Measurements at 0° of Negatively Charged Particles and Antinuclei Produced in Collision of 14.6A GeV/c Si on Al, Cu, and Au Targets

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We report measurements of $\bar{d}$, $\bar{p}$, K^-, and π^- produced at 0° in collisions of 14.6A GeV/c ^{28}Si on Al, Cu, and Au targets. A beam-line focusing spectrometer was used to identify particles at rigidities from -2 to -8 GV. The ratio of $\bar{d}/\bar{p}$ invariant cross sections at midrapidity ($y=1.7$) is $(1\pm0.7)\times10^{-5}$, larger than expected from a calculation of $d\bar{d}$ direct production but smaller than predicted by a simple coalescence model. We also report limits on the production of exotic particles.

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The yield of antinucleons and antinuclei from nucleus-nucleus collisions is regarded as a sensitive probe of the space-time evolution of the interactions [1]. We have performed an experiment to measure $\bar{p}$ and $\bar{d}$ production in 14.6A GeV/c Si+A collisions at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) using a two-segment focusing beam-line spectrometer to measure long-lived ($\tau \geq 10$ ns), negatively charged particles produced at 0°. We report here cross sections of π^-, K^-, $\bar{p}$, and $\bar{d}$, and we discuss limits on the production of new, stable, negatively charged high-mass particles, such as strangelets [2].

Although the production of $\bar{d}$'s has previously been measured in $p+p$ and $p+A$ collisions at higher energies [3,4], this observation of $\bar{d}$'s is the first reported for AA collisions. In high-energy collisions, at least two models can be imagined for the formation of antideuterons. The first is direct production through a process such as $NN \rightarrow NNd\bar{d}$. The momentum threshold for this reaction is 15.9 GeV/c in a fixed-target experiment, higher than the AGS beam momentum per nucleon. The second model is through the coalescence of $\bar{p}$'s and $\bar{n}$'s created in separate elementary processes. The coalescence picture has been used, with great success, to describe the spectra of deuterons, tritons, and other light nuclei emitted in medium-energy AA collisions [5]. It has also been used to describe the production of light nuclei in 14.6A GeV/c AA collisions [6] and the production of light antinuclei ($\bar{d}$, $\bar{t}$, and $^3\overline{\mathrm{He}}$) in high-energy pp and pA collisions [4]. In this Letter we compare our data to simple calculations using both these models.

One of the intriguing features of heavy-ion collisions in the AGS energy domain is a copious production of strange particles, K^+ and possibly Λ [7]. In this environment, the formation of a new form of strange matter [2,8] or multistrangeness hypernuclei [9] may be possible. Simultaneous with sampling the momentum range over which we expect $\bar{p}$ and $\bar{d}$ production to peak, we produced a data set which also allows us to place significant limits on production of new stable particles over the range of mass-to-charge ratio from -1 to -7.

The experimental layout is shown schematically in Fig. 1. The beam was incident on the AGS "A" primary station at intensities up to 10^8 s^{-1} over a 1-s spill on targets of Al, Cu, and Au each having a thickness between 3% and 30% of a Si+A interaction length (λ_i). A portion of the data was taken with a combination Au-Pb target with a total thickness of 60%λ_i. Two ionization chambers

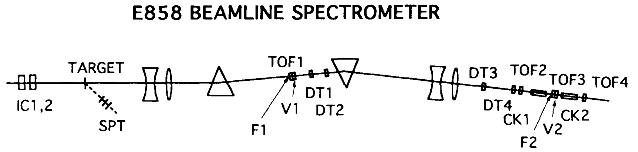

FIG. 1. Experimental layout showing the beam-line spectrometer. The time-of-flight counters consisted of 5-mm-thick scintillator viewed at both ends by photomultiplier tubes. The 3-atm-gas Freon-12 Cerenkov detectors were used to veto π^-'s in the trigger as well as in supplementing particle identification capabilities at high and low momentum. The four drift-tube arrays provided acceptance and particle trajectory information.

