First results are presented from BNL experiment E910 on pion production and stopping in proton-Be, Cu, and Au collisions at a beam momentum of 18 GeV/c. We characterize the centrality of the collisions using the measured number of “grey” tracks, $N_{\text{grey}}$, and a derived quantity, $\nu$, the number of inelastic nucleon-nucleon scatterings suffered by the projectile during the collision. We find that for the three targets the average backward rapidity shift of the leading proton follows a common trend versus $\nu$ with the projectile losing, on average, 2 units of rapidity in the first 2-3 scatterings. The average rapidity shift increases more slowly with subsequent scatterings reaching a maximum of 2.5 units. The $\pi^-$ multiplicity measured within the E910 acceptance saturates with increasing $\nu$ in p-Au collisions while the $\pi^-$ multiplicity in p-Be collisions increases faster with $\nu$ than expected from the wounded-nucleon model. Comparisons of our data with the RQMD cascade model suggest that in very central p-Au collisions most of the pions are produced near zero rapidity in the lab.
For several years experiments at the Brookhaven National Laboratory AGS and at the CERN SPS accelerators have studied fixed-target collisions between nuclei to search for the formation of the quark gluon plasma. However, interpreting results from these experiments has often been difficult due to our imprecise knowledge of the complicated hadronic interactions that take place during nuclear collisions. In particular, the physics of the initial multiple scattering of and energy release from the incident nucleons is poorly understood, especially at the lower energies of the AGS. Proton-nucleus (p-A) collisions provide a way to study this energy deposition process, but limitations of past experiments have reduced the utility of p-A data in understanding the physics of heavy ion collisions. Past measurements were obtained using either small-acceptance spectrometers capable only of inclusive measurements or low-rate “visual” detectors (emulsion, bubble chambers or streamer chambers) with limited particle identification capabilities.

AGS Experiment 910 was designed to address the deficiencies in existing p-A data-sets by performing semi-inclusive measurements of p-A collisions at AGS energies in a large-acceptance, moderate-rate detector. In this letter we present new measurements of two basic properties of p-A collisions, the backward rapidity shift of the projectile (“stopping”) and the subsequent production of negative pions at a beam momentum of 18 GeV/c. Both studies are performed as a function of the multiplicity of “grey” protons and deuterons ($N_{\text{grey}}$), and we use $N_{\text{grey}}$ to estimate $\nu$, the number of discrete inelastic nucleon-nucleon (N-N) scatterings of the projectile in the target nucleus.

The E910 spectrometer was designed to have both large geometric acceptance and extensive particle identification coverage. Its main component is the EOS TPC, a large volume (150 cm x 100 cm x 75 cm) TPC read out on a 128 x 120 pad segmented cathode plane. The experiment was staged in the Multi-Particle Spectrometer (MPS) facility at the AGS with the TPC located at the center of the 6 m MPS “C” magnet which was operated with a nominal central field of 0.5 T. The TPC was oriented with its long axis parallel to the incident beam and its short axis (drift direction) parallel to the primary component of the magnetic field. It was operated with P10 gas at atmospheric pressure and a drift field of 120 V/cm. Particle identification in E910 is provided by $dE/dx$ measurements in the TPC, a 32-slat time-of-flight (TOF) wall and a 96-mirror segmented gas Cherenkov counter operated with Freon 114 at atmospheric pressure. Additional details on the E910 apparatus may be found in.

The data presented in this paper were obtained from a secondary proton beam of typical intensity $3 \times 10^4 s^{-1}$ normally incident on Be, Cu, and Au targets of thickness 3.9, 4.2, and 3.4 g cm$^{-2}$, respectively. The secondary beam was measured to have an actual mean momentum of $17.5 \pm 0.2$ (syst) GeV/c with a fractional spread of 1%. Pions and kaons in the beam were rejected using three beam-line Cherenkov counters. Beam protons were detected in two scintillator counters and tracked in two MWPC’s upstream of the target while halo was rejected using two “veto” counters. The data presented here were triggered on the presence of a beam proton upstream of the target and its subsequent absence in a downstream “Bull’s- Eye” (BE) counter with 0.13 msr aperture centered on the beam. Using pulse-height information from the TPC we calculated the average $dE/dx$ of all reconstructed particles using a 70% “truncation” cut, obtaining a resolution $\sigma/(dE/dx) = 8\%$ for “typical” track lengths. This resolution allows 3-σ or better $\pi$-p separation up to a momentum of 1.2 GeV/c. For the leading particle analysis we identify and reject $\pi^+$’s with $p > 3.5$ GeV/c using the Cherenkov counter with an estimated 90% efficiency, and in the interval $1.2 < p < 2.7$ GeV/c we reject pions at the 3-σ level using time-of-flight. Due to the large acceptance of the TPC and the particle identification detectors, we have essentially complete acceptance for protons down to $y \sim 0.3$.

