Antiproton Production in p-Nucleus and Nucleus-Nucleus Collisions within a Relativistic Transport Approach

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Stefan Teis, Wolfgang Cassing, Tomoyuki Maruyama and Ulrich Mosel
Institut für Theoretische Physik, Universität Giessen
D-35392 Giessen, Germany
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Abstract

The production of antiprotons in proton-nucleus and nucleus-nucleus reactions is calculated within the relativistic BUU approach employing proper selfenergies for the baryons and antiprotons and treating the $\bar{p}$ annihilation nonperturbatively. The differential cross section for the antiprotons is found to be very sensitive to the $\bar{p}$ selfenergy adopted. A detailed comparison with the available experimental data for p-nucleus and nucleus-nucleus reactions shows that the antiproton feels a moderately attractive mean-field at normal nuclear matter density $\rho_0$ which is in line with a dispersive potential extracted from the free annihilation cross section.

The production of particles at energies below the free nucleon-nucleon threshold (‘subthreshold production’) constitutes one of the most promising sources of information about the properties of nuclear matter at high densities since the particles are produced predominantly during the compressed stage at high density [1, 2, 3]. Antiproton production at energies of a few GeV/u is the most extreme subthreshold production process and has been observed in proton-nucleus collisions already more than 20 years ago [4, 5, 6]. Experiments at the JINR [7] and at the BEVALAC [8, 9] have provided, furthermore, first measurements of subthreshold antiproton production in nucleus-nucleus collisions. Since then the problem was taken up again

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at KEK [10] and GSI [11] with new detector setups. Various descriptions for these data have been proposed. Based on thermal models it has been suggested that the antiproton yield contains large contributions from $\Delta N \rightarrow \bar{p} + X$, $\Delta \Delta \rightarrow \bar{p} + X$ and $pp \rightarrow \bar{p}N$ production mechanisms [12, 13, 14]. Other models have attempted to explain these data in terms of multiparticle interactions [15].

In a first chance nucleon-nucleon collision model (assuming high momentum tails consistent with data on backward proton scattering) Shor et al. [13] succeeded in reproducing the antiproton yield for the proton-nucleus case, however, underestimated the yield by more than 3 orders of magnitude for nucleus-nucleus collisions. This problem was partly resolved by Batko et al. [17] who performed the first nonequilibrium $\bar{p}$-production study on the basis of the VUU transport equation. Within this approach it became possible to describe simultaneously the $\bar{p}$-data from $p + A$ and $A + A$ reactions; however, the yield was still underestimated when including the strong $\bar{p}$ annihilation. Nevertheless, it became clear, that in $A + A$ reactions the dominant production channel proceeds via an intermediate nucleon resonance which allows to store a sizeable amount of energy that can be used in a subsequent collision for the production of a $pp$ pair. Later on, these results were also confirmed by Huang et al. [18] within the QMD model; the authors achieved a reproduction of nucleus-nucleus data only when neglecting the annihilation channel.

These results have led to the suggestion that the quasi-particle properties of the nucleons might be important for the $\bar{p}$ production process which become more significant with increasing nuclear density. Schaffner et al. [19] found in a thermal relativistic model, assuming kinetic and chemical equilibrium, that the $\bar{p}$-abundancy might be dramatically enhanced when assuming the antiproton selfenergy to be given by charge conjugation of the nucleon selfenergy. This leads to strong attractive vector selfenergies of the antiproton. However, the above concept lacks unitarity between the real and the imaginary part of the $\bar{p}$-selfenergy and thus remains questionable. Besides this, even in the $\sigma - \omega$ model the Fock terms lead to a suppression of the attractive $\bar{p}$-field [20], such that the production threshold is shifted up in energy again as compared to the simple model involving charge conjugation. Furthermore, the assumption of thermal and especially chemical equilibrium most likely is not fullfilled e.g. in Si + Si collisions around 2 GeV/u [21].

