LOW P_t PARTICLE SPECTRA AND STRANGELET SEARCH FROM AU + AU COLLISIONS: FINAL RESULTS FROM BNL-AGS EXPERIMENT E878

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INTRODUCTION

The primary motivation for the E878 experiment was to perform a high sensitivity study of rare processes in relativistic heavy ion collisions; in particular, we wanted to investigate antinuclei production and to try to detect (if they exist) small "chunks" of strange quark matter, usually referred to as strangelets.[1, 2] Of course, as events were sampled looking for the production of one of these rare particles, more copiously produced particles were detected as well. Thus, the E878 results include pion, kaon, proton and light nuclei production cross sections, in addition to antiproton spectra and production limits on strangelets. As is indicated in the title of this talk, the analysis of E878 data has been completed, and here we wish to review some of the more interesting physics to come out of this experiment.

THE EXPERIMENT

The E878 apparatus consisted of a beamline focussing spectrometer, as detailed elsewhere.[3] When a beam particle underwent an inelastic interaction in the target, only those produced secondary particles which fell within $\sim \pm 2\%$ of the chosen tuned rigidity (ratio of momentum to electric charge) and within $\sim$15-20 mr of the beam direction were propagated down the spectrometer to be detected. This acceptance was sufficiently small that only about 1 in 10^4 events produced a detected particle. However, since triggers were only generated by particles in the spectrometer, this small acceptance allowed for a very high event rate; the event rate was pushed even higher by identifying and downscaling copiously produced particles (i.e. pions and protons) at the trigger level. Thus, the data set shown here represents a sampling of over 2 *trillion* Au + A inelastic interactions, integrated over a 6 week time period during the AGS Au beam run in the fall of 1993. By spreading this large number of events over numerous rigidity tunes, E878 was able to execute an efficient high sensitivity search for rare particles.

Another strength of E878 was redundant measurement, which allowed for clean particle identification with virtually no background. Particle identification was accomplished via a combination of the knowledge of the particle momentum (which was well defined due to two momentum-selecting bends in the spectrometer) and its time-of-flight over a known flight path, which was measured at four points along the beamline. Non-target related background was greatly reduced by measuring the particle trajectory with drift chambers after each of the momentum-selecting bends in the beamline. Additional particle identification information came from two aerogel Cerenkov detectors and two gas Cerenkov detectors, which were used primarily to identify pions and which were incorporated in the trigger scheme.

For the two gas-based Cerenkov detectors, the threshold velocity could be chosen by varying the pressure and composition of the radiator gas. This allowed for pion-kaon identification up to very high momentum; included in this data set are pion and kaon spectra up to a longitudinal momentum of 20 GeV/c (due to time constraints, this high rigidity data was taken only for negative rigidities). The ability to measure cross sections in this extreme phase space region is unique to E878.

STRANGELET SEARCH

Over the past several years, numerous theoretical studies have suggested the existence of *strange quark matter*[1], i.e. novel states of hadronic matter which would consist of multiquark combinations of roughly equal numbers of up, down and strange quarks. In particular, Farhi and Jaffe investigated strange quark objects over a wide range of baryon number A and found, using the MIT bag model[2], that *strangelets*, i.e. strange quark matter of small A, could be stable. Due to the high strangeness content produced, relativistic heavy-ion collisions provide a promising mechanism for forming strange quark matter. Strangelets could be created by either the coalescence of strange and non-strange baryons at freeze-out[4], or as a residue of the distillation of a quark-gluon plasma formed in the collision.[5,6]