(IC) upstream of the target and a scintillator secondary-particle telescope (SPT) served to monitor the beam fluence. Secondaries emitted within $\Delta\Omega = 200$ μsr around 0° and within ±3% of the tuned rigidity were transported through a 4° bend and brought to a focus (F1) at a collimator 30 m downstream. From F1 they were transported another 28 m downstream through a $-7°$ bend and brought to a second focus (F2). To be open to as wide a range of A and Z as possible, trigger conditions were kept loose: A LOOSE trigger was defined as the coincidence between either photomultiplier tube (PMT) on TOF1 and either PMT on TOF3, the scintillators at the foci. A PIBAR trigger was defined as LOOSE$\cdot(\overline{\mathrm{CK1}}+\overline{\mathrm{CK2}})$. All PIBAR events were recorded, while LOOSE triggers were prescaled by a factor of 100 before being recorded. The live time fraction for data acquisition was typically $\gtrsim 85\%$. The LOOSE trigger had a coincidence gate of 60 ns and was therefore sensitive to any particle having an $|A/Z|$ ratio of 7 or less over most of the rigidity range scanned. We did not observe any $|Z| > 1$ particles. We did observe events in which two π^- or $\pi^- K^-$ were present, consistent with combinatoric expectations.

Four multiplane drift-tube modules (DT) were used to determine the trajectory of the particle in each recorded event, and to distinguish those few events with two particles in the spectrometer. We were able to reconstruct valid trajectories for approximately 95% of the particles having valid time-of-flight (TOF) signatures. This reconstruction was used to verify the spectrometer's acceptance, and to verify on an event-by-event basis that each particle had followed an allowed trajectory. The overall spectrometer acceptance was arrived at through a comparison of the observed trajectories with the results of a simulation which transported a white spectrum of momenta and production angles through the system.

In counting π^-, K^-, and $\bar{p}$'s for cross-section determination, we required four valid TOF signals, and identified the particle by a combination of TOF and the presence or absence of a CK signal. In our search for rare high-mass particles we additionally required TOF consistency between the four independent measurements, charge consistency in all counters, a single valid trajectory pointing to the target, and a single hit within the 60-ns window. After these requirements were imposed no events with a flight time greater than that of the $\bar{p}$ remained in our sample except two $\bar{d}$'s at -6.1 GV. The resulting TOF spectrum for all particles at -6.1 GV is shown in Fig. 2. The mass resolution indicated here is 30 MeV/c^2 in the $\bar{p}$ region.

The cross section for each species-momentum-target combination was determined as

$$E\frac{d^3\sigma}{d^3P} = \frac{N_0 \epsilon_{\mathrm{decay}} \epsilon_{\mathrm{reint}}}{N_{\mathrm{IC}} C_{\mathrm{IC}} a \rho_{\mathrm{target}} \eta_{\mathrm{live}} \eta_{\mathrm{eff}} P^3/E}, \quad (1)$$

where N_0 is the observed number of that species, N_{IC} is the ion chamber count, C_{IC} is a constant such that $N_{\mathrm{IC}} C_{\mathrm{IC}}$ is the number of primaries on target, a is the spectrometer acceptance [nominally $(10^{-5}$ sr$)\delta P/P$], ρ_{target} is the density of target nuclei per unit area, $\epsilon_{\mathrm{decay}}$ is a correction to the π and K yields for decays in flight, $\epsilon_{\mathrm{reint}}$ is a correction for the reinteraction of secondaries inside the target and along the spectrometer, η_{live} is the live time fraction, η_{eff} is the overall trigger-detection efficiency (90%), and E and P are the energy and momentum of that species at that rigidity. The uncertainties in our measured cross sections are dominated by a 20% systematic uncertainty in flux and acceptance caused by variations in beam position on target.

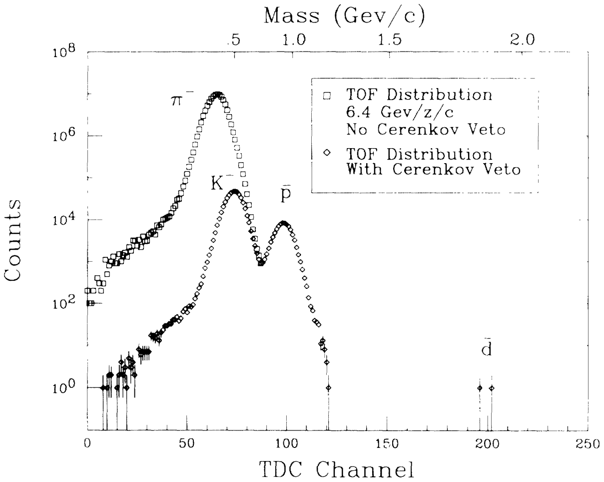

FIG. 2. Mass resolution from timing distributions showing π^-, K^-, and $\bar{p}$ peaks at 6.1 GV rigidity. Note the prescaled π spectrum. The width reflects the fact that these include the full momentum bite of the spectrometer. The time-to-digital-converter (TDC) sensitivity was 30 ps per channel.

