Antiproton-nucleus reactions at intermediate energies

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I will discuss the microscopic transport calculations of the antiproton-nucleus reactions with a focus on the possibility of strongly bound antiproton-nucleus systems and on strangeness production.

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I. MOTIVATION

It is difficult to produce antiproton beams. However, antiproton-nucleus interactions attract experimentalists and theorists since about 30 years when the KEK and LEAR data appeared. Since this time significant progress is done to describe these data on the basis of optical and cascade models. Still, antiproton interactions inside nuclei remain to be better understood. One example is an antiproton-nucleus optical potential. According to the low-density theorem, it can be expressed as

\[ V_{\text{opt}} = -\frac{2\pi\sqrt{s}}{E_p E_p} f_{pp}(0) \rho, \]

where at threshold \( \sqrt{s} \approx 2m_N \), \( E_p \approx m_N \), \( f_{pp} \approx (-0.9+\ldots) \) fm [1]. Being extrapolated to the normal nuclear density \( \rho_0 = 0.16 \) fm\(^{-3} \), Eq. (1) predicts a repulsive antiproton-nucleus potential, \( V_{\text{opt}} \approx 75 \) MeV. In contrast, the \( p \)-atomic X-ray and radiochemical data analysis favors a strongly attractive antiproton-nucleus potential, \( V_{\text{opt}} \approx -100 \) MeV in the nuclear center. Thus the \( \bar{p}A \) optical potential is not a simple superposition of vacuum \( p\bar{p}N \) interactions. The strongly attractive \( \bar{p}A \) potential is consistent with Relativistic Mean Field (RMF) models and has a consequence that a nucleus may collectively respond on the presence of an implanted antiproton. The formation of strongly bound \( \bar{p} \)-nuclei becomes possible [3, 4].

Another very interesting aspect is \( \bar{p} \)-annihilation in the nuclear interior. This results in a large energy deposition \( \geq 2m_N \) in the form of mesons, mostly pions, in a volume of hadronic size \( \sim 1-2 \) fm [4, 5]. After the passage of annihilation hadrons through the nuclear medium a highly excited nuclear residue can be formed and evaporation explosive multifragment breakup [5, 6]. The annihilation of an antiproton at \( p_{\text{lab}} \approx 5 \) GeV/c on a target nucleus gives an excellent opportunity to study the interactions of secondary particles (pions [3], kaons and hyperons [8], charmonia [3, 10]) with nucleons. This is because most of annihilation hadrons are slow (\( \gamma < 2 \)) and have short formation lengths. Thus their interactions are governed by usual hadronic cross sections.

Antiproton-nucleus reactions at \( p_{\text{lab}} \approx 1.5 \)–\( 15 \) GeV/c will be a part of the PANDA experiment at FAIR. In this talk I will report on the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model results for \( \bar{p} \)-nucleus interactions at \( p_{\text{lab}} \approx 0.1 \)-\( 15 \) GeV/c. The details of calculations can be found in Refs. [11, 13].

II. GIBUU MODEL

The GiBUU model [14, 15] solves the coupled set of kinetic equations for baryons, antibaryons, and mesons. In the RMF mode, this set can be written as (c.f. Refs. [16, 17])

\[ (p^0)^{-1} \left[ p^\mu \partial_\mu + \left( m_\rho F^\mu_j + m_\omega \partial^\mu m_\omega^j \right) \frac{\partial}{\partial p^\mu} \right] f_j(x, p^*) = I_j\{f\}, \]

where \( \alpha = 1, 2, 3 \), \( \mu = 0, 1, 2, 3 \), \( x = (t, r) \); \( j = N, \bar{N}, \Delta, \bar{\Delta}, Y, \bar{Y}, \pi, K, \bar{K} \) etc.. \( f_j(x, p^*) \) is the distribution function of the particles of sort \( j \) normalized such that the total number of particles of this sort is

\[ \int \frac{g_j d^3r d^3p^*}{(2\pi)^3} f_j(x, p^*) = 1, \]

with \( g_j \) being the spin degeneracy. A Vlasov term (the L.h.s. of Eq.(2)) describes the evolution of the distribution function in smooth mean field potentials. A collision term (the r.h.s. of Eq.(2)) accounts for elastic and inelastic binary collisions and resonance decays. The Vlasov term includes the effective (Dirac) mass \( m_j^* = m_j + S_j \), where \( S_j = g_{\sigma j} \sigma \) is a scalar field; the field tensor \( F^\mu_j = \partial^\mu V^3_j - \partial^\nu V^\mu_j \), where \( V^\mu_j = g_{\omega j} \omega^\mu + g_{\rho j} \tau^3 p^\mu + q_j A^\mu \) is a vector field, \( \tau^3 = +1 \) for \( p \) and \( \bar{n} \), \( \tau^3 = -1 \) for \( \bar{p} \) and \( n \); and the kinetic four-momentum \( p^\mu = \mu - V^3 \) satisfying the effective mass shell condition \( p^\mu p^*_\mu = m_j^* \).

