Nuclear Modification of Electron Spectra and Implications for Heavy Quark Energy Loss in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX experiment has measured midrapidity ($|\eta| < 0.35$) transverse momentum spectra ($0.4 < p_T < 5.0$ GeV/c) of electrons as a function of centrality in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Contributions from photon conversions and from light hadron decays, mainly Dalitz decays of π^0 and η mesons, were removed. The resulting nonphotonic electron spectra are primarily due to the semileptonic decays of hadrons carrying heavy quarks. Nuclear modification factors were determined by comparison to nonphotonic electrons in $p + p$ collisions. A significant suppression of electrons at high p_T is observed in central Au + Au collisions, indicating substantial energy loss of heavy quarks.

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It is well established that neutral pions and charged hadrons are strongly suppressed at high transverse momentum (p_T) in high energy Au + Au collisions [1–5]. The suppression, which is absent in d + Au collisions at midrapidity, implies that hard scattered partons traversing the medium created in Au + Au collisions experience considerable energy loss. Although high p_T suppression is expected for charm quarks as well, their interaction with the medium has been predicted to be smaller than for light quarks, i.e., they should lose a lower fraction of their energy, as their large mass decreases the phase space available for gluon radiation, which is known as the "dead cone" effect [6]. If the medium is indeed less opaque to charm quarks, they will also participate less in the collective expansion of the medium, leading to a smaller elliptic flow strength v_2 [7] for particles carrying charm quarks compared to those solely composed of light quarks. Such medium effects should be even less pronounced for bottom than for charm quarks.

The interaction of heavy quarks with the medium can be studied experimentally through systematic measurements of the p_T spectra of open heavy flavor, i.e., hadrons composed of a heavy and a light quark. While the full reconstruction of D meson decays at the Relativistic Heavy Ion Collider (RHIC) is reported for d + Au collisions [8], indirect measurements of open heavy flavor via semileptonic decays are available for $p + p$ and d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [8–10] as well as for Au + Au collisions at 130 and 200 GeV [11,12]. In $p + p$ collisions, the extracted electron p_T spectrum from heavy flavor decays is in reasonable agreement with perturbative quantum chromodynamics (pQCD) calculations in next-to-leading order. However, the data leave room for contributions from further production mechanisms in which the heavy quarks are not created in the initial hard parton scattering, e.g., via jet fragmentation [9]. In d + Au collisions, no indications for strong cold nuclear matter effects were found [8,10]. For Au + Au collisions of different centrality, the total electron yield from heavy flavor decays was observed to scale with the nuclear overlap integral $\langle T_{AA} \rangle$ as expected for pointlike pQCD processes [12]. However, these electrons show an azimuthal anisotropy with respect to the reaction plane [13], consistent with the notion of charm quark flow in Au + Au collisions. It has been pointed out that if the charm quarks flow along with the bulk of the medium, this is evidence for thermalization of charm. In this situation, the medium modifications of the charm spectrum should be substantial [14].

In this Letter, we report on the p_T spectra of nonphotonic electrons, $(e^+ + e^-)/2$, measured at midrapidity ($|\eta| < 0.35$) up to $p_T = 5$ GeV/c by the PHENIX experiment in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The photonic electron background was removed by a *cocktail* subtraction, in contrast to the *converter* subtraction used in [12], where a subset of the current data sample was analyzed. The converter method is better suited for a determination of the total yield of heavy flavor electrons, while the cocktail subtraction used here provides a precision measurement of the spectral shape [15]. The nuclear modification is then determined by comparing the spectra to those in $p + p$ collisions [9].

The data used in this analysis were collected by the PHENIX detector [16] during the 2001 run of RHIC. A coincidence of the beam-beam counters (BBC) and the zero degree calorimeters (ZDC) provided the minimum bias trigger ($92.2^{+2.5}_{-3.0}$% of the Au + Au inelastic cross section). The centrality was determined by the correlation between the multiplicity measured by the BBC and the energy of spectator neutrons measured by the ZDC. After restricting the vertex range to $|z| < 20$ cm to eliminate background originating from the central magnet, a data sample of 25×10^6 minimum bias events was analyzed.

For the electron analysis, charged particle tracks were reconstructed with the drift chamber and the first layer of pad chambers of the PHENIX east-arm spectrometer ($|\eta| < 0.35$, $\Delta\phi = \pi/2$), as discussed in detail elsewhere [12]. Tracks were confirmed by matching hits in the electromagnetic calorimeter (EMC) within 2σ in position. Electron candidates had at least three associated hits in the ring imaging Čerenkov detector (RICH). After an additional cut on the correlation between the momentum p and the energy E deposited in the EMC [$-2\sigma < (E - p)/p < 3\sigma$], the only background remaining in the electron sample was due to accidental coincidences between RICH hits and hadron tracks. This background was estimated ($\approx$15% at low p_T in central collisions, decreasing towards high p_T and for peripheral events) and subtracted statistically by an event-mixing method.