The experimental signature for strangelets is a charge to mass ratio outside of the normal range for known particles. The resolving power of the E878 spectrometer was sufficient to allow the rejection of all background events, such that we see *no* candidate strangelet events.[7] In order to determine the E878 sensitivity to strangelet production, a phase space distribution model has been used which incorporates a Gaussian rapidity distribution with a mean at $y_{cm} = 1.6$, and an exponential distribution in transverse momentum. The E878 sensitivity (i.e. the upper limit on the total number of particles produced over all phase space per minimum bias collision) is shown in Figures 1 and 2 for negatively and positively charged strangelets, respectively. The three curves correspond to different assumptions regarding the width of the Gaussian rapidity distribution; σ_y is given by $0.5/\sqrt{A}$, $1.0/\sqrt{A}$ and 0.5 for curves (1), (2) and (3) respectively. The circular symbols represent RQMD-based coalescence calculations for the production of chiral soliton states.[8] The square symbols represent calculated coalescence production rates for various multihypernuclei[4], which could then decay into metastable strangelets. In most cases, E878 has set stringent limits on the branching ratio of these "doorway states" to decay to strangelets. The triangular symbols represent calculated rates for the production of various strangelet states in the hadronization of a quark-gluon plasma.[5] Unfortunately, E878 is not sufficiently sensitive to test these predictions; ongoing experiments may eventually be able to address this issue.[9]

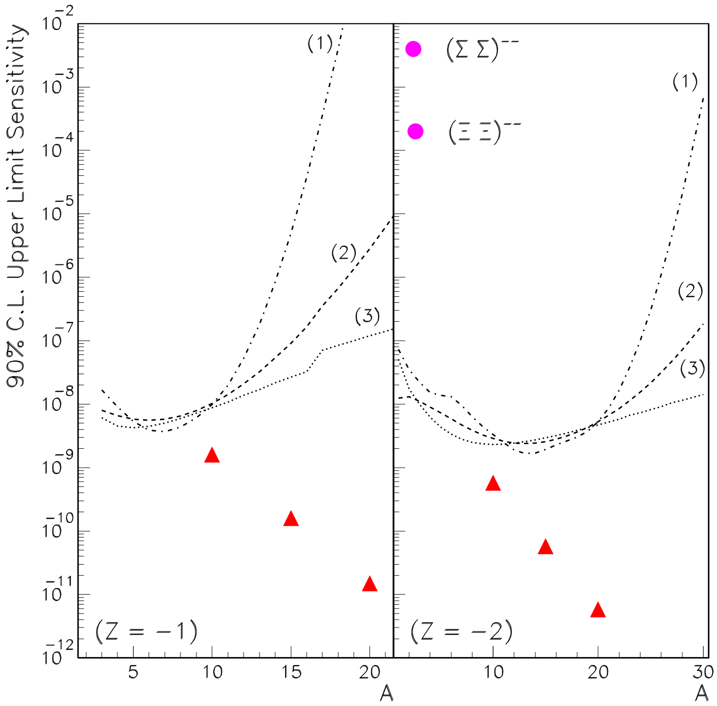

Figure 1. The sensitivity of the E878 experiment for the detection of charge -1, -2 strangelets. The three curves are the 90% sensitivity upper limits on specific models of strangelet production. Chiral soliton predictions[8] and strangelet predictions of Crawford *et al.*[5] are shown as circles and triangles, respectively.

