Electron-positron pairs from thermal resonances in ultrarelativistic nuclear collisions

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We use a boost-invariant one-dimensional (cylindrically symmetric) fluid dynamics code to calculate e^+e^- production from ρ^0 and ω decay in the central rapidity region of a central S+Au collision at $\sqrt{s}=20$ GeV/nucleon. We use equations of state with a first-order phase transition between a massless pion gas and quark gluon plasma, with transition temperatures in the range 150–200 MeV. The production cross section at the ρ mass loosely constrains the transition and freeze-out temperatures, and we find that the m_T spectrum is a good thermometer for sufficiently high T_c.

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One of the most important problems in nuclear physics today is the study of the equation of state (EOS) of high-temperature and high-density hadronic matter; the former is necessary to understand the first few microseconds of the big bang, and the latter for elucidating the physics of neutron stars and similar dense astrophysical objects. In order to investigate the nature of the transition from normal ($T=0$) hadronic matter to deconfined quark gluon plasma (QGP), or whatever the high-temperature phase may be, experiments are being performed at Brookhaven's Alternating Gradient Synchrotron (AGS) and CERN's Superconducting Proton Synchrotron (SPS), and future experiments are being planned for Brookhaven's Relativistic Heavy Ion Collider (RHIC) and CERN's Large Hadronic Collider (LHC). In these experiments, the only particles expected to emerge from the early part of the collision (and thus the only probes of the high-temperature EOS) are photons and leptons, which therefore may provide the most important information obtained from these collisions.

Predicted e^+e^- transverse mass m_T spectra from resonance decays in ultrarelativistic nuclear collisions are sensitive to the hadronic transition temperature, T_c, when transverse expansion is neglected [1–3]. Thus, measurements of these spectra may place strong constraints on T_c, as well as other parameters of the hadronic EOS [3]. However, the photon transverse momentum spectrum was also predicted to be sensitive to T_c [4], but the sensitivity disappeared when transverse expansion was included [5]. The next natural step is to study e^+e^- transverse mass spectra with a model including transverse expansion. This is the subject of the present paper. Since transverse expansion may increase the contribution of mesons decaying after freeze-out, a careful treatment of freeze-out is necessary. We find that the m_T spectra are in fact dominated by the freeze-out contribution for sufficiently high m_T, but can still be fitted with apparent temperatures correlated to T_c. This may provide a method to determine T_c experimentally, even though the underlying physics is more complicated than originally envisioned in the treatment of lepton pairs without transverse expansion [1]. We show that the correlation between T_c and the m_T spectrum of dileptons from ρ^0 and ω decay persists in the presence of transverse expansion, and thus that a determination of the transverse mass spectrum of dileptons in the $\rho^0-\omega$ peak would yield useful constraints on T_c.

Here we adopt the position that in strongly interacting matter at sufficiently high temperature and/or density a transition takes place to a high-energy phase. In the present paper, we are interested in the possibility of extracting the transition temperature assuming a first-order phase transition. We assume a boost-invariant longitudinal expansion as discussed by Bjorken [6], coupled to a cylindrically symmetric transverse expansion. For the initial evolution, we use a simple model for production of longitudinally free-streaming hot matter [7]. After the hot matter has thermally equilibrated, we use thermal equilibrium fluid-dynamical evolution, but consider deviations from chemical equilibrium in the high-temperature phase by allowing the quark and antiquark densities to be a (fixed) fraction x of their equilibrium values. When particle mean free paths become comparable to the radius of the cylinder of hot matter, which we take to occur at some freeze-out temperature, $T_{\rm fo}$, we assume that the particles crossing the freeze-out surface $T=T_{\rm fo}$ stream freely until they either decay or reach the detectors. We then calculate the e^+e^- production rate from ρ^0 and ω decays; these are not separated, as the masses are almost degenerate and the experimental resolution is typically not good enough to resolve the individual peaks. We investigate the sensitivity to different assumptions about the initial temperature, freeze-out temperature, and quark fraction, and compare production rates to the preliminary NA45 data [8]. We use standard high-energy conventions $c=\hbar=k_B=1$.