The raw electron spectra were corrected as a function of p_T for geometrical acceptance and reconstruction efficiency [12]. The multiplicity dependent efficiency loss was estimated by embedding simulated electrons into real events. This loss increased from 5% to 26% from peripheral to central collisions without a significant p_T dependence in the range relevant here. The 1σ systematic uncertainty of all corrections is 11.8%, after correction for the effect of finite bin width in p_T. The fully corrected inclusive electron spectrum is shown in Fig. 1(a) for minimum bias collisions.

The spectra of electrons from heavy flavor decays were determined by subtracting cocktails of background contributions from other sources from the inclusive data. The most important background is the π^0 Dalitz decay which was calculated individually for each centrality class with a hadron decay generator using parametrizations of measured π^0 [2] and $\pi^\pm$ [17] spectra as input. The spectral shapes of other light hadrons h were obtained from the pion spectra, assuming a universal spectrum in $m_T = \sqrt{p_T^2 + m_h^2}$. Within this approach the ratios h/π^0 are constant at high p_T with the values [11]: $\eta/\pi^0 = 0.45 \pm 0.10$, $\rho/\pi^0 = 1.0 \pm 0.3$, $\omega/\pi^0 = 1.0 \pm 0.3$, $\eta'/\pi^0 = 0.25 \pm 0.08$, and $\phi/\pi^0 = 0.40 \pm 0.12$. Only the η contribution is of any practical relevance, and the chosen parametrization is in good agreement with the measured η meson spectra [18]. Another major electron source is the conversion of photons, mainly from $\pi^0 \to \gamma\gamma$ decays, in material in the acceptance ($\approx 1\%$ X/X_0). The spectra of electrons from conversions and Dalitz decays are very similar. In a GEANT simulation [19] of π^0 decays, the ratio of conversion electrons to Dalitz electrons was determined to be 1.25 ± 0.10, essentially p_T independent. Contributions from photon conversions from other sources were taken into account as well. Electrons from kaon decays (K_{e3}), determined in a GEANT simulation based on measured kaon spectra [17], and electrons from external as well as internal conversions of direct photons [20,21] were included.

All background sources are compared with the inclusive data in Fig. 1(a). Further background from $J/\psi \to e^+e^-$ decays and from Drell-Yan pairs [22] is negligible. A possible low mass dilepton enhancement through $\pi + \pi \to \rho \to e^+e^-$, as reported in Pb + Pb collisions at lower $\sqrt{s_{NN}}$ [23], would constitute another background source

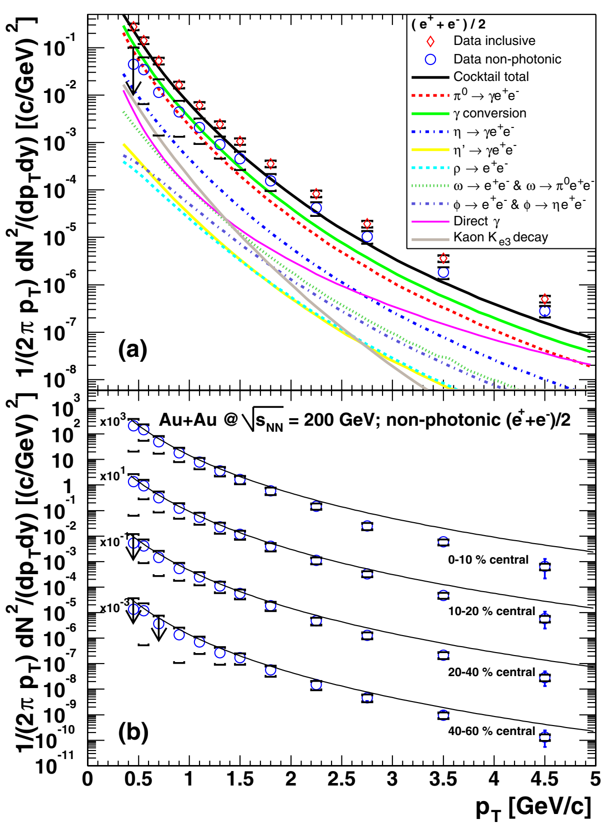

FIG. 1 (color online). (a) Inclusive and nonphotonic electron invariant yields in minimum bias Au + Au collisions at $\sqrt{s_{NN}} =$ 200 GeV, compared with contributions from all background electron sources included in the cocktail. (b) Invariant yields of electrons from heavy flavor decays for different Au + Au centrality classes, scaled by powers of ten for clarity, together with the best fit to the $p + p$ reference scaled with the appropriate nuclear overlap integrals $\langle T_{AA} \rangle$. The error bars (brackets) correspond to statistical (systematic) uncertainties.