Our total data sample over all rigidities contains approximately 5×10^6 π^-, 10^6 K^-, 3×10^5 $\bar{p}$, and 2 $\bar{d}$, noting that the π^- sampling was prescaled by a factor of 100. Invariant cross sections for these particles are summarized in Table I and in Fig. 3.

The AGS experiment E802 has measured spectra for π^-, K^- [7], and $\bar{p}$ [10] at lower values of rapidity (y) and at angles of $\gtrsim 5°$, a kinematic regime complementary to ours. Our observed invariant cross-section ratio at $p_\perp = 0$ and $y = 3.2$ is $K^-/\pi^- = 0.0028 \pm 0.0007$. The ratio determined from E802 by extrapolating their minimum-bias Si+Au data to $p_\perp = 0$ at $y = 1.3$ is 0.01 ± 0.003. Note that these are quite different rapidity regimes; our data are near the beam rapidity while E802 is below the c.m. rapidity. The $\bar{p}$ cross section from E802 at $y = 1.3$ extrapolated to $p_\perp = 0$ is 15 ± 7 mb/GeV^2; this is larger than our value of 4.6 ± 1.1 mb/GeV^2 at nearly the same rapidity, $y = 1.25$. The AGS experiment E814 has recently reported a $\bar{p}$ cross section at $p_\perp = 0$ of 6.5 ± 1 mb/GeV^2, in reasonable agreement with our value [11].

We have observed a $\bar{d}$ cross section at only one momentum setting: $Ed^3\sigma/d^3P = (4 \pm 3)\times10^{-5}$ mb/GeV^2 at

TABLE I. E858 invariant cross sections (mb/GeV^2). Statistical errors are less than 3% on all points except the $\bar d$'s. Systematic uncertainties in rigidity are 5%. Systematic uncertainties in cross section of 20% apply in a comparison between cells in the table, but not within a cell.

Momentum P	1.5	2.2	2.9	3.7	4.5	5.8	6.1	7.9
Si+Al								
π^-		7410	5090	3160	2850	1100	1200	
K^-		80.6	83.3	55.6	46.2	18.7	21.5	
$\bar p$	1.49	2.11	2.40	1.82	1.74	0.66	0.76	
Si+Cu								
π^-		12400	8110	5100	4130	1740	1840	
K^-		1.06	127	81.1	64.0	26.5	29.6	
$\bar p$	2.08	3.66	3.86	3.13	2.66	1.23	1.31	
Si+Au								
π^-		19100	14600	9280	7150	2590	3010	1000
K^-		285	276	188	134	52.4	53.4	19.0
$\bar p$	4.59	6.50	7.67	6.39	5.25	2.23	2.52	1.10
$\bar d$							0.00004	

$p = 6.1$ GeV/c; here we compare this value with predictions from the two models mentioned in the introduction.

The first model is direct $\bar d$ creation through $NN \to NNd\bar d$ or $NN \to NNNN\bar d$. Using the double-Gaussian functional form for the Fermi momentum distribution, reported by Ref. [12] to fit the backward particle production, we were able to fit the $\bar d/\bar p$ ratio data [13] measured in near-threshold pA collisions at $E_p = 19$–70 GeV. Using the same Fermi momentum distribution for both Si and Au, we then estimated the $\bar d/\bar p$ ratio for the present subthreshold reaction. The calculated cross section due to this direct process is 4×10^{-7} mb/GeV^2 at $\langle P\rangle \simeq 14.6$ GeV/c, 2 orders of magnitude smaller than the observed cross section. This implies that direct $d\bar d$ production is not the dominant process for $\bar d$ production in these Si+Au collisions.

