Antiproton Production and Annihilation in Nuclear Collisions at 15*A* GeV

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We present a calculation of antiproton yields in Si+Al and Si+Au collisions at 14.5*A* GeV in the framework of the relativistic quantum molecular dynamics approach (RQMD). Multistep processes lead to the formation of high-mass flux tubes. Their decay dominates the initial antibaryon yield. However, the subsequent annihilation in the surrounding baryon-rich matter suppresses the antiproton yield considerably: Two-thirds of all antibaryons are annihilated even for the light Si+Al system. Comparisons with preliminary data of the E802 experiment support this analysis.

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Antibaryons may be useful to probe the space-time evolution of the baryon-rich matter formed in heavy ion collisions [1]: Antibaryon annihilation probes the local density and excitation energy as can be seen from the annihilation rate $R_{\rm ann} = \langle \sigma_{\rm ann} v_{\rm rel} f_B \rangle$ (f_B denotes the baryon phase-space density). The annihilation rate has to be integrated over time to give the total fraction of annihilated antibaryons. Therefore the total time-integrated antibaryon yields are also sensitive to both the lifetime of the fireball produced in heavy ion collisions and as well as the initial formation time.

Experiments with light ion beams at energies of 10–15*A* GeV have been carried out at the Alternating Gradient Synchrotron (AGS) at BNL. They may allow for the formation of a nearly thermalized short-lived fireball of strongly interacting matter at high baryon density [2]. This expectation is supported by calculations based on relativistic nuclear fluid dynamics [3] and relativistic quantum molecular dynamics [4], as well as by the success of the Landau fireball model [5] in explaining experimental observations.

In contrast, recent preliminary measurements of antiprotons taken for central collisions of Si(14.5*A* GeV) +Al and Si(14.5*A* GeV)+Au seemed to be explainable by a rather simple model, assuming production of antibaryon in the first collisions between target and projectile nucleons and no further antiproton scattering or absorption at all [6]. Additional antiproton measurements exist at forward emission angles for different targets irradiated with protons of momentum 10 GeV/c [7]. Including only the production of $\bar{p}$'s in the first collision of a projectile proton one would need a rather large formation time of about 5–7 fm/c to explain the observed data in a Glauber model [7]. Unfortunately no systematic measurements of $\bar{p}$ yields exist to date in the target fragmentation region for which the final spectra are most sensitive to the value of the formation length. A rather large formation time, i.e., small rescattering effects are extracted from $\bar{p}$ data from pA as well as from AA collisions at AGS energies if the first-collision model is used. However, in this Letter a microscopic multiple-collision approach is used to demonstrate that such first-collision models are *not* trustworthy.

The fate of the antiprotons produced in Si+A is followed in time with the relativistic quantum molecular dynamics model (RQMD 1.07) [8]. RQMD includes the formation and decay of color strings and resonances followed by rescattering and absorption between all particles, i.e., both the original constituents as well as the produced hadrons. The number of produced baryons in elementary hadronic collisions depends strongly on the diquark suppression factor $P(qq)/P(q)$, which, as in the LUND model [9], reflects the diquark suppression relative to the $q\bar{q}$ pair production by pair creation in the strong color flux tube "string" field. The diquark suppression parameter is fixed to 0.085 in our calculation. This value has been extracted from high-energy pp collisions and from e^+e^- string fragmentation [10]. This scheme, however, would be at variance with pp data near AGS energy if the geometry of the string is treated too simplistically: Too many $\bar{p}$'s were created per collision. Therefore, in addition, the effect of diquark suppression at the ends of a flux tube is employed giving much better agreement with the elementary hh data. The qq suppression parameter is multiplied with a string-area-dependent factor to take the additional suppression of qq pairs at the ends of a color flux tube into account. This factor is determined from the ratio of the ineffective strip in which diquark-antidiquark tunneling from the vacuum is forbidden to the whole string world sheet [11,12]. The average number of $\bar{p}$'s produced in pp collisions as a function of energy $\sqrt{s}$ is shown in Fig. 1. The RQMD curves are calculated with (solid line) and without (dashed line) this geometrical diquark suppression factor.

The RQMD approach contains a formation time for the antiprotons (and other secondaries), because the flux tubes need some time before they break. The formation time of an antibaryon in its rest system is about 1.5 fm/c in pp collisions at AGS energies. It depends only weakly on the beam energy.

