Search for New Meta-stable Particles Produced in Au + Au Collisions at 10.8 A GeV/c

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We have investigated particle production using a zero degree two-segment focusing beam-line spectrometer, examining 2×10^{12} Au+Au interactions at a beam momentum of 10.8 A GeV/c. We have measured invariant cross sections for protons, various light nuclei (through A=6), antiprotons, and have set upper limits on the production of heavier nuclei, antideuterons and strangelets. There is no evidence, within the sensitivity of our measurements, for the formation of new particles having lifetimes > 100ns.

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I. INTRODUCTION

The existence of dense states of 'collapsed' nuclear matter was contemplated by Bodmer over twenty years ago [1]. Chin and Kerman [2] suggested that ultra relativistic heavy ion collisions could be used to create novel states of hadronic matter which would have as their ground state matter made of three quark flavors, u, d, and s, instead of the usual two, u and d. Witten suggested [3] that such strange quark matter (SQM) could be *completely* stable and therefore be the true ground state of matter. He also argued that a substantial fraction of the mass of the universe could have remained in the quark phase at the time of the phase transition from quarks and gluons to hadrons. Farhi and Jaffe have investigated strange quark objects over a wide range of baryon number A and find, using the MIT Bag Model [4] with reasonable parameters, that strangelets (SQM with small A) could be stable. Such calculations have been investigated more recently in their single particle and bulk limits to derive mass formulae [5–7]. The implications of the existence of strange quark matter to Quantum Chromodynamics in a non-perturbative regime and to cosmology and astrophysics are significant, and provide the impetus for experimental searches.

Over the past several years, searches have been conducted for primordial strange quark matter. In each case, upper limits were determined for the abundances of such matter in terrestrial samples and in cosmic rays [8]. Heavy-ion collisions provide a unique environment for the creation of multi-strange composite particles. Data from several experiments have shown that the production of strange and multi-strange baryons is enhanced in nucleus+nucleus collisions relative to p+p collisions [10]. Strangelets can either be created by the coalescence of strange and non-strange baryons at freeze-out [11], or as a residue of the distillation of a quark gluon plasma formed early in the collision [12], as will be discussed further.

Searches for the production of strangelets have been conducted using relativistic heavy ion beams of ^{28}Si at the BNL-AGS [13,14] and ^{32}S at the CERN SPS [15]. Here we describe the first attempts to detect strangelets in experiments using the recently available Au beams. In central Au + Au collisions, nuclear matter is expected to be created at 10 times its normal density for durations in excess of 5 fm/c [9]. Both the density and duration in Au induced reactions exceed what is achievable in ^{28}Si and ^{32}S induced reactions making Au + Au collisions a potentially more fertile environment in which to produce strangelets. Hence we believe our results are of greater significance than previous measurements using light ion beams.

It should be noted that all heavy ion strangelet search experiments rely on the detection of particles with mass to charge ratios outside the range expected for normal nuclei. Strangelets have roughly equal numbers of up, down and strange quarks. Hence, their charge is expected to be either small or zero. Any strangelet candidate states observed would then have to be studied in a separate experiment to establish their strangeness content.

II. THE EXPERIMENT

Experiment 878 at the BNL-AGS is a two-segment focusing beam-line spectrometer which has a geometrical acceptance of 200μsr centered around zero degrees. The apparatus which is described in more detail elsewhere [16] is a single particle spectrometer providing excellent particle identification at extremely high interaction rates. Two sets of dipole magnets provide good momentum selection at each tune ($\delta P/P = \pm 3\%$). There are four scintillator time-of-flight walls providing both charge information from energy loss (dE/dx) signals, and velocity information from a measurement of flight time and known flight path length. Time-of-flight (TOF) detector planes 1 and 3 each consist of a single paddle, while planes 2 and 4 are segmented to help in background rejection. Particle identification is further aided by two gas Čerenkov counters and two aerogel Čerenkov counters. There are four sets of drift chambers providing position information allowing the reconstruction of particle trajectories. Particle rigidity (P/Z) is determined from trajectory information and a knowledge of the magnetic fields. The particle mass is calculated from the rigidity, charge, and velocity. The spectrometer was operated at a number of fixed rigidities ranging from +15.0 GV to -20.0 GV. We used beam fluxes in the range 10^7 - 10^8 per one second spill. Approximately 22% of the Au beam experienced hadronic interactions in the Au target.

