Refraction of light in the quark-gluon plasma

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Electromagnetic probes in high-energy heavy-ion collisions provide us with important information on the quark-gluon plasma (QGP) because experimental data indicate that the hot medium is color opaque but electromagnetically transparent. An important discovery regarding such probes is the excessive yield of direct photon elliptic (v_2) and triangular flow (v_3).[1)] Direct photons consist of prompt photons created in the initial hard processes and thermal photons emitted from the medium. Flow harmonics is defined as a Fourier expansion coefficient of particle spectra in the azimuthal angle and is induced by geometrical anisotropy in the system via medium interaction. Since hadronic flow harmonics follows hydrodynamic description and is considered as an evidence for the existence of a strongly coupled medium, quantitative understanding of the direct photon flow harmonics is an important issue in heavy-ion phenomenology.

I have investigated the effect of refraction on prompt photons by the QGP medium in the transverse plane (Fig. 1).[2)] The emission rate for prompt photons is derived from p-p collision data.[3)] The path of a ray in a medium with the refractive index n is given as $d^2x/d\tau^2 = (1/2)dn^2/dx$ according to Fermat's principle. The dynamical evolution of an inhomogeneous medium should be considered, because the typical lifetime and size of the system are comparable. Here, I use a (2+1)-dimensional ideal hydrodynamic model with Monte-Carlo Glauber initial conditions and a lattice QCD equation of state. The initial time is 0.4 fm/c and the freeze-out temperature is 0.15 GeV. The temperature and frequency dependence of the refractive index is parametrized as $n^2(T,\omega) = 1-\omega_p^2/\omega^2$, where the plasma frequency is parametrized as $\omega_p^2 = a^2T^2$. In the high-temperature limit, $\omega_p^2 \sim m_D^2 \sim e^2T^2$ is obtained using the Debye mass m_D. This implies $a^2 \sim 10^{-1}$ since $e^2 = 4\pi\alpha_{\rm EM}$. The frequency ω is Doppler-shifted from the original frequency as $\omega = \omega_0/\gamma(1+\beta\cos\Delta\phi)$, where $\Delta\phi$ is the angle between the flow and the direction of a ray. It should be noted that the phase velocity in the QGP medium, $v_{\rm ph} = 1/n$, exceeds the speed of light, but causality is not violated because the group velocity remains smaller than unity. When $n^2 < 0$, the medium does not bend a ray but partially absorbs it.

The elliptic flow of prompt photons is shown in Fig. 2. When there is no refraction, the quantity vanishes. For non-unity refractive indices, on the other hand, positive v_2 is observed above plasma frequencies. The magnitude, however, is not large enough to account for the large photon v_2 found in collider experiments. Below the plasma frequency, the high-temperature region near the center of the medium becomes semitransparent and suppresses photons traveling horizontally, leading to negative v_2. Once the entire system becomes translucent at low momentum, v_2 again becomes positive because photons have better chance of moving out of the medium in the direction of the minor axis. This implies that the QGP plasma frequency can be constrained from measurements. The absorptive behavior has not been found in photon p_T spectra above 0.5 GeV at RHIC and 1 GeV at LHC.[4)] Here, the former condition is more stringent and the maximum refraction parameter allowed is $a^2 \sim$ 1-2. Higher-order harmonics, v_3-v_5, are found to be positive but small. Note that the above argument depends on the choice of refractive index. Numerical analyses with different indices and introduction of thermal photons will be performed in the future.

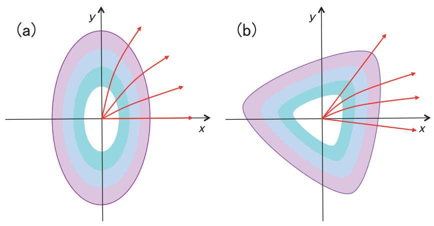

Fig. 1. Schematic of medium refraction for (a) elliptic flow and (b) triangular flow.

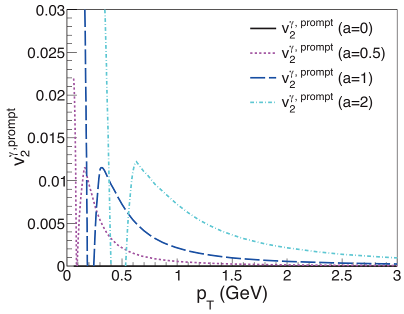

Fig. 2. Differential elliptic flow of prompt photons for different refraction parameters.

References

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