

PROBING THE FIREBALL AT SIS-18 ENERGIES WITH THERMAL DILEPTON RADIATION*

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(Received February 16, 2017)

Electromagnetic probes are radiated during all stages of a heavy-ion collision and leave the fireball without further rescattering. Thus, they transmit important information about the matter created in the interior of the collision zone. Utilizing a coarse-graining method, we extract local thermodynamic properties from hadronic transport simulations at SIS energies. These serve as an input for the calculation of the pertinent radiation of thermal dileptons based on an in-medium ρ spectral function that describes available spectra at ultrarelativistic collision energies. The results provide a baseline for future measurements by the HADES and CBM experiments at GSI/FAIR.

DOI:10.5506/APhysPolBSupp.10.717

1. Introduction

Extreme states of matter with temperatures resembling those in the early universe and densities as high as in the core of neutron stars can be studied in detail in laboratory experiments using heavy-ion collisions (HICs). Systematic investigations of such reactions provide insights into the different phases in which strongly interacting QCD matter can exist in nature. By varying the energy and species of the colliding nuclei, one can alter the chemical composition of the system and learn about the changes of hadron properties across the QCD phase diagram.

Electromagnetic (EM) probes constitute an excellent tool for these investigations as they are radiated during the whole time evolution of a HIC and decouple from the collision zone once they are produced. Thus, they carry

* Presented at the “Critical Point and Onset of Deconfinement” Conference, Wrocław, Poland, May 30–June 4, 2016.

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information about the properties of matter created inside the hot and dense fireball to the detector which is irretrievable from the spectra of final-state hadrons due to rescattering.

In particular, the excess yield of low-mass dileptons above the hadronic cocktail contributions was identified to be sensitive to the fireball lifetime, while the slope in the intermediate-mass region of the dilepton invariant-mass spectrum can serve as a thermometer which is unaffected by blue-shift effects caused by the collective expansion of the medium [1].

2. Thermal rates applied to coarse-grained fireball evolution

Realistic thermal dilepton emission rates and an accurate description of the fireball's space-time evolution in terms of temperature and chemical potentials are needed to properly describe the contribution of in-medium signals to the dilepton invariant-mass spectrum.

At SIS energies of $E_{\text{lab}} = 1\text{--}2A$ GeV, hadronic transport models are commonly used to describe the fireball evolution. However, the incorporation of in-medium effects into these off-equilibrium approaches remains challenging. A complete hydrodynamic description as employed at high energies is also challenging since the incoming nuclei need a long time to fully overlap which raises the question if and when local thermalization occurs. As a hybrid approach to bridge microscopic transport and macroscopic hydrodynamics, a coarse-graining procedure was proposed [2], and recently applied to the SIS energy regime [3,4]. By dividing the space-time evolution into 4-dimensional cells and averaging over an ensemble of many simulated transport events, one obtains smooth particle distributions. Meaningful temperatures, baryon and pion densities as well as collective flow patterns can then be extracted from cells which fulfill certain criteria that are favorable for (the onset of) thermalization (*e.g.*, a minimum number of collisions of the incoming nucleons).

The extracted bulk properties of the cells are used as an input for the calculation of thermal dilepton radiation using the standard rate expression

$$\frac{d^8 N}{d^4 x d^4 p} = \frac{\alpha_{\text{EM}}^2}{\pi^2 M^2} f_{\text{B}}(p_0, T) \varrho_{\text{EM}}(M, p; T, \rho_{\text{eff}}, \mu_{\pi}) , \quad (1)$$

where $M = \sqrt{p_0^2 - p^2}$ is the invariant mass of the virtual photon, f_{B} denotes the thermal Bose distribution function, and ϱ_{EM} the EM spectral function of the QCD medium depending on the temperature, T , the effective baryon density, $\rho_{\text{eff}} = \rho_N + \rho_{\bar{N}} + \frac{1}{2}(\rho_R + \rho_{\bar{R}})$ (N refers to nucleons, R to baryonic resonances), and an effective chemical potential of pions, μ_{π} . For ϱ_{EM} , we employ the in-medium ρ spectral function of Ref. [5] which describes dilepton data in ultrarelativistic HICs (URHICs). The effect of the chemical potential

of pions on the EM spectral function is encoded in an overall fugacity factor, $z^\kappa = \exp(\mu_\pi/T)^\kappa$, where κ specifies the average number of pions figuring in the production of ρ mesons. Using UrQMD, we estimated this number to be close to 1 at SIS energies [4] as the main production channels are baryon resonance decays rather than $\pi\pi$ annihilation.