First fully relativistic transport calculations for antiproton production including $\bar{p}$ annihilation as well as the change of the quasi-particle properties in the medium have been reported in [22]. There it was found that according to the reduced nucleon mass in the medium the threshold for $\bar{p}$-production is shifted to lower energy and the antiproton cross section prior to annihilation becomes enhanced for Si + Si at 2.1 GeV/u by roughly 2 orders of magnitude as compared to a relativistic cascade calculation where no in-medium effects are incorporated. The enhancement of the antiproton yield then was dramatically reduced again when including the strong annihilation channel which, however, lead - accidentally, as noted in [22] - to a reasonable reproduction of the $\bar{p}$ data for Si + Si at 1.65 and 2.1 GeV/u. A final answer on the antiproton problem especially with respect to the $\bar{p}$ selfenergy in the medium could not be given in [22] since the explicit momentum dependence of the nucleons scalar and vector selfenergies had not been accounted for.
In this letter we therefore analyze the production of antiprotons within the framework of the relativistic transport theory (RBUU) that calculates $\bar{p}$ production perturbatively as in [17, 22] from the channels $NN \rightarrow NN\bar{p}, \Delta N \rightarrow NN\bar{p}$ as well as $\Delta\Delta \rightarrow NN\bar{p}$. The quasi-particle properties, i.e. the nucleon selfenergies $U_s(p, \rho), U_\mu(p, \rho)$, are taken from [23, 24, 25] and are in line with the results of Dirac-Brueckner calculations [26] whereas the antiproton selfenergies are described on the basis of the $\sigma - \omega$ model [27] with free coupling parameters $g_\bar{p}^s$ and $g_\bar{p}^v$.

Antiprotons are propagated explicitly in the respective time dependent potentials and their annihilation is calculated nonperturbatively by means of individual rate equations. A comparison with the most recent data from KEK and GSI on $\bar{p}$-production will allow to approximately determine the free parameters $g_\bar{p}^s$ and $g_\bar{p}^v$ and provide first information on the antiproton potential in the medium. We finally compare the numerical results for the Schrödinger equivalent antiproton potential with a dispersive potential as evaluated from the annihilation rate and the charge conjugate potential as expected from simple relativistic mean-field theory.

Since the covariant BUU approach has been extensively discussed in the reviews [28, 29] we only recall the basic equations and the corresponding quasi-particle properties that are required for a proper understanding of the results reported in this study. The relativistic BUU (RBUU) equation with momentum-dependent mean-fields or selfenergies is given by

$${\{[\Pi_\mu - \Pi_\nu (\partial_\mu U_\nu) + M^* (\partial_\mu U_s)]\partial_\mu + [-\Pi_\nu (\partial_\mu U_\nu) + M^* (\partial_\mu U_s)]\partial_\mu\}} f(x, p) = I_{\text{coll}}, \quad (1)$$

where $f(x, p)$ is the Lorentz covariant phase-space distribution function, $I_{\text{coll}}$ is a collision term given in Ref. [28], and $U_s$ and $U_\mu$ are the scalar- and the vector-mean-fields. The effective mass $M^*$ and the kinetic momentum $\Pi_\mu$ are defined in terms of the fields by

$$\Pi_\mu(x, p) = p_\mu - U_\mu(x, p) \quad (2)$$

$$M^*(x, p) = M + U_s(x, p), \quad (3)$$

while the quasi-particle mass-shell constraint is obtained as

$$V(x, p)f(x, p) = 0 \quad (4)$$

with the pseudo potential

$$V(x, p) \equiv \frac{1}{2}(\Pi^2(x, p) - M^*2(x, p)). \quad (5)$$

The above equation implies that the phase-space distribution function $f(x, p)$ is nonvanishing only on the hypersurface in phase-space defined by $V(x, p) = 0$.

In order to implement proper selfenergies for the nucleons in the $\bar{p}$ production processes we follow ref. [24] and separate the mean-fields into a local part and an explicit momentum-dependent part, i.e.

$$U_s(x, p) = U^H_s(x) + U^{MP}_s(x, p) \quad (6)$$

$$U_\mu(x, p) = U^H_\mu(x) + U^{MP}_\mu(x, p), \quad (6)$$
where the local mean-fields are determined by the usual Hartree equation:

\[
U_s^H(x) = -g_s \sigma_H(x) \\
U_\mu^H(x) = g_\nu \omega_\mu^H(x)
\]  

(7)

with

\[
m_s^2 \sigma_H(x) + B_s \sigma_H^2(x) + C_s \sigma_H^3(x) = g_s \rho_s(x) \\
m_\mu^2 \omega_\mu^H(x) = g_\nu j_\mu(x).
\]  

(8)

In the above equations the scalar density \( \rho_s(x) \) and the current \( j_\mu(x) \) are given in terms of the phase-space distribution function by

\[
\rho_s(x) = \frac{4}{(2\pi)^3} \int d^4 p \ M^s(x, p) f(x, p) \\
j_\mu(x) = \frac{4}{(2\pi)^3} \int d^4 p \ \Pi_\mu(x, p) f(x, p).
\]  

(9)

The free parameters of the above expressions are fixed to reproduce the saturation properties of nuclear matter, the empirical proton-nucleus optical potential as well as the density dependence of \( U_s \) and \( U_\mu \) from Dirac-Brueckner theory \[26\]. Explicit values for these parameters are given in \[23, 24, 25\]. The actual results for \( U_s(p) \) and the zero’th component of the vector field \( U_0(p) \) are displayed in Fig.1 for \( \rho_0(\approx 0.17 \text{ fm}^{-3}) \), \( 2\rho_0 \), and \( 3\rho_0 \).