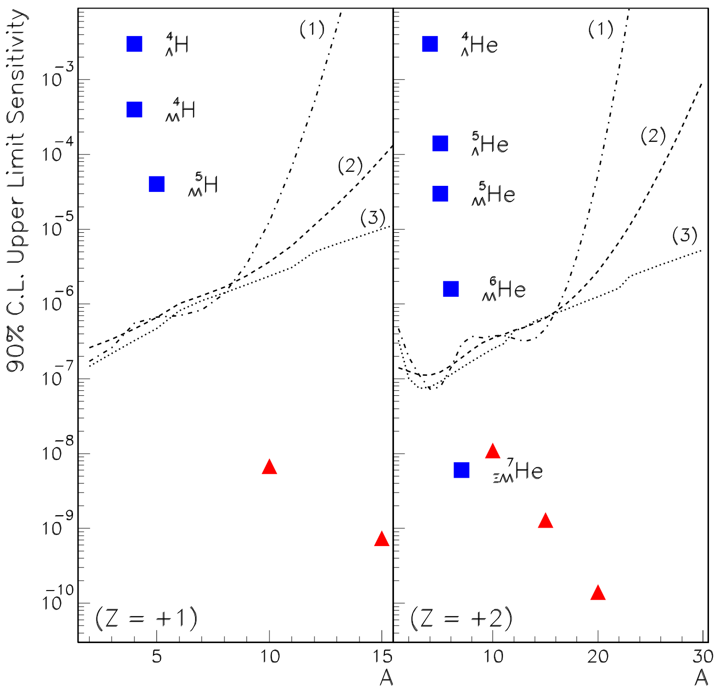

Figure 2. The sensitivity of the E878 experiment for the detection of charge +1, +2 strangelets. The three curves are 90% sensitivity upper limits based on specific models of strangelet production. Hypernuclear predictions of Baltz *et al.*[4] and strangelet predictions of Crawford *et al.*[5] are shown as squares and triangles, respectively.

LIGHT NUCLEI SPECTRA

The formation of light nuclei near central rapidity in relativistic heavy-ion collisions is understood to occur as a result of the *coalescence* process, whereby nucleons which happen to be close to each other in six-dimensional phase space can coalesce to form a nucleus. Thus, it seems reasonable that the yields of light nuclei relative to that of nucleons are sensitive to the nucleon source size at the time of freeze-out. Several theoretical approaches have been formulated[10,11] to estimate the source size based on the coalescence parameter B_A, where $E_A \cdot d^3N_A/dp_A^3 = B_A \cdot (E_p \cdot d^3N_p/dp_p^3)^A$.

E878 has measured light nuclei yields up to A=4 for several momenta at $p_t = 0$; for each species, a cross section at mid-rapidity has been included.[12] The nature of the E878 apparatus was such that measured cross sections were inherently minimum bias; however, multiplicity information regarding the interaction which produced the particle was also recorded. This information made it possible to investigate how the coalescence parameter B_A changes for various interacting systems. The results of this study are shown in Figure 3, where, for A=2 through 4 at mid-rapidity, B_A values for different centrality bins are plotted against the mean number of interacting nucleons (as determined by Monte Carlo[15]). In our data set, B_2 decreases by a factor of two from the most-peripheral to the most-central bin, while B_3 decreases by a factor of ten and B_4 by a factor of a hundred; data from the various targets are qualitatively consistent with each other. This trend is qualitatively consistent with that seen by other experiments, e.g. E814 from Si + A interactions.[16] Since nucleons must be close to each other in position space as well as in momentum space in order to coalesce, the observed decrease in B_A is consistent with a simple picture of an expanding system. However, caution must be used when simple models are applied to extract precise quantitative information about the dimensions of the collision volumes at freeze-out. Implicit in the systematic behavior of B_A is the interplay of competing effects–increased source size, which decreases B_A, balanced against collective flow, which increases the correlation between position and momentum, and thus would increase B_A.

MESON SPECTRA

In addition to light nuclei, E878 has also measured production cross sections for pions and kaons.[17] Since we measure in a region of phase space which is not covered by other experiments, the E878 yields provide a unique data set for comparison to various models. A comparison of the E878 measured pion and kaon yields to predictions of the RQMD model are shown in Figure 4, for both 10% central and minimum bias Au+Au interactions. (Strictly speaking, since E878 triggers only on produced particles in the spectrometer, we measure invariant cross section, not invariant multiplicity; in order to facilitate comparison, our cross sections have been converted to multiplicity assuming a total Au+Au inelastic cross section of 6850 mb.) The predictions for 10% central interactions are from RQMD version 2.2[13], while those for minimum bias interactions are from an older version of RQMD, version 1.07.[18] The minimum bias data set for π^- and K^- includes data points at very high rapidity; in order to make a meaningful comparison to RQMD, a high number of simulated events were needed, which we had on hand from version 1.07. As can be seen in Figure 4, RQMD matches the E878 yields very well, even for the high rapidity π^- data. Unfortunately, even the large number of RQMD events used ($\sim 18,500$) did not provide sufficient statistics to compare to the high rapidity E878 K^- data. We note that the minimum bias π^- data contain several points with momenta beyond that of the beam, i.e. with $x_F > 1$. The ability of RQMD