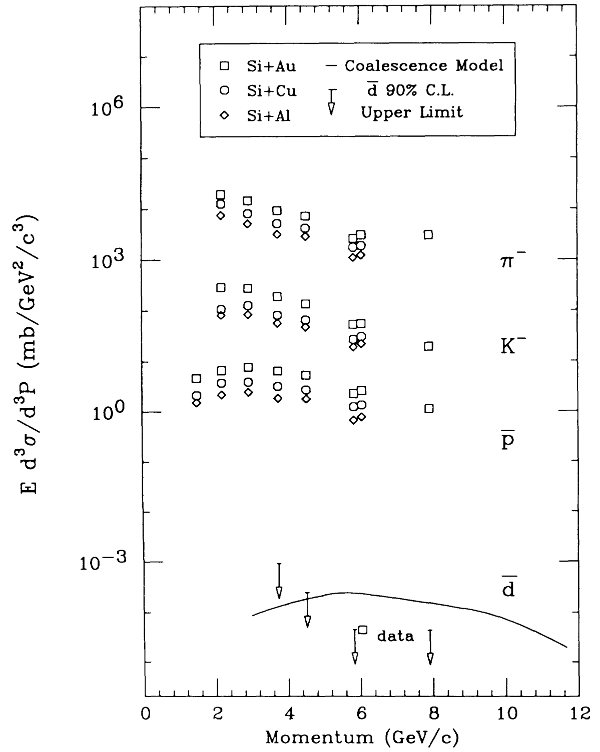

FIG. 3. Particle distributions: $Ed^3\sigma/dp^3$ for π^-, K^-, and $\bar p$ from Al, Cu, and Au targets; the $\bar d$ prediction from the coalescence model calculation is shown as a solid line. The 90%-C.L. upper limits to the invariant cross section for $\bar d$'s reflect the number of interactions sampled at each rigidity; the two $\bar d$'s are shown in the point at 6.1 GV. To compute the number of interactions sampled at each setting, multiply the upper limit values by $10^{-5}p^3/E$ assuming a deuteron mass particle.

The second model is coalescence [14]. In coalescence, the probability of forming a d ($\bar d$) is proportional to the product of the probabilities of forming a p ($\bar p$) and an n ($\bar n$) (assumed equal). The simplest relativistic formulation of this is

$$\left[E\frac{d^3\sigma}{d^3P}\right]_{d(\bar d)} = B\left[E\frac{d^3\sigma}{d^3P}\right]^2_{p(\bar p)} \tag{2}$$

evaluated at the momentum $P_{p(\bar p)} = \frac{1}{2}P_{d(\bar d)}$. In a wide variety of experiments the $d/\bar d$ spectra are well reproduced by (3) and the value of B consistently falls in or near the range $(1\text{–}2)\times10^{-2}$ GeV^2 [4,5]. Using a value of $B = 1.5\times10^{-2}$ GeV^2 we can predict the expected $\bar d$ spectrum based on our $\bar p$ cross sections; the result is plotted as a line in Fig. 3. At $P = 6.1$ GeV/c, the calculated cross section is 4×10^{-4} mb/GeV^2 which is a factor of 10 larger than the measured cross section. Using our data point at 6.1 GeV/c as well as the upper limits quoted, we find $B \le 1.5\times10^{-3}$ GeV^2 at 90% C.L.

The coalescence model was used successfully for the interpretation of deuteron production in 14.6A GeV/c Si+Au collisions [6]. The constant B had a nominal value of $(1\text{–}2)\times 10^{-2}$ GeV^2 in a low-multiplicity sample, but fell to as low as $(0.15\text{–}0.30)\times 10^{-2}$ for the highest-multiplicity events. Formulations of the model using density matrix formalisms [15] or a thermal model framework [16] indicate that B should depend on the size and shape of the emission-source region. The recent relativistic coalescence calculation [14] using an extended fireball source calculated a $\bar{d}/\bar{p}$ ratio of 6×10^{-5}, again appreciably larger than our result. These facts, together with our low $\bar{d}$ cross sections, suggest that the emission-source region for $\bar{p}$'s (and hence $\bar{d}$'s) may be larger than that for other particles, possibly reflecting a longer formation (hadronization) or freezeout time.

Our experiment provides new limits on the production of negatively charged exotic particles with lifetime in excess of ≈ 10 ns. In the region of $m > m_{\bar{p}}$ the stringent analysis requirements described above removed all particles except for two $\bar{d}$'s at 6.1 GeV/c. This fact sets the limit for the existence of a new exotic particle, within the framework of a production model based on exponential $p_\perp$ and Gaussian rapidity distributions, to the sensitivity level of a few 10^{-9} for low mass to a few 10^{-10} for large mass [17]. This sensitivity level is equivalent to 20 mb/GeV^2.

We have measured the cross sections of negatively charged particles at 0° in 14.6A GeV/c ^{28}Si collisions with Al, Cu, and Au targets. The $\bar{d}$ yield is smaller by a factor of 10 than the prediction of a simple coalescence model which otherwise works very well both for describing deuteron yields in the same reaction and for describing $\bar{d}$ yields in pA collisions at higher energies. The observed $\bar{d}$ yield is larger by a factor of 100 than a prediction of a simple direct process calculation. We found no new particles in our experiment at the level above 20 nb/GeV^2 for rigidities up to 8 GV and over the range of mass-to-charge ratio from -1 to -7.

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