As mentioned before, the phase-space distribution function for the antiprotons \( f_\bar{p}(x, p) \) is assumed to follow an equation of motion as in (1), however, with scalar and vector potentials of different strength, i.e.

\[
U_\bar{s}^p(x) = -g_\bar{s}^p \sigma_H(x) \\
U_\bar{\mu}^p(x) = g_\bar{\nu} \omega_\mu^H(x)
\]  

(10)

where \( g_\bar{s}^p \) and \( g_\bar{\nu}^p \) are treated as independent parameters and are fixed in comparison to the experimental data (see below). The collision term (r.h.s. of eq. (1)) for the antiproton phase-space distribution besides elastic scattering also includes a direct coupling to the nucleons which describes the \( \bar{p} \)-annihilation channel (cf. discussion below).

The antiproton invariant differential multiplicity is obtained by summing incoherently the elementary antiproton multiplicities over all collisions and integrating over the residual degrees of freedom \[1\]. If we consider that the antiprotons are produced via processes of the type \( BB \rightarrow \bar{p}p + NN \equiv \bar{p} + 3 + 4 + 5 \) (\( B \) stands for either nucleon or \( \Delta \)) we can write the antiproton invariant multiplicity as \[17\]

\[
E_{\bar{p}} \frac{d^3 N(b)}{d^3 p_{\bar{p}}} = \sum_{BBcoll} \int d^3 p_3 d^3 p_4 d^3 p_5 \frac{1}{\sigma_{BB}(\sqrt{s})} E_{\bar{p}} \frac{d^3 \sigma_{BB \rightarrow \bar{p}}(\sqrt{s})}{d^3 p_\bar{p}' d^3 p_3 d^3 p_4 d^3 p_5} \\
\left[ 1 - f(\vec{r}, \vec{p}_{3}; t) \right] \left[ 1 - f(\vec{r}, \vec{p}_{4}; t) \right] \left[ 1 - f(\vec{r}, \vec{p}_{5}; t) \right].
\]  

(11)
Here, the quantities $p'_i$ denote baryon momenta in the individual BB center-of-mass system which have to be transformed into the laboratory frame or the midrapidity frame, respectively, and $s = (p_1 + p_2)^2$ is the squared invariant energy of the collision. Finally, the antiproton invariant differential cross section is obtained by integrating the differential multiplicity \( \frac{d\sigma_{BB \rightarrow \bar{p}}}{d^3p_\bar{p}} \) over the impact parameter $b$.

In order to proceed in the evaluation of \( \frac{d\sigma_{BB \rightarrow \bar{p}}}{d^3p_\bar{p}} \) we assume, as in refs. [16, 15, 17], that the differential elementary antiproton cross section is proportional to the phase-space available for the final state:

\[
\sigma_{BB \rightarrow \bar{p}}(\sqrt{s}) \frac{1}{16 R_4(\sqrt{s})} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5 - p_\bar{p}).
\]  

The factor $1/R_4(\sqrt{s})$ is the 4-body phase-space integral [30] and has been included in order to normalize the differential distribution. It should be noted that the 4-body phase-space integral contrary to ref. [17] now strongly depends on the quasi-particle properties in the medium defined by eqs. (2) - (5) and (10). The total cross section for antiproton production $\sigma_{BB \rightarrow \bar{p}}(\sqrt{s})$ has been extracted from the experimental data corresponding to the inclusive process $pp \rightarrow \bar{p} + X$. Unfortunately, there are no data available at $\sqrt{s} - 4m < 1$ GeV so that we perform an extrapolation to lower energies. In line with [17, 22, 18] we adopt the parametrization:

\[
\sigma_{pp \rightarrow \bar{p} + X}(\sqrt{s}) = 0.01 \left( \sqrt{s} - \sqrt{s_0} \right)^{1.846} \text{[mb]}
\]  

and assume that $\sigma_{pp \rightarrow \bar{p} + X}(\sqrt{s}) = \sigma_{BB \rightarrow \bar{p} + NN}(\sqrt{s})$. Whereas $\sqrt{s_0} = 3.7532$ GeV for free particles, we replace $\sqrt{s_0}$ by the corresponding threshold $\sqrt{s_0(\rho, p_i)}$ for the quasi-particles as defined by eqs. (2) - (5) in the medium. Though the latter assumption is not controlled by experimental data so far - and can hardly be measured - it is well in line with the concept of a phase-space dominated elementary production cross section.

