Hadronic spectra in Au+Au reactions at 11.6 A·GeV/c: rapidity and $m_t$ distributions

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ABSTRACT

In central Au+Au collisions, the rapidity distribution of measured protons integrated over $m_t$ indicates almost complete stopping, hence high baryon density. For a given rapidity, low $m_t$ enhancement has been observed for $\pi^{-}$ production over that of $\pi^{+}$. The Coulomb interaction with the co-moving medium has been invoked to explain the difference. The inverse slope parameters of the $m_t$ spectra for protons and deuterons increases from peripheral to central events, while the parameter for pions stays the same. This may indicate that a radial expansion follows the high density stage of the reaction.

1. Introduction

At AGS energies collisions of heavy ions provide a unique opportunity for studying nuclear matter far from its normal density. This condition is made possible because of the large degree of stopping of the incident nucleons. Hadron spectra which result from collisions of silicon beams with targets ranging from aluminum to gold indicate that the projectile deposits essentially all its incident energy in targets larger than copper [1]. It is anticipated that an interaction region of even larger volume, longer lifetime, and higher maximum density could be achieved by the collision of two truly heavy ions such as gold. With the installation of the Booster, the Brookhaven Tandem-AGS complex is capable of accelerating Au ions with energies up to 11.6 A·GeV/c. The basic information about the dynamics of these reactions comes from measurements of the transverse momentum and rapidity distributions of hadron spectra. In particular, the proton distributions allow the determination of the nucleonic stopping in the reactions. In this article, preliminary results from E866 on hadronic spectra will be presented, and physics discussion will be made based on these results.
2 Preliminary Results

Fig. 1 shows the measured invariant spectra for protons at different rapidity intervals. On the horizontal axis, $m_t$ is the so-called transverse mass defined as $m_t = \sqrt{p_t^2 + m_0^2}$, where $p_t$ is the transverse momentum and $m_0$ is the rest mass of the identified particle. On the vertical scale is the invariant cross-section divided by the trigger cross section $\sigma_{\text{trig}}$ where $\sigma_{\text{trig}} = 350 \text{ mb}$ corresponds to 6% of the total interaction cross section. The solid points are the measurement from the Forward Spectrometer while the open ones are from the large aperture spectrometer. Beam rapidity for Au ions at 11.6 A-GeV/c is 3.2. Since projectile and target are identical, the cross-section is therefore symmetric around the mid-rapidity, $y_{nn} = 1.6$. This symmetry is used to fold spectra of same $\delta y$ together, where $\delta y$ is the distance of the rapidity $y$ from the central rapidity $y_{nn} = |y - y_{nn}|$. This experiment covers a rapidity range up to $\delta y = 1.05$ with the projectile (or target) rapidity corresponds to $\delta y = 1.6$. The curves in the figure are the fits to the spectra with a two exponential function,

$$\frac{d^2\sigma}{2\pi m_t\sigma_{\text{trig}}dm_tdy} = A_1 \cdot e^{-(m_t-m_0)/B_1} + A_2 \cdot e^{-(m_t-m_0)/B_2}$$

where $A_1, B_1, A_2, B_2$ are fit parameters.

To inspect the shapes of the particle spectra in more detail, the measured particle distributions for $\pi^\pm$, and protons are displayed in Fig. 2 as a function of $m_t - m_0$ for the central rapidity interval of $0 < \delta y < 0.2$, where the proton spectrum has been multiplied by 0.5 for clarity. Clearly, the proton spectrum is much flatter compared with those for pions, and it
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Figure 2: Measured invariant cross-section divided by the trigger cross-section for identified pions and protons in the rapidity interval $0 < \delta y < 0.2$ as a function of transverse kinetic energy $m_t - m_0$. The spectra for protons, plotted as solid points, is scaled down by a factor of 2. The open circles in the figure are the spectra for $\pi^-$, and the solid squares are that for $\pi^+$. The insert shows the ratio of $\pi^-/\pi^+$ as a function of $m_t - m_0$ in a larger rapidity interval, $0 < \delta y < 0.4$.

