Particle production in Au+Au collisions at beam energy scan II energies at STAR

Matthew Harasty1 for the STAR Collaboration

1University of California, Davis

Abstract. We report on measurements of light charged hadron production in Au+Au collisions at \( \sqrt{s_{NN}} = 14.6, 19.6, 27, \) and 54.4 GeV from the second phase of the beam energy scan (BES-II) program at RHIC. Transverse mass spectra and rapidity density distributions of \( \pi^\pm, K^\pm, p, \) and \( \bar{p} \) are measured as a function of collision energy, centrality, and rapidity. This work extends the previously published BES-I mid-rapidity (\( |y| < 0.1 \)) measurement to a rapidity of 0.9. This new rapidity dependence highlights the effects of baryon stopping for proton yields and the different production mechanisms of \( \pi^\pm \) and \( K^\pm \). The relative abundance of these light hadrons indicates different thermodynamic environments at different energies, centralities, and rapidities. The temperature (\( T \)) and chemical potentials (\( \mu_B \) and \( \mu_S \)) at chemical freeze-out are reported with their dependence on rapidity to further understand the QCD phase diagram.

1 Introduction

Quantum Chromodynamics (QCD), the theory of strong interactions, predicts that at sufficiently high temperature and high energy density, normal nuclear matter converts into a deconfined state of quarks and gluons, known as the Quark-Gluon Plasma (QGP). To investigate the phase diagram of QCD matter, the Relativistic Heavy Ion Collider (RHIC) performed the first phase of the Beam Energy Scan (BES-I) program in 2010. The success of the BES-I program justified the second phase of Beam Energy Scan (BES-II) with higher statistics and detector upgrades. Au+Au collisions at \( \sqrt{s_{NN}} = 7.7 - 54.4 \) GeV were collected during 2017-2021, covering a large area of the QCD phase diagram. Through the measurement of light hadron spectra and \( dN/dy \) distributions, we are able to extract the temperature and baryon chemical potential as a function of the collision energy, centrality, and rapidity by fitting the yields to thermal models. The spectra and \( dN/dy \) are also valuable to theorists to benchmark physics simulations of heavy ion collisions. Sect. 2 explains the methodology of measuring the spectra and \( dN/dy \) in STAR. Sect. 3 compares the different production mechanisms of \( \pi^\pm, K^\pm, p, \) and \( \bar{p} \). The rapidity dependence of thermodynamic variables at chemical freeze-out at \( \sqrt{s_{NN}} = 27 \) GeV are discussed in Sect. 4. Sect. 5 examines the collective radial flow at kinetic freeze-out at \( \sqrt{s_{NN}} = 54.4 \) GeV for mid-rapidity.

2 Particle Identification and Corrections

Two major detectors at STAR are capable of identifying charged hadrons to ultimately measure the rapidity density distributions of pions, kaons and protons. The time projection chamber (TPC) provides the momentum and energy loss (\( dE/dx \)) of charged particles. The barrel
time-of-flight (BTOF) detector can measure the precise timing information of particles to help construct a particle mass used for particle identification. The events are partitioned into several centrality classes with the tracks further partitioned into rapidity and $m_T - m_0$ bins. The particle yields are extracted in each bin by fitting the $dE/dx$ and $m^2$ distributions with Gaussian and Student-T distributions, respectively. These yields are corrected for energy loss through detector materials, tracking efficiency, and acceptance by a study of Monte Carlo simulations of the STAR detector at each energy. The weak decays of hyperons, including $\Lambda$, $\Xi^-$, and $\Omega^-$, contaminate the primordial yields, so the feed-down contributions are estimated by a mixture of UrQMD and mid-rapidity measurements. The primordial $m_T - m_0$ spectra are fitted at low and high $p_T$ to estimate the $dN/dy$ contributions in the regions that we are unable to measure due to acceptance and statistics. The spectra are also fit with alternate functional forms to estimate the systematic uncertainty in the extrapolation. The final $dN/dy$ values are averaged symmetrically across mid-rapidity.

![Figure 1](image_url). The rapidity density distributions of $\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$ in the most central (0-5%) Au+Au collisions at $\sqrt{s_{NN}} = 14.6$, 19.6, and 27 GeV. The error bars show the combined statistical and systematic uncertainties.

3 dN/dy of Charged Particles

Pair production is the dominant pion production mechanism, but the decays from the $\Delta$ resonance and neutron rich initial conditions contribute to an excess of $\pi^-$ at lower $\sqrt{s_{NN}}$. The $dN/dy$ of pions, kaons, and protons are shown in Fig. 1. Kaons are also produced in pairs, but in less abundance compared to pions due to their mass. An additional channel is available to $K^+$ through the associated production with a $\Lambda$ baryon from an interaction of a proton. The $uud$ quarks from proton and an $s\bar{s}$ quark pair form the $\Lambda$ and $K^+$. Since there are no anti-protons in the colliding gold nuclei, this channel is suppressed for the $K^-$, resulting in the differences of the $dN/dy$ distributions of $K^+$ and $K^-$. This associated production mechanism contributes less at higher $\sqrt{s_{NN}}$ as pair production dominates. The $dN/dy$ of protons are heavily influenced by the effects of baryon stopping. Baryon stopping quantifies the amount of rapidity loss of the participant nucleons from the initial beam rapidity caused by the interactions with the other colliding nucleus. At mid-rapidity, the shape of the proton $dN/dy$ distribution lowers and widens in more peripheral collisions as well as lower $\sqrt{s_{NN}}$. The change in relative abundances of $\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$ in each rapidity region indicates a different thermodynamic environment, discussed in Sect. 4.
4 Temperature and Chemical Potential at Chemical Freeze-Out