Here we describe the initial conditions and assumptions about the EOS; the details of the fluid-dynamical calculation can be found elsewhere [9,5]. We consider a central collision of two large nuclei at SPS energy ($\sqrt{s}=20$ GeV/nucleon). For such high collision energies we expect approximate longitudinal boost invariance [6], so the behavior of the produced matter at different rapidities is the same in the longitudinally comoving frame for fixed proper time $\tau=\sqrt{t^2-z^2}$, where z is the distance along the beam axis. At

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$\tau=0$ the colliding nuclei reach the point of maximum overlap and are assumed to form a longitudinally expanding pancake. The hot matter has thermalized at $\tau=\tau_0$ (≈ 0.2 fm/c) [10,11], when a cylindrically symmetrical transverse expansion begins, coupled to the longitudinal expansion.

From $\tau=0$ until the transverse expansion starts at $\tau=\tau_0$, we assume a boost-invariant cylinder of radius $R_<$ (the radius of the smaller nucleus), filled uniformly with QGP at temperature $T=T_0$. This is approximately compatible with the initial entropy density for short times [7]. We determine T_0 by assuming entropy conservation for $\tau>\tau_0$, hence

$$s(T_0)=\frac{3.6 dN_\pi/dy}{\pi R_<^2 \tau_0}, \tag{1}$$

where s is the entropy density, with total (charged plus neutral) multiplicity density dN_π/dy.

The equations of state (EOS's) that we use here are of the form

$$\begin{aligned}
T<T_c:&\quad e=\frac{\pi^2}{10}T^4, && P=\frac{e}{3},\\
T=T_c:&\quad \frac{\pi^2}{10}T_c^4 \leqslant e \leqslant \frac{\pi^2}{30}g_q T_c^4+B, && \frac{\pi^2}{30}T_c^4=P=\frac{\pi^2}{90}g_q T_c^4-B,\\
T>T_c:&\quad e=\frac{\pi^2}{30}g_q T^4+B, && P=\frac{\pi^2}{90}g_q T^4-B,
\end{aligned} \tag{2}$$

where g_q is the number of massless degrees of freedom in the deconfined phase. We treat only the case of zero baryon density, so the entropy density is $s=(e+P)/T$ independent of the phase of the matter. Below T_c, the EOS is that of a massless pion gas. Because recent calculations have predicted that the quarks may reach only a fraction of their equilibrium number by the beginning of transverse expansion [10,11], we take $g_q=16+21x$, where x is a parameter that we vary between 0 and 1 to simulate the effect of reducing the quark density in the QGP below the equilibrium value ($x=1$ is equilibrium for two flavors of massless quarks). The vacuum energy density in the deconfined phase B is related to the transition temperature T_c by requiring equal pressures in the deconfined and hadronic phases at $T=T_c$ so that $B=\pi^2(g_q-3)T_c^4/90$. The value of B we use away from equilibrium is calculated by assuming $x=1$ and supplying an equilibrium transition temperature T_c'. It is this T_c' that is actually used on the graphs and is useful for comparison purposes.

We calculate the central rapidity region m_T distribution from both interacting and frozen-out hot matter. The contribution from the interacting hot matter is

$$\left.\frac{d^2N_{e^+e^-}^{(\rho^0+\omega)}}{m_T dm_T dy}\right|_{y=0}=\int d\eta \int d\tau\ \tau \int dr\ 2\pi r \int_0^\pi d\theta\ \sin\theta \int_0^{2\pi} d\phi \int_0^\infty dp\ p^2 \frac{dR}{d^3p}\,\delta\!\left(\tfrac{1}{2}m_T^2-\tfrac{1}{2}m_T'^2\right)$$
$$\times\,\delta\!\left(\eta+\tanh^{-1}\left[\frac{p\ \cos\theta}{\gamma(\sqrt{p^2+m^2}+pv\ \sin\theta\ \cos\phi)}\right]\right)\Theta(T-T_{\rm fo}). \tag{3}$$

