Antibaryons in massive heavy ion reactions: Importance of potentials

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In the framework of relativistic quantum molecular dynamics we investigate antiproton observables in massive heavy ion collisions at alternating-gradient synchrotron energies and compare to preliminary results of the E878 Collaboration. We focus here on the considerable influence of the *real* part of an antinucleon-nucleus optical potential on the $\bar{p}$ momentum spectra.

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Antibaryon production is a promising observable for collective effects in nucleus–nucleus collisions. On the other hand, $\bar{N}$'s suffer strong final-state interactions. These interactions have two components which can be related to the $\bar{N}$ self-energy in matter: collisions and annihilation on baryons [1] (imaginary part, semiclassically given by $2\,\mathrm{Im}V=\sigma v \rho$) and a piece in the real part ($\mathrm{Re}V=t_{NN}\rho$ in the impulse approximation). In the semiclassical limit the real part of the self-energy can be approximated by potential-type interaction [2] or a mean field.

Here we will focus on the effect of the real part. The motivation is that the long-range force of baryons acting on a $\bar{p}$ is expected to be stronger than for protons since the Lorentz-scalar and the Lorentz-vector parts of a meson exchange potential now have the same sign. The influence of baryonic mean fields on baryons and mesons is well established. Therefore there should also be some influence on $\bar{p}$'s.

The substantial impact of mean fields on particle spectra was studied earlier [3,4]. Following these ideas, we now investigate observables in nucleus-nucleus collisions, where $\bar{B}B$ potentials come into play. For this purpose, we employed a simple model interaction, knowing that this choice is far from being unique.

In principle, one has to calculate the medium-dependent mean field and the cross section self-consistently to understand $\bar{N}$ behavior in matter. We calculate the forces acting on a $\bar{N}$ in a baryonic medium only *after* freeze-out. However, by taking the free interaction — annihilation, elastic scattering, nonannihilating inelastic channels — for $\bar{N}N$ in the collision term during the dynamical evolution the real potential is included effectively. Yet it is far from clear that the cumulative effect of the real potential from all of the baryons present is equivalent to multiplying the cross section by the number of baryons. Our approach is similar in its spirit to the usual treatment of the Coulomb distortion of particle spectra which is also restricted to final-state interactions [5]. However, while Coulomb interaction may be safely neglected in the stages of interparticle distance less than the range of the strong interactions, it may well be that the strong forces under consideration here are of importance during the whole dynamical evolution.

Addition of free interactions and mean-field contribution would cause double counting of interactions: any geometric cross section will appear as a larger physical cross section if the particles' trajectories are bent due to attractive forces. Figure 1 shows this effect for our model potential. Due to the strong attraction for the $\bar{B}B$ case, a reduced geometric annihilation cross section suffices to account for the measured free annihilation probability in binary $\bar{N}N$ reactions. This is in rough correspondence to phenomenological models of $\bar{p}p$ interaction [6], where the characteristic range of the imaginary potential is chosen to be less than 1 fm, which corresponds to a disk much smaller than the free annihilation cross section. For the same reason the insertion of *free* cross sections in the collision term of Vlasov-type models seems questionable.

The great success of Dirac equation optical model calculations for pA scattering [7] led us to using these relativistic potentials (Lorentz-scalar and vector interaction) with Yukawa functions as form factors — applying G-parity