In the present calculations, the nucleon-meson coupling constants \( g_{\sigma N}, g_{\omega N}, g_{\rho N} \) and the selfinteraction parameters of the \( \sigma \)-field have been adopted from a non-linear Walecka model in the NL3 parameterization [13]. The latter gives the compressibility coefficient \( K = 271.76 \) MeV and the nucleon effective mass \( m_N^* = 0.60 m_N \) at \( p = \rho_0 \). The antinucleon-meson coupling constants have been determined as

\[ g_{\sigma N} = -\xi g_{\omega N}, \quad g_{\rho N} = \xi g_{\rho N}, \quad g_{\sigma N} = \xi g_{\sigma N}, \]

where \( 0 < \xi \leq 1 \) is a scaling factor. The choice \( \xi = 1 \) corresponds to the \( G \)-parity transformed nuclear potential. In this case, however, the Schrödinger equivalent
becomes unphysically deep, $U_\bar{N} = -660$ MeV. The empirical choice of $\xi$ will be discussed in the following section.

The GiBUU collision term includes the following channels\[10\] (notations: $B$ – nonstrange baryon, $R$ – nonstrange baryon resonance, $Y$ – hyperon with $S = -1$, $M$ – nonstrange meson):

- Baryon-baryon collisions:
  elastic (EL) and charge-exchange (CEX) scattering $BB \leftrightarrow BB$; s-wave pion production/absorption $NN \leftrightarrow \Delta N\pi \ (21)$; $NN \leftrightarrow \Delta \Delta; \ NN \leftrightarrow NR; \ N(\Delta, N^\star)N(\Delta, N^\star) \leftrightarrow N(\Delta)YK; \ YN \leftrightarrow YN; \ \Xi N \leftrightarrow \Lambda \Lambda; \ \Xi N \leftrightarrow \Lambda \Sigma; \ \Xi N \leftrightarrow \Xi N$.
  For invariant energies $\sqrt{s} > 2.6$ GeV the inelastic production $B_1B_2 \rightarrow B_3B_4 (+$ mesons) is simulated via the PYTHIA model.

- Antibaryon-baryon collisions:
  annihilation $\bar{B} \bar{B} \leftrightarrow$ mesons$^{[21]}$; EL and CEX scattering $BB \leftrightarrow BB; \ \bar{N}N \leftrightarrow N\Delta (+$ c.c.); $\bar{N}N \rightarrow \Lambda \Lambda; \ \bar{N}(\Delta)N(\Delta) \rightarrow \Lambda \Sigma (+$ c.c.); $\bar{N}(\Delta)N(\Delta) \rightarrow \Xi \Xi$.
  For invarient energies $\sqrt{s} > 2.4$ GeV (i.e. $p_{lab} > 1.9$ GeV/c for $\bar{N}N$) the inelastic production $B_1B_2 \rightarrow B_3B_4 (+$ mesons) is simulated via the FRITIOF model.

- Meson-baryon collisions:
  $MN \leftrightarrow R$ (baryon resonance excitations and decays, e.g. $\pi N \leftrightarrow \Delta$ and $\bar{K}N \leftrightarrow Y^\star$); $\pi(\rho)\Delta \leftrightarrow R; \ \pi N \rightarrow \pi N; \ \pi N \rightarrow \pi N; \ \eta N \rightarrow \eta N; \ \rho N \rightarrow \rho N; \ \bar{\rho} N \rightarrow \rho \rho N; \ \pi N \rightarrow \rho N; \ \eta N \rightarrow \phi N; \ \bar{\rho} N \rightarrow \rho \rho N; \ \bar{\rho} N \rightarrow \phi N; \ \bar{\rho} N \rightarrow \phi N$.
  ($\pi(\rho, \omega)N \rightarrow Y K; \ \rho N \rightarrow K K N; \ \pi N \rightarrow Y K; \ \pi \Delta \rightarrow Y K; \ K N \rightarrow K N$ (EL, CEX); $\bar{K}N \rightarrow \Xi K$).
  At $\sqrt{s} > 2.2$ GeV the inelastic meson-baryon collisions are simulated via PYTHIA.