Figure 2 shows RQMD calculations for central

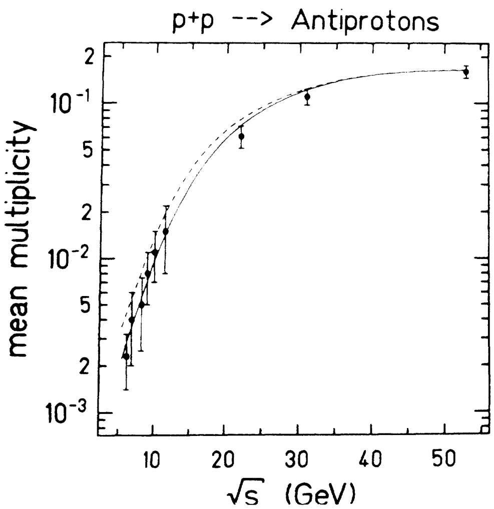

FIG. 1. The calculated mean multiplicity of antiprotons produced in $p+p$ collisions as a function of $\sqrt{s}$, the available center-of-mass energy, are compared with experimental measurements [13]. The RQMD calculations shown are with (solid line) and without (dashed line) the finite-area suppression for diquark production as discussed in the text.

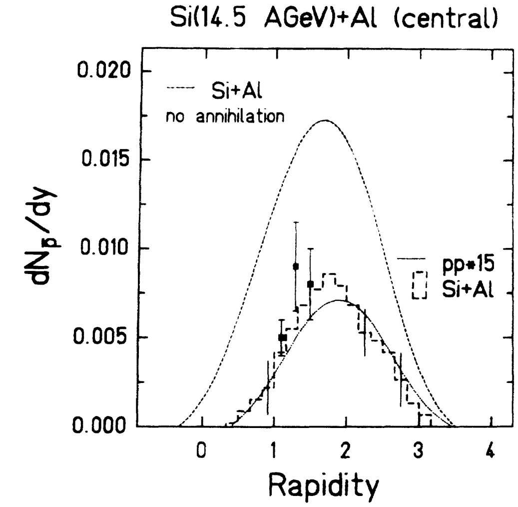

FIG. 2. The antiproton rapidity distribution, $dN_{\bar{p}}/dy$, is shown for central Si+Al collisions at 14.5A GeV. The two thin (dashed/dotted) theoretical curves represent the RQMD results for (dotted) pp collisions multiplied by the number of first collisions and (dashed) final $\bar{p}$ yield in Si+Al without annihilation. The fat histogram shows the default RQMD calculation with rescattering and annihilation included. Preliminary E802 data [6] are also shown for comparison.

Si(14.5A GeV)+Al collisions. The rapidity distribution of the antiprotons, $dN_{\bar{p}}/dy$, is shown for central collisions with (histogram) and without annihilation (dashed curve). In addition, the RQMD calculation for the $\bar{p}$ distributions in p(14.6 GeV/c)+p collisions, but multiplied by the calculated number of first nucleon-nucleon collisions in Si+Al, is shown here (dotted curve). Let us first investigate the validity of the first-collision model, but neglecting the $\bar{p}$ annihilation. Note that the antiproton yields in the Si+Al calculation are a factor of 3–4 higher than in the first-collision model. This is due to a collective process: Baryons, which are *below* the threshold for antiproton production after their first collision, can be excited to high-lying resonances in subsequent collisions which can then decay into antibaryons. Such multistep processes do become more and more important at lower and lower beam energies. In fact, this phenomenon can provide an explanation for the surprisingly high antiproton yields observed in subthreshold nucleus-nucleus collisions at the LBL [14] and at GSI [15]. It had been claimed that this process is also most important for $\bar{p}$ yields in subthreshold $p+A$ collisions [16].

Thus, in the RQMD calculation a higher number of antiprotons is initially produced than expected from the simple first-collision model. However, it turns out that in the RQMD model a large fraction of $\bar{p}$'s ($\sim$65%) is annihilated subsequently—due to annihilation in the surrounding baryon-rich matter. The agreement of the RQMD model including annihilation with the experimental antiproton data [6] is reasonable. This strong (a factor of 2/3) relative suppression seems to be of uniform magnitude at rapidities ranging from $y=0.5$ to $y=2.5$. This can only be understood if the number of baryons per rapidity interval were roughly constant. Indeed the Si+Si system exhibits a nearly flat dN_p/dy spectrum for central collisions at 10 GeV/nucleon, both theoretically [8] and experimentally [17].