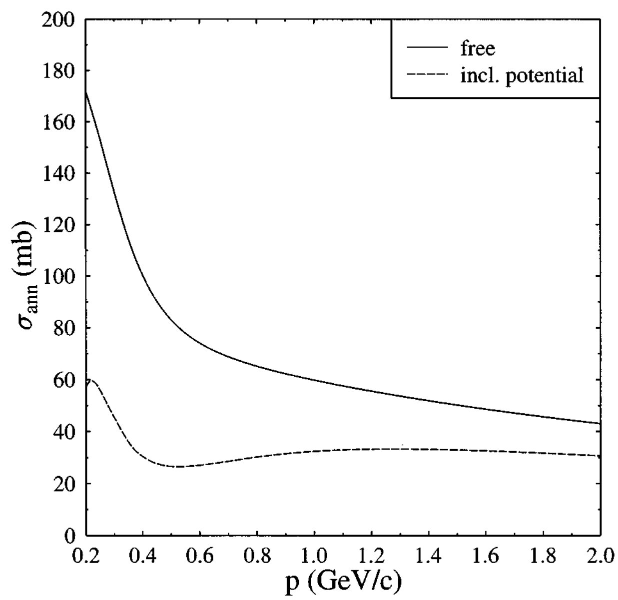

FIG. 1. $\bar{p}p$ annihilation cross section as a function of p_{lab}. Parametrization of the free measured cross section (full line) and the corrected value, if potential interaction is added (dashed line).

transformation — for the $\bar{p}$ case[1]: The mass parameters are $\mu_V = 3.952\ \mathrm{fm}^{-1}$ and $\mu_S = 2.787\ \mathrm{fm}^{-1}$; the coupling constants are $g_V = 13.5$ MeV fm and $g_S = 10.9$ MeV fm. In line with [7] we used Gaussians as baryon profiles with a mean square radius of 0.8 fm. The central part of an effective Schrödinger equivalent potential (SEP) is constructed from the above potentials:

$$U_{\mathrm{SE}} = \frac{1}{2E}(2EU_V + 2mU_S - U_V^2 + U_S^2),$$

where E is the total energy of the incident particle.

The $\bar{p}$'s are produced and propagated with the usual relativistic quantum molecular dynamics (RQMD) simulation [10] (NN potentials are switched off, i.e., pure cascade mode) until they undergo the last strong interaction. Afterwards the trajectories of the $\bar{p}$'s are calculated under the influence of the relativistic optical potentials, while the remaining particles continue to interact within the cascade calculation.

For $\bar{N}N$ distances, smaller than the corresponding annihilation cross section, the real potential should not show an effect, since the huge imaginary part absorbs the particular $\bar{p}$ anyhow. We have chosen 1.5 fm as cutoff distance corresponding to an averaged $\bar{p}p$-annihilation cross section of ≈ 70 mb.

The Schrödinger equivalent potential with the above parameters results in a mean $\bar{p}$ potential in nuclear matter at ground state density of about -250 MeV ($p_{\bar{p}} = 0$ GeV/c), increasing with energy towards -170 MeV at $p_{\bar{p}} = 1$ GeV/c. These values are much more in accord with estimations on the basis of dispersion relations [11] than just taking the sum of the scalar and vector potentials without any cutoff. The actual (averaged) SE potential of the $\bar{p}$'s at freeze-out is about -70 MeV in central Au+Au collisions at 10.7 GeV. We have also studied the influence of Coulomb effects on the $\bar{p}$ momentum spectrum. It shows that the average potential is less than -10 MeV and therefore of less importance.[2]

For central collisions of Au+Au at 10.7 GeV we find a substantial change in the final phase space distribution of the $\bar{p}$'s at low p_t, deviating from results of a pure cascade, due to the potential interaction during the last stage of the collision. Without potentials, we find a clearly nonthermal spectrum with a dip at midrapidity for $p_t = 0$. Due to the strong momentum dependence of the $\bar{p}p$-annihilation cross section, $\bar{p}$'s with low transverse momentum are suppressed.

Figure 2 shows the p_t spectrum at midrapidity ($-0.4 < y < 0.4$) of the antiprotons with and without the inclusion of potential interaction. With potential interaction included the dip at low p_t gets filled without changing the shape of the spectrum at higher momenta. Figure 3 shows the invariant multiplicity $(1/2\pi p_t)(d^2N/dy\, dp_t)$ of $\bar{p}$'s with $p_t < 200$ MeV. RQMD 1.07 calculations with and without potentials are compared to preliminary data of the E878 Collaboration [12]. In addition to the presented result for the proposed model interaction we calculated the effect for the same potentials arbitrarily reduced by 50%. Still the dip at midrapidity vanishes although the change is less pronounced. Note that the p_t-integrated spectrum at midrapidity is affected by less than 25 percent in comparison to the calculation without potential interaction. This number is important to assess previously published model results [16–18] with respect to possible mean-field effects.

