2007
1 Introduction

The FAIR (Facility for Antiproton and Ion Research) [1] accelerators will provide heavy ion beams up to Uranium at beam energies ranging from 2 - 45 AGeV (for \(Z/A=0.5\)) and up to 35 AGeV for \(Z/A=0.4\). The maximum proton beam energy is 90 GeV. The planned ion beam intensity is \(10^9\) per second.

The CBM (Compressed Baryonic Matter) [2] detector will have good possibilities for vertex reconstruction, tracking and identification of particles (hadrons, leptons and photons). Though direct photons are of great interest for the research program of the CBM experiment, a feasibility study has not been done yet.

During high-energy heavy-ion collisions direct photons, defined as photons not from particle decays, have very little interaction with the surrounding medium and are therefore not altered by rescattering. Therefore, they provide a very interesting probe and convey unique and unperturbed information on the all stages of the collision (see, e.g. the review [3]).

On the quark-gluon level the main processes are Compton scattering \(qg \rightarrow q\gamma\) and annihilation \(q\bar{q} \rightarrow g\gamma\). Photons from initial hard NN collisions are named prompt photons and are the main source at large \(p_t\). On the hadron level the main source of direct photons is meson rescatterings: \(\pi\rho \rightarrow \pi\gamma\), \(\pi\pi \rightarrow \rho\gamma\), \(\pi K \rightarrow K^\ast\gamma\), \(K\rho \rightarrow K\gamma\), ... First two channels are most important.

Direct photons from a thermalized quark-gluon or hadron system, if any, are named thermal photons and are the main source at low \(p_t\). Most of theoretical predictions for direct photons assume the local thermalization, evaluate photon production rates from the equilibrated quark-gluon or hadron system which then are convoluted with space-time evolution of the system.

Of cause, during the nucleus-nucleus collision there is a non-equilibrium stage. It can be described by the transport approach free from the local thermalization assumption. However, most of existing transport codes do not include the hadronic source (meson rescatterings) of direct photons [4].

Identification of direct photons in heavy-ion collisions is a very difficult experimental task, especially at low transverse momentum, because of the large background from decay photons, mostly from \(\pi^0\) decays. First direct photons, \(\gamma_{\text{direct}}/\gamma_{\text{measured}} \simeq 20\%\) at \(p_t > 1.5\) GeV/c, have been extracted by the WA98 collaboration at SPS [5]. The PHENIX collaboration at RHIC using a novel analysis technique decreased a systematic error to 2-3% and revealed direct photons since \(p_t > 1\) GeV/c, \(\gamma_{\text{direct}}/\gamma_{\text{measured}} \simeq 10\%\) at \(p_t = 1 - 2\) GeV/c [6].

Here we would like to estimate for the FAIR energies: prompt photons using the extrapolation of existing \(p + p \rightarrow \gamma X\) data and photon contribution from hadron sources exploiting as the microscopic Hadron-String-Dynamics (HSD) transport approach [7] and the Bjorken Hydro-Dynamics (BHD) [8].
2 Prompt photons

Existing $p + p(\bar{p}) \rightarrow \gamma X$ data [9] cover the energy range $\sqrt{s} = 20 - 1800$ GeV. Thus, The CBM experiment at the FAIR accelerator can fill the gap $\sqrt{s} < 14$ GeV.

At transverse momentum $x_t = 2p_t/\sqrt{s} > 0.1$ cross sections can be fitted in the central rapidity region by the formula $Ed^3\sigma^{pp}/d^3p = 575(\sqrt{s})^{3.3}/p_t^{0.14}$ pb/GeV$^2$ [10]. Using this fit one can estimate the prompt photon spectrum in nucleus-nucleus, A+B, collisions at the impact parameter $b$: $Ed^3N^{AB}(b)/d^3p = Ed^3\sigma^{pp}/d^3p \cdot AB \cdot T_{AB}(b)$, where the nuclear overlapping function is defined as $T_{AB}(b) = N_{coll}(b)/\sigma^{pp}_{in}$, where $N_{coll}(b)$ is the average number of binary NN collisions. Nuclear effects (Cronin, shadowing) are ignored in this approach. Fig. 1 demonstrates extrapolated yield of prompt photons at FAIR energies. For central

![Figure 1: Rapidity density at $y = y_{c.m.}$ of prompt photons with $p_t > p_t^0$ at FAIR energies.](image)

Au+Au events ($N_{coll}=650$) at 25 AGeV one can expect $\sim 10^{-4}$ prompt photons with $p_t > 1.5$ GeV/c. At the beam intensity $10^9$ per second and 1% interaction probability, for 10% of most central collisions $\sim 10^2$ prompt photons per second are expected.
Figure 2: The invariant direct photon spectra for central Pb+Pb events at 158 AGeV in the central rapidity region $|y - y_{c.m.}| < 0.5$.

PYTHIA [11] simulations agree reasonably with the data extrapolation to FAIR energies [4]. For the prompt photon cross section PYTHIA predicts: $\sigma \approx 2 \cdot 10^{-4}$ mb, 85% from the process $gq \rightarrow \gamma q$ and 15% from $q\bar{q} \rightarrow \gamma g$.

3 Rescattering and decay photons from HSD

Cross sections for meson rescatterings $\pi\rho \rightarrow \pi\gamma$ and $\pi\pi \rightarrow \rho\gamma$ evaluated in the theory of the $\pi$ and $\rho$ meson gas [12] have been prepared by the ITEP group [4] and implemented by E.Bratkovskaya into the HSD code. The cross sections diverge at a threshold but averaging over the spectral function of the $\rho$ meson solves the problem.