3. Results

Building on our results obtained for Au+Au collisions at 1.23A GeV [4], we repeat the same steps for the medium-heavy collision system of Ar+KCl at 1.76A GeV ($\sqrt{s_{NN}} = 2.6$ GeV) that was measured by HADES [6] in the year 2005. The left panel of Fig. 1 shows the evolution of temperature, effective baryon density and pion chemical potential for central collisions averaged over the inner cube of $5 \times 5 \times 5$ cells, each of a volume of 1 fm^3 . These are used as an input to Eq. (1) to calculate the spectra of thermal dileptons. The resulting invariant-mass spectrum of thermal radiation inside the HADES acceptance shows a fair agreement with the experimental data of the excess yield above a “cocktail” of long-lived EM decays at freeze-out plus a superposition of $p+p$ and $n+p$ reactions [6,7], see left panel of Fig. 2.

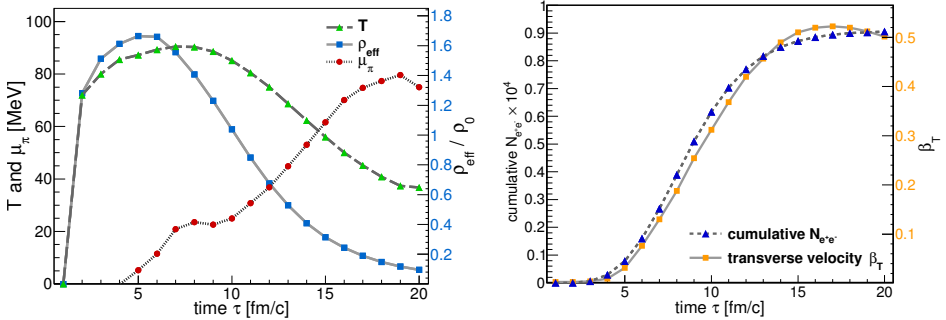


Fig. 1. (Color online) Left panel: Time evolution of temperature (green triangles), effective baryon density (blue squares, right scale) and pion chemical potential (red circles) averaged over an inner cube of $5 \times 5 \times 5$ cells (1 fm^3 each) in central Ar(1.76A GeV)+KCl collisions. Right panel: Evolution of the transverse flow (orange squares, right scale) and the cumulative yield of dileptons radiated into the mass region $M_{ee} = 0.3\text{--}0.7 \text{ GeV}/c^2$ (blue triangles).

In the right panel of Fig. 1, we compare the time development of the collective radial-flow velocity of nucleons with the cumulative yield of thermal dileptons in the low-mass region, $M_{ee} = 0.3\text{--}0.7 \text{ GeV}/c^2$. The latter has been found previously to “measure” the lifetime of the fireball quite accurately [1]. We find that “thermal” dilepton radiation and the build-up of collectively coincide remarkably well. These *a priori* independent quantities

are thus intimately related: the same interactions drive collectivity while exciting resonances which radiate dileptons. This corroborates that both are a measure of the interacting fireball lifetime, which amounts to about $\tau_{\text{fb}} = 8 \text{ fm}/c$, from 5 to 13 fm/c after the collision started.

