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Photons from Pb-Pb collisions at ultrarelativistic energies

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High energy photon emission rate from matter created in Pb+Pb collisions at CERN SPS energies is evaluated. The evolution of matter from the initial state up to freeze-out has been treated within the framework of (3+1) dimensional hydrodynamic expansion. We observe that the photon spectra measured by the WA98 experiment are well reproduced with hard QCD photons and photons from a thermal source with initial temperature $\sim$200 MeV. The effects of the spectral changes of hadrons with temperature on the photon emission rate and on the equation of state are studied. Photon yield for Au+Au collisions at RHIC energies is also estimated.

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Ultrarelativistic collisions of heavy nuclei have brought us within reach of creating and studying various aspects of quark-gluon plasma (QGP), which so far was believed to exist in the microsecond old universe or possibly in the cores of neutron or quark stars. We are at a very interesting situation in this area of research where the Super Proton Synchrotron (SPS) era has drawn to a close and the first results from the Relativistic Heavy Ion Collider (RHIC) have started to appear. Already from the results of the Pb run at the SPS quite a few of the signatures of QGP, e.g., J/Ψ suppression, strangeness enhancement, etc., are reported to have ‘‘seen’’ unmistakable hints of the existence of QGP [1]. Electromagnetic probes, viz., photons and dileptons have long been recognized as the most direct probes of the collision [2]. Owing to the nature of their interaction they undergo minimal scatterings and are by far the best markers of the entire space-time evolution of the collision.

The single photon data, obtained from Pb-Pb collisions at CERN SPS reported by the WA98 Collaboration [3] have been the focus of considerable interest in recent times [4–8]. While in Ref. [4], the contribution from hard photons and the effects of transverse expansion on the thermal photons were neglected, in [5] the thermal contribution was not taken into account. Again, in [6,7] the thermal shift on hadronic masses was neglected, whereas, in [8] both the intrinsic k_T distribution of partons and thermal shift of hadronic masses were ignored. In this Rapid Communication we present the results of an analysis of the photon spectra in a realistic framework using a reasonable set of parameters and consistently taking into account all the effects mentioned above. We emphasize the effects of in-medium modifications of hadrons on the photon spectra considering the fact that as yet it has not been possible to explain the observed low-mass enhancement of dileptons measured in the Pb+Au as well as S+Au collisions at the CERN SPS in a scenario which does not incorporate in-medium effects on the vector meson mass (see [9] for a review).

Let us first identify the possible sources of ‘‘excess’’ photons above those coming from the decays of pseudoscalar π^0 and η mesons, as provided by the data. First, one has the prompt photons coming from the hard collisions of initial state partons in the colliding nuclei. These populate the high transverse momentum region and can be estimated by perturbative QCD. The thermal contribution depends on the space-time evolution scenario that one considers. In the event of a deconfinement phase transition, one first has a thermalized QGP which expands and cools, reverts back to hadronic matter, again expands and cools, and eventually freezes out into hadrons most of which are pions. Photon emission in the QGP occurs mainly due to QCD annihilation and Compton processes between quarks and gluons. In order to estimate the emission from the hadronic matter we will consider a gas of light mesons viz. π, ρ, ω, and η.

It has been emphasized that the properties of vector mesons may change appreciably because of interactions among the hadrons at high temperatures and/or densities (see the reviews [9–13]). This modifies the rate of photon emission as well as the equation of state (EOS) of the evolving matter. Among various models for vector mesons available in the literature [13], we examine two possibilities for the hadronic phase in this Rapid Communication: (i) no medium modifications of hadrons, and (ii) the scenario of the universal scaling hypothesis of the vector meson masses [11]. In principle, we can think of a third scenario: (iii) the large collisional broadening of the vector mesons [9]. Both (ii) and (iii) can reproduce the enhancement of the low-mass dileptons measured by the CERES Collaboration at CERN SPS, but scenario (iii) has been found to have a negligible effect on the emission rate of photons [13]. The effect of temperature dependent mass as described in case (ii) has also been incorporated in the EOS of the hadronic matter undergoing a (3+1) dimensional expansion. We will see that the resulting photon spectra reproduce the experimental data quite well.