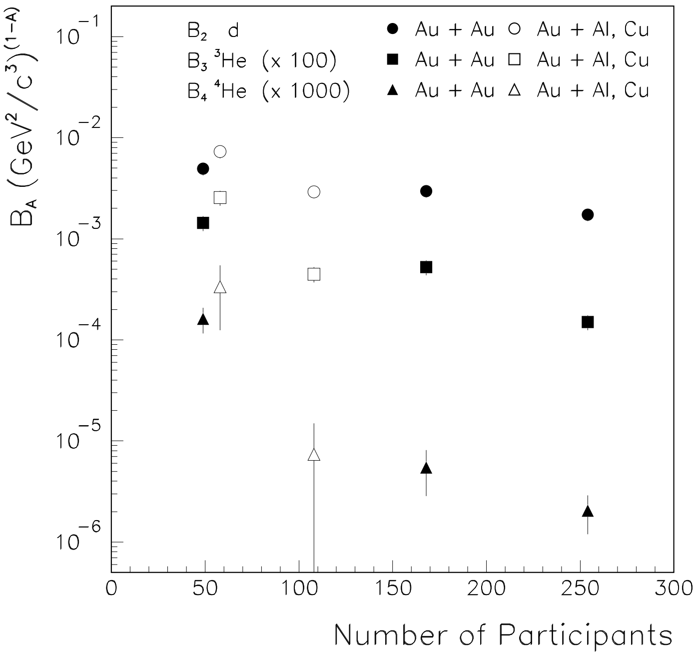

Figure 3. Dependence of the B_A parameter on the number of participants in Au+Al, Au+Cu and Au+Au reactions. For the Au+Au data, we show points for each of three centrality bins; for the lighter targets, only the data from the most-central bin is shown.

to match this data suggests that the mechanisms which lead to the production of these high momentum particles are already implicit in the model, and it is not necessary to invoke exotic mechanisms to explain the E878 data.

One point where RQMD is somewhat inconsistent with the E878 data is for the lowest rapidity π^- data points, which are at $y = 3.44$. A possible explanation for this discrepancy are Coulomb interactions between the pions and beam-rapidity spectator protons, which would be at $y_{beam} = 3.14$; Coulomb interactions are not included in the RQMD model. Of course, it would be unwise to read too much into a disagreement with just two data points; however, the importance of Coulomb interactions can be seen clearly by comparing the E878 π^- and π^+ yields directly, as shown in Figure 5. For each of the two rows in Figure 5, as one looks from left to right, two things are happening: the colliding systems are changing such that the mean number of beam-rapidity spectators per interaction is increasing, and the π^- and π^+ spectra begin to diverge considerably for $y < 4$. The latter effect can be compared to data above $y = 4$, where the two pion species have very similar yields for all systems. Since these points are near beam rapidity, the observed divergence can be attributed, at least in part, to Coulomb effects. However, there are several existing formalisms for estimating the effect of Coulomb interactions on particle spectra; if we apply one of those[19] to pions near beam-rapidity, we arrive at an interesting result. Even in the extreme case where all 79 protons from the beam nucleus remain at beam rapidity, the enhancement factor for π^- is only $\sim$30%; since this factor works in opposite directions for the two charged pion states, we should expect at most a discrepancy of a factor of 2 between π^- and π^+ yields at beam rapidity. At face value, the trends of the E878 spectra would seem to suggest a difference which is larger than that expected from a simple modelling of Coulomb effects alone. Any attempt to describe π^-/π^+ discrepancies at low p_t near mid-rapidity in terms of Coulomb interactions will also need to account for data near