As the fireball expands, it reaches a stage where the inelastic collisions cease, which is known as chemical freeze-out. At this point, the total yields of each particle species are fixed. Chemical freeze-out is one location we can measure along the matter’s trajectory in the QCD phase diagram. This work expands upon the previous mid-rapidity studies of BES-I[1][2] to understand chemical freeze-out as a function of rapidity. Treating each rapidity slice with its own local equilibrium, the $dN/dy$ of the six light hadrons can serve as inputs to THERMUS, a chemical equilibrium model, to extract the temperature, $T_{chem}$, baryon chemical potential ($\mu_B$), and strangeness chemical potential ($\mu_S$).

Figure 2 shows the thermodynamic variables at chemical freeze-out at different centralities and rapidities at $\sqrt{s_{NN}} = 27$ GeV. The temperature exhibits a slight centrality dependence, with $T_{chem}$ rising from central to mid-central collisions and falling from mid-central to peripheral collisions. The baryon chemical potential lowers in peripheral collisions due to the fewer nucleon-nucleon collisions for each participating nucleon. The rapidity dependence of $\mu_B$ is fairly consistent across different centralities with a $\Delta \mu_B \sim 25$ MeV for a unit change in rapidity. This change in $\mu_B$ can be attributed to the differing rapidity distributions for $p$ and $\bar{p}$ from the stopped protons. The previously published BES-I measurement of protons[1][2] did not include a feed-down correction, which explains the discrepancy in $\mu_B$ at mid-rapidity in comparison to the new BES-II result. The additional associated production channel for $K^+$ widens its $dN/dy$ distribution compared to $K^-$. The third panel of Fig. 2 highlights the rapidity dependence of $\mu_S$ with $\Delta \mu_S \sim 10$ MeV for a unit away from mid-rapidity. Despite the net-zero strangeness in the initial conditions, the $\Lambda$ and $K^+$ move to different regions of phase space through the process of strangeness distillation[4], resulting in a non-zero strangeness chemical potential.

5 Temperature and Radial Flow Velocity at Kinetic Freeze-Out

After the total yields of particles are fixed at chemical freeze-out, the last elastic collisions occur. This point is known as kinetic freeze-out. These two freeze-out points have been shown to differ when the collision energy rises above $\sqrt{s_{NN}} \approx 7$ GeV[1]. The most central mid-rapidity $p_T$ spectra at $\sqrt{s_{NN}} = 54.4$ GeV are depicted in Fig. 3 are simultaneously fit with
Figure 3. (a) Simultaneous Blast-Wave fit of the mid-rapidity $p_T$ spectra of $\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$ at 54.4 GeV. (b) The temperature and the average collective radial flow velocity at kinetic freeze-out for several centrality bins, compared to BES-I measurements.

a Blast-Wave model[3], where all particles share a common temperature ($T_{\text{kin}}$) and average transverse radial flow velocity ($\langle \beta \rangle$) for each centrality bin. Irrespective of collision energy, the $T_{\text{kin}}$ and $\langle \beta \rangle$ all lie on the same contour, but the $T_{\text{kin}}$ decreases from peripheral to central collisions while $\langle \beta \rangle$ increases. The 54.4 GeV result agrees with the previously established trends at kinetic freeze-out.

6 Summary

The $m_T - m_0$ spectra and $dN/dy$ distributions are presented for $\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$ at a subset of BES-II energies at STAR, including $\sqrt{s_{NN}} = 14.6, 19.6, 27$, and $54.4$ GeV. At 54.4 GeV, the collective radial flow velocity and temperature at kinetic freeze-out at mid-rapidity agree well with the other energies of BES-I. These results expand on the previously published BES-I studies at mid-rapidity by examining the rapidity dependence of the rapidity density distributions and thermodynamic variables at chemical freeze-out. The additional production of $K^+$ in association with a $\Lambda$ generates a non-zero $\mu_S$ that increases with rapidity with $\Delta \mu_S \sim 10$ MeV for a unit change in rapidity at 27 GeV. The stopped participant protons contribute to the difference in shape of the $dN/dy$ distributions of $p$ and $\bar{p}$, leading to a $\Delta \mu_B \sim 25$ MeV for a unit change in rapidity. These measurements extend our knowledge of the QCD phase diagram by examining how the thermodynamic quantities at chemical freeze-out change with rapidity.

References