Here $m_T=\sqrt{m^2+p_T^2}$, R is the e^+e^- production rate per unit four volume in the fluid frame, v is the transverse velocity of the fluid in the cell characterized by proper time τ, space-time rapidity η and radial position r (measured in the frame moving with transverse velocity zero and longitudinal velocity $\tanh\eta$ in the laboratory), and $\gamma=(1-v^2)^{-1/2}$. The e^+e^- production rate from ρ^0 and ω mesons in thermally and chemically equilibrated hadron gas is

$$\frac{dR}{d^3p}=\frac{m(g_{\rho^0}\Gamma_{\rho^0\to e^+e^-}+g_\omega\Gamma_{\omega\to e^+e^-})}{E(2\pi)^3}(e^{E/T}-1)^{-1}, \tag{4}$$

where $g_{\rho^0}=g_\omega=3$ are the degeneracies of the ρ^0 and ω mesons, and the partial widths are $\Gamma_{\rho^0\to e^+e^-}=6.77$ keV and $\Gamma_{\omega\to e^+e^-}=0.60$ keV. E is the energy measured in the fluid frame, and we use the average mass of the ρ and ω, $m=0.775$ GeV. No mesons exist in the QGP, and hence the resonant e^+e^- production rate is zero for that part of the fluid.

Mesons which pass through the freeze-out surface $T=T_{\rm fo}$ are no longer subject to fluid-dynamic flow, as their mean free paths are so long that they do not interact with the surrounding matter. As these frozen-out mesons free stream toward the detectors they decay to e^+e^- pairs as before, but the number of mesons decreases exponentially in time, with time constant equal to the free space meson decay time. The contribution from the decay of frozen-out ρ^0 and ω mesons is thus

$$\left.\frac{d^2N_{e^+e^-}^{(\rho+\omega)}}{m_T dm_T dy}\right|_{y=0} = \left(\frac{g_{\rho^0}\Gamma_{\rho^0\to e^+e^-}}{\Gamma_\rho}+\frac{g_\omega\Gamma_{\omega\to e^+e^-}}{\Gamma_\omega}\right)\int d\tau\ \tau 2\pi r(\tau) \times\int_{-1}^{1} d(\cos\theta)\int_0^{2\pi} d\phi\int_0^\infty dp\ p^2\gamma(2\pi)^{-3} \times(e^{E/T}-1)^{-1} \times\left(v_x-\frac{dr}{d\tau}\right)\Theta\left(v_x-\frac{dr}{d\tau}\right)\delta(\tfrac{1}{2}m_T^2-\tfrac{1}{2}m_T'^2) \quad (5)$$

where

$$v_x=\frac{p\ \sin\theta\ \cos\phi+v\sqrt{p^2+m^2}}{\sqrt{p^2+m^2}+pv\ \sin\theta\ \cos\phi} \quad (6)$$

is the component of the meson velocity perpendicular to the freeze-out surface, and $\Gamma_\rho=151$ MeV and $\Gamma_\omega=8.43$ MeV are the total widths for the ρ and ω. $dr/d\tau$ is the radial velocity of the freeze-out surface and $r(\tau)$ is its location. The Θ function ensures that only mesons going through the freeze-out surface in the outward direction are counted.

Finally, we extract the fit temperature $T_{\rm fit}$ by performing a least-squares fit to our calculated spectrum (equilibrium plus freeze-out) in the window $1.155\leqslant m_T\leqslant 1.755$ GeV, which is dominated by freeze-out. The part of the spectrum that is dominated by the equilibrium contribution is much smaller, typically $0.8\leqslant m_T\leqslant 0.9$ GeV. Unfortunately this is of the order of a single experimental bin, so we choose instead to focus on the freeze-out contribution, in anticipation of fitting experimental data with both equilibrium and freeze-out contributions. Furthermore, a measurement of an m_T spectrum from the $\rho-\omega$ peak would look at a finite range of m, so we filter the simulated data through an invariant mass bin of size $0.475<m<1.075$ GeV, assuming a Breit-Wigner distribution for each species. For our fitting function, we take Eq. (3) with $v=0$ (i.e., ignoring transverse expansion), resulting in the formula [1]

$$\frac{d^2N_{e^+e^-}^{(\rho+\omega)}}{m_T dm_T dy}\sim\left(\frac{m_T}{T_{\rm fit}}\right)^{1/2}\exp\left(-\frac{m_T}{T_{\rm fit}}+0.4\frac{T_{\rm fit}}{m_T}\right). \quad (7)$$