tends to bend down at low $m_t - m_0$. Hence unlike the proton spectra measured in reactions induced by lighter projectiles at similar incident energy per nucleon, namely p+A [2] and Si+A [3] [4], the proton spectrum here cannot be described satisfactorily by a single exponential fit. The spectrum for $\pi^-$ is also impossible to describe satisfactorily with a single exponential, since it shows a strong rise at low $m_t - m_0$. The rise at low $m_t - m_0$ for $\pi^+$ is much less. The rise of both pion spectra at the low $m_t - m_0$ can be explained, in part, by the decay of resonances such as $\Delta$'s which tend to produce relatively low momentum pions [5]. Spectra for $\pi^-$ increase faster than those for $\pi^+$ in this region, and there are several reasons for this. The weak decay of the lambda produces relatively low momentum $\pi^-$, and some of the $\pi^-$ survive the target position cut and show up in the low $m_t$ region. Also the production of low momentum pions through $\Delta$'s prefers $\pi^-$ [6] because there are more neutrons than protons in the projectile/target. However, a main contribution to the difference between the $\pi^-$ and $\pi^+$ spectra may well be their Coulomb interaction with the rest of the co-moving medium [7] [8] [9] which on average is positively charged. In the insert, the ratio $(\pi^-/\pi^+)$ is plotted with a larger rapidity bin, $0 < \delta y < 0.4$, and the normalization is absolute. At high $m_t - m_0$, the ratio approaches one.

Fig. 3 shows the same ratio, $\pi^-/\pi^+$, at the same rapidity in reactions of different centralities. The spectra are scaled up by a factor of 2 successively, and the horizontal lines are the corresponding positions for the ratio 1. In peripheral reactions, the ratio is flat over the entire $m_t$ range and its value above one. This is consistent with the fact that there are more neutrons than protons in the colliding nuclei. For comparison, the ratio not only rises at low
Figure 3: The centrality dependence of the ratio, $\pi^-/\pi^+$, for Au+Au reactions at 11.6 A·GeV/c. The ratio is scaled up successively by a factor of 2 from the peripheral to the central.  

$m_t$ but also falls down to unity at high $m_t$ in central collisions. This is what would happen if the positive pions were pushed away and the negative pions were pulled in, for example, by Coulomb interaction. So the centrality dependency of the $\pi^-/\pi^+$ ratio provides support to the picture of pions interacting with a co-moving medium of positive charge in average.

By integrating the parametrization of the spectra over $m_t - m_0$ in each rapidity bin, one can obtain the distribution of particle yield over rapidity, $dn/dy$. (Other parametrizations tried yield results similar to within a few percent). The upper and middle panels of Fig. 4 show the $dn/dy$ distribution for pions, and protons. Unlike the mean $p_t$ distribution which only depends on the shape of the spectra, $dn/dy$ is proportionally dependent on the absolute normalization of the spectra. We estimate this overall systematic error in the normalization is about $\pm(10-15)\%$. However, the error bars shown in the figure are statistical only and do not reflect the systematic error. It is clear that the protons pile up at mid-rapidity, confirming the expectation of a large amount of stopping, hence a high baryon density in central Au nuclei collisions. For comparison, the dotted line in the figure is the proton rapidity distribution from central Si+Al at 14.6 A·GeV/c [4], multiplied by the mass ratio of the two reactions $197/27=7.3$. This reaction has a maximum around $\delta y = 0.8$, and a minimum around $\delta y = 0$ indicating that there is less stopping and more transparency in Si+Al than in Au+Au collisions. Correspondingly, the resulting baryon density achieved is lower. Model calculations based on A Relativistic Cascade (ARC) [11] predict this rapidity distribution for protons, and suggest a baryon density of more than 4 times nuclear normal density has been achieved during the evolution of the dynamical process. Both $\pi^+$ and $\pi^-$ distributions basically have the same shape in rapidity, with yields for $\pi^-$ about 25% higher than that for $\pi^+$. As can be seen in the figure, the distribution of pions is narrower in
Figure 4: Rapidity distribution of $dn/dy$ (upper and middle panels) and mean transverse momentum (lower panel) for pions and protons in central Au+Au reactions, where $\delta y$ is the distance of the measured rapidity of the spectra from the central rapidity $y_{nn} = 1.6$. The open circles in the figure are for $\pi^-$, and the solid squares for $\pi^+$. Protons are plotted with solid round points. For comparison, the dotted lines are for protons in central Si+Al reactions at 14.6 $A\cdot GeV/c$ (The $dn/dy$ for Si+Al is scaled by a factor of $197/27=7.3$, the mass ratio of the two reactions). The error bars are statistical only.
rapidity than that of the protons.