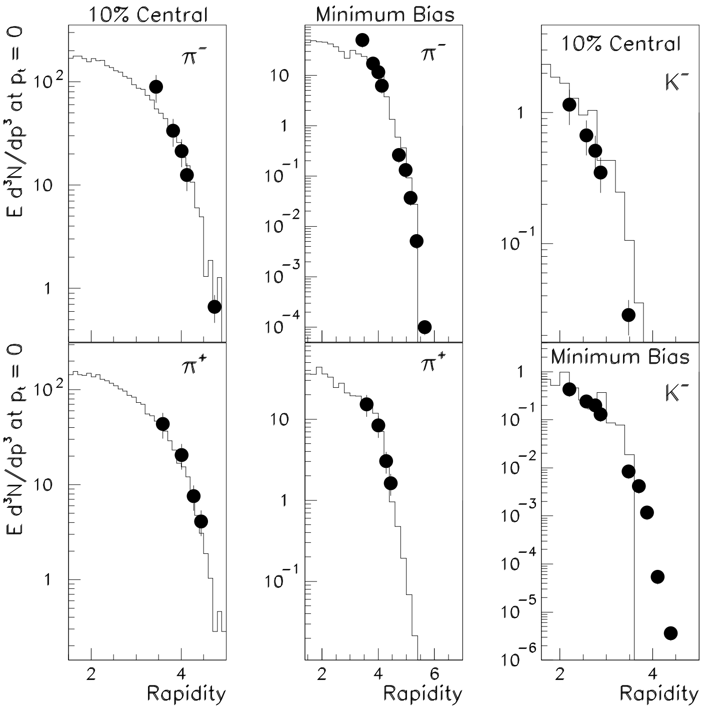

Figure 4. Comparison of E878 meson yields to predictions of RQMD, for Au+Au interactions. Predictions for 10% central collisions are from 1000 RQMD version 2.2[13] events, while predictions for minimum bias events come from ~18,500 RQMD version 1.07[18] events. Error bars on the E878 data points reflect a 30% systematic uncertainty; statistical errors are negligible.

beam rapidity as well.

ANTIPROTON SPECTRA

The study of antiprotons ($\overline{p}$) is a very fertile topic within the field of relativistic heavy-ion physics. In particular, the enhanced production of antibaryons is a proposed signature for the formation of a quark-gluon plasma.[20] On the other hand, even without the formation of a plasma, $\overline{p}$ yields can be enhanced by collective effects, e.g. resonance formation, reduced mass resulting from strong mean fields, etc. However, an overall increase in initial $\overline{p}$ production may not result in an increase in measured yields. After being produced, the $\overline{p}$ must still escape the collision region in order to be detected; due to the very large $\overline{p} - p$ annihilation cross section and the high baryon density formed in the collision, most antiprotons formed are subsequently annihilated. Thus, observed yields of antiprotons reflect an interplay between the competing effects of enhanced production and large annihilation probability.

One approach which can be used to assess whether observed $\overline{p}$ yields have been enhanced beyond those expected in a purely hadronic scenario is to compare to cascade models, which include the annihilation process and at least some of the hadronic mechanisms which could lead to enhanced production. Shown in Figure 6 is a comparison of the E878 $\overline{p}$ yields to predictions of two cascade models: ARC version 1.9.5[21] and RQMD version 1.07[18], both run in cascade mode, i.e. no mean potentials are used. Both models match the most peripheral data well, but fail to match the most central data near mid-rapidity. The difference between the two model predictions for the most central data can primarily be ascribed to the fact that in the ARC model $\overline{p}$ annihilation

