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Antiproton production from heavy ion collisions at 14.6 GeV/c

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Antiproton production from heavy ion collisions involves a strong competition between creation and annihilation mechanisms. Due to the high threshold energy, antiprotons mostly arise from the highest energy baryon-baryon collisions. We have identified a three-body screening mechanism which strongly reduces the subsequent absorption of antiprotons in the medium. We have used a relativistic cascade code to study this effect, and find that it is essential to obtaining good agreement with recent $\bar{p}$ production data from Brookhaven experiment E802.

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It has been suggested [1,2] that anomalously high levels of antinucleon production may be a good signature of QCD plasma generation in relativistic heavy ion collisions. The argument in favor of such a signal is similar to that for enhanced strangeness production; that is, the dense plasma should contain a much higher concentration of antiquarks than represented by the sea quarks seen in proton-proton interactions. In this Rapid Communication we examine the evidence for this in nucleus-nucleus collisions at Brookhaven AGS energies. Our analysis uses the hadronic cascade code ARC (a relativistic cascade) [3–5] which provides an excellent description of the general features of such collisions over a broad range of kinematic situations, covering the observed [6–8] laboratory rapidities $0.6 \leq y \leq 3.8$ for 14.6 GeV/c per nucleon collisions between a variety of projectile and target nuclei. The data examined here for $\bar{p}$ production are from the AGS experiment E802 presented in parallel with this analysis [9]. Earlier collections of these data were discussed in detail by Costales [10] and the E802 Collaboration [11]. Previous theoretical treatments [10,12,13] have had trouble obtaining enough antiprotons relative to experimental data, and have resorted to rather artificial, nonhadronic production mechanisms, or to lengthened formation times [10,12] for the antiprotons. In the present work, we find it possible to understand the experimental evidence on a hadronic cascade level, without enhanced production from quark substructure [13] while using a formation time near the standard value 1 fm/c which we employ for all produced species [3,4]. However, we do need to take note of the long spatial reach of annihilation at the low relative energies experienced by antiprotons in the present investigations, and to incorporate this feature properly into the structure of the cascade. This requires at least a primitive understanding of three body correlations within the code, and leads to a great reduction in absorption of produced antiprotons.

The antiproton yield from nuclear collisions depends on two factors: the elementary production in baryon-baryon interactions and the absorption by annihilation of antiparticles in the nuclear material. Nucleon-nucleon collisions at 14.6 GeV/c momentum in the laboratory, or 5.4 GeV energy in the center of momentum frame, are not far above the threshold for $N\bar{N}$ production (3.76 GeV). Thus almost all of the produced antiparticles arise from the first high energy baryon-baryon collisions. In Si + Au collisions, we find that only a small amplification in $\bar{p}$ yield results from meson-baryon collisions, about 10%; this percentage is negligible in proton-nucleus collisions.

The relatively low antiproton kinetic energy after production, 400 MeV on the average in the center of momentum, creates a favorable situation for annihilation. In Fig. 1, the total annihilation cross section [14] drops from 100 mb and higher at relative $N\bar{N}$ momenta $k < 500$ MeV/c, to 45 mb for $k \sim 2$ GeV/c. The difficulty in a cascade calculation is first to handle the implicitly long range effect of such large absorption cross sections and secondly to correctly describe the rapidity distribution of antinucleons during their passage through the target material. To illustrate the strong effect of annihilation in nuclear matter we note in previous theoretical treatments [10,12] the $\bar{p}$ yields could be enhanced by an order of magnitude by lengthening the $\bar{p}$ formation time (τ_f) from 1 fm/c to 6 fm/c. In our complete calculation this effect is not nearly so strong. We later document this variation

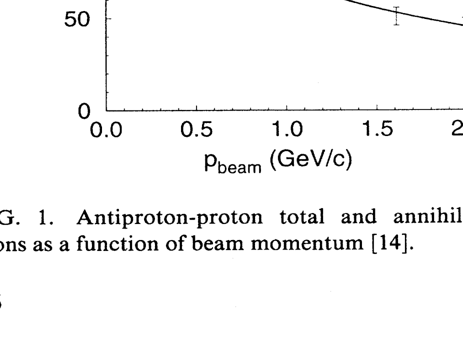

FIG. 1. Antiproton-proton total and annihilation cross-sections as a function of beam momentum [14].

in yield (Table III) but at this point note that exploiting the dependence on τ_f to explain the data would not only be highly artificial but cannot explain both the pA and AA data.