Figure 1 shows the energy losses versus times-of-flight of particles detected in the spectrometer passing the same data quality cuts used in the strangelet search (consistent time-of-flight, energy deposition, and trajectory throughout the spectrometer). The particle identification clearly shows excellent separation. Having identified the particles, one determines the invariant cross section through a knowledge of the detector acceptance and the integrated beam flux. The cross section is then converted to invariant multiplicity using a Au+Au interaction cross section of 6850 mb. Beam flux monitoring is done using two ionization chambers. These are cross-calibrated with two secondary particle telescopes.

III. RESULTS AND DISCUSSION

From our positive rigidity running we have measured yields of protons, deuterons, tritons, ^{3}He, ^{4}He, and only one ^{6}Li candidate for particles with $A > 4$ as shown in figure 2. From our negative rigidity running we show a spectrum for antiprotons. Statistical errors are smaller than the symbols except for ^{6}Li. Systematic errors of 30% result from uncertainties in point to point and overall normalization and efficiencies. We use these data to demonstrate the ability of E878 to measure particle spectra over several orders of magnitude in sensitivity. The positive-rigidity data show, at $p_t = 0$ and central rapidity, there is a penalty factor of $\approx 1/50$ for the addition of a nucleon (d/p $\approx$ t(^{3}He)/d $\approx$ ^{4}He/t(^{3}He) $\approx$ 1/50). The ratio $\bar{p}/p \approx 10^{-4}$ is lower than that of E858 [14], because of a lower beam energy and possibly increased annihilation. We observed no antideuterons and thus show our 90% confidence upper limit sensitivity as arrows. Using the $\overline{d}/\overline{p}$ ratio from the E858 result in Si + Au collisions [14] and our measured antiproton yields, we can estimate a production rate for antideuterons. This prediction is shown in figure 2 as a solid curve. This estimate would be justified in a thermodynamic model assuming the same freeze-out density and temperature [17] in Au+Au collisions as in Si+Au collisions. Such a simple estimate would have to be improved to include the effects of collective flow and strong annihilation as described elsewhere [18,19]. Our experimental limits are an order of magnitude above the predicted curve. We see **no** evidence in our data for the presence of particles with masses in excess of A=3 for charge Z=+1, A=6 for Z=+2, A=6 for Z=+3, A=1 for Z=-1, and we see no particles with Z=-2 or Z=-3.

Our apparatus measures only in a limited region of phase space. Therefore, we need to use a strangelet production model to convert our measurements to a sensitivity (defined as the upper limit on the total number of particles produced over all phase space per minimum bias collision). Strangelets have not been observed before. Hence, there is no measured kinematic distribution for their production. We have chosen three possible production models in order to evaluate the significance of our measurements. We chose the transverse momentum and rapidity distributions independently, as described below.

$$\frac{dN}{dp_t dy} \propto e^{\frac{-(y-y_0)^2}{2\sigma_y^2}} p_t e^{-2p_t/<p_t>} \tag{1}$$

where $y_0 = 1.6$ is the center of mass rapidity, $<p_t> = 0.6\sqrt{A}$ GeV/c is the mean transverse momentum, and σ_y is a variable to be discussed. Our sensitivity improves slightly with decreasing $<p_t>$, but is more dependent on the choice of the rapidity distribution. The most optimistic picture (see [15]) is a Gaussian distribution with a width $\sigma_y = 0.5$ units, independent of the mass of the particle species. However, one could imagine a more realistic model based on a coalescence or random walk accretion picture. Here, σ_y would have a $1/\sqrt{A}$ dependence. In figures 3 and figure 4 we show three curves corresponding to rapidity widths of $1.0/\sqrt{A}$, $0.5/\sqrt{A}$ and 0.5 with labels (1), (2), and (3) respectively. For particle species with $A > 8$, even at our highest rigidities, we no longer measure at mid-rapidity. Thus the sensitivity of our measurements become extremely model dependent.