There is still substantial debate on the order of the phase transition as well as the value of the critical temperature (T_c). To address this aspect we will also consider a scenario where the system begins to evolve from a high temperature phase where all the hadronic masses approach zero (pion

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mass is fixed at its vacuum value). As the system expands and cools, the hadrons acquire masses [as in case (ii) above] till freeze-out. Incorporation of medium modified masses and the EOS in this case also provides a reasonable explanation of the data.

We start with the direct QCD photons originating from hard scattering of partons embedded in the nucleons of the colliding nuclei in the very early stages of the collision. We will see later that they make a significant contribution to the total photon yield. These are estimated using perturbative QCD as

$$E\frac{dN}{d^3p}=T_{AA}(b=0)E\,\frac{d\sigma_{pp}}{d^3p}, \tag{1}$$

where $T_{AA}(b)$ is the nuclear thickness at impact parameter b. Its value at $b=0$ is taken as 220/fm^2 [3]. σ_{pp} includes the pp cross section for Compton and annihilation processes among the partons. At SPS energies one should include the effects of intrinsic k_T distribution of partons [14] to account for the fact that the colliding partons might have some initial transverse momenta with respect to the incoming hadrons (analogous to the Fermi motion of nucleons in the nucleus). This leads to substantial enhancement in the photon spectra [5]. In practice such an effect is implemented by multiplying each of the parton distribution functions appearing in the right-hand side of the above equation by a Gaussian function of the type $f(k_T)=\exp[-k_T^2/\langle k_T^2\rangle]/\pi\langle k_T^2\rangle$ and integrating over d^2k_T. We use CTEQ5M partons [15] and $\langle k_T^2\rangle=0.9\ \mathrm{GeV}^2$ [5] for evaluating the hard QCD photons ($\sqrt{\langle k_T^2\rangle}=0.8$ GeV is taken in [6]). The photons from hard QCD processes have been used to normalize the p-p data. The higher order effects have been taken into account through a K factor ~ 2. An enhanced production in A-A collisions compared to p-p will presumably mark the presence of a thermal source [3].

The lowest order processes contributing to hard thermal photon emission from quark gluon plasma are the QCD Compton and annihilation processes [16]. It has been shown recently [17] that the two-loop contribution leading to bremsstrahlung and $q\bar{q}$ annihilation with scattering is of the same order as the lowest order processes. The total rate of emission per unit four-volume at temperature T is given by

$$E\frac{dR}{d^3p}=\frac{5}{9}\,\frac{\alpha\alpha_s}{2\pi^2}\exp(-E/T)\left[\ln\left(\frac{2.912\,E}{g^2T}\right)+16\,\frac{(J_T-J_L)}{\pi^3}\left\{\ln 2+\frac{E}{3T}\right\}\right], \tag{2}$$

where $J_T\simeq 4.45$ and $J_L\simeq -4.26$. The QCD coupling, "g" is given by

$$g^2/4\pi\equiv\alpha_s=\frac{6\pi}{29\ln(8T/T_c)} \tag{3}$$

for two quark flavors [18]. For photon energies in the range $1\leqslant E\ (\mathrm{GeV})\leqslant 5$, the static emission rate given by Eq. (2) at $T\sim 200$ MeV is about an order of magnitude larger than the rate due to Compton and annihilation processes [16]. We will see below that within the present framework the space-time integrated photon yield from quark matter is less than that from hadronic matter due to the smaller lifetime of the QGP phase as a result of a moderate value of the initial temperature considered. Therefore, the overall thermal photon yield remains largely unaffected by the two-loop contribution.

To estimate the photon yield from the hadronic matter (HM) (see first of [16]), we have considered the reactions, $\pi\rho\to\pi\gamma$, $\pi\pi\to\rho\gamma$, $\pi\pi\to\eta\gamma$, $\pi\eta\to\pi\gamma$ and the decays $\rho\to\pi\pi\gamma$ and $\omega\to\pi\gamma$. The invariant amplitudes for all these processes are given in Ref. [19]. In the present work we have also considered photon production due to the process $\pi\rho\to a_1\to\pi\gamma$ [13].

