Particle production at very low transverse momenta in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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We present results on charged particle production at very low transverse momenta in the 15% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV obtained with the PHOBOS detector at RHIC. The invariant yields were measured at mid-rapidity in the transverse momentum ranges from 30 to 50 MeV/c for charged pions, 90 to 130 MeV/c for charged kaons and 140 to 210 MeV/c for protons and antiprotons. No significant enhancement in low transverse momentum particle production is observed as compared to extrapolations of identified particle spectra measured at an intermediate $p_T$ range. The spectra tend to flatten at low $p_T$, consistent with the expectations of transverse expansion of the system.

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Collisions of gold nuclei at the Relativistic Heavy Ion Collider (RHIC) provide the means to study strongly interacting matter under conditions of high temperature and energy density. The study of low-$p_T$ particle production is particularly interesting as it is directly associated with the long-distance scales, accessible in heavy ion collisions but out of reach in hadronic interactions. Any enhancement of the low-$p_T$ yields compared to extrapolations from higher transverse momenta could indicate interesting effects, e.g. new long-wavelength physics phenomena. Pion production may also be modified if a transient state with partially restored chiral symmetry is produced in the early stage of the collision.

The spectra of identified hadrons measured at RHIC at $\sqrt{s_{NN}} = 200$ GeV tend to flatten in the low $p_T$ region. This effect is more pronounced for heavier particles and is commonly attributed to a collective transverse expansion of the system. Hydrodynamics-based models incorporating transverse expansion provide a satisfactory description of the spectra measured above 0.2 GeV/c. Other mechanisms, such as initial state parton interactions or final state hadron reinteractions, can also describe the broadening of the spectra and an increase of $(p_T)$ with particle mass. Still, if transverse flow develops during the evolution of the system produced in heavy ion collisions, the effects of flow would likely be observed at very low $p_T$.

In this paper we present data on particle production at very low transverse momenta, $p_T < 0.2$ GeV/c, a region thus far not explored at RHIC energies. The PHOBOS detector at RHIC has the unique capability to detect particles with very low $p_T$ in the two-arm spectrometer. Each spectrometer arm consists of 16 layers of Si detectors. The six innermost layers are located in an approximately field-free region near the beam pipe. The proximity of the sensitive detector layers to the interaction region, the small amount of material between the collision vertex and the Si layers, and the high segmentation of the Si detectors permit a precise measurement of particles with small $p_T$.

The data were taken during the 2001 RHIC run. The event triggering, determination of the collision centrality and the position of the collision vertex were as described in previous works. For this analysis we selected the 15% most central Au+Au collisions ($N_{\text{part}} = 303$, where $N_{\text{part}}$ is the number of participating nucleons). Events with the reconstructed vertex position along the beam axis between -7 cm and +14 cm, relative to the nominal interaction point were accepted. The centrality and vertex selections yielded $2 \times 10^6$ events.
In this analysis we searched for particles stopped in the 5th spectrometer layer. The reconstruction of particle trajectories and determination of the particle mass was based on a detailed analysis of the measured energy depositions in the first five spectrometer layers. Selection criteria based on the energy depositions for track candidates were derived from an analysis of single stopping particles obtained from GEANT simulations of the PHOBOS detector. Initially, all possible 5-hit track candidates were formed from hits with large energy depositions \((dE/dx > 0.5\text{ MeV normalized to } 300\mu\text{m of Si, roughly 6 times the deposition of a minimum ionizing particle})\). For the kinetic energies of particles stopping in the 5th layer (about 8 MeV for pions, 19 MeV for kaons and 21 MeV for protons) the energy losses depend on the particle mass as shown in the inset in Fig. 1. Each track candidate satisfied the requirement \(|dE/dx| < 1.4\sigma_i\), \(i = 1, ..., 4\), where the mean and the rms value \(\sigma_i\), are calculated from the \((dE/dx)_i\) distributions for single simulated stopping particles.