For the multiplicity analysis, we identify $\pi^-$’s by requiring them to have a measured $dE/dx$ within 2.6-σ of the nominal pion $dE/dx$ at any given momentum. We ignore the presence of $K^-$’s and $\bar{p}$’s which contaminate the $\pi^-$ multiplicities by at most 2%. A larger contamination results from electrons produced primarily by photon conversions in the target. In this analysis we implemented an $e^+/e^-$ reconstruction algorithm that removes 50% of the conversion electrons. Fig. shows E910’s $\pi^-$ acceptance as a function of rapidity ($y$) and $p_L$. The acceptance has a relatively sharp cutoff at $y = 0.5$. We make no correction to our multiplicities for localized tracking and particle-identification inefficiencies for pions within our geometric aperture but we estimate these losses to be typically of order 3-4%.

In the final stages of analysis we apply cuts to all reconstructed events to remove off-target, upstream, and downstream interactions. We require “interactions” to have either two charged particles in the final state or a single charged particle with $p < 12$ GeV/c and $p_L > 0.06$ GeV/c. A study of “target-out” data indicates that after these cuts, approximately 3% of our accepted events result from off-target interactions. After all of our cuts, the data sample for this letter contains 101k, 49k, and 36k events for the Be, Cu, and Au targets, respectively.

As noted above, we characterize the centrality of p-A collisions using $N_{\text{grey}}$, which has been shown to be related to $\nu$, the number of inelastic N-N scatterings suffered by the projectile in traversing the target. The grey tracks result from the recoil nucleon “shower” induced by the scatterings of the projectile in the nucleus. Due to intrinsic fluctuations in this recoil shower and the acceptance of the experiment, the dependence of $\nu$ on $N_{\text{grey}}$ is “statistical” and is not valid event-by-event. Nonetheless, the correlation between $\nu$ and $N_{\text{grey}}$ is sufficiently strong that an extracted average $\nu$ for a given bin in $N_{\text{grey}}$ ($\bar{\nu}(N_{\text{grey}})$) provides an effective measure of collision centrality. Different techniques for calculating this
quantity \[1, 3\] have been used by other experiments in the past \[14\], and these techniques plus a new variant have been studied in the context of E910 \[8\]. We define \(N_{\text{grey}}\) to be the sum of the multiplicity of protons in the momentum range \([0.25, 1.2] \text{ GeV/c}\) and the multiplicity of deuterons in the range \([0.5, 2.4] \text{ GeV/c}\) \[8\]. The lower limits are set at the approximate momentum above which secondary recoil nucleons dominate over nuclear fragmentation products \[8\]. The upper limits are determined by our ability to uniquely identify protons and deuterons using only \(dE/dx\). We use both \(N_{\text{grey}}\) and \(\bar{\nu}(N_{\text{grey}})\) for centrality measurements in the analysis described below.

The dynamics of secondary particle production in p-A collisions must depend on the energy loss of the projectile and we have chosen to study this problem using the “leading-particle” technique \[4, 15\] where we assume that the largest rapidity (identified) proton in an event carries the baryon number of the projectile. We quantify the projectile stopping by the backward rapidity shift, \(\Delta y\), where we assume that the largest rapidity (identified) proton in an event carries the baryon number of the projectile. We quantify the projectile stopping by the backward rapidity shift, \(\Delta y = y_{\text{beam}} - y_{\text{lead}}\). We note that for \(p_{\text{beam}} \gg \sqrt{m^2 + p_{\perp}^2}\), \(y_{\text{beam}} \approx \ln(2p_{\text{beam}}/m)\). Using this approximation the final momentum of the leading proton is

\[
p' \approx p_{\text{beam}} e^{-\Delta y}.
\]

The assumption that the leading proton is a direct fragment of the projectile can be violated in various ways, but the most significant contribution comes from charge-exchange events with high momentum neutrons and a low-momentum (leading) protons. We have attempted to remove such events using a variety of cuts, the most effective of which appears to be a requirement that the \(\sum p_{\perp}\) in an event satisfies

\[
\sum p_{\perp} > 1.5 \text{ GeV/c} \cdot (\Delta y - 1.1), \text{ for } \Delta y > 1.1.
\]

This cut requires that large \(\Delta y\) events have a corresponding fraction of the released energy observed in the transverse motion of the particles in the final state, and it has the largest effect for small \(N_{\text{grey}}\) since these interactions typically have small “true” \(\Delta y\)'s but large observed \(\Delta y\)'s. The parameters were chosen based on studies of both data and the RQMD cascade model \[10\].