Fig. 2 shows comparison of HSD predictions with the data of the WA98 collaboration at the SPS energy [5]. Besides the meson rescatterings, photons from decays of short-living resonances (e.g. $\omega \rightarrow \pi^0\gamma$) are also taken into account. In the case when the life time of a resonance is less than characteristic time of the nucleus-nucleus collision it is difficult to reconstruct the resonance because the decay hadron ($\pi^0$) can reinteract with surrounding medium especially if this
medium is dense. About 10% of $\omega \to \pi^0\gamma$ decays take place during the dense nuclear matter stage when $\rho/\rho_0 > 1$ ($\rho_0$ is the normal nuclear density). We will assume that it will not be possible to reconstruct these decays.

From Fig. 2 one can see that at $p_t=0.5 - 1$ GeV/c the decay photon contribution is comparable with the contribution from $\pi\rho \to \pi\gamma$. The model prediction is $\sim$ 10 times lower than one can expect from the experimental data. There are other sources of direct photons as on the hadron ($K\rho \to K\gamma$, ...) and the quark-gluon ($qg \to q\gamma$, $qq \to g\gamma$) levels which are so far not taken into account in the HSD transport code. Thus the HSD results can be considered as a lower estimate of data. Photon rapidity densities $dN/dy$ at $y = y_{c.m.}$ are 0.38, 0.26 and 0.17 for $\pi\rho$, $\pi\pi$ and $\omega$ respectively. On the same plot the prompt photon estimation (see the section 2) is also presented by a line at $p_t > 1.5$ GeV/c.

Fig. 3 demonstrates predictions of the HSD code at the FAIR energy 25 AGeV for Au+Au central collisions. As at the SPS energy here at $p_t = 0.5 - 1$ GeV/c one can observe significant contribution of photons from the decays $\omega \to \pi^0\gamma$ in the dense matter. On the same plot the photon spectrum from $\pi^0$ decays is also shown. In the region $p_t = 0.5 - 1$ GeV/c $\gamma_{direct}/\gamma_{\pi^0} \simeq 0.5\%$. As have been
Figure 4: Comparison of the BHD ($\tau_0 = 1$ fm, $T_0 = 180$ MeV) and HSD invariant photon spectra for central Au+Au events at 25 AGeV in the central rapidity region.

mentioned it is a lower estimate. Rapidity densities dN/dy at $y = y_{c.m.}$ are 0.10, 0.12 and 0.09 for $\pi\rho$, $\pi\pi$ and $\omega$ respectively. Average multiplicities per event are 0.31, 0.32 and 0.25 for $\pi\rho$, $\pi\pi$ and $\omega$ respectively. At high $p_t = 1.5 - 2$ GeV/c the part of direct photons is higher $\gamma_{\text{prompt}}/\gamma_{\pi^0} \simeq 2\%$.

4 Direct photons from BHD

In the Bjorken hydrodynamics [8] it is assumed that during the ion-ion collision the system is mainly expanding in beam direction in a boost-invariant way. Natural variables are the proper time $\tau = \sqrt{t^2 - z^2}$ and rapidity. Thermodynamical variables (pressure, temperature, ...) do not depend on the rapidity but are functions of $\tau$, e.g. $T = T_0(\tau_0/\tau)^{1/3}$ for an ideal ultrarelativistic gas. Main initial parameters are the proper time $\tau_0$ and temperature $T_0$. Viscosity and conductivity effects are neglected. For this simple space-time evolution one can evaluate simple formula for photon spectrum with the photon emission rate as input (the section 2.2.2 of [3]). Photon yield is proportional to $\sim \tau_0^2$. Though the Bjorken
Figure 5: Direct photon spectrum in the central rapidity region predicted by the BHD model for central Au+Au collisions at 25 AGeV for different values of the initial parameter $T_0$.

The scenario is expected to be valid for ultrarelativistic energies (RHIC, LHC) one can assume it can be used for estimations at SPS and FAIR energies. The parameterizations presented in [13] have been used for the thermal photon emission rates of the channels $\pi\rho \to \pi\gamma$ and $\pi\pi \to \rho\gamma$. The direct photon WA98 data can be reproduced at $p_t > 1.5$ GeV/c by the BHD model with the parameters $\tau_0 = 1$ fm and $T_0 = 235$ MeV [14].

Fig. 4 shows BHD predictions with the parameters $\tau_0 = 1$ fm, $T_0 = 180$ MeV at the FAIR energy 25 AGeV for central Au+Au events side by side with the HSD results discussed before. The BHD spectra are broader than ones in the HSD transport approach. The main reason is the local termalization assumption used in the BHD model. $\gamma_{direct}/\gamma_{\pi^0} \simeq 0.5\%$ and 3\% at $p_t = 1$ and 1.5 GeV/c respectively.

Fig. 5 demonstrates a sensitivity of the direct photon spectrum to the initial parameter $T_0$. The 10 MeV increase in the $T_0$ value leads to 1.5 and 2.5 times higher photon yield at $p_t = 0.1$ GeV/c and 2 GeV/c respectively.
5 Summary

Using the extrapolation of existing data estimations of prompt photon production at FAIR energies have been made. At $y = y_{c.m.}$ the rapidity density of prompt photons with $p_t > 1.5$ GeV/c per central Au+Au event at 25 AGeV is estimated as $\sim 10^{-4}$. With the planned beam intensity $10^{9}$ per second and 1% interaction probability, for 10% of most central events one can expect the prompt photon rate $\sim 10^2$ photons per second.

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This work was partially supported by the Russian Foundation for Basic Research, grant number 06-08-01555 and Federal agency of Russia for atomic energy (Rosatom).

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