The lifetimes of such new particles are also unknown. The sensitivity plots have not been corrected for decay. The length of the apparatus is 60 m. The survival probability of particles will therefore be large if their lifetimes are in excess of $60/\gamma c \sim 10^{-7}$ s. For particles with shorter lifetimes, one would have to modify quoted sensitivities by particle decay probabilities.

There are two plausible scenarios by which strangelets may be produced in relativistic heavy ion collisions. If the collision volume could undergo a phase transition to a quark-gluon plasma, the plasma will be rich in u and d quarks, and have an initial net strangeness of zero. As the plasma expands and cools, $\bar{s}$ quarks find it easier to combine with u or d quarks to escape from the plasma as K^+ and K^0. The plasma thus gains in net strangeness [12]. A droplet of strange matter might then result, and if sufficiently long lived, be detected by experiments. We show in figure 3 and figure 4 the predictions of Crawford *et al.* [20]. The model assumes plasma formation in the 10% of Au + Au collisions that have impact parameter b< 4.4 fm.

A second way to produce strangelets involves the coalescence of hypernuclei which may transform into strangelets [11]. The hypernuclei themselves have natural lifetimes too short to be measured by experiments like E878. However, if a strangelet of similar quark content were more stable, the hypernucleus may decay into strangelets which E878 could then detect. Thus, we can set limits on the branching ratio for hypernuclei into long lived strangelets (assuming the production model). Coalescence may also result in the production of multiply strange baryon clusters which are predicted to be stable against strong decay, and possibly even semi-leptonic weak decay according to a version of the SU(3) chiral soliton (Skyrme) model [21]. The existence of chiral solitons would be a confirmation of the short range chiral dynamics of the SU(3) soliton model. Unlike strangelets, chiral solitons would be stable for low mass (A=2,3,4). Thus, the existence of bound states such as $\Sigma^-\Sigma^-$ and $\Xi^-\Xi^-$ should be experimentally measurable. We show in figure 3 and figure 4 the predictions of a coalescence model [11] for the production of hypernuclear states. The yields for central collisions from [11] have been divided by ten for comparison with our minimum bias sensitivities. We have also made predictions for the formation of two possible chiral soliton states. Our coalescence calculations are similar to the previous work [11] and use the phase space output for strange baryons from the RQMD model (version 1.08). The coalescence parameters are chosen to be the same as for the deuteron [22]. As seen in figure 4, our experimental sensitivity lies many orders of magnitude below these predictions.

IV. SUMMARY AND CONCLUSIONS

We have measured the production of light nuclei and antiprotons at zero degrees and have set significant limits on the production of antideuterons, strangelets and other exotic particles. We have also compared our experimental sensitivities with the predictions of two models. We do not have enough sensitivity to test the predictions of Crawford *et al.* [20] for strangelets ($A \geq 10$); however, we do set interesting limits on chiral solitons (assuming they are long lived), and on the branching ratios of hypernuclei ($A \leq 6$) decaying into meta-stable strangelets. The combination of our use of Au beams, and experimental sensitivities that equal or exceed all previous measurements, make our result the most significant to date. Experiments are being commissioned which will extend these measurements to higher sensitivity [23] and the ability to detect shorter lifetimes [24].

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FIG. 1. A plot of dE/dx vs. time-of-flight (relative to a $v = c$ particle), measured in a single run at a rigidity setting of 3.87 GV. It should be noted that the π, K and p peaks have been downscaled.

FIG. 2. The invariant multiplicities at zero degrees of light nuclei (left) and antiprotons (right) produced in minimum bias Au+Au collisions shown as functions of rapidity. Open symbols are data points reflected about $y_{NN} = 1.6$. Antideuteron upper limits are shown as arrows and the prediction based on the $\overline{d}/\overline{p}$ ratio from E858 is shown as a curve.

FIG. 3. 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. Strangelet predictions of Crawford *et al.* [20] are shown as triangles and hypernuclei predictions of Baltz *et al.* [11] are shown as squares.

FIG. 4. The sensitivity of the E878 experiment for the detection of charge -1, -2, strangelets. The three curves are the 90% sensitivity upper limits based on specific models of strangelet production. Strangelet predictions of Crawford *et al.* [20] are shown as triangles and chiral soliton predictions are shown as circles.