Dependence of lepton pair emission on EoS and initial state

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We present results from a hydrodynamic calculation for thermal emission of lepton pairs in central lead-lead collisions at the CERN SPS energy. Dependence of the emission on the initial conditions and Equation of State (EoS) is considered and the spectra are compared with CERES data and calculated distribution of Drell–Yan pairs.

1. Parametrization of initial conditions for hydrodynamics

A major problem in using hydrodynamics to describe a high energy nucleus-nucleus collision is how to include the primary production stage. At low energies hydrodynamics can be used for the description of the whole collision process starting with the incoming nuclei as approaching droplets of nuclear fluid which meet, compress and heat up, followed by the expansion of this dense fireball. At high energies the nuclei become increasingly transparent and it becomes unrealistic to describe the formation of the initial dense matter as a fusion of the colliding nuclei into a single fluid droplet. Instead, one can parametrize the formation of matter in the form of initial conditions for the subsequent hydrodynamic expansion. In principle these initial distributions should be calculated from the dynamics of strong interactions but in practice such calculations involve modelling, usually with several phenomenological parameters.

For our study we have adopted a simpler approach in which we parametrize the initial state and constrain the parametrization by experimental hadron distributions. We base our parametrization on the local (in transverse plane) nuclear thickness. When combined with nuclear geometry such parametrization gives the initial conditions for collisions of nuclei with arbitrary mass numbers A and B [1,2]. Energy and baryon number conservation is imposed also locally in transverse plane. With only a few parameters we are able to reproduce the main features of hadronic spectra in all nucleus-nucleus collisions measured at CERN SPS [2]. Even though the parametrization is ad hoc the results contain nontrivial correlations between different measured quantities like longitudinal and transverse spectra and the mass dependence of the slopes of transverse spectra. E.g., too strong stopping leads both to too narrow rapidity distributions and too shallow transverse distributions showing the correlation between longitudinal and transverse flow.

In Fig. 1 we illustrate the mass dependence of transverse momentum spectra on the transverse flow and the freeze-out temperature. Lower freeze-out temperature is reached later and leads to stronger flow. The net effect on the negative particles, mainly pions,
which constitute the main bulk of the matter is not large but the heavier protons gain more from the increased common flow velocity than what they lose in the decrease of temperature. We observe that the lower freeze-out temperature, $T_f \approx 120$ MeV is favoured.

For further systematic see Ref. [2].

Fitting the hadron spectra is not sufficient to fix the initial conditions unambiguously. First, some variation in stopping or initial volume can be compensated by change of initial densities. Second, different equations of state (EoS) lead to slightly different initial conditions. For the EoSs we use, see Ref. [3].

2. Emission rates and spectra of lepton pairs

Since the electromagnetic emission from the secondary collisions depends on the local conditions, one can expect independent constraints on the expansion from lepton pair and photon spectra. Below, we compare lepton spectra for different initial conditions and for EoSs with transition temperatures $T_c = 165$ and 200 MeV. The main difficulty are the contributions from many background processes to these spectra.

We have studied the thermal emission of lepton pairs in the mass range $0.3 \text{ GeV} \leq M \leq 3 \text{ GeV}$ where excess over conventional sources has been reported [4–6]. We do not consider medium effects on the $\rho$-meson parameters which are expected to be crucial for $M \leq 1 \text{ GeV}$. In this regime our aim is to see if the thermal contribution is of right magnitude when the evolution of the nuclear fireball is constrained to be consistent with the observed hadron spectra.

Our initial conditions are such that at central rapidities a large fraction of the matter starts in the QGP phase. For the emission rate from the plasma we use the lowest order perturbative rate for an ideal QGP [7]. Higher order corrections are known to be important for the emission of very low-mass pairs [8,9] but the hadronic sources dominate the total spectra in this mass region [9].

In the hadron gas phase we use the binary rates of Gale and Lichard [10]. In the vicinity of the transition temperature one can argue that the thermodynamics of the hadron gas...
can be described by a Hagedorn gas of noninteracting resonances. In this picture the strong interaction effects are embedded in the spectrum of resonances including the vector mesons. Assuming vector meson dominance and quark-hadron duality, the lepton pair emission from the resonance gas is given by the decays of vector mesons. This result can be considered as an upper limit for the emission from hadron gas when processes with extra particles in initial or final states are neglected. Since duality works better for heavy, overlapping states we use this result for $M \geq 1.5$ GeV.

The excess observed by the CERES has been fitted employing rates which take into account medium modifications but using a simplified description of the hydrodynamic expansion or RQMD simulation which does not admit a phase transition. In fig. 2 we show our results with CERES data. The dashed line is the background from the calculated final hadrons after the freeze-out. The full (dashed) line is the result for $T_c = 200 (165)$ MeV when the thermal contribution is added. We see that without medium modifications the thermal emission does not fill the observed excess of low-mass pairs even though in the $\rho$-mass region it is twice as big as the background. At $M \approx 500$ MeV thermal contribution is equal to the background but the total is below the data by a factor of 4...5. Thus an enhancement factor of $\approx 8...10$ is needed here if the thermal emission is the source of the excess. The thermal emission in the CERES region is dominated by the contribution from hadron gas and it decreases when $T_c$ is lowered. Since for lower $T_c$ the hadron gas phase occurs at lower temperatures and smaller nucleon densities, the medium effects can be expected to depend strongly on the EoS.

In Fig. 3 we show the mass spectrum for $M \gtrsim 1.5$ GeV. In the analysis of NA50 the data is roughly a factor of 2 above the sum of the Drell–Yan pairs and pairs from charm decays. Since the NA50 acceptance cuts are difficult to implement we compare the thermal spectra with Drell-Yan pairs. To account for the excess, the thermal contribution should be of the same magnitude as the Drell–Yan emission.

Because $M \gg T$ in this mass region and the emission rates are (approximately) $\propto \exp(-M/T)$, the thermal contribution is sensitive to the initial conditions. This is seen in Fig. 3 where the dashed and dotted lines correspond to the opposite extremes of the average initial energy density, $\langle \epsilon_i \rangle$, which can reproduce the hadron spectra. The first conclusion is that indeed the lepton pair contribution from the secondary collisions can distinguish between different initial conditions. Secondly, this contribution can be at least an important part of the observed excess in this mass region. With our initial conditions this region is less sensitive to the EoS.

3. Summary

We have studied lepton pair emission using a simple parametrization of initial conditions based on nuclear thickness and conservation of energy and baryon number. Since the parametrization is implemented locally in the transverse plane it applies, when combined with nuclear geometry, to collisions with arbitrary mass numbers and can be extended to nonzero impact parameters. It correlates the stopping with transverse geometry. Main features of hadronic spectra in all nucleus-nucleus collisions measured at SPS can be well reproduced with the same parametrization.

Hadronic observables do not completely fix the initial conditions. Stopping and initial densities can be varied to some extent and different choices of the EoS lead also to
slightly different initial conditions. In the low mass region, $M < 1$ GeV, the hadron phase completely dominates the thermal emission and the yield is not sensitive to the initial conditions. The yield depends on the EoS and with the medium effects one can expect greater sensitivity to the transition temperature $T_c$. In the mass region, $M > 1.5$ GeV $\gg T$ the emission is quite sensitive to the changes in initial conditions but not on the EoS. Since the thermal emission can be of same strength as Drell-Yan it can be an important contribution to the excess observed by NA50.

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