Apart from the perturbative production scheme discussed above, the antiprotons produced in individual baryon-baryon collisions can be annihilated on their way out of the dense nuclear medium into the continuum. Since a proper treatment of $\bar{p}$-annihilation is decisive for a comparison with experimental data, we perform this task nonperturbatively in the following way: For each baryon-baryon collision event $i$ at space-time position $x_i$ we evaluate the differential production probability $P_i(\bar{p}_j)$ for an antiproton with momentum $\bar{p}_j$ on a grid in momentum space. Then each grid point in momentum space $j$ (for each collision event $i$) is represented by an antiproton testparticle which is propagated in time under the influence of its selfenergies (10) according to the respective equations of motions for point particles which provides individual trajectories $r_{ij}(t)$. In order to account for annihilation, the individual probabilities $P_i(\bar{p}_j; t)$ are integrated in time according to the following rate equation

\[
\frac{d}{dt} P_i(\bar{p}_j; t) = -\frac{4}{(2\pi)^3} \int d^3p \ v_{12} \sigma_{\text{ann}}(\bar{p}_j, p) \ f(r_{ij}(t), p; t) P_i(\bar{p}_j; t)
\]  

(14)
where $v_{12}$ is the Lorentz-invariant relative velocity, $f(r, p; t)$ the baryon phase-space distribution from eq. (1) and $\sigma_{\text{ann}}$ the $\bar{p}$ annihilation cross section which is taken from the experimental data [31] and parametrized as a function of $\sqrt{s} - \sqrt{s_0}$. Though it will remain a matter of debate, how $\sigma_{\text{ann}}$ might change in the nuclear medium, we follow our concepts above and use the free annihilation cross section, however, modify $\sqrt{s_0}$ in the medium according to the quasi-particle properties described above. We note that the validity of this concept can in part be controlled via the experimental mass dependence of the $\bar{p}$ yield when comparing light and heavy systems. For further details we refer the reader to ref. [32].

We have applied the above mentioned formalism to evaluate the antiproton cross section for the reactions $p + ^{12}C$ and $p + ^{63}Cu$ at bombarding energies of 5, 4, and 3.5 GeV. The corresponding invariant cross sections in comparison with the data of ref. [10] are shown in Fig. 2 (a + b) as a function of the momentum of the emitted antiproton in the lab frame at $\Theta = 0^\circ$, assuming free antiprotons, i.e. $g_{\bar{p}}^s, g_{\bar{p}}^v = 0$. The calculations slightly underestimate the experimental data, but already approximately reproduce the shape of the momentum-spectra as well as the dependence on bombarding energy and mass. When adopting a slightly attractive scalar $\bar{p}$ selfenergy of - 50 to - 100 MeV the reproduction of the data improves at all energies significantly which is exemplified for 4.0 GeV by the dashed line in Fig. 2. We note that in the above comparison we cannot distinguish between scalar and vector antiproton selfenergies because both yield similar results for the $\bar{p}$ spectrum if the same Schrödinger-equivalent optical potential is achieved. Furthermore, when using antiproton selfenergies in line with the relativistic mean-field theories [27], i.e. changing only the sign of nucleon vector potential, we overestimate the $\bar{p}$ yield by more than an order of magnitude at all energies for both systems.

We now turn to the nucleus-nucleus case. The calculated antiproton invariant differential cross section for the reaction $^{28}$Si+$^{28}$Si at 2.1 GeV/A and Ni + Ni at 1.85 GeV/u is shown in Figure 3 in comparison to the experimental data of ref.[8] and ref. [11]; the upper lines represent the results of the calculations for free antiprotons without including any reabsorption. When taking care of antiproton annihilation according to eq. (14) the yields drop to the lower full lines which now underestimate the data sizeably. However, using attractive scalar (or vector) selfenergies at $\rho = \rho_0$ of about - 100 to -150 MeV we nicely reproduce the data again. Since the two systems studied differ quite substantially in mass we infer that the description of $\bar{p}$ annihilation appears to be sufficiently accurate.

We note in passing that the contribution due to collisions involving resonances is a factor 10 larger than those involving only nucleons thus confirming again the main results of ref. [12, 17]. A detailed investigation of the baryonic decomposition for the present reactions is given in ref. [32].