- Meson-meson collisions:
  $M_1M_2 \leftrightarrow M_3$ (meson resonance excitations and decays, e.g. $\pi \pi \rightarrow \rho$ and $K \pi \leftrightarrow K^\star$); $M_1M_2 \leftrightarrow K K; \ M_1M_2 \leftrightarrow K K^\star (+$ c.c.).

\section{Antiproton Absorption and Annihilation on Nuclei}

Without mean field acting on an antiproton the GiBUU model is expected to reproduce a simple Glauber model result for the $\bar{p}$-absorption cross section on a nucleus (left Fig. 1):

\begin{equation}
\sigma_{\text{abs}}^{\text{Glauber}} = \int d^2b \left( 1 - e^{-\sigma_\text{tot}^{\text{Glauber}}} \right), \ (6)
\end{equation}

where $\sigma_\text{tot}$ is the isospin-averaged total $\bar{p}N$ cross section. The attractive mean field bends the $\bar{p}$ trajectory to the nucleus (right Fig. 1). Thus the absorption cross section should increase.

Fig. 2 shows the GiBUU calculations of antiproton absorption cross sections on $^{12}$C, $^{27}$Al and $^{64}$Cu in comparison with experimental data\[22, 27\] and with the Glauber formula\[10\]. Indeed, GiBUU calculations without mesonic components of the $\bar{p}$ mean field, i.e. with scaling factor $\xi = 0$, are very close to Eq. 6 at $p_{lab} > 0.3$ GeV/c. At lower $p_{lab}$, the Coulomb potential makes the difference between GiBUU ($\xi = 0$) and Glauber results. Including the mesonic components of the $\bar{p}$ mean field ($\xi > 0$) noticeably increases the absorption cross section at $p_{lab} < 3$ GeV/c. The best fit of the KEK data\[22\] at $p_{lab} = 470 - 880$ MeV/c is reached with $\xi = 0.21 \pm 0.03$. This produces the real part of the antiproton-nucleus optical potential $ReV_{\text{opt}} \equiv U_{\bar{p}} \simeq -(150 \pm 30)$ MeV at normal nuclear density. The corresponding imaginary part is

\begin{equation}
\text{Im}V_{\text{opt}} = -\frac{1}{2} <v_{\bar{p}N}\sigma_\text{tot}> \rho . \ (7)
\end{equation}

At $\rho = \rho_0$ this gives $\text{Im}V_{\text{opt}} \simeq -(100 - 110)$ MeV independent on the choice of $\xi$. It is interesting that the BNL\[23\] and Serpukhov\[24\] data at $p_{lab} = 1.6 - 20$ GeV/c favor $\xi = 1$, i.e. $ReV_{\text{opt}} \simeq -660$ MeV at $\rho = \rho_0$. This discrepancy needs to be clarified which could be possibly done at FAIR.

Fig. 6 displays the calculated momentum spectra of positive pions and protons for antiproton interactions at
$p_{\text{lab}} = 608$ MeV/c with the carbon and uranium targets. GiBUU very well reproduces a quite complicated shape of the pion spectra which appears due to the underlying $\pi N \leftrightarrow \Delta$ dynamics. The absolute normalization of the spectra is weakly sensitive to the $\bar{p}$ mean field. Best agreement is reached for $\xi = 0.3$, i.e. for $\text{Re}V_{\text{opt}} \simeq -(220 \pm 70)$ MeV.

### IV. SELFCONSISTENCY EFFECTS

Strong attraction of an antiproton to the nucleus has to influence on the nucleus itself. This back coupling effect can be taken into account by including the antinucleon contributions to the source terms of the Lagrange equations for $\sigma$, $\omega$, and $\rho$-fields:

$$
\partial_\mu \partial^\mu \sigma(x) + \frac{dU(\sigma)}{d\sigma} = - \sum_{j=N,N} g_{\sigma j} \langle \tilde{\psi}_j(x) \tilde{\psi}_j(x) \rangle,
$$

(8)

$$
(\partial_\mu \partial^\mu + m_\rho^2) \rho^\nu(x) = \sum_{j=N,N} g_{\rho j} \langle \tilde{\psi}_j(x) \gamma^\nu \tilde{\psi}_j(x) \rangle,
$$

(9)

with $U(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} g_2 \sigma^2 + \frac{1}{2} g_3 \sigma^4$, or, in other words, by treating the meson fields selfconsistently. As follows from Eqs. (8) and (9), nucleons and antinucleons contribute with the same sign to the source term of the scalar field $\sigma$, and with opposite sign – to the source terms of the vector fields $\omega$ and $\rho$. Hence, attraction is enhanced and repulsion is reduced in the presence of an antiproton in a nucleus.