Our "standard" parameter set is $\tau_0=$ 0.2 fm/c, $x=1$, $T_{\rm fo}=120$ MeV, and $150<T_c<200$ MeV; if different values of any of the parameters are given, all the others are held at the standard values. We use $dN_\pi/dy=188$ for central S+Au collisions at SPS energy (the NA45 experimenters estimate $dN_{ch}/d\eta=125$ for their S+Au collision sample, and we assume isospin symmetry). Our standard value for the equilibration time $\tau_0=$ 0.2 fm/c implies an initial temperature $T_0=327$ MeV. Figure 1 shows the equilibrium, freeze-out, and total contributions for the standard set with $T_c=170$ MeV.

In the absence of transverse expansion, $T_{\rm fit}$ is a monotonically increasing function, and comparable to T_c, so one can infer T_c given $T_{\rm fit}$ from the measured e^+e^- spectrum [1]. In Fig. 2, we vary T_c from 150 to 200 MeV and calculate the resulting values of $T_{\rm fit}$ while including transverse expansion. We find that $T_{\rm fit}$ is higher than in the case of longitudinal-only expansion, but still monotonic (except where $T_{\rm fo}$ approaches T_c). $T_{\rm fit}$ is 10–20 MeV lower for $\tau_0=1$ fm ($T_0=192$ MeV), which we attribute to the fact that transverse expansion develops relatively little in this case.

Note that freeze-out is treated dynamically in the present calculation in contrast to an earlier investigation [1] where transverse expansion was neglected and thus freeze-out was approximated as occurring at a fixed proper time. We consider a moving freeze-out surface here, and the yield from mesons crossing this surface is integrated over the history of

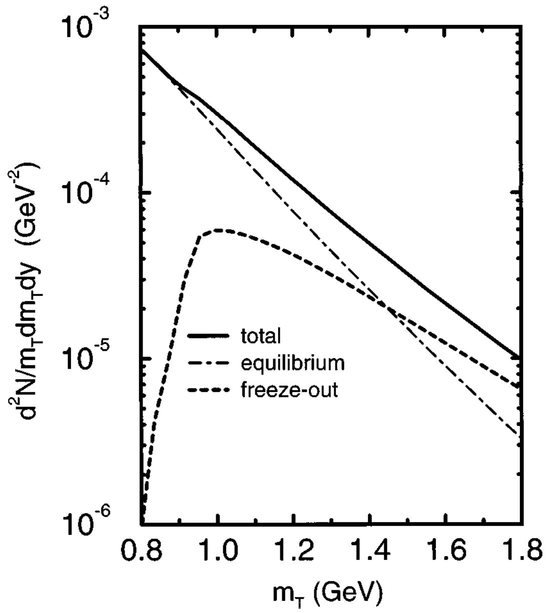

FIG. 1. A central S+Au collision at SPS energy, using our standard set of parameters and $T_c=170$ MeV.

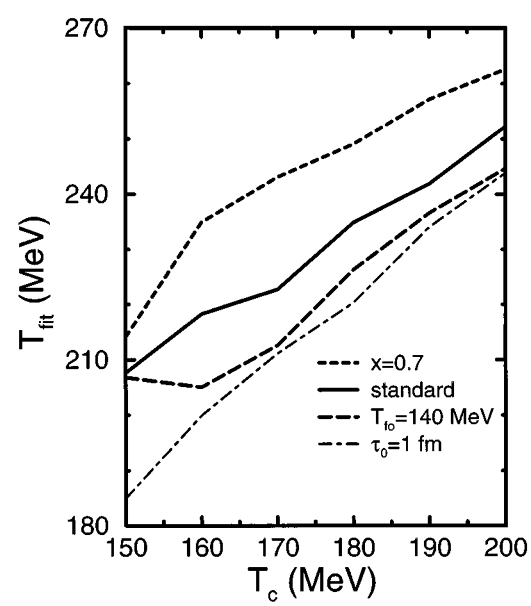

FIG. 2. $T_{\rm fit}$ for various parameter sets as a function of T_c.

the collision. This contribution is enhanced by transverse expansion; the larger the temperature difference $T_c - T_{fo}$, the stronger the enhancement. We find that increasing T_{fo} to 140 MeV from its standard value decreases T_{fit}. For larger T_{fo} the hadronic matter near the freeze-out surface expands outward at a lower velocity, so that there is less contribution to m_T from the fluid motion. Thus T_{fit}, which depends strongly on the fluid motion, is lowered.