In previous work [3,4], describing the general features of the ion-ion collisions at 14.6 GeV/c, the cascade ARC was applied in one of two modes: a naive direct production form (DIR) in which elementary hadron-hadron collisions led directly to the observed final states, or a resonant form (RES) in which baryonic (Δ) and mesonic (ρ) resonances appear in intermediate states of two-body collisions. In RES, it is to a large extent the resonances which reinteract rather than on-shell nucleons. The average energy for secondary baryonic and mesonic interactions in nuclear material is considerably higher in RES than in DIR and the dynamics is significantly altered. Baryon transverse mass distributions are broader, while less π mesons and more strange mesons are created. In this earlier work [3,4] we indicated that RES is to be preferred both theoretically, incorporating as it does the actual excitation of low-lying resonances in the input nucleon-nucleon interactions, as well as phenomenologically, because of its excellent description of a broad range of data. Henceforth, we employ only ARC-RES now referred to as simply ARC. We emphasize again that the only inputs to ARC are the fundamental hadron-hadron cross sections. There are no other free parameters.

As discussed earlier, it is necessary to have the elementary hadron-hadron cross sections for both the production and absorption of antinucleons as input to the cascade. The $N\bar{N}$ absorption cross section is well known [14] and is shown in Fig. 1. However, no data exist for the total $N\bar{N}$ production cross section below 19.2 GeV/c. Costales [10] has used high energy data [15,16] to extrapolate to lower energies using the form

$$\sigma_{pp\to\bar{p}X}/\sigma_{\text{inelastic}}=a\epsilon+b\epsilon^2 \,, \tag{1}$$

where ϵ is the available energy (in GeV) above the $p\bar{p}$ production threshold in the pp center of mass and

$$a=3.696\times10^{-4} \text{ and } b=2.031\times10^{-4} \,. \tag{2}$$

Using this fit ARC produces 30% more $\bar{p}$'s than E802 measurements [9] in minimum bias $p+$Be collisions at 14.6 GeV/c. Because of the large uncertainty in the extrapolation, the E802 measurement of $p+$Be is used to obtain $\sigma(pp\to\bar{p}X)$ at 14.6 GeV/c. The $N\bar{N}$ production cross section is fit using an alternative form, valid below 20 GeV/c,

$$\sigma_{pp\to\bar{p}X}/\sigma_{\text{inelastic}}=a'\epsilon^2+b'\epsilon^3 \tag{3}$$

where

$$a'=3.645\times10^{-5} \text{ and } b'=1.478\times10^{-4} \,. \tag{4}$$

This reduces the pA and AA $\bar{p}$ production by about 30% at 14.6 GeV/c as compared to using Eq. (1). However our results depend on the accuracy of the E802 measurement.

A separate serious problem is encountered in dealing with hadron-antihadron events involving, as they do, cross sections considerably larger than those for baryon-baryon events. The Monte Carlo treatment in the cascade triggers on events in which the paths of particles (ij) approach within $r_{ij}=(\sigma_{ij}/\pi)^{1/2}$. This is clearly an oversimplification and becomes a problem when this collision distance is of the order of, or larger than, the mean distance between particles. Thus in deciding whether or not an antinucleon may annihilate with a nearby baryon one should properly check for the presence of other hadrons which may collide with either the antiparticle or the selected baryon before annihilation. Nearby nonannihilating particles, generally mesons, effectively screen the annihilation process, a dynamic on-shell screening to be distinguished from density-dependent changes in interparticle potentials. Annihilation within the nuclear medium produced by the ion-ion collision has thus become a three-body problem. A very straightforward fix for this is to introduce an annihilation time delay, related to both the distance of closest approach R between an antinucleon and its targeted nucleon and their velocity v of approach, i.e., $\tau_a=R/v$; a causality limit for τ_a is clearly R/c. The large annihilation cross section in $p\bar{p}$ at low relative velocity presumably arises from the attractive force between these particles; introducing a delay simply allows for a finite time of approach. By adding τ_a to the collision time we treat the approach of a $p\bar{p}$ pair in an average fashion but can then account in detail for the position and motion of a third particle. The introduction of interparticle potentials to describe the approach between annihilating baryons would not remove the necessity for this quasiscreening and hence would not add appreciably

TABLE I. Ratios of antiproton production for Si+Al and Si+Au compared with E802 [9].

