

Antiproton-nucleus reactions at intermediate energies (Postprint)

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Abstract

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Full Text

Preamble

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Antiproton-nucleus reactions at intermediate energies

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Antiproton-induced reactions on nuclei at beam energies from hundreds of MeV up to several GeV provide an excellent opportunity to study interactions

between the antiproton and secondary particles (mesons, baryons, and antibaryons) with nucleons. The antiproton projectile is unique in the sense that most of the annihilation particles are relatively slow in the target nucleus frame. Hence, prehadronic effects do not significantly influence their interactions with the nucleons of the nuclear residue. Moreover, particles with momenta less than about 1 GeV/c are sensitive to nuclear mean field potentials. This paper discusses microscopic transport calculations of antiproton-nucleus reactions and focuses on three related problems: (i) antiproton potential determination, (ii) possible formation of strongly bound antiproton-nucleus systems, and (iii) strangeness production.

Keywords: Antiproton-nucleus reaction, GiBUU model, Relativistic mean field, Optical potential, Compressed nuclear configuration

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I. MOTIVATION

It is difficult to produce antiproton beams. However, antiproton-nucleus interactions have attracted experimentalists and theorists for about 30 years since the KEK and LEAR data appeared. Since that time, significant progress has been made to describe these data on the basis of optical and cascade models. Still, antiproton interactions inside nuclei need to be better understood. One example is the antiproton-nucleus optical potential. According to the low-density theorem, it can be expressed as

$$V_{\text{opt}} = -\frac{E_{\bar{p}}E_p}{2m_N}f_{\bar{p}p}(0)\rho,$$

where at threshold $E_{\bar{p}} \simeq m_N$, $E_p \simeq m_N$, $f_{\bar{p}p} \simeq (-0.9 + i0.9)$ fm [?]. Being extrapolated to the normal nuclear density $\rho_0 = 0.16$ fm⁻³, Eq.(1) predicts a repulsive antiproton-nucleus potential, $\text{Re}V_{\text{opt}} \simeq 75$ MeV. In contrast, the \bar{p} -atomic X-ray and radiochemical data analysis [?] favors a strongly attractive antiproton-nucleus potential, $\text{Re}V_{\text{opt}} \simeq -100$ MeV in the nuclear center. Thus the $\bar{p}A$ optical potential is not a simple superposition of vacuum $\bar{p}N$ interactions. The strongly attractive $\bar{p}A$ potential is consistent with Relativistic Mean Field (RMF) models and has the consequence that a nucleus may collectively respond to the presence of an implanted antiproton, making the formation of strongly bound \bar{p} -nuclei possible [?, ?].

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 [?, ?]. After the passage of annihilation hadrons through the nuclear medium, a highly excited nuclear residue can be formed and even experience explosive multi-fragment breakup [?, ?]. The annihilation of an antiproton at $p_{\text{lab}} \lesssim 5$ GeV/c on a nuclear target gives an excellent opportunity to study the interactions of secondary particles (pions [?], kaons

and hyperons [?], charmonia [?, ?]) with nucleons because most annihilation hadrons are slow ($\gamma < 2$) and have short formation lengths, so their interactions are governed by usual hadronic cross sections.

Over the last decades, several microscopic transport models have been developed to describe particle production in $\bar{p}A$ interactions [?, ?, ?]. Nowadays there is a renaissance in this field, since antiproton-nucleus reactions at $p_{\text{lab}} \simeq 1.5 - 15$ GeV/c will be part of the PANDA experiment at FAIR. The most recent calculations are done within the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model [?] and the Lanzhou quantum molecular dynamics (LQMD) model [?, ?]. In this paper, I report some results of the GiBUU calculations for \bar{p} -nucleus interactions at $p_{\text{lab}} \simeq 1.5 - 15$ GeV/c.

II. GIBUU MODEL

The GiBUU model [?, ?] solves a coupled set of kinetic equations for baryons, antibaryons, and mesons. In RMF mode, this set can be written as [?, ?]

$$[(p_0^*)^{-1} p^{*\mu} \partial_\mu + (p_\mu^* F^{\alpha\mu} - m^{*j} \partial^\alpha m^*) \partial_\alpha] f_j(x, p^*) = I_j[\{f\}],$$

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

$$\int \frac{g_j d^3r d^3p^*}{(2\pi)^3} f_j(x, p^*),$$

with g_j being the spin degeneracy factor. The Vlasov term (the l.h.s. of Eq.(2)) describes the evolution of the distribution function in smooth mean field potentials. The 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 $F_j^{\mu\nu} = \partial^\mu V_j^\nu - \partial^\nu V_j^\mu$, where $V_j^\mu = g_{\omega j} \omega^\mu + g_{\rho j} \tau_3 \rho_3^\mu + q_{jA}^\mu$ 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 $p^{*\mu} = p^\mu - V_j^\mu$ satisfying the effective mass shell condition $p^{*\mu} p_\mu^* = m_j^{*2}$.