which is neglected here since the estimated ρ contribution in the absence of enhancement is small ($<1\%$ at all p_T). The total cocktail systematic uncertainty increases from 10% (at $p_T = 0.4$ GeV$/c$) to 15% (at $p_T = 5$ GeV$/c$), dominated by the systematic error of the pion input spectra ($\approx$8%–10%). Other systematic uncertainties, mainly the η/π^0 normalization and, at high p_T, the contribution from direct radiation, are much smaller. The background cocktail calculated here and the photonic electron background measured via the converter method [12] agree within 10%.

After subtracting the cocktail from the inclusive electron data, the invariant spectrum of electrons from heavy flavor decays is shown in Fig. 1(a) for minimum bias collisions. For $p_T > 2$ GeV$/c$ the signal to background ratio is larger than 1. Figure 1(b) shows the electron spectra from heavy flavor decays in four centrality classes, 0%–10%, 10%–20%, 20%–40%, and 40%–60% central collisions. More peripheral collisions have insufficient electron statistics to reach $p_T = 5$ GeV$/c$.

PHENIX has also measured electrons from heavy flavor decays in $p + p$ collisions at $\sqrt{s} = 200$ GeV [9]. The curves shown in Fig. 1(b) depict the best fit of the corresponding spectrum from $p + p$ collisions, scaled by the nuclear overlap integral $\langle T_{AA} \rangle$ calculated within a Glauber model [2] for each Au + Au centrality class. At low p_T the Au + Au spectra are in reasonable agreement with the $p + p$ fit in all centrality bins, but a clear suppression of the spectra in Au + Au with respect to $p + p$ develops towards high p_T.

To quantify this effect we calculate for each individual bin in p_T the nuclear modification factor R_{AA} defined as

$$R_{AA} = \frac{dN_{\mathrm{Au+Au}}}{\langle T_{AA} \rangle d\sigma_{p+p}}, \tag{1}$$

where $dN_{\mathrm{Au+Au}}$ is the differential electron yield from heavy flavor decays in Au + Au collisions and $d\sigma_{p+p}$ is the corresponding differential cross section in $p + p$ collisions [9] in any given p_T bin.

Figure 2 shows R_{AA} as a function of p_T in the four Au + Au centrality classes. At low p_T, the electron R_{AA} is consistent with one within substantial uncertainties in all centrality classes, in agreement with the observation of binary collision scaling of the total charm yield in Au + Au collisions at RHIC [12]. Since the ratio of electrons from heavy flavor decays to background increases with increasing p_T, the systematic uncertainties of R_{AA} decrease towards high p_T. R_{AA} falls well below one for electron $p_T \geq 2$ GeV$/c$, providing clear evidence for heavy quark medium modifications. The observed high p_T suppression is most significant for central collisions. However, the limited statistics do not allow one to quantify the centrality dependence of heavy quark medium modifications. At the highest p_T, the electron R_{AA} becomes as small as that for π^0 [2], indicating substantial energy loss of heavy quarks in the medium. It is important to note that electrons at a given p_T originate from decays of higher p_T D or B

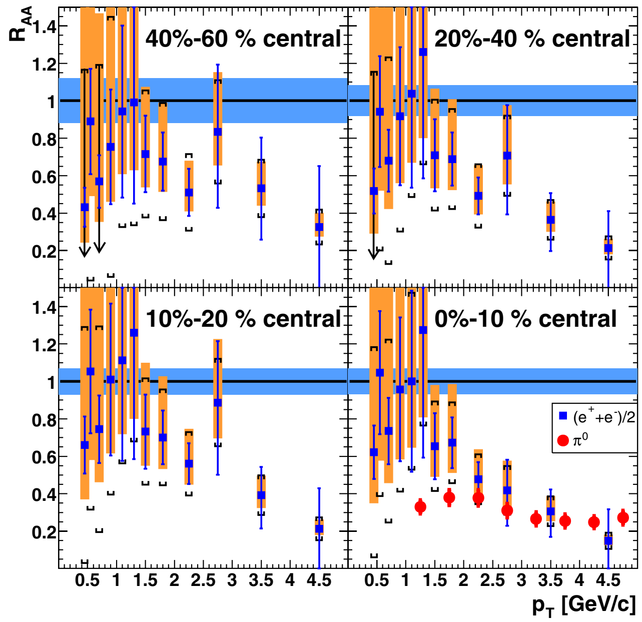

FIG. 2 (color online). Nuclear modification factor R_{AA} for electrons from heavy flavor decays as function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the different centrality classes. The error bars are statistical only. Error brackets (boxes) indicate the systematic errors related to the uncertainties in the Au + Au ($p + p$) measurements. The bands around one show the relative systematic uncertainties in T_{AA}. For the most central collisions the π^0 R_{AA} is shown for comparison [2]. For these data, a 13% p_T independent systematic uncertainty (not plotted) represents the uncertainty in $\langle T_{AA} \rangle$ and in the π^0 yield normalization.