	E802	ARC
SiAl/pAl	21±6	13±2
SiAu/pAu	28±6	26±5

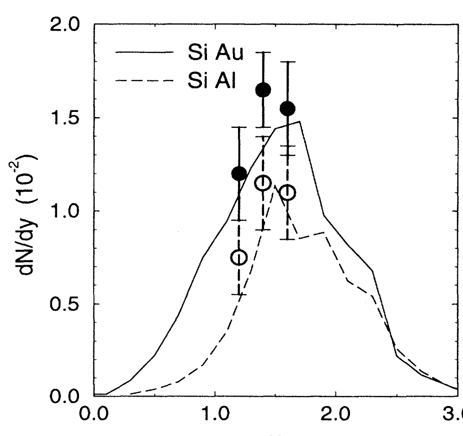

FIG. 2. ARC antiproton rapidity distributions for Si+Au and Si+Al at 14.6 GeV/c. The E802 measurements for these nuclei are indicated by solid and open circles respectively. The experimental errors are explicitly shown and the theoretical uncertainties are approximately ±30%.

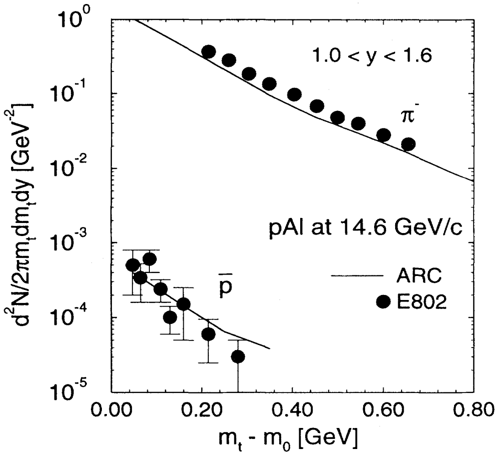

FIG. 3. Transverse mass spectra from ARC and E802 [9] for antiproton and π^- from $p+$Al at 14.6 GeV/c in the rapidity range [1.0,1.6].

to the accuracy of our treatment of annihilation. We believe however a sufficiently quantitative picture is obtained from the introduction of the time delay as a test for neighboring potentially screening particles. For higher energies, perhaps already at the CERN Proton Synchrotron, low energy $\bar{p}$ annihilation might not present as much of a problem. One should point out that any multiscattering treatment of $\bar{p}$ absorption in the medium must take account of the screening or shielding described here. This is a very real physical effect.

In the preceding communication [9] from the E802 Collaboration, $\bar{p}$ production data are shown for $p+$Be, $p+$Al, $p+$Cu, $p+$Au, as well as for Si+Al and Si+Au [11] at 14.6 GeV/c per nucleon collisions. Table I shows Si+Al/$p+$Al and Si+Au/$p+$Au ratios from Ref. [9] compared with ARC. Comparison for K and π data has already been described in our earlier work [3,4]. Figure 2 contains rapidity spectra from ARC and E802, while Fig. 3 shows the comparison with $p+$Al transverse mass distributions for π^- and $\bar{p}$. The quality of the ARC reproduction of the m_t distribution for Si+Au can be inferred from a comparison of the theoretical effective temperature $T_{\bar{p}}=170\pm20$ MeV compared to the experimental value 141 ± 20 MeV [11]. The effective $\bar{p}$ temperatures are lower than their nucleon values [3] because the amount of rescattering of the $\bar{p}$ is reduced by annihilation.

From Table II one can comment directly on the effect of absorption. Comparing the yields with shielding to that for pure production, i.e., with no annihilation, one finds a reduction of 47% for $p+$Au and 48% for Si+Au. These suppressions in $\bar{p}$ numbers would have been considerably larger without shielding but are by no means negligible. The fractional suppression is however surprisingly flat with A, the result of competition between increases in both shielding and absorption.