Figure 2 shows \(\langle \Delta y \rangle\) as a function of both \(N_{\text{grey}}\) and \(\bar{\nu}\) for the three targets. We observe that the data from all three targets follow the same trend with \(\nu\) and that \(\langle \Delta y \rangle\) rises quickly at low \(\nu\) and then reaches an asymptotic value of \(\approx 2.4\). The slight offset of the p-Be data points from the other targets is well within the systematic errors in the \(\bar{\nu}(N_{\text{grey}})\) extraction procedure. Comparisons of various charge-exchange cuts indicate a small systematic error, \(\approx 0.2\), on the maximum \(\langle \Delta y \rangle\) associated with the choice of charge-exchange cut because events with large \(N_{\text{grey}}\) or \(\nu\) rarely have a high-momentum projectile fragment of either sign. We note, however, that we can under-estimate \(\langle \Delta y \rangle\) for the most central collisions if a recoil proton is ejected from the target with a rapidity larger than that of the projectile fragment. This will most often happen when the projectile leaves the collision with a rapidity less than or comparable to that of a typical recoil nucleon \((y \sim 1)\). Thus, we will lose sensitivity to the stopping of the projectile for \(\Delta y > 2.5\).

It is important to note that our results at \(\nu = 1\) are consistent with the well-established \(\Delta y \approx 1\) in p-p collisions noted by Busza \[17\]. We observe a \(\Delta y\) for central events which is at least as large as that obtained at higher energies \[14\], and which is quantitatively consistent at mid-centrality where the bias from target nucleons is not expected to be significant. This agreement with the higher energy data suggests that the stopping of the projectile, expressed in terms of \(\Delta y\) is independent of beam energy down to AGS energies.

An interesting implication of the fact that \(\Delta y \sim 2\) for \(\nu > 2-3\) is that if the backward rapidity shift comes from incremental energy loss of the projectile during the multiple collision process, after the first few collisions the projectile would have a momentum of only 2-3 GeV/c. As a result, little or no particle production would be expected from subsequent scatterings. Future results on strange particle production should test whether this naive stopping picture is valid.

To study secondary particle production we have chosen to focus on \(N_{\pi^-}\), the multiplicity of \(\pi^-\)'s within the E910 acceptance. Given our acceptance, the measured multiplicities include all \(\pi^-\) except for those produced at or near \(y = 0\). We plot in Fig. 3 \(N_{\pi^-}\) as a function of \(N_{\text{grey}}\) and \(\bar{\nu}\) for the three different targets. These yields have been corrected for electrons that survive the \(e^+e^-\) rejection cuts. We observe that \(N_{\pi^-}\) increases approximately proportionally to \(N_{\text{grey}}\) and \(\bar{\nu}\) for all three targets at small values of \(N_{\text{grey}}\) or \(\nu\) but that the yields from the Cu and Au targets subsequently saturate. The effect is most dramatic for the Au target where \(N_{\pi^-}\) remains constant for \(\nu > 3\).

The saturation in the observed \(\pi^-\) yields in p-Au and p-Cu collisions is both striking and qualitatively consistent with the remarks made above regarding the effects of the stopping of the projectile on the production of secondary particles. However, the interpretation of this effect also depends on our low-rapidity acceptance cut-off. Since it is known that \(\pi\) rapidity distributions in p-A collisions shift to lower rapidities with increasing target size \[10\], the acceptances losses in our \(\pi^-\) yields will likely also vary with \(N_{\text{grey}}\). We show in Fig. 3 comparisons of our \(\pi^-\) yields with those from the RQMD before and after the application of E910’s acceptance. The RQMD data are plotted vs \(\bar{\nu}(N_{\text{grey}})\) obtained by performing the E910 \(\bar{\nu}(N_{\text{grey}})\) extraction procedure \[8\] on RQMD data. The RQMD \(4\pi N_{\pi^-}\) values increase monotonically with \(\nu\) reaching a maximum of \(\approx 6\) \(\pi^-\)'s per event whereas the multiplicity in acceptance shows good agreement with our results. The implication of this comparison is that \(\approx 2/3\) of the \(\pi^-\)'s in the most central p-Au collisions lie below \(y = 0.5\). Irrespective of RQMD, since we see no saturation in the \(N_{\pi^-}(\bar{\nu})\) for Be but similar \(\Delta y(\nu)\), the saturation in the \(\pi^-\) yields in Cu and Au seems not to
result from stopping but may indicate an effect of the heavier targets.