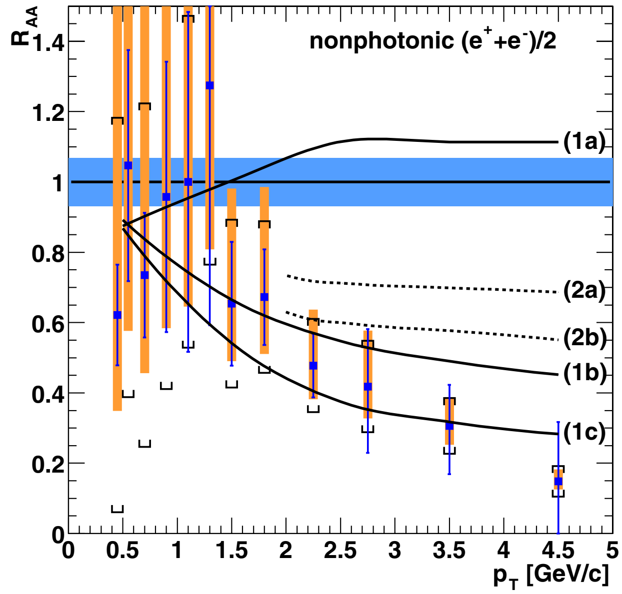

FIG. 3 (color online). Nuclear modification factor R_{AA} for electrons from heavy quark decays as function of p_T for the 10% most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV in comparison with predictions from models incorporating charm quark energy loss. Curves (1a)–(1c) and (2a)–(2b) are taken from [24,25], respectively, where contributions from B meson decays are included in (2a) and (2b) only. Experimental uncertainties are shown as described in Fig. 2.

mesons, making model independent comparisons of R_{AA} for light and heavy quarks impossible.

The observed R_{AA} is remarkable, as electrons with $p_T > 3.5$ GeV/c are expected to include significant contributions from B meson decays, and B mesons should suffer less than D mesons from medium modifications. Depending on their time scales, mechanisms by which heavy quarks are produced after the initial hard parton scattering, such as gluon splitting in jets, might lead to an attenuation at high p_T which then is due to a mixture of light parton and heavy quark energy loss in the medium created at RHIC.

Figure 3 confronts current model calculations [24,25] utilizing induced gluon radiation as the heavy quark energy loss mechanism with the data for the 10% most central collisions. The three curves (1a)–(1c) include electrons from charm decays only [24]. They correspond to different values of the time-averaged transport coefficient $\hat{q}$, which denotes the average squared transverse momentum transferred from a hard parton per unit path length while traversing the medium and, as such, is proportional to the density of scattering centers in the medium. Curve (1a) applies for the case without the presence of any medium causing heavy quark energy loss ($\hat{q} = 0$ GeV^2/fm). The $\hat{q}$ values of 4 and 14 GeV^2/fm, which correspond to curves (1b) and (1c), lead to light quark energy losses which bracket the observed high p_T suppression of neutral pions and charged hadrons. Predictions for charm energy loss from [24] for medium densities at the extreme high end of those allowed by the observed light quark energy loss are consistent with the electron data. Contributions from bottom decays, which are expected to be significant for $p_T > 3$ GeV/c, should lead to an increase of the predicted R_{AA} since b quarks are presumably less affected by energy loss than c quarks [6]. Curves (2a) and (2b) are taken from [25]. They include electrons from both D and B meson decays and correspond to initial gluon densities of $dN_g/dy = 1000$ and 3500 for curves (2a) and (2b), respectively, which again lead to light parton energy losses bracketing the observed high p_T pion suppression. However, at high p_T the predicted R_{AA} for electrons from heavy flavor decays is larger than observed. The present data pose a challenge to existing calculations of radiative energy loss in the medium produced at RHIC, and will help to distinguish between different energy loss scenarios.

In conclusion, we have measured electron spectra from heavy flavor decays in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In central collisions, nuclear modification factors $R_{AA} \ll 1$ are observed at high p_T, providing clear evidence for strong medium effects. Current models involving energy loss via induced gluon radiation for heavy quarks traversing the medium created in heavy ion collisions at RHIC are challenged by the data even considering extremely high medium densities.

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