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

$$g_{\omega \bar{N}} = -\xi g_{\omega N}, \quad g_{\rho \bar{N}} = \xi g_{\rho N}, \quad g_{\sigma \bar{N}} = \xi g_{\sigma N},$$

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 potential becomes unphysically deep, $U_{\bar{N}} = -660$ MeV. The empirical choice of ξ will be discussed in the following section.

The GiBUU collision term includes the following channels (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 $BB \rightarrow BB$; s -wave pion production/absorption $NN \leftrightarrow NN\pi$; $NN \leftrightarrow \Delta\Delta$; $NN \leftrightarrow NR$; $N(\Delta, N^*)N(\Delta, N^*) \rightarrow N(\Delta)YK$; $YN \rightarrow YN$; $\Xi N \rightarrow \Lambda\Lambda$; $\Xi N \rightarrow \Lambda\Sigma$; $\Xi N \rightarrow \Xi N$. 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: $\bar{N}N \leftrightarrow \bar{N}\Delta$ (+ c.c.); annihilation $\bar{B}B \rightarrow$ mesons; EL and CEX scattering $\bar{B}B \rightarrow \bar{B}B$; $\bar{N}N \rightarrow \bar{\Lambda}\Lambda$; $\bar{N}(\bar{\Delta})N(\bar{\Delta}) \rightarrow \bar{\Lambda}\Sigma$ (+ c.c.); $\bar{N}(\bar{\Delta})N(\Delta) \rightarrow \bar{\Xi}\Xi$. For invariant energies $\sqrt{s} > 2.4$ GeV (i.e. $p_{\text{lab}} > 1.9$ GeV/c for $\bar{N}N$) the inelastic production $\bar{B}_{1B}2 \rightarrow \bar{B}_{3B}4$ (+ 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 $\bar{K}N \leftrightarrow Y^*$); $\pi(\rho)\Delta \leftrightarrow R$; $\pi N \rightarrow \pi N$; $\pi N \rightarrow \pi\pi N$; $\pi N \rightarrow \eta\Delta$; $\pi N \rightarrow \omega N$; $\pi N \rightarrow \phi N$; $\pi N \rightarrow \omega\pi N$; $\pi N \rightarrow \phi\pi N$; $\pi(\eta, \rho, \omega)N \rightarrow YK$; $\pi N \rightarrow K\bar{K}N$; $\pi N \rightarrow YK\pi$; $\pi\Delta \rightarrow YK$; $KN \rightarrow KN$ (EL, CEX); $\bar{K}N \rightarrow \bar{K}N$ (EL, CEX); $\bar{K}N \leftrightarrow Y^*\pi$; $\bar{K}N \rightarrow \Xi K$. For $\sqrt{s} > 2.2$ GeV the inelastic meson-baryon collisions are simulated via PYTHIA. $\bar{K}N \leftrightarrow Y\pi$; $\bar{K}N \rightarrow Y^*$; $\bar{K}N \rightarrow Y^*\pi$.

Meson-meson collisions: $M_{1M}2 \leftrightarrow M_3$ (meson resonance excitations and decays, e.g., $\pi\pi \leftrightarrow \rho$ and $K\pi \leftrightarrow K^*$); $M_{1M}2 \leftrightarrow K\bar{K}$, $M_{1M}2 \leftrightarrow K\bar{K}$ (+ c.c.).

III. ANTIPROTON ABSORPTION AND ANNIHILATION ON NUCLEI

Without a 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 panel, [Figure 1: see original paper]):

$$\sigma_{\text{Glauber}} = \int d^2b \left[1 - \exp \left(-\sigma_{\text{tot}} \int_{-\infty}^{+\infty} dz \rho(b, z) \right) \right],$$

where σ_{tot} is the isospin-averaged total $\bar{p}N$ cross section. An attractive mean field bends the \bar{p} trajectory toward the nucleus (right panel, [Figure 1: see original paper]), thus the absorption cross section should increase.

