

TRANSPORT CALCULATIONS OF $\bar{p}$ -NUCLEUS INTERACTIONS*

A.B. LARIONOV^{a,b,†}, I.N. MISHUSTIN^{a,c}, I.A. PSHENICHNOV^{a,d}
L.M. SATAROV^{a,c}, W. GREINER^a

^aFrankfurt Institute for Advanced Studies, J.W. Goethe-Universität
60438 Frankfurt am Main, Germany

^bInstitut für Theoretische Physik, Universität Giessen, 35392 Giessen, Germany

^cRussian Research Center Kurchatov Institute, 123182 Moscow, Russia

^dInstitute for Nuclear Research, Russian Academy of Science
117312 Moscow, Russia

(Received December 1, 2009)

The Giessen Boltzmann–Uehling–Uhlenbeck transport model is extended and applied to the $\bar{p}$ -nucleus interactions in a wide beam momentum range. The model calculations are compared with the experimental data on $\bar{p}$ -absorption cross-sections on nuclei with an emphasis on extraction of the real part of an antiproton optical potential. The possibility of the cold compression of a nucleus by an antiproton in-flight is also considered.

PACS numbers: 25.43.+t, 21.30.Fe, 24.10.Lx, 24.10.-i

1. Introduction

Antiproton interactions with nuclei are of big interest since they deliver the information on in-medium $\bar{p}N$ interactions [1] related to the antiproton optical potential. The real and imaginary parts of $\bar{p}$ optical potential close to the nuclear centre are still poorly known [2, 3]. As shown in [4–7], a deep enough real part, $\text{Re}(V_{\text{opt}}) = -(150\text{--}200)$ MeV, might cause sizeable compressional effects in $\bar{p}$ -doped nuclei.

Here, we present some results of the microscopic transport simulations within the Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) model [8]. Our goal is twofold: *(i)* to determine the $\bar{p}$ optical potential by comparison with the data on $\bar{p}$ absorption cross-sections on nuclei; *(ii)* to evaluate the probability of $\bar{p}$ annihilation in a compressed nuclear zone for the beam momenta 0.1–10 GeV/ c .

* Presented at the XXXI Mazurian Lakes Conference on Physics, Piaski, Poland, August 30–September 6, 2009.

† larionov@fias.uni-frankfurt.de

The model is described in Sec. 2. In Secs. 3 and 4, the calculations of $\bar{p}$ absorption cross-section on nuclei and of the dynamical compression of the ^{16}O nucleus by moving antiproton are presented. The results are summarized in Sec. 5.

2. The GiBUU model

The GiBUU model [8] solves the coupled set of kinetic equations for different hadrons ($N, \bar{N}, \Delta, \bar{\Delta}, \pi \dots$). These equations describe the time evolution of a system governed by the two-body collisions and resonance decays. The Pauli blocking for the nucleons in the scattering final states is accounted for. Between the two-body collisions, the particles propagate according to the Hamiltonian-like equations in the mean field potentials defined by the (anti)baryon densities and currents.

We use the GiBUU model in the relativistic mean field mode. The single-particle energies $\epsilon_i = V_i^0 + \sqrt{\mathbf{p}_i^{*2} + m_i^{*2}}$ of the nucleons ($i = N$) and antinucleons ($i = \bar{N}$) depend on the effective mass $m_i^* = m_i + S_i$, where $S_i = g_{\sigma i}\sigma$ is the scalar field, kinetic three-momentum $\mathbf{p}_i^* = \mathbf{p} - \mathbf{V}_i$, and vector field $V_i^\mu = g_{\omega i}\omega^\mu + g_{\rho i}\tau^3\rho^{3\mu} + e_i A^\mu$. Here, σ , ω , ρ and A are, respectively, the isoscalar-scalar, isoscalar-vector and isovector-vector meson fields, and the electromagnetic field.

The meson-nucleon coupling constants $g_{\sigma N}$, $g_{\omega N}$ and $g_{\rho N}$ are taken from the NL3 set of parameters [9] of a non-linear Walecka model. The meson-antinucleon coupling constants are motivated by the G -parity transformation, however, allowing for their strengths to be rescaled by a factor $0 < \xi \leq 1$ as $g_{\sigma \bar{N}} = \xi g_{\sigma N}$, $g_{\omega \bar{N}} = -\xi g_{\omega N}$ and $g_{\rho \bar{N}} = \xi g_{\rho N}$ ¹.

The following two-body collision processes involving an antinucleon are implemented in the model: elastic scattering and charge exchange $\bar{N}N \rightarrow \bar{N}N$, inelastic production $\bar{N}N \rightarrow \bar{B}B + \text{mesons}$, and annihilation $\bar{N}N \rightarrow \text{mesons}$. Further details of the model can be found in [6, 8, 10–12] and in references therein.

3. Antiproton absorption and annihilation on nuclei

Fig. 1 shows the antiproton absorption cross-section on ^{12}C . The GiBUU calculation without nuclear part of the antibaryon mean field ($\xi = 0$) is in a very close agreement with the Glauber model prediction [13]².

¹ Pure G -parity transformed nuclear fields are obtained with $\xi = 1$, but this leads to an unrealistically deep real part of the $\bar{p}$ optical potential, $\text{Re}(V_{\text{opt}}) \simeq -660$ MeV.

² Except for momenta less than ~ 0.2 GeV/ c , where the Coulomb potential causes the deviation.