The different value for the attractive antiproton field at $\rho = \rho_0$ in $p + A$ and $A + A$ reactions is due to the fact that in $p + A$ collisions the antiprotons move with momenta of 1 - 2 GeV/c with respect to the nuclear medium, whereas in $A + A$ collisions the antiprotons are almost at rest in the nucleus-nucleus center-of-mass frame. In view of uncertainties of our present studies with respect to the elementary production cross sections close to the thresholds we provide areas for
the antiproton Schrödinger equivalent potential at $\rho = \rho_0$ in Fig. 4, as extracted from the comparison with the experimental data for p + A and A + A reactions. These areas are far from the values expected by charge conjugation from the familiar $\sigma - \omega$ model \cite{27} (dashed line) and thus exclude relativistic mean-field models with the same parameter-sets for nucleons and antinucleons. However, our extrapolated values are well in line with a Schrödinger-equivalent potential (solid line in Fig. 4) as extracted from the dispersion relation (P: principle value)

$$Re(U^p(E, \rho_0)) = \frac{1}{\pi} P \int dE' \frac{Im(U^p(E', \rho_0))}{E - E'}$$

(15)

whereas the imaginary part is determined from the annihilation rate at density $\rho_0$ according to

$$2Im(U^p(E, \rho_0)) = -\frac{p}{E} \sigma_{ann}(E) \rho_0$$

(16)

with $E = \sqrt{p^2 + m^2}$ and $\sigma_{ann}$ from ref. \cite{31}. The real part of the $\bar{p}$-potential (as shown in Fig. 4 by the solid line) is well in line with the potential analysis for $\bar{p} + A$ reactions \cite{33}.

In summary, we have evaluated the differential cross section for $\bar{p}$ production for p-nucleus and nucleus-nucleus reactions in the subthreshold regime by considering incoherent on-shell baryon-baryon production processes involving nucleons and $\Delta$’s with their in-medium quasi-particle properties and treating $\bar{p}$ annihilation non-perturbatively. The quasi-particle properties of the nucleons are fixed within our study by the nuclear saturation properties, the proton-nucleus empirical potential as well as Dirac-Brueckner calculations at higher density. In comparing our calculations to the most recent data from KEK \cite{10} and SIS \cite{11} we find a consistent description of the experimental results with a rather weak attractive potential for the antiprotons which is almost perfectly in line with a dispersive potential extracted from the dominant imaginary part of the antiproton selfenergy due to annihilation. Though we cannot exclude uncertainties due to uncertain elementary production cross sections we can infer, that relativistic mean-field theories - which predict antiproton selfenergies according to charge conjugation (and violate unitary) - are definitely inadequate for the description of antimatter in a dense baryonic environment.

We note in closing that the antiproton production studies at the AGS \cite{34, 35, 36} around 15 GeV/u might yield further information on the dynamics and selfenergies of antiprotons at even higher densities although these processes occur far above threshold.

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Figure Captions

Fig.1: Scalar and vector selfenergies $U_s(p)$ and $U_0(p)$ for nucleons at different densities in units of $\rho_0 \approx 0.17 \, fm^{-3}$ as used in the relativistic transport equation (1).

Fig.2: Invariant cross section for antiproton production in the reactions $p + ^{12}C$ and $p + ^{63}Cu$ at $\Theta = 0^\circ$ as a function of the antiproton momentum $p$ in the lab system. The experimental data are taken from ref. [11] and correspond to bombarding energies of 5.0 GeV, 4.0 GeV and 3.5 GeV. The full lines represent calculations for free antiprotons. The dashed lines indicate the result for an antiproton selfenergy of - 100 MeV at 4.0 GeV.

Fig.3: Invariant cross section for antiproton production in the reaction $^{28}Si + ^{28}Si$ at 2.1 GeV/u and Ni + Ni at 1.85 GeV/u for $\Theta = 0^\circ$ as a function of the momentum $p$ of the emitted antiproton in the lab-system. The experimental data have been taken from refs. [8] and [11], respectively. The upper lines indicate the calculated cross section for free antiprotons without reabsorption whereas the lower solid line is obtained when including $\bar{p}$ annihilation. The dashed line represents the cross section adopting an attractive potential of the antiproton of - 150 MeV.

Fig.4: Comparison of our extracted values for the Schrödinger equivalent antiproton potential from $p + A$ and $A + A$ reactions with the prediction from the $\sigma - \omega$ model (dashed line) and the dispersive potential according to eq. (15) (solid line).