Abstract

We present recent results from Al(beam)+Au(target) collisions at $\sqrt{s_{NN}} = 4.9$ GeV and Au+Au collisions at $\sqrt{s_{NN}} = 4.5$ GeV from the STAR fixed-target (FXT) program. We report transverse mass spectra of protons, $K_0^0$ and $\Lambda$, rapidity density distributions of $\pi^\pm$, $K_0^0$ and $\Lambda$, directed flow of protons, $\pi^\pm$, $K_0^0$ and $\Lambda$, and elliptic flow of protons and $\pi^\pm$. These are the first measurements of pion directed and elliptic flow in this energy range at RHIC. Pion and proton elliptic flow show mass ordering. Measurements are compared with the published results from AGS and RHIC. These results demonstrate that STAR has good performance in the FXT configuration. The implications of these results for future STAR FXT runs are discussed.

Keywords: STAR, fixed-target, FXT, spectra, directed flow, elliptic flow, strangeness, rapidity density

1. Introduction

The goals of the STAR beam energy scan (BES) program include searches for a possible QCD critical point and for the turn-off of signatures of quark-gluon plasma (QGP), and a determination of the nature of the phase transition between hadronic and partonic matter [1]. RHIC BES phase I (BES-I) has shown interesting results below $\sqrt{s_{NN}} = 19.6$ GeV in azimuthal anisotropy for identified hadrons, kaon to pion ratios, and net-proton higher moments. These interesting features continue to the lowest RHIC collider-mode energy, $\sqrt{s_{NN}} = 7.7$ GeV, and motivate the investigation at even lower energies. The STAR fixed-target (FXT) program extends the energy reach from

1A list of members of the STAR collaboration and acknowledgements can be found at the end of this issue.
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\[ \sqrt{s_{\text{NN}}} = 7.7 \text{ GeV} \] to \[ \sqrt{s_{\text{NN}}} = 3.0 \text{ GeV} \], corresponding to baryon chemical potentials from 420 MeV to about 720 MeV. The directed flow \( (v_1) \) for the proton and \( \Lambda \) [2, 3] suggests a qualitative resemblance to the “softest point” of the equation of state predicted by hydrodynamic models.

And the net-proton higher moments measurement from energies below 7 GeV could help determine the type of phase transition or reveal the evidence for critical fluctuations [4]. However, it is not feasible for RHIC to operate in collider mode below 7 GeV due to steeply decreasing luminosity. By inserting a target into the beam pipe and circulating one beam in RHIC, we can instead study FXT collisions in the center-of-mass energy below 7 GeV. Figure 1 shows an example of a schematic phase diagram, and illustrates the possible region probed by FXT measurements.

During a brief test in 2015, STAR collected approximately 1.3 million FXT events with centrality 0-30%.

2. Results

2.1. STAR FXT Particle Yield Results

Fig. 2 presents proton spectra for 0-5% centrality in Au+Au collisions at \( \sqrt{s_{\text{NN}}} = 4.5 \text{ GeV} \) as a function of transverse mass \( m_T - m_T \) in several rapidity bins, each with a width \( \Delta y = 0.1 \). These spectra were fitted using the Blast-Wave model, after correcting for detector efficiency, acceptance, energy loss and hadronic background. Overall, fits describe the data across the STAR FXT acceptance range.

![Fig. 2: Proton transverse mass spectra in 4.5 GeV Au+Au collisions.](image)

In Fig. 3, \( K^0_s \) transverse mass spectra for central \( \sqrt{s_{\text{NN}}} = 4.5 \text{ GeV} \) Au+Au and 4.9 GeV Al+Au collisions are shown for 0-5% centrality in several rapidity bins of width \( \Delta y = 0.25 \). These spectra are fitted using the Blast-Wave model, after confirming the previously reported agreement [5] between STAR FXT and AGS publications.

![Fig. 3: \( K^0_s \) transverse mass spectra for central \( \sqrt{s_{\text{NN}}} = 4.5 \text{ GeV} \) Au+Au and 4.9 GeV Al+Au collisions.](image)
2.2. STAR FXT Flow Results

The left panel of Fig. 5 presents proton \( v_1(y) \) from 4.5 GeV Au+Au (red markers). E895 data for 4.3 GeV Au+Au at similar \( p_T \) and centrality are also plotted [17]. STAR FXT results are consistent with E895 but have much smaller statistical errors. In the right panel of Fig. 5, proton \( v_1(y) \) is plotted in narrow intervals of \( p_T \). The proton acceptance in FXT mode at this beam energy, with the standard selection of \( 0.4 < p_T < 2.0 \text{ GeV}/c \) used in prior studies [2, 3, 17], was found to have negligible impact on proton \( v_1(y) \) down to \( y - y_{CM} = 0 \).

FXT directed flow slope \( dv_1/dy \) near midrapidity for protons, \( \pi^+ \), \( K^0 \) and \( \Lambda \) at 4.5 GeV are compared in the left panel of Fig. 5 with STAR collider-mode results and with E895 [2, 3, 17]. The STAR FXT \( \pi^+, K^0 \) measurements continue the trend of negative \( dv_1/dy \) for mesons observed at 7.7 GeV and above. The STAR FXT \( dv_1/dy \) for protons at 4.5 GeV is in good agreement with E895 at 4.3 GeV, and both are consistent with a smooth interpolation between higher and lower energies.

Figure 7 presents FXT 4.5 GeV Au+Au proton and pion elliptic flow \( v_2(p_T) \). The observed mass ordering of proton and pion \( v_2 \) resembles measurements at higher energies [20, 22].
3. Future FXT Plans

In future runs, STAR will have multiple detector upgrades\cite{23}, including the Inner Time Projection Chamber (ITPC), Endcap Time Of Flight (eTOF) and Event Plane Detector (EPD; already operational for 2018). These upgrades extend the detector acceptance, and improve the particle identification capability, event plane resolution and centrality determination. Running in FXT mode for two days at each of several energies between $\sqrt{s_{NN}} = 3.0$ GeV and 7.7 GeV will permit acquisition of ~100 million events per energy and will extend the reach of baryon chemical potential to about 720 MeV. The highest FXT energy will overlap with the lowest collider-mode energy, allowing detailed cross checks.

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