In Ref. [13] we have studied the effects of spectral changes of hadrons on the electromagnetic probes in detail. It was observed that the gauged linear and nonlinear σ models and the model with hidden local symmetry do not show any appreciable effect on photon emissions. In the Walecka model, the universal scaling hypothesis for the vector meson masses as well as the large collisional broadening of vector mesons produces a large enhancement in low mass dileptons. However, the photon emission rate does not suffer substantial medium effect in the latter case, since the spectral function is smeared out. Nevertheless, the scaling hypothesis with particular exponent $\lambda=1/2$ (called the Nambu scaling in [11]) has been seen to enhance photon emission among the others.

To consider the effect of the spectral modifications of hadrons we adopt two extreme cases: (i) no medium modifications of hadrons, and (ii) the scaling hypothesis with $\lambda=1/2$. In case (ii), the parametrization of in-medium quantities (denoted by an asterisk) at finite T is

$$\frac{m_V^*}{m_V}=\frac{f_V^*}{f_V}=\frac{\omega_0^*}{\omega_0}=\left(1-\frac{T^2}{T_c^2}\right)^{\lambda}, \tag{4}$$

where V stands for vector mesons, f_V is the coupling between the electromagnetic current and the vector meson field and ω_0 is the continuum threshold. Mass of the nucleon also varies with temperature as Eq. (4). Note that there is no definite reason to believe that all the in-medium dynamical quantities are dictated by a single exponent λ. This is the simplest possible ansatz (see [13] for a discussion). The effective mass of a_1 is estimated by using Weinberg's sum rules [20]. We have seen earlier that the baryon chemical potential has a small effect on the photon yield [4]. Moreover, in the central rapidity region the entropy per baryon is quite large $\sim$40–50 [21,22]. Thus the finite baryon density effects are neglected here.

We will assume that the produced matter reaches a state of thermodynamic equilibrium after a proper time ~ 1 fm/c [23]. If a deconfined matter is produced, it evolves in space and time till freeze-out undergoing a phase transition to hadronic matter in the process. The (3+1) dimensional hydrodynamic equations have been solved numerically by the relativistic version of the flux corrected transport algorithm [24], assuming boost invariance in the longitudinal direction [23] and cylindrical symmetry in the transverse plane. The initial temperature T_i can be related to the multiplicity of the event dN/dy by virtue of the isentropic expansion as [25]

$$\frac{dN}{dy}=\frac{45\zeta(3)}{2\pi^4}\pi R_A^2 4 a_k T_i^3 \tau_i, \tag{5}$$

where R_A is the initial radius of the system, τ_i is the initial thermalization time, and $a_k=(\pi^2/90)g_k$; g_k being the effective degeneracy for the phase k (QGP or hadronic matter). The bag model EOS is used for the QGP phase. $g_H(T)$, the statistical degeneracy of the hadronic phase, composed of π, ρ, ω, η, a_1, and nucleons is a temperature dependent quantity in this case and plays an important role in the EOS [13]. As a consequence the square of sound velocity, $c_s^{-2}=[(T/g_H)(dg_H/dT)+3]>3$, for the hadronic phase, indicating nonvanishing interactions among the constituents (see also [26]). The hydrodynamic equations have been solved with initial energy density, $\epsilon(\tau_i,r)$ [24], obtained from T_i through the EOS. We use the following relation for the initial velocity profile which has been successfully used to study transverse momentum spectra of hadrons [21,27] and also photons [6,7]:

$$v_r=v_0\frac{\delta+2}{2}\left(\frac{r}{R_A}\right)^{\delta}. \tag{6}$$

For our numerical calculations we choose $\delta=1$ and sensitivity of the results on v_0 will be shown. It is observed that the results do not change substantially with reasonable variation of the parameter δ for a given value of v_0.

For central collisions of Pb nuclei at 158*A* GeV at the CERN SPS, we assume that QGP is produced at $\tau_i=1$ fm/c which expands in (3+1) dimension and undergoes a first order phase transition to hadronic matter at $T_c=160$ MeV. Taking $dN/dy=700$ (last of Ref. [3]), and $g_k=g_{QGP}=37$ for a two-flavor QGP, the initial temperature T_i comes out as 196 MeV. In a first order phase transition one has a mixed phase of coexisting QGP and hadronic matter which persists till the phase transition is over. Thereafter the hadronic matter expands, cools, and freezes out at a temperature T_f and radial velocity v_r^f. The sum total of the photon yields from the QGP phase, the mixed phase, and the hadronic phase constitutes the thermal yield. The values of (T_f,v_r^f) should in principle be obtained from the analysis of hadronic spectra. However, at present it is not possible to do so without ambiguity. In Ref. [28] it is shown that the experimental data from Pb+Pb collisions allow values of (T_f,v_r^f) ranging from (180 MeV,0) to (120 MeV,0.7). In the present work we take $T_f=120$ MeV and the initial velocity profile of Eq. (6) with v_0 as a parameter.