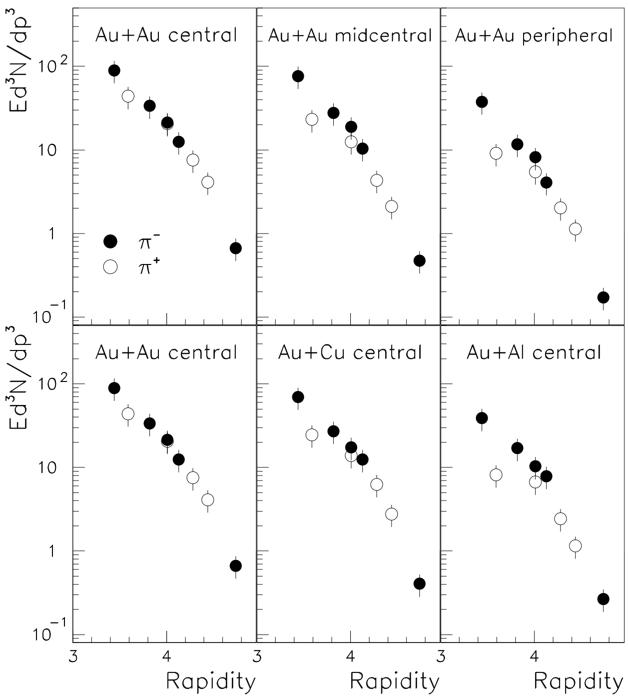

Figure 5. A comparison of E878 measured π^+ and π^- yields for various interacting systems. π^- yields are shown as solid circles and π^+ yields are shown as open circles. Error bars reflect a 30% systematic uncertainty; statistical errors are negligible. Note that beam rapidity is at 3.14.

is suppressed in high density environments through a third body screening mechanism. The shape of the E878 distribution is suggestive of suppressed $\overline{p}$ annihilation. Since the original appearance of this comparison in the literature[22], both ARC and RQMD have changed the way in which they model $\overline{p}$ annihilation–some details of the screening mechanism have been changed in the ARC model[23], while in RQMD version 2.2, a $\overline{p}-p$ resonance state with a lifetime of 1 fm/c has been added, which reduces the effective annihilation cross section in the dense medium.[24] With these changes, both models come much closer to matching the E878 data.[3] However, even with a reduced annihilation cross section in the dense medium, the overall survival probability for produced antiprotons is still $<\sim$ 10%.

Another approach to assessing the level of $\overline{p}$ enhancement is to look at how $\overline{p}$ yields scale for various colliding systems. At the AGS, the center-of-mass energy available in a collision between a beam-rapidity nucleon and a target-rapidity nucleon is only $\sim$1 GeV over the $\overline{p}$ production threshold. Thus, in the absence of enhanced production or annihilation, one may expect that $\overline{p}$ production would scale with the number of these collisions, i.e. that $\overline{p}$ yields would obey *first collision scaling.* Note that first collision scaling is meant only as a benchmark, and not as a realistic picture of the detailed physics of $\overline{p}$ production and annihilation. However, for Si-induced reactions at the AGS, several experiments observed antiproton yields which were consistent with scaling $\overline{p}$ yields from $p+A$ collisions by the number of first collisions.[25] This result was interpreted as a (perhaps accidental) counterbalancing of annihilation with enhanced production. With the E878 data set, we can investigate whether this scaling extends to the much larger systems available with Au beams. To this end, a simple phase-space/first-collision model has been constructed.[3,15] The phase space distribution is generated assuming that production is dominated by the simplest possible channel, i.e. $p+p \rightarrow p+p+p+\overline{p}$, and that the full center-of-mass energy of the initial colliding pair