[Figure 2: see original paper] shows the GiBUU calculations of antiproton absorption cross sections on ^{12}C , ^{27}Al , and ^{64}Cu in comparison with experimental

data [?] and the Glauber formula. 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 $p_{\text{lab}} > 0.3$ 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 $p_{\text{lab}} < 3$ GeV/c. The best fit of the KEK data [?] at $p_{\text{lab}} = 470 - 880$ MeV/c is reached with $\xi = 0.21 \pm 0.03$. This produces the real part of the antiproton-nucleus optical potential $\text{Re}V_{\text{opt}} \equiv U_{\bar{p}} \simeq -(150 \pm 30)$ MeV at $\rho = \rho_0$. The corresponding imaginary part is $\text{Im}V_{\text{opt}} = -\langle v_{\bar{p}N} \sigma_{\text{tot}} \rangle \rho$. At $\rho = \rho_0$ this gives $\text{Im}V_{\text{opt}} \simeq -(100 - 110)$ MeV independent of the choice of ξ . It is interesting that the BNL [?] and Serpukhov [?] data at $p_{\text{lab}} = 1.6 - 20$ GeV/c favor $\xi = 1$, i.e. $\text{Re}V_{\text{opt}} \simeq -660$ MeV at $\rho = \rho_0$. This discrepancy needs to be clarified, which could possibly be done at FAIR.

[Figure 3: see original paper] displays the calculated momentum spectra of positive pions and protons for antiproton interactions at $p_{\text{lab}} = 608$ MeV/c with carbon and uranium targets. GiBUU reproduces the 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. The best agreement is reached for $\xi = 0.3$, i.e., for $\text{Re}V_{\text{opt}} \simeq -(220 \pm 70)$ MeV.

IV. SELFCONSISTENCY EFFECTS

The strong attraction of an antiproton to the nucleus must influence the nucleus itself. This back-coupling effect can be taken into account by including the antinucleon contributions in the source terms of the Lagrange equations for ω -, ρ -, and σ -fields:

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

$$(\partial_\mu \partial^\mu + m_\rho^2) \rho_3^\nu(x) = \sum_{j=N, \bar{N}} g_{\rho j} \langle \bar{\psi}_j(x) \gamma^\nu \tau_3 \psi_j(x) \rangle,$$

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

with $U(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4$, or in other words, by treating the meson fields self-consistently. As follows from Eqs. (4) and (8)-(10), nucleons and antinucleons contribute with opposite sign to the source terms of the vector fields ω and ρ , and with the same sign to the source term of the scalar field σ . Hence, repulsion is reduced and attraction is enhanced in the presence of an antiproton in the nucleus.

[Figure 4: see original paper] shows the density profiles of nucleons and an antiproton at different times when the \bar{p} is implanted at $t = 0$ in the center of

the ^{40}Ca nucleus. As a consequence of the pure Vlasov dynamics of the coupled antiproton-nucleus system (annihilation is turned off), both the nucleon and 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 $\rho \simeq 2\rho_0$.

[Figure 5: see original paper] displays the time evolution of the central nucleon density. The \bar{p} annihilation is simulated at time t_{ann} . The case $t_{\text{ann}} = 0$ corresponds to the usual annihilation of a stopped \bar{p} in the nuclear center. In this case, the nucleon density remains close to the 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 ($\rho \lesssim 0.6\rho_0$), where the sound velocity squared $c_s^2 = \partial P / \partial \rho|_{s=\text{const}}$ becomes negative. 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_{inv} of emitted mesons:

$$M_{\text{inv}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \mathbf{p}_i\right)^2}.$$

For the annihilation of a stopped antiproton on a proton at rest in vacuum, $M_{\text{inv}} = 2m_N$. In a nuclear medium, the proton and antiproton vector fields largely cancel each other. Therefore, it is expected that in the nuclear medium the peak will appear at $M_{\text{inv}} \simeq 2m_N^*$. This simple picture is illustrated by GiBUU calculations in [Figure 6: see original paper]. In calculations where $t_{\text{ann}} = 0$, we clearly see a sharp medium-modified peak shifted downwards by $\simeq 200$ MeV from $2m_N$. The final state interactions of mesons create a broad maximum at $M_{\text{inv}} \simeq 1$ 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_{inv} . This effect becomes stronger with decreasing mass of the target nucleus (e.g., for ^{16}O the spectrum shift is nearly 500 MeV [?]).