A mass parameter was defined as \((M_p)_i = (dE/dx)_i \sum_{k=1}^{5} E_k\), for the first four layers, where \(E_k\) denotes the energy deposited in the \(k\)th layer. For non-relativistic particles, the mass parameter \((M_p)_i\) depends only on the particle mass, since \((dE/dx)_i \sim 1/\beta^2\) and \(\sum_{k=1}^{5} E_k \sim m\beta^2/2\). Since the measured energy deposition in the fifth layer \((E_5)\) cannot be used, due to contributions from annihilation and decay products, we estimated \(E_5\) using the properties of the mass parameter and the assumption that the particle stops in the 5th layer. Having estimated \(E_5\) we calculate the average mass parameter, \(M_{p_{\text{avg}}}\), and the total deposited energy, \(E_{\text{tot}} = \sum_{i=1}^{5} E_i\). Fig. 1 shows a scatter plot of \(M_p\) vs. \(E_{\text{tot}}\), for track candidates found in the data which satisfy the selection criteria on \(dE/dx\) in the first four Si layers.

The momenta of stopped particles are restricted by imposing cuts on \(E_{\text{tot}}\) (see Fig. 1). For track candidates with emission angles smaller than 60°, we applied corrections to the raw yields to account for acceptance, reconstruction and particle identification inefficiencies, and absorption in the beam pipe. These corrections were obtained by embedding simulated low-momentum particle tracks into real data events, and range between 0.2 and 0.7%.

The acceptance and efficiency corrected particle yields are contaminated by various background contributions: feed-down from weak decays and contributions from secondary, misidentified and ghost particles. For protons and antiprotons the dominant background contributions originate from secondary particles produced in the beam pipe or detector material and products from weak decays. To estimate the background contamination of the \((p+\overline{p})\) yields, we analyzed the distributions of the measured distance of closest approach (DCA) from the vertex position to the particle trajectory, determined by a straight line passing through the hits in the first and third spectrometer layers. The experimental DCA distribution is broader and has a tail to larger DCA values compared to the same distribution for reconstructed primary proton tracks. Parameterized shapes of the DCA distributions for reconstructed primary, secondary and feed-down protons, obtained from an analysis of HIJING events, were used to describe the measured DCA spectrum. An example of the fit, assuming equal weights of the two background components, is shown in Fig. 3. The fitted fraction of background particles, averaged over all possible weights for the two background components amounts to \(0.31 \pm 0.04\text{\,(stat.)} \pm 0.19\text{\,(syst.)}\). The large systematic
error assigned to this fraction reflects the dependence of the total background estimate on the relative importance of secondary and feed-down contributions. The fraction of background particles thus determined agrees with the estimate of 0.34±0.03, obtained directly from the reconstruction of HIJING events.

To estimate the background corrections for kaons and pions we used HIJING simulations with yields tuned to account for the fact that HIJING overpredicts the yields of different particle species. This adjustment of HIJING yields is important for evaluating the background correction for charged kaons which is dominated by misidentified protons. The estimated background in the measured kaon sample is 0.10±0.04, while the background level in the unscaled HIJING events is higher (0.23±0.03) due to the larger relative yield of protons to kaons. For protons and kaons the corrections are averaged over the full $p_T$ range.

The charged pion background estimates for scaled and unscaled HIJING events agree. In this case, feed-down from weak decays and ghost tracks are the main source of the background contamination. The large number of reconstructed pions in the simulated events permit the determination of the $p_T$ dependence of the background corrections, which varies between 0.31±0.04 and 0.22±0.02 for $p_T$ of 0.03 GeV/c to 0.05 GeV/c.

The relative statistical uncertainties from the data as well as the statistical errors on the acceptance, efficiency and background corrections are 4% for $\pi^\pm$, 10% for $K^\pm$ and 12% for $(p + \bar{p})$. Various sources of systematic errors were investigated, related to the backgrounds, the analysis method, and detector effects. Table I summarizes the final estimates of the systematic uncertainties.

The dominant contribution to the systematic errors is due to the uncertainty in the background estimates which are evaluated to be approximately 28% for $(p + \bar{p})$ and about 10% for charged pions and kaons.

| Source  | $\pi^+ + \pi^-$ | $K^+ + K^-$ | $(p + \bar{p})$ |
|---------|----------------|-------------|----------------|
| Method  | 7.5            | 12.1        | 13.5           |
| Detector| 3.8            | 7.7         | 9.9            |
| Background | 9.0        | 10.0        | 27.5           |

The uncertainties related to the analysis method were estimated by performing the reconstruction with varied selection criteria. There are also contributions estimated by the reconstruction of HIJING events, and of events which were generated with $p_T$ spectra approximately consistent with our measured data and with intermediate-$p_T$ results from other experiments. In addition, a 5% uncertainty in the $p_T$ scale and the sensitivity of the GEANT energy threshold contribute to the systematic uncertainty of the reconstruction method.