In Fig. 1, we show only the *thermal photon* spectra originating from quark matter (QM≡QGP+QGP part of mixed phase) and hadronic matter (HM≡hadronic part of mixed phase+hadronic phase) with $v_0=0$. The solid and dashed lines correspond to the case (i) and (ii), respectively. The case with large collisional broadening shows no deviation from (i). At low p_T the difference between (i) and (ii) is negligible because in this region of phase space most of the photons are emitted from the late stage of the evolution where the in-medium effects are small. The increased photon yield at large p_T is caused by the enhancement in the Boltzmann factor due to the reduction in meson (particularly, ρ) masses. However, in the total photon emission this difference of thermal photons at high p_T is masked by the hard photon contribution. The thermal photon yield with hadronic mass variation due to Walecka model or Brown-Rho scaling [11] [$\lambda=1/6$ in Eq. (4)] will lie in between the two curves in Fig. 1.

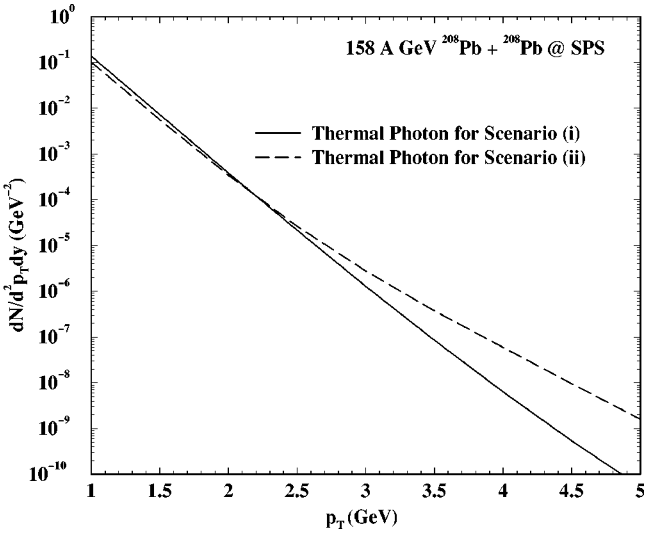

FIG. 1. Transverse momentum distribution of thermal photons with and without medium effects.

In Fig. 2, results for the total photon emission are shown for three different values of the initial transverse velocity

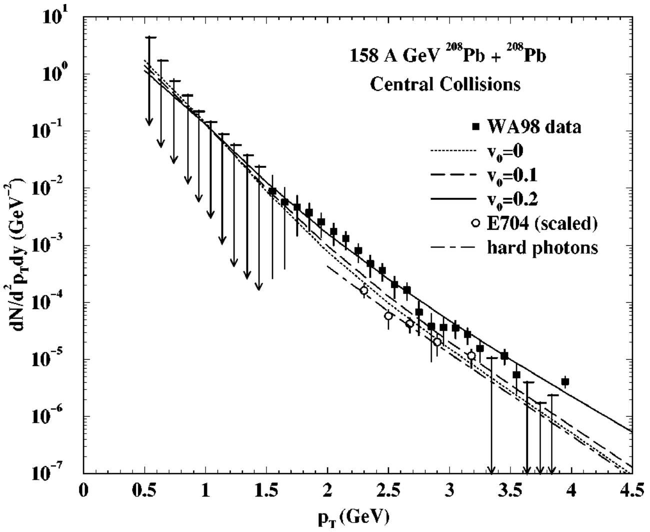

FIG. 2. Total photon yield in Pb+Pb collisions at 158*A* GeV at CERN SPS. The theoretical calculations contain hard QCD and thermal photons. The system is formed in the QGP phase with initial temperature $T_i=196$ MeV.