V. STRANGENESS PRODUCTION

Originally, the main motivation of experiments on strangeness production in antiproton-nucleus collisions was to find signs of unusual phenomena, particularly multinucleon annihilation and/or quark-gluon plasma (QGP) formation. In Ref. [?], cold QGP formation was suggested to explain the unusually large ratio $\Lambda/K_S^0 \simeq 2.4$ measured in the reaction $\bar{p}^{181}\text{Ta}$ at 4 GeV/c [?]. On the other hand, in Refs. [?, ?, ?, ?] most features of strangeness production in $\bar{p}A$ reactions have been explained by hadronic mechanisms.

[Figure 7: see original paper] presents the rapidity spectrum of $(\Lambda + \Sigma^0)$ hyperons, K_S^0 mesons, and $(\bar{\Lambda} + \bar{\Sigma}^0)$ antihyperons for $\bar{p}(4 \text{ GeV}/c) + ^{181}\text{Ta}$ collisions in

comparison with data [?] and intranuclear cascade (INC) calculations [?]. The GiBUU model underpredicts hyperon yields at small forward rapidities $y \simeq 0.5$ and overpredicts K_S^0 yields. In the GiBUU calculation without hyperon-nucleon scattering, the $(\Lambda + \Sigma^0)$ spectrum is shifted to forward rapidities. However, the problem of underpredicted total $(\Lambda + \Sigma^0)$ yield remains. A more detailed analysis [?] shows that 72% of Y and Y^* production rates in GiBUU are due to antikaon absorption processes $\bar{K}B \rightarrow YX$, $\bar{K}B \rightarrow Y^*$, and $\bar{K}B \rightarrow Y^*\pi$. The second largest contribution, 23% of the rate, is caused by nonstrange meson-baryon collisions. The antibaryon-baryon (including the direct $\bar{p}N$ channel) and baryon-baryon collisions contribute only 3% and 2%, respectively, to the same rate. The underprediction of the hyperon yield in GiBUU could be due to the used partial $\bar{K}N$ cross sections, particularly the problematic K^-n channel. The possible in-medium enhancement of hyperon production in antikaon-baryon collisions is also not excluded.

As shown in [Figure 8: see original paper], at higher beam momenta the agreement between calculations and data on neutral strange particle production becomes visibly better. The 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 Ξ ($S = -2$) hyperon production. Direct production of Ξ in collisions of nonstrange particles would require producing two $s\bar{s}$ pairs simultaneously. Thus, Ξ production could be even more strongly enhanced in a QGP compared to enhancement for $S = -1$ hyperons. [Figure 9: see original paper] shows the rapidity spectra of different strange particles in $\bar{p}+^{197}\text{Au}$ collisions at 15 GeV/c. Even at such 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 contribution ($\sim 18\%$) to Ξ production is given by endothermic double strangeness exchange reactions $\bar{K}N \rightarrow \Xi K$. 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 Ξ 's are shifted forward with respect to the Λ rapidity spectra. However, in the QGP fireball scenario [?], the rapidity spectra of all strange particles would be peaked at the same rapidity.

VI. SUMMARY

This work focused on the dynamics of a coupled antiproton-nucleus system and strangeness production in $\bar{p}A$ interactions. The calculations were based on the GiBUU transport model. The main results can be summarized as follows: The reproduction of experimental data on $\bar{p}A$ absorption cross sections at $p_{\text{lab}} < 1$ GeV/c and on π^+ and p production at $p_{\text{lab}} = 608$ MeV/c requires a strongly attractive $\bar{p}A$ optical potential, $\text{Re}V_{\text{opt}} \simeq -(150 - 200)$ MeV at $\rho = \rho_0$. As a response of a nucleus to the presence of an antiproton, the nucleon density can be increased locally up to $\rho \sim (2 - 3)\rho_0$ near the \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 a substantial ($\sim 300 - 500$ MeV) shift of the 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, strangeness production remains to be better understood (overestimated K_S^0 and underestimated $(\Lambda + \Sigma^0)$ production). The forward rapidity shift of Ξ hyperons with respect to Λ is suggested as a test of hadronic and QGP mechanisms of strangeness production in $\bar{p}A$ reactions.

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Note: Figure translations are in progress. See original paper for figures.

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