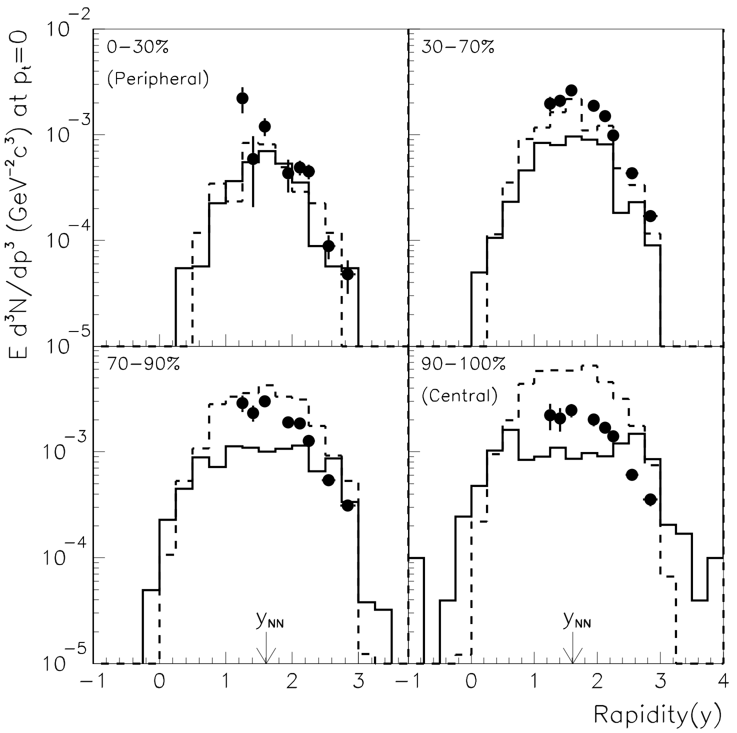

Figure 6. The invariant multiplicities of antiprotons as measured by E878 in Au+Au collisions, plotted as functions of rapidity for four non-overlapping centrality bins. The data are shown as symbols, RQMD calculations as solid lines, and ARC calculations as dashed lines. Error bars are statistical only.

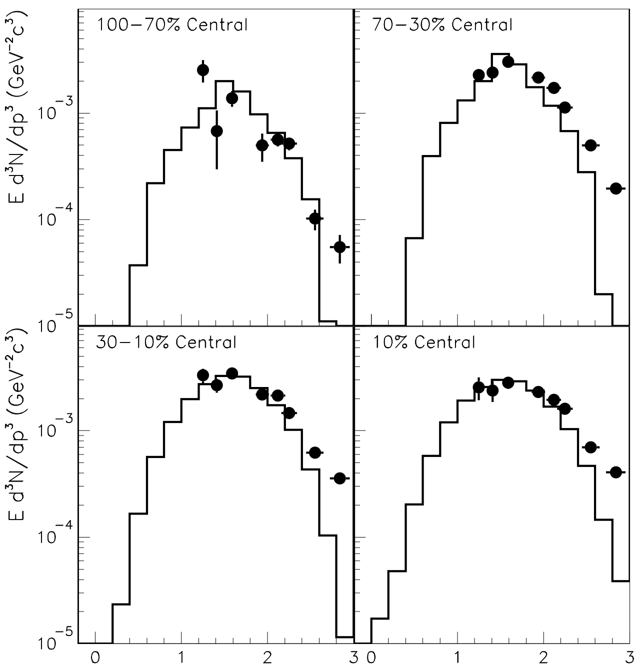

Figure 7. $\overline{p}$ yields from Au+Au collisions as measured by E878, compared to a phase-space/first-collisions model with radial hydrodynamic expansion (see text for details of model). Error bars are statistical only.

is shared equally among the four resultant particles. The normalization is provided by the $\overline{p}$ yield from RQMD for $p + p$ collisions at the appropriate energy, multiplied by the number of first collisions, as determined by Monte Carlo.[15] As has been shown elsewhere,[3] the E878 data for central Au+Au collisions is substantially suppressed relative to this model. However, an important effect has not been considered in this model, namely the effect of hydrodynamic expansion on the phase space distribution. Shown in Figure 7 is a detailed comparison of E878 $\overline{p}$ yields from Au+Au collisions to the phase-space/first-collision model, where hydrodynamic expansion has been added to the model. Expansion has been implemented by randomly choosing a production point for the $\overline{p}$, assuming a spherically symmetric source of uniform density; the $\overline{p}$ is then boosted in the radial direction by a velocity $\beta(r) = \beta_{max} \times (r/R)$, where R is the radius of the interaction region. In Figure 7, no expansion has been added for the two most peripheral bins, while $\beta_{max} = 0.4$ for the mid-central bin and $\beta_{max} = 0.6$ for the most-central bin. The effect of the expansion is such that antiprotons are removed from the p_t acceptance of E878, yielding predictions which match the E878 data very well. The choice of the boost parameters used for the expansion are not intended to constitute a fit for the "correct" boost velocity; rather, they were chosen as being reasonable estimates based on values derived for Si+A events.[26] The conclusion drawn from this study is that, given reasonable estimates of the effects of system expansion, the $\overline{p}$ yields observed by E878 in Au + Au collisions are consistent with first collision scaling.