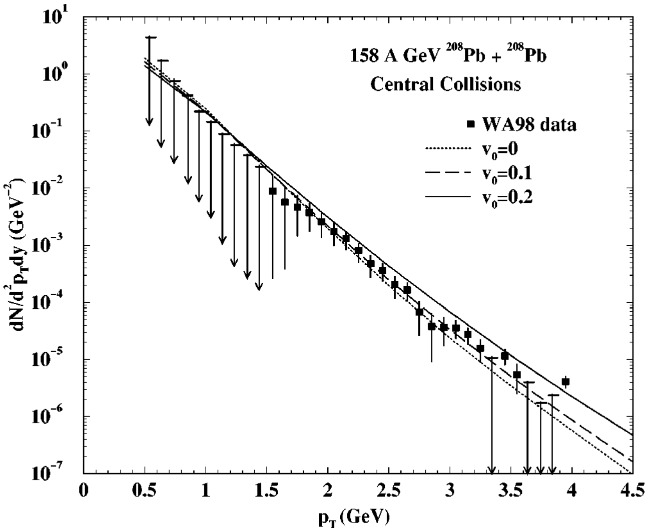

FIG. 3. Total photon yield in Pb+Pb collisions at 158*A* GeV at CERN SPS. The theoretical calculations contain hard QCD and thermal photons. The system is formed in the hadronic phase with the hadronic masses approaching zero at initial temperature $T_i = 205$ MeV.

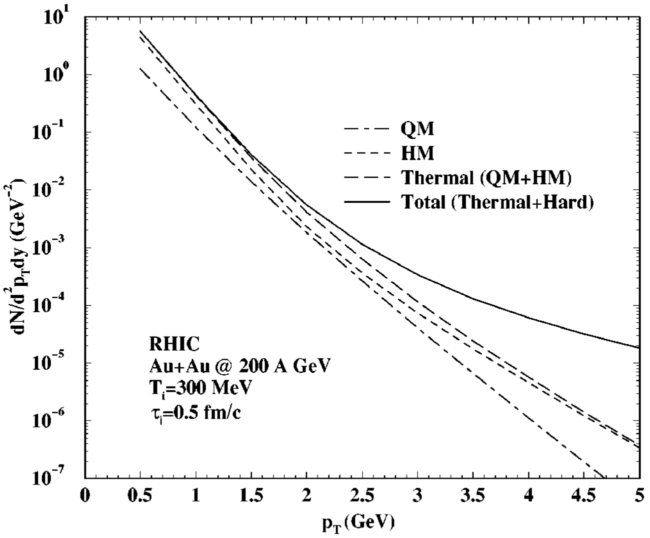

FIG. 4. Photon spectra at RHIC for Au+Au collisions.

with medium effects as in case (ii). All three curves represent the sum of the thermal and the prompt photon contribution which includes possible finite k_T effects of the parton distributions. The latter, shown separately by the dot-dashed line also explains the scaled pp data from the E704 experiment [29]. We observe that the photon spectra for the initial velocity profile given by Eq. (6) with $v_0 = 0.2$ explains the WA98 data reasonably well. A similar value of the initial radial velocity has been obtained in [7] from the analysis of transverse momentum spectra of hadrons and photons (see also [6]). It is found that a substantial fraction of the photons comes from mixed and hadronic phase. The contribution from the QGP phase is small because of the small lifetime of the QGP (~ 1 fm/c).

The last statement together with the current uncertainty of the critical temperature T_c [30] poses the following question: Is the existence of the QGP phase essential to reproduce the WA98 data? To study this problem, we have considered two possibilities: (a) pure hadronic model without medium modifications, and (b) pure hadronic model with scaling hypothesis according to Eq. (4). In the former case, T_i is found to be ~ 250 MeV for $\tau_i = 1$ fm/c and $dN/dy = 700$, which appears to be too high for the hadrons to survive. Therefore this possibility should be excluded. On the other hand, the second case with an assumption of $T_i = T_c$ (which is just for simplicity) leads to $T_i \sim 205$ MeV, at $\tau_i = 1$ fm/c, which is not unrealistic. In this case, the hadronic system expands and cools and ultimately freezes out at $T_f = 120$ MeV. The masses of the vector mesons increase with reduction in temperature (due to expansion) according to Eq. (4). The results of this scenario for three values of the initial radial velocity including the prompt photon contribution are shown in Fig. 3. The experimental data are well reproduced for vanishing initial transverse velocity also. This indicates that a simple hadronic model is inadequate. Either substantial medium modifications of hadrons or the formation of QGP in the initial stages is necessary to reproduce the data. It is rather difficult to distinguish between the two at present.