The strong sensitivity of the antibaryon absorption to the mass of the system is demonstrated in Fig. 3, which shows the RQMD results for Si(14.5A GeV)+Au with (solid histogram) and without (dashed histogram) annihilation. We find an enhancement of a factor of 3 for the initially produced antiprotons as compared to the light Al target. However, now the corresponding survival rate is predicted to be only about 15%. Hence, we infer that also in the case of the heavy gold target the enhanced production of antibaryons is counter balanced by the strong suppression due to annihilation. Results from the RQMD calculation with an antiproton formation time of $\tau\sim$6.5 fm/c as suggested in Ref. [7] are also shown in Fig. 3. The increase of the formation time leads to a dramatic rise in the antiproton survival rate, because the $\bar{p}$'s materialize only outside of the baryon-rich matter. The RQMD calculation results in a mean $\bar{B}$ formation time of about 1.5 fm/c, when the default parameters are used. Here the formation point of a hadron is defined as the arithmetic mean of the two string break points from which the constituent quarks emerge which build up the hadron. However, the agreement with the data is far from perfect. We can enforce good agreement with both the Si+Al and the Si+Au preliminary E802 data [6] if a larger formation time, τ about 2.5 fm/c, is used in the RQMD model. Such a large formation time could point towards the importance of direct, i.e., three-

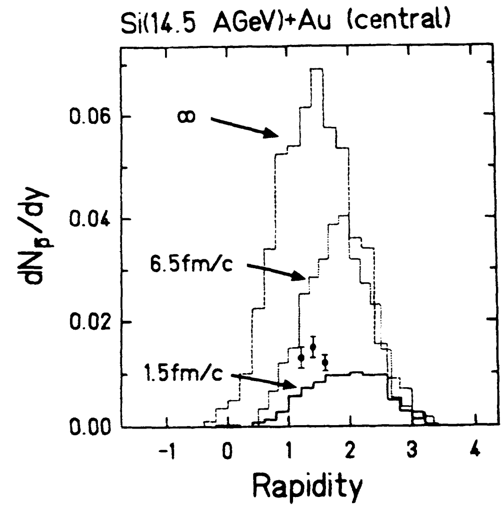

FIG. 3. Antiproton rapidity distribution, $dN_{\bar{p}}/dy$, is shown for central Si(14.5A GeV)+Au collisions as calculated with the RQMD model for different antiproton formation times ($\tau = \infty$, 6.5, 1.5 fm/c). An infinite formation time corresponds here to a calculation without annihilation. Also shown are preliminary data of the E802 group [6].

fold q production, which might be favored as compared to the diquark formation process assumed here.

However, in the present work, only the usual elementary absorption process of $\bar{p}p \rightarrow n\pi$ is included. There are others: E.g., there could be absorption of multiple nucleons. Although small in normal nuclei, such a process will go as the square of the density rather than linearly and thus may become important at the high densities achieved in heavy ion reactions. Also medium renormalization effects might strongly affect the calculated results. We have discussed this problem in previous papers (with regard to pion production) [18].

Furthermore, the use of the successive rescattering scenario at high energies is questionable. At AGS energies, we observe on the average ~ 5 collisions for each hadron in a time period ~ 10 fm/c, i.e., the mean time between subsequent collisions is about 2 fm/c. At higher energies the number of hadrons increases and the collision time decreases. Therefore, the assumptions of the successive-collision models become more and more questionable as the bombarding energy is increased ([8], see also [19]).

These effects are subject of detailed investigations beyond the scope of the present Letter.

In conclusion, the experimentally observed systematics of the antiproton production from $p+p$ to $A+A$ collisions at AGS energies points towards both an enhanced multistep production (due to very large heavy resonances) as well as to substantial absorption effects. Microscopic RQMD calculations support such a scenario. Future AGS data for heavy projectiles will provide important tests of theoretical models. This offers the unique opportunity to obtain information about the baryon densities and the extension of the reaction zone: We expect to get a direct handle on the intricate physics involved by the systematic study of the antibaryon production with various projectile-target combinations and at different energies.

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