Fig. 4 shows the density profiles of nucleons and of an antiproton at the different time moments for the case of the $\bar{p}$ implanted at $t = 0$ in the center of the $^{40}$Ca nucleus. As the consequence of a pure Vlasov dynamics of the coupled antiproton-nucleus system (annihilation is turned off), both the nucleon and the antiproton densities grow quite fast. At $t \sim 10$ fm/c the compressed state is already formed, and the system starts to oscillate around the new equilibrium density $\rho \simeq 2\rho_0$. 

Fig. 5 displays the time evolution of the central nucleon density. The $\bar{p}$ annihilation is simulated at the time moments $t_{\text{ann}}$. The choice $t_{\text{ann}} = 0$ corresponds to the usual annihilation of a stopped $\bar{p}$ in the nuclear center. In this case, the nucleon density remains close to the

![Figure 2](image2.png)

**FIG. 2.** Antiproton absorption cross section on various nuclei vs the beam momentum. The GiBUU results are shown by the lines marked with the value of a scaling factor $\xi$. Thin solid lines represent the Glauber model calculation, Eq. (9). For the $\bar{p}^{12}$C system, a calculation with $\xi = 0$ without annihilation is shown by the dotted line.

![Figure 3](image3.png)

**FIG. 3.** Momentum differential cross sections of $\pi^+$ and $p$ production in $\bar{p}$ annihilation at 608 MeV/c on $^{12}$C and $^{238}$U. The different lines are denoted by the value of a scaling factor $\xi$. The data points are from [26].
ground state density. However, if the annihilation is simulated in a compressed configuration ($t_{\text{ann}} > 0$), then the residual nuclear system expands. Eventually the system reaches the low-density spinodal region ($\rho < \sim 0.6\rho_0$), where the sound velocity squared $c_s^2 = \partial P/\partial \rho_{\text{s}}=\text{const}$ becomes negative. (Here, $P$ is a pressure and $s$ is an entropy per nucleon.) This should result in the breakup of the residual nuclear system into fragments.

A possible observable signal of $\bar{p}$ annihilation in a compressed nuclear configuration is the total invariant mass $M_{\text{inv}}$ of emitted mesons

$$M_{\text{inv}}^2 = \left( \sum_i p_i \right)^2 . \quad (11)$$

For the annihilation of a stopped antiproton on a proton at rest in vacuum, $M_{\text{inv}} = 2m_N$. In nuclear medium, the proton and antiproton vector fields largely cancel each other. (The cancellation is exact for the $\bar{p}$ vector fields obtained by $G$-parity transformation from respective $p$ vector fields, i.e. when $\xi = 1$.) Therefore, it is expected that in nuclear medium the peak will appear at $M_{\text{inv}} \approx 2m_N$. This simple picture is illustrated by GiBUU calculations in Fig. 5. In calculations with $t_{\text{ann}} = 0$ we clearly see a sharp medium-modified peak shifted downwards by $\sim 200$ MeV from $2m_N$. The final state interactions of mesons make a broad maximum at $M_{\text{inv}} \sim 1$ GeV. For annihilation in compressed configurations ($t_{\text{ann}} = 10$ and 60 fm/c), the total spectrum further shifts by about 100 MeV to smaller $M_{\text{inv}}$. This effect becomes stronger with decreasing mass of the target nucleus (e.g., for $^{16}$O the spectrum shift is nearly 500 MeV [11]).
V. STRANGENESS PRODUCTION

Originally, the main motivation of the experiments on strangeness production in antiproton-nucleus collisions was to find the signs of unusual phenomena, in particular, of a multinucleon annihilation and/or of a quark-gluon plasma (QGP) formation. In Ref. [27], the cold QGP formation has been suggested to explain the unusually large ratio $\Lambda/K_S^0 \simeq 2.4$ measured in the reaction $\bar{p}\text{Ta}$ at 4 GeV/c [28]. On the other hand, in Refs. [8, 13, 29–33] the agreement with data was not always good.