We now show our prediction of the photon yield in central collisions of Au nuclei at 200*A* GeV at RHIC in Fig. 4 for scenario (ii) with $v_0 = 0$. Enhancement due to intrinsic motion of the partons has been ignored at RHIC, because at higher beam energies such effects are small [5]. The initial temperature and thermalization time are taken as 300 MeV and 0.5 fm/c, respectively [22]. It is seen that up to $p_T = 2$ GeV, most of the photons are emitted from the thermal source. We also observe that photons from quark matter make a substantial contribution to the thermal yield (dash-dotted line in Fig. 4), because of the higher initial temperature and larger lifetime of the QGP phase realized at RHIC compared to SPS. The effect of the transverse expansion on the QGP phase is small. However, photons from the hadronic phase (short-dashed line in Fig. 4), particularly during the late stage of the evolution, receive a large kick due to the radial expansion and consequently populate the high p_T region, as shown in Fig. 4.

In summary, we have evaluated the high energy photon yield in Pb+Pb collisions at CERN SPS energies with two different initial conditions. In the first scenario, we start with the assumption of the formation of a QGP phase at $T_i \sim 196$ MeV and then the system continues through mixed phase and hadronic phase before freeze-out. In the second scenario, we assume a chirally symmetric phase where the hadronic masses approach zero at a temperature ~ 205 MeV and then the system evolves towards freeze-out. The effects of the variation of hadronic masses on the photon yield have been considered both in the cross section as well as in the EOS. The photon spectra reported by the WA98 Collaboration are well reproduced in both cases. We thus conclude that the thermal photon spectra resulting from the Pb+Pb collisions at CERN SPS energies are emitted from a source with an initial temperature ~ 200 MeV. A similar value of T_i is also obtained from the analysis of photon and dilepton data from CERN SPS [7,31]. At RHIC energies the total yield of photons increases by an order of magnitude compared to SPS with a substantial contribution from QM.

In spite of the above encouraging situation, a firm conclusion about the formation of the QGP at SPS necessitates a closer look at some pertinent but unsettled issues. In the evaluation of the hard photon contribution the value of the K factor and the intrinsic k_T distribution of partons are adjusted so as to reproduce the scaled p-p data of the E704 Collaboration. However, it is extremely important to know quantitatively the contribution from the hard processes. The possibility of A and k_T dependence of the K factor [32], the energy loss of fast partons, the shadowing of the structure functions, and the broadening of transverse momentum distribution of partons are some of the vital issues related to photon production in nucleus-nucleus collisions which have not been considered in the present work. Again, the assumption of complete thermodynamic equilibrium for quarks and gluons may not be entirely realistic for SPS energies; lack of chemical equilibrium will further reduce the thermal yield from QGP. We have assumed $\tau_i = 1$ fm/c at SPS energies, which may be considered as the lower limit of this quantity, because the transit time (the time taken by the nuclei to pass through each other in the c.m. system) is ~ 1 fm/c at SPS energies and the thermal system is assumed to be formed after this time has elapsed. In the present work, when the QGP initial state is considered, we have assumed a first order phase transition with bag model EOS for the QGP for its simplicity, although it is not in complete agreement with the lattice QCD simulations [30]. However, it is difficult to distinguish among different EOS with the current resolution of the photon data. As mentioned before, there are uncertainties in the value of T_c [30], a value of $T_c \sim 200$ MeV may be considered as an upper limit. Moreover, the photon emission rate from QGP given by Eq. (2), evaluated in Refs. [16,17] by resuming the hard thermal loops is strictly valid for $g \ll 1$ whereas the value of g obtained from Eq. (3) is ~ 2 at $T \sim 200$ MeV. At present it is not clear whether the rate in Eq. (2) is valid for such a large value of g or not.

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