The theoretical understanding of $\bar{p}$ propagation in a baryon-dense medium is far from satisfying. For instance, the absorption strength differs by orders of magnitude if one compares different transport calculations [11,13–18]. The basic assumption of the results presented here has been that

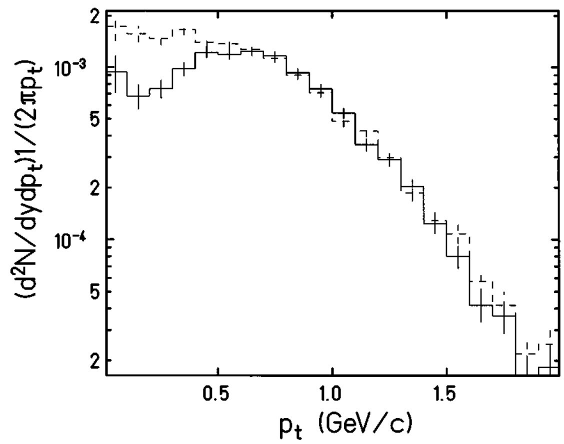

FIG. 2. Invariant p_t spectrum of the $\bar{p}$'s at midrapidity ($-0.4 < y < 0.4$) for central reactions of Au+Au ($b < 4$ fm) at 10.7 GeV/u. Shown is the spectrum of the RQMD calculation (full line) and with an additional optical potential (dashed line).

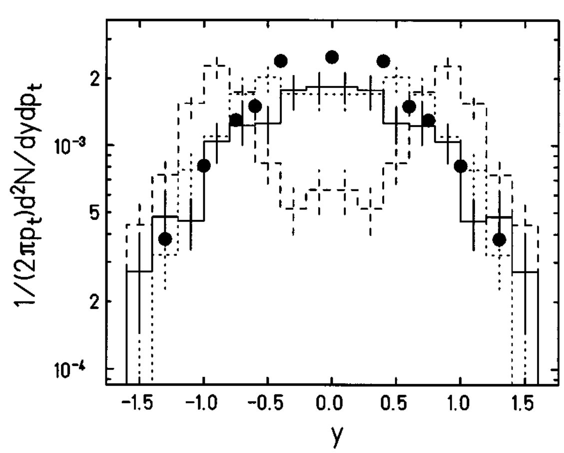

FIG. 3. Invariant rapidity distribution of the $\bar{p}$'s with $p_t < 200$ MeV for Au+Au ($b < 4$ fm) at 10.7 GeV/u. Shown is the RQMD calculation (dashed line), with the additional optical potential (full line) and the 50% reduced potential (points). Preliminary data (full circles) from [12] (the error bars are omitted).

[1]Optical model calculations for intermediate energy antiproton scattering like in [8,9] cannot provide unambigous values of the real part of the optical potential, since the imaginary part dominates the behavior.

[2]The effect may be relevant for pions: in the above system the ratio π^-/π^+ for $p_t < 100$ MeV increases according to our simulation by 25 percent due to the Coulomb potential.

the considerable repulsion between nucleons in the vector piece of their potentials implies an equally strong additional attraction for antinucleons in nuclear matter. We have found that residual attraction after freeze-out may considerably distort the final antinucleon momentum spectra. There is little reason to assume that inclusion of these effects during the dynamical evolution would produce only small effects. This certainly expresses the need for a truely self-consistent treatment of antibaryon propagation in nuclear matter, including the collision terms and realistic mean fields. The annihilation process will have to be modified, e.g., the strength of the cross section as discussed in this paper. It will also be required to develop a model for $\bar{N}N$ annihilation below the 2 m_N threshold, because the antibaryons acquire effective masses in the medium. Our study should be seen as a modest first step on the way towards a self-consistent treatment of the real and the imaginary parts of the $\bar{N}N$ potential in the framework of the RQMD approach. We note that ‘‘screening of the long-range part of antibaryon absorption in a dense medium’’ has been suggested as another mechanism for larger antibaryon survival rates [15]. It will be interesting to study such a process as well — alternatively or in addition to mean field effects — in future work.

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