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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0031-9007/06/96(3)/032301(6)$23.00 032301-1 © 2006 The American Physical Society
nonphotonic electrons in decays of hadrons carrying heavy quarks. Nuclear modification factors were determined by comparison to mesons, were removed. The resulting nonphotonic electron spectra are primarily due to the semileptonic central Au /0.0025 contributions from photon conversions and from light hadron decays, mainly Dalitz decays of $p_T < 0.0135$ /0.0135 transverse momentum spectra ($Au$ collisions at $p_sNN = 200$ GeV is observed in $0 < 0.35$ $p_T < 5.0$ GeV/$c$) of electrons as a function of centrality in $Au$ collisions. A significant suppression of electrons at high $p_T$ is observed in central $Au + Au$ collisions, indicating substantial energy loss of heavy quarks. 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 $\pi^0$ and $\eta$ 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.

DOI: 10.1103/PhysRevLett.96.032301 PACS numbers: 25.75.Dw
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±2.3% 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 \( 25 \times 10^6 \) 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 2\( \sigma \) 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 (≈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 1\( \sigma \) 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 \( \pi^0 \) Dalitz decay which was calculated individually for each centrality class with a hadron decay generator using parametrizations of measured \( \pi^0 \) [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 \( h/\pi^0 \) are constant at high \( p_T \) with the values [11]: \( \eta/\pi^0 = 0.45 \pm 0.10, p/\pi^0 = 1.0 \pm 0.3, o/\pi^0 = 1.0 \pm 0.3, \eta^'/\pi^0 = 0.25 \pm 0.08, \) and \( \phi/\pi^0 = 0.40 \pm 0.12. \) Only the \( \eta \) contribution
is of any practical relevance, and the chosen parametrization is in good agreement with the measured $\eta$ 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 ($=1\% \times X_{0}$). The spectra of electrons from conversions and Dalitz decays are very similar. In a GEANT simulation [19] of $\pi^0$ decays, the ratio of conversion electrons to Dalitz electrons was determined to be $1.25 \pm 0.10$, 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 $\pi^+ + \pi^- \to e^+ e^-$, as reported in Pb + Pb collisions at lower $\sqrt{s_{NN}}$ [23], would constitute another background source which is neglected here since the estimated $\rho$ 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 ($=8\%$--10%). Other systematic uncertainties, mainly the $\eta/\pi^0$ 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 ($T_{AA}$) 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

$$R_{AA} = \frac{dN_{Au+Au}}{dN_{p+p}} = \frac{dN_{Au+Au}}{(T_{AA})d\sigma_{p+p}},$$

where $dN_{Au+Au}$ 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 $\pi^0$ [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 $B$.
mesons, making model independent comparisons of \( R_{AA} \) for light and heavy quarks impossible.

The observed \( R_{AA} \) is remarkable, as electrons with \( p_T > 3.5 \text{ GeV}/c \) 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 energy loss scenarios. Curves (1a)–(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 \( p_T > 3 \text{ GeV}/c \), 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 \( dN_q/dy = 1000 \) 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 \( \text{Au + Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). 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.

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

FIG. 3 (color online). Nuclear modification factor \( R_{AA} \) for electrons from heavy flavor decays as function of \( p_T \) for the 10% most central \( \text{Au + Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 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.
We thank the staff of the Collider-Accelerator and Physics Departments at BNL for their vital contributions. We acknowledge support from the Department of Energy and NSF (USA), MEXT and JSPS (Japan), CNPq and FAPESP (Brazil), NSFC (China), CNRS-IN2P3 and CEA (France), BMBF, DAAD, and AvH (Germany), OTKA (Hungary), DAE and DST (India), ISF (Israel), KRF and CHEP (Korea), RMIST, RAS, and RMAE (Russia), VR and KAW (Sweden), U.S. CRDF for the FSU, U.S.-Hungarian NSF-OTKA-MTA, and U.S.-Israel BSF.

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