To provide further interpretation of our results, we show with a solid line in Fig. 2d expectations for the \( N_{\pi^-} (\nu) \) based on the wounded-nucleon (WN) model which in its most extreme form states that the pion yield in p-A interactions depends on \( \nu \) as

\[
N_{\pi} = \frac{N_{pp}^{\pi}}{2} (\nu + 1).
\]

We have used both measurements of \( \pi^- \) production in p-p collisions at 12 and 24 GeV/c [2] and parameterizations of the \( \sqrt{s} \) dependence of \( \pi^- \) yields [10] to estimate \( N_{pp}^{\pi} \) at 18 GeV/c. We corrected these yields downward by a factor of 0.9 to account for acceptance losses in E910 [20] and upward by a factor of 1.2 to account for isospin differences. We observe that Eq. 3 agrees with the p-Au data for \( \nu < 3 \) but over-predicts at larger \( \nu \) where the \( \pi^- \) yields saturate. A surprising result from Fig. 2 is that the \( \pi^- \) yields in p-Be collisions increase faster with \( \nu \) than suggested by the WN prescription. In fact, a “binary collision” model with \( N_{\pi^-} (\nu) = N_{pp}^{\pi} \nu \), shown in Figs. 2 with dashed lines, does a much better job of describing our p-Be yields than the WN model. We note that this surprising conclusion may be affected by systematic errors in our \( \nu (N_{grey}) \) extraction procedures, but to make our results consistent with the WN expectation, the most central p-Be \( N_{grey} \) point would have to have \( \bar{\nu} \approx 3.5 \) which is very unlikely.

In summary, we have presented first results from experiment 910 at the BNL AGS on projectile stopping in p-A collisions at 18 GeV/c and the subsequent production of \( \pi^- \)'s. We observe a common trend in the backward rapidity shift of the projectile as a function of \( \nu \) for all three targets and we observe that the projectile loses 2 units of rapidity in the first 2-3 collisions. The observed \( \pi^- \) multiplicities show no common trend among the three targets as a function of \( \nu \), a result that differs from previous measurements at higher energies [8]. The pion yields in p-Au collisions saturate for \( \nu > 3 \) whereas the pion yields in p-Be collisions increase faster with \( \nu \) than expected based on the wounded-nucleon prescription. RQMD comparisons suggest that the saturation of \( N_{\pi^-} \) is due to the low-rapidity cutoff in the E910 acceptance and a dramatic backward shift of the \( \pi^- \) distributions to \( y = 0 \) in the most central events. Ongoing analysis of E910 pion spectra should provide an experimental test of this inference in the near future. The difference in the behavior of the two observables that we have studied with target mass is worth emphasizing. Our data suggests that the stopping of the projectile is determined predominantly by \( \nu \) whereas the production of secondary pions is strongly dependent on the mass of the target. We note that our analysis is the first to study the centrality dependence of p-Be interactions where the multiple interactions of the incident proton can be cleanly studied without substantial final state interactions of secondary particles.

We wish to thank Dr. R. Hackenburg and the MPS staff, J. Scaduto and Dr. G. Bunce for their support during E910 data-taking. We also thank Dr. Thomas Kirk, BNL Associate Director for High Energy and Nuclear Physics, for his support of our physics program.

This work has been supported by the U.S. Department of Energy under contracts with BNL (DE-AC02-98CH10886), Columbia University (DE-FG02-86ER40281), ISU (DOE-FG02-92ER4069), KSU (DE-FG02-89ER40531), LBNL (DE-AC03-76SF00098), LLNL (W-7405-ENG-48), ORNL (DE-AC05-96OR22464) and the University of Tennessee (DE-FG02-96ER40982) and the National Science Foundation under contract with the Florida State University (PHY-9523974).

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FIG. 1. The E910 acceptance for \( \pi^- \)'s identified by dE/dx in the TPC.
FIG. 2. Avg. leading proton $\Delta y$ and in-acceptance $\pi^-$ multiplicity for p-Be, Cu, and Au collisions plotted vs $N_{\text{grey}}$ (a, c), $\bar{\nu}(N_{\text{grey}})$ (b, d) Solid(dashed) line in d shows expectation from wounded-nucleon(binary-collision) model.

FIG. 3. Comparison of $\pi^-$ yields from the RQMD cascade model with E910 data as a function of $\bar{\nu}(N_{\text{grey}})$ for p-Au collisions at 18 GeV/c. closed triangles - RQMD in $4\pi$, diamonds - RQMD in E910 acceptance, circles - E910 data.