Also in Tables II and III, the effect of formation time and shielding on the ARC results are shown. One expects a more or less monotonic increase in $\bar{p}$ yield with increasing formation time until finally the $\bar{p}$, after production, makes no further interactions within the nucleus. Interestingly, if one examines Table III, a formation time varying with A is clearly required to fit the data. For example, a 2 fm/c formation time is sufficient to describe pA, but greater than 4 fm/c is necessary for Si+Au. Completely turning off shielding, as indicated in Table III for Si+Au, reduces $\bar{p}$ production by close to a factor of 4. Clearly, then, one must take account of the screening, and this is why previous calculations [12,13] cannot get sufficient production without invoking additional mechanisms. Reducing τ_a by a factor of 2 reduces the Si+Au production by only 30%, which suggests that the results are not overly sensitive to appreciable changes about some realistic central value for this delay. One can conclude that the error in our treatment of screening is perhaps of order 15%. Added to the uncertainty in the basic $\bar{p}$ production cross section, of some $\pm20\%$, one then finds an overall theoretical uncertainty in absolute scale of perhaps 30%. The predictions in Fig. 3, involving only pA, are less uncertain. Certainly we will not ascribe much meaning to deviations between ARC and experiment of less than these amounts. Correspondingly, it will be difficult to use $\bar{p}$ production, at least at low energy, as a signal of noncascade behavior.

Our interpretation of the physics of $\bar{p}$ production in nucleus-nucleus collisions is rather simple. Roughly half of the large uncertainty associated with theory comes

TABLE II. Rapidity distribution dN/dy of $\bar{p}$'s in the range $y=[1.0,1.6]$ from ARC for pure production (no rescattering), no shielding, and shielding all compared to E802 [9,11]. The stated expermental errors are purely statistical. When the systematic uncertainties of 15–20 % (Table I, Ref. [11]) are included, theory and experiment are completely consistent for the entire range of nuclei examined. The shielding column is to be taken as the standard ARC prediction. Clearly absorption is a much bigger effect in the absence of shielding but can never be neglected. Its dependence on A is weakened by competition between increases in both shielding and annihilation.

	E802	Shielding	No shielding	Pure production
pp (inelastic)	—	0.00045	0.00045	0.00045
pBe (Min. bias)	0.00038(8)	0.00038(5)	0.00038(5)	0.00044(4)
pAl (Min. bias)	0.00047(10)	0.00050(6)	0.00041(5)	0.00059(4)
pCu (Min. bias)	0.00049(14)	0.00042(5)	0.00039(5)	0.00063(4)
pAu (Min. bias)	0.00049(11)	0.00040(5)	0.00030(4)	0.00075(5)
SiAl (Central)	0.010(1)	0.0064(3)	0.0033(2)	0.0095(4)
SiAu (Central)	0.014(1)	0.0105(4)	0.0028(2)	0.0200(5)

TABLE III. Rapidity distribution of $\bar{p}$'s in the range [1.0,1.6] from ARC for various formation times. An infinite time corresponds to production without annihilation. No single formation time can explain the target or projectile A dependence exhibited in Table II, E802 [9,11].

Formation time	1 fm/c	2 fm/c	4 fm/c	∞
pp (inelastic)	0.00045	0.00045	0.00045	0.00045
pBe (Min. bias)	0.00038(5)	0.00039(5)	0.00042(5)	0.00044(4)
pAl (Min. bias)	0.00041(5)	0.00048(6)	0.00058(6)	0.00059(4)
pCu (Min. bias)	0.00039(5)	0.00050(6)	0.00059(6)	0.00063(4)
pAu (Min. bias)	0.00030(4)	0.00043(5)	0.00056(6)	0.00075(5)
SiAl (Central)	0.0033(2)	0.0053(3)	0.0078(3)	0.0095(4)
SiAu (Central)	0.0028(2)	0.0051(3)	0.0088(4)	0.0200(5)

from the lack of precise constraints on the input which can be removed by using pBe rather than pp production. This can be improved by analyzing existing minimum bias nucleus-nucleus collisions at these energies. Systematic study of the centrality dependence of $\bar{p}$ production in pA and AA collisions should also cast more light on the nature of the shielding mechanism. Given this, one can perhaps still use $\bar{p}$ production as a meaningful probe in Au+Au collisions. Calculations [17] show that very high baryon densities occur in such collisions at 11.7 GeV/c. Without shielding, antibaryons are unlikely to emerge from the high baryon density regions. With shielding, antibaryons will have a much higher probability of surviving, and the resulting production rate should be eminently observable. Comparison of peripheral antiparticle production, where our simple ideas should work, with central production yields a self-correcting means of looking for collective phenomena, such as chiral restoration [18,19], at high density.

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