The dominant contributions to the detector-related error come from the differences in particle yields measured separately in the two spectrometer arms and under different magnetic field polarities, and the calibration of energy depositions. Other detector effects such as misalignment of the spectrometer layers, and the accuracy of the vertex position, were found to be negligible.

The individual contributions from different sources of systematic uncertainty are added in quadrature to derive the total systematic error for these measurements: 12% for $\pi^\pm$, 18% for $K^\pm$ and 32% for $(p + \bar{p})$.

The fully corrected invariant yields, $(2\pi p_T)^{-1}d^2N/dp_Tdy$, of charged particles produced in the 15% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 3 together with the yields of identified hadrons measured by PHENIX for the same centrality selection. Different parameterizations have been used to extrapolate the measurements at higher $p_T$ to $p_T \approx 0$ in order to determine the mean $p_T$ and integrated particle yields. Measurements at very low $p_T$ provide some constraints on the choice of the functional form which fits the $p_T$ spectra. The functional form $A[\exp(m_T/T_{f_{1d}})+\epsilon]^{-1}$, with $\epsilon = -1(1)$ for mesons (baryons), reasonably well describes the intermediate-$p_T$ PHENIX measurements ($m_T \leq 1$ GeV/c$^2$). The fit parameter, $T_{f_{1d}}$, equals 0.229±0.005, 0.293±0.01 and 0.392±0.015 GeV/c$^2$ correspondingly for charged pions, kaons and $(p + \bar{p})$. An extrapolation of the fits to low $p_T$ agrees with the measured low-$p_T$ yields (see Fig. 3).

It was predicted that the $m_T$ spectra of different particle species should follow a universal function of $m_T$. One implication of the $m_T$ scaling described in is that the spectral shapes should be independent of particle mass over a wide range of $m_T$. In Fig. 4 the yields normalized at $m_T = 2$ GeV/c$^2$ are shown as a function of $m_T$. This choice of normalization was mo-
from about 1.5 to 2.2 GeV/c observed for the \((\pi^+ \pi^-)\) from the charged pion spectrum, with larger deviations to the threshold, the spectra for heavier particles deviate from the charged pion spectrum, with larger deviations observed for the \((p+\bar{p})\) yields than for the charged kaons.

This observation is consistent with mass dependent flattening of the spectra at low \(p_T\), expected in the presence of transverse expansion of the system, and contradicts the suggested \(m_T\) scaling \[12\].

In summary, the yields of identified particles have been measured at very low \(p_T\) (below 210 MeV/c) in central \(\sqrt{s_{NN}} = 200\) GeV Au+Au collisions. We see no enhancement in the production of particles with very low transverse momenta, which might have indicated the presence of unusual long-wavelength phenomena. The low-\(p_T\) yields agree with extrapolations from intermediate-\(p_T\) measurements. Finally, the measurements in this region of phase space, unexplored until now, show clear flattening of particle spectra that increases with particle mass. This observation supports an interpretation of the data in terms of a collective transverse expansion of the system.

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FIG. 3: Invariant yields as a function of \(p_T\). For low-\(p_T\) yields (closed symbols) the boxes show systematic uncertainties. For comparison the intermediate-\(p_T\) measurements from PHENIX are depicted by open symbols. The fits to PHENIX measurements (solid curves) are extrapolated to low \(p_T\) (dashed curves). See text for more details.

FIG. 4: Invariant yields, normalized at \(m_T = 2\) GeV/c, as a function of \(m_T\). Lower panel shows the \(m_T\) dependence of the local inverse slopes.

activated by an analysis of the local inverse slopes, \(T_{loc}\), obtained from the exponential fits done with a sliding window enclosing 5 consecutive \(m_T\) points. (The first inverse slope is from the fit to our average yield and the first four PHENIX points.) As illustrated in the lower panel of Fig. 4 these local inverse slopes converge at \(m_T \approx 2\) GeV/c. The normalized \(m_T\) spectra are consistent with the scaling hypothesis in the range of \(m_T\) from about 1.5 to 2.2 GeV/c. However at low \(m_T\), close to the threshold, the spectra for heavier particles deviate from the charged pion spectrum, with larger deviations observed for the \((p+\bar{p})\) yields than for the charged kaons.

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