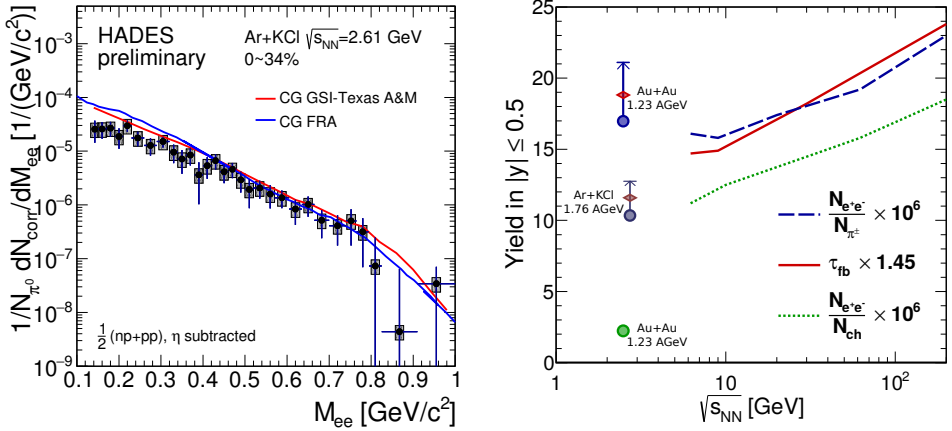


Fig. 2. (Color online) Left panel: Comparison of dilepton excess spectra from two independent coarse-graining approaches [3, 4] and the experimentally extracted yield above the cocktail in Ar+KCl at 1.76 A GeV from HADES [6, 7]. Right panel: Excitation function of the low-mass thermal-dilepton yield in central Au+Au collisions normalized to N_{π^\pm} (dashed blue line) and N_{ch} (dotted green line), together with the lifetime of the system (solid red line). The curves have been calculated using a fireball model with QGP and in-medium hadronic emission [1], while the diamonds and circles represent the yields and lifetime obtained within our coarse-graining approach.

For URHICs, the relation of Ref. [1] between fireball lifetime and thermal-dilepton yield normalizes the latter to the number of charged particles, N_{ch} . However, at smaller collision energies, $\sqrt{s_{\text{NN}}} \leq 5 \text{ GeV}$, the fireball is increasingly dominated by the incoming nucleons, not the produced particles, and thus N_{ch} is not a good proxy for the thermal excitation energy in the system. Therefore, we replot in Fig. 2 the low-mass thermal-dilepton yields by normalizing them to the number of charged pions, N_{π^\pm} . For URHICs, the proportionality to the lifetime,

$$\left. \frac{N_{ll}}{N_{\pi^\pm}} \right|_{|y| \leq 0.5} \times 10^6 = 1.45 \tau_{\text{fb}} [\text{fm}/c], \quad (2)$$

remains intact with a slightly larger normalization of 1.45 (which includes strong final-state decays in the dilepton yield) [4], *cf.* right panel of Fig. 2.

The extracted lifetime, $\tau_{\text{fb}} \simeq 12 \text{ fm}/c$ for central Au+Au(1.23A GeV) collisions, approximately agrees with the interaction window of $\sim 13 \text{ fm}/c$ identified in Ref. [4], indicating an increasing trend of τ_{fb} toward SIS energies, albeit not dramatic. Utilizing this relation for the Ar+KCl system with $N_{ll}|_{|y|\leq 0.5} = 6.6 \times 10^{-5}$ and $N_{\pi\pm}|_{|y|\leq 0.5} = 6.4$, we obtain $\tau_{\text{fb}} \simeq 7.1 \text{ fm}/c$, in approximate agreement with the $8 \text{ fm}/c$ long radiation window.

4. Conclusions

We presented a coarse-graining approach to couple in-medium thermal dilepton rates to hadronic transport in heavy-ion collisions at relativistic bombarding energies, and applied it to Ar+KCl collisions at 1.76A GeV. The resulting dilepton spectra for this medium-heavy system confirm the close correlation between the build-up of collectivity and the time-window of thermal dilepton emission found earlier, as well as the possibility to track the lifetime of the system with the radiation yield in the mass window $0.3 \text{ GeV}/c^2 \leq M_{ll} \leq 0.7 \text{ GeV}/c^2$.

We thank the HADES Collaboration for providing the data points of the dilepton excess spectrum in Ar+KCl and H. van Hees and S. Endres for their coarse-graining curve. This work was supported by the U.S. National Science Foundation under grant PHY-1614484, the A.-v.-Humboldt Foundation (Germany), the Helmholtz-YIG grant VH-NG-823 at GSI and TU Darmstadt (Germany), and the Hessian Initiative for Excellence (LOEWE) through the Helmholtz International Center for FAIR (HIC for FAIR).

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