Given this result, what have we learned? Previous interpretations of first collision scaling were that enhanced production was just counterbalanced by annihilation. This interpretation is not particularly informative, since it reveals nothing about the individual processes of production and annihilation. Further, it is difficult to see why this precise balancing should hold over a wide range of colliding systems. However, there is another way of approaching the problem which is perhaps more enlightening. The number of first collisions depends simply on the geometry of the colliding systems; it can be shown that another geometric factor which is linearly related to the number of first collisions is the surface area of the interaction region. Thus, since $\overline{p}$ yields scale linearly with first collisions, they must also scale linearly with the surface area of the interaction region. This finding is consistent with a picture in which only those antiprotons near the surface of the interaction region survive to be detected, while those in the dense central region have a very low survival probability. In this scenario, any enhancement in production in the central region is overwhelmed by the large annihilation probability, and observed yields are dominated by surface emission, where the baryon density is low and the effects of enhancement and annihilation processes are minimal.

Recently, $\overline{p}$ yields at low p_t from Au + Pb interactions have been measured[27] by E864. Interestingly, the E864 $\overline{p}$ yields at mid-rapidity are a factor of $\sim$4 higher than those from E878. However, there is good agreement for other particle species which are measured by both experiments. A plausible explanation for the different observed yields is the contribution of $\overline{p}$'s from $\overline{\Lambda}$ decays. Detailed acceptance calculations indicate that E878 has a small acceptance for $\overline{p}$'s from $\overline{\Lambda}$ decays (relative to primordial $\overline{p}$'s), while E864, being an open geometry spectrometer, has a very high relative acceptance for decay $\overline{p}$'s. Recent analysis of the centrality dependence of the E878/E864 discrepancy,[28] and preliminary $\overline{p}$ yields from E866[29] and E877[30], which lie between E878 and E864, lend credence to this interpretation. However, in order for this interpretation to be correct, the ratio of strange antibaryons to antiprotons[27] would have to be $\overline{Y}/\overline{p} >\sim 3$, which is much larger than expected (see, for example, G. Welke's contribution in this volume). We look forward to future direct measurements of $\overline{\Lambda}$ yields (from, for example, E896 at the AGS) which should shed more light on this surprising result.

CONCLUSIONS

Analysis of the E878 data set has been completed, including production limits on strangelets as well as single particle rapidity spectra at low p_t for various species. We have set stringent constraints on the branching ratio of various (multi)hypernuclear "doorway states" to decay to metastable strangelets. Our light nuclei data are consistent with a large increase in source size for increasing centrality. RQMD matches the measured meson spectra, including π^- data at very high rapidity. A comparison of our π^+ and π^- spectra suggest a discrepancy between the yields of these two species near beam rapidity which is larger than that expected from simple Coulomb interactions with spectator protons. Our antiproton spectra are consistent with a reduced annihilation cross section in the dense medium; however, the scaling behavior of the antiproton yields suggest that the survival probability in the central region is still very low, which could mask any enhancement in that region. A comparison of the E878 $\overline{p}$ yields to those of E864 suggest that the ratio $\overline{\Lambda}/\overline{p}$ is much higher than expected. Strange antibaryon yields remain an interesting open question, and we look forward to future direct measurements of $\overline{\Lambda}$ production.

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