Fig. 4 presents the rapidity spectrum of $(\Lambda + \Sigma^0)$ hyperons, $K_S^0$ mesons and $(\bar{\Lambda} + \bar{\Sigma}^0)$ antihyperons for collisions $\bar{p}(4 \text{ GeV/c})\text{Ta}$ in comparison with the data [31] and the inelastic nuclear cascade (INC) calculations [29]. The GiBUU model underpredicts hyperon yields at small forward rapidities $y \simeq 0.5$ and overpredicts $K_S^0$ yields. The GiBUU calculation without hyperon-nucleon scattering produces the $(\Lambda + \Sigma^0)$ spectrum shifted to forward rapidities. However, the problem of underpredicted total $(\Lambda + \Sigma^0)$ yield remains. A more detailed analysis 13 shows that 72% of $Y$ and $Y^*$ production rate in GiBUU is due to antikaon absorption processes $KB \rightarrow YX$, $KB \rightarrow Y^*$, and $KB \rightarrow Y^*\pi$. The second largest contribution, 23% of the rate, is caused by the nonstrange meson - baryon collisions. The antibaryon-baryon (including the direct $\bar{p}N$ channel) and baryon-baryon collisions contribute only by 3% and 2%, respectively, to the same rate. The underprediction of the hyperon yield in GiBUU could be due to the used partial $KN$ cross sections, in particular, due to the problematic $K^-\Lambda$ channel. (The latter channel has been improved in the recent GiBUU releases, however, after the present calculations were already done.) The possible in-medium enhancement of the hyperon production in antikaon-baryon collisions is also not excluded.

As shown in Fig. 5 at higher beam momenta the agreement between the calculations and the data on neutral strange particle production becomes visibly better. Exception is again the region of small forward rapidities $y \simeq 0.5$ where both GiBUU and INC calculations underpredict the $(\Lambda + \Sigma^0)$ yield.

Finally, let us discuss the $\Xi$ ($S = -2$) hyperon production. The direct production of $\Xi$ in the collision of nonstrange particles would require to produce two $s\bar{s}$ pairs simultaneously. Thus $\Xi$ production could be even stronger enhanced in a QGP as compared to the enhancement for the $S = -1$ hyperons. Fig. 6 shows the rapidity spectra of the different strange particles in $\bar{p}\text{Au}$ collisions at 15 GeV/c. Even at such a high beam momentum, the $S = -1$ hyperon spectra still have a flat maximum at $y \simeq 0$ due to exothermic strangeness exchange reactions $\bar{K}N \rightarrow Y\pi$ with slow $\bar{K}$. In contrast, the second largest ($\sim 18\%$) contribution to the $\Xi$ production is given by endothermic double strangeness exchange reactions $\bar{K}N \rightarrow \Xi K$. (The main ($\sim 24\%$) contribution to the total yield of $\Xi$'s at 15 GeV/c is given by $\Xi^* \rightarrow \Xi\pi$ decays. The direct channel $\bar{N}N \rightarrow \Xi\Xi$ contributes by $\sim 10\%$ only.) Since the threshold beam momentum of $\bar{K}$ for the process $\bar{K}N \rightarrow \Xi K$ is 1.05 GeV/c, which corresponds to the $\bar{K}N$ c.m. rapidity of 0.55, the rapidity spectra of $\Xi$'s are shifted forward with respect to the $\Lambda$ rapidity spectra. However, in the QGP fireball scenario [27], the rapidity spectra of all strange particles would be peaked at the same rapidity.
FIG. 8. Rapidity spectra of $(\Lambda + \Sigma^0)$, $K^0_S$, and $(\bar{\Lambda} + \Sigma^0)$ from $\bar{p}d$ collisions at 8.8 GeV/c. The data and INC calculations are from [31].

VI. SUMMARY

This talk was focused on the dynamics of a coupled antiproton-nucleus system and on the strangeness production in $\bar{p}A$ interactions. The calculations were based on the GiBUU transport model. The main results can be summarized as:

- The reproduction of experimental data on $\bar{p}A$ absorption cross sections at $p_{lab} < 1$ GeV/c and on $\pi^+$ and $p$ production at $p_{lab} = 608$ MeV/c requires to use a strongly attractive $\bar{p}A$ optical potential, $V_{opt} \approx -(150 - 200)$ MeV at $\rho = \rho_0$.

- As the response of a nucleus to the presence of an antiproton, the nucleon density can be increased up to $\rho \sim (2 - 3)\rho_0$ locally near $\bar{p}$. Annihilation of the $\bar{p}$ in such a compressed configuration can manifest itself in the multifragment breakup of the residual nuclear system and in the substantial ($\sim 300 - 500$ MeV) shift of annihilation event spectrum on the total invariant mass of produced mesons $M_{inv}$ toward low $M_{inv}$.

- GiBUU describes the data on inclusive pion and proton production fairly well. Still, the strangeness production remains to be better understood (overestimated $K^0_S$ - and underestimated $(\Lambda + \Sigma^0)$ - production).

- $\Xi$ hyperon forward rapidity shift with respect to $\Lambda$ is suggested as a test of hadronic and QGP mechanisms of strangeness production in $\bar{p}A$ reactions.

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