The lower panel of Fig. 4 shows the mean transverse momentum, $<p_t>$, as a function of rapidity for protons. The mean transverse momenta for protons have their maximum at the mid-rapidity, and fall gradually toward the target (or projectile) rapidity. Again, for comparison, the dotted line in the figure is data for protons from central Si+Al at 14.6 A-GeV/c (with no factor multiplied). These values are generally lower than those of Au+Au, indicating a possible radial expansion in central Au+Au collisions.

Fig. 5 shows the $m_t$ spectra for deuterons at $y=1.3$ for centralities ranging from the peripheral to the central. The spectra again are scaled up by a factor of 2 successively. It is clear that the spectrum in the central reactions is much flatter than that in the peripheral collisions. The straight lines are attempt to fit the spectra with a single exponential. As discussed before, in general particle spectra deviate from a single exponential parameterization in central Au+Au reactions, so the fit in the figure is intended to be qualitative to reveal any systematic trend of the spectrum shape for different centralities and/or reactions. This systematic comparison is summarized in Fig. 6, where the inverse slope parameters for pions, protons, and deuterons are plotted for a combination of reactions at various centralities. The horizontal axis is the number of participants estimated from the centrality cut of the reactions. The solid points are from Au+Au reactions at 11.6 A-GeV/c, the open squares are data from p+Au reactions at 14.6 GeV/c [2], and the open diamond is from central Si+Au reaction at 14.6 A-GeV/c [3] [4]. For pions, there is little change of the inverse slope parameter from the p+Au reactions to that of the central Au+Au reactions. The inverse slope parameter increases for protons as the number of participants in the reactions increases, and the increase is most pronounced for deuterons. This is consistent with the picture that radial expansion exists after the high density stage is reached [10]. In this picture, qualitatively speaking the larger the mass of a particle, the larger the transverse momentum it gains from the radial expansion – hence higher inverse slope parameter in its spectrum [12].

In summary, hadron spectra measured in Au+Au reactions have been presented. The proton $m_t$ distribution cannot be described satisfactorily by a single exponential fit, and it bend down at low $m_t$ range at central rapidities. The pion spectra, however, rise at low $m_t$ at central rapidities, and $\pi^-$ rises faster than $\pi^+$. The rapidity dependence of the ratio, $\pi^-/\pi^+$, indicates the possible influence of Coulomb interaction of pions with the co-moving medium. The systematic study of the inverse slope parameters for pions, protons, and deuterons highlights the possible radial expansion in the central Au+Au reactions.

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Figure 5: Centrality dependence of the deuteron $m_t$ spectra at rapidity $y=1.3$. The spectra are scaled up by a factor of 2 successively as more central events are selected.

Figure 6: Inverse slope parameters as a function of the estimated number of participants in the reactions for pions, protons, and deuterons. The data included in the and Au+Au reactions at 11.6 A·GeV/c.
4. References