The curve for $x=0.7$ shows that T_{fit} is about 15 MeV higher than for $x=1$. The increase occurs because the temperature of the mixed phase, which makes a large contribution to the e^+e^- spectrum, is raised when x is lowered and B is held constant.

Our overall production at the $\rho^0-\omega$ peak is up to a factor 3 below the value measured by the NA45 experiment. We take the value measured in the experimental bin $0.7<m<0.8$ GeV (which contains the $\rho^0-\omega$ peak), assuming that the signal is all from meson decay, obtaining $d^2N_{e^+e^-}^{(\rho^0+\omega)}/dm\, d\eta = 1.7\times10^{-3}$ GeV^{-1}. We calculate the same quantity for our simulated data from the standard calculation with $T_c=150$ MeV, including the experimental acceptance by counting only e^+e^- pairs whose members both have $2.1<\eta<2.65$, and integrating over a Breit-Wigner distribution for each species, giving us $d^2N_{e^+e^-}^{(\rho^0+\omega)}/dm\, d\eta = 5.9\times10^{-4}$ GeV^{-1} for our standard parameter set. Increasing T_c to 200 MeV makes $d^2N_{e^+e^-}^{(\rho^0+\omega)}/dm\, d\eta = 1.2\times10^{-3}$ GeV^{-1}, still below the preliminary NA45 data. Additional pair-producing processes not included here will increase the cross-section. Also, one likely effect of a departure from chemical equilibrium in the hadronic phase is an excess of ρ mesons, increasing the strength of the peak and thus accounting for some of the missing signal. The overall production rate is sensitive to T_{fo}: increasing T_{fo} from 120 to 140 MeV while keeping $T_c=150$ MeV gives $d^2N_{e^+e^-}^{(\rho^0+\omega)}/dm\, d\eta = 8.5\times10^{-4}$ GeV^{-1} ($T_{fo}=140$ MeV with $T_c=200$ MeV gives $d^2N_{e^+e^-}^{(\rho^0+\omega)}/dm\, d\eta = 1.5\times10^{-3}$ GeV^{-1}); on the other hand, sensitivity to increasing τ_0 or decreasing x is minimal. Omitting transverse expansion gives a value that is a factor of 2–3 too high. Since the estimated error in the NA45 data is of order 50%, we would not rule out any of the calculations except that with no transverse expansion.

Partial restoration of chiral symmetry in hot and dense matter [12] is expected to modify the masses and lifetimes (widths) of vector mesons. Changes in the ρ-meson properties may indicate chiral restoration through modified e^+e^- production. However, there is no consensus at present on the behavior of the ρ [17]. Arguments based on QCD sum rules [13] and effective Lagrangians [14] point to decreasing meson masses with increasing temperature and density, while vector-meson dominance studies [15] and consistency arguments [16] have been used to support the opposing view. For the time being, we therefore use the free mass and width of the resonances as a first approximation. The study of the effects of in-medium modifications on e^+e^- production from thermal resonances as a probe for chiral restoration is left for future work.

It is tempting to carry out a calculation without a transition to a high-energy phase in the present model. However, this would not be sensible with the massless pion gas approximation. The complete resonance spectrum would have to be taken into account and such an investigation is beyond the scope of the present paper.

We have shown that transverse expansion does not destroy the correlation suggested in Ref. [1]. If T_c is close to the high end of the interval considered here ($T_c \simeq 200$ MeV) and T_{fo} is not too low, we come close to reproducing the preliminary NA45 data, so that the shape of the e^+e^- m_T spectrum, as parametrized by T_{fit}, should make a good thermometer to measure T_c in this region. If, however, $T_c \simeq 150$ MeV or $T_{fo}<140$ MeV, the contribution from other (potentially long-lived) resonances appears to be significant, and therefore the usefulness of the ρ meson as a thermometer in that region is questionable. The preliminary NA45 data appear to rule out high freeze-out temperatures and models in which transverse expansion plays no role, but otherwise place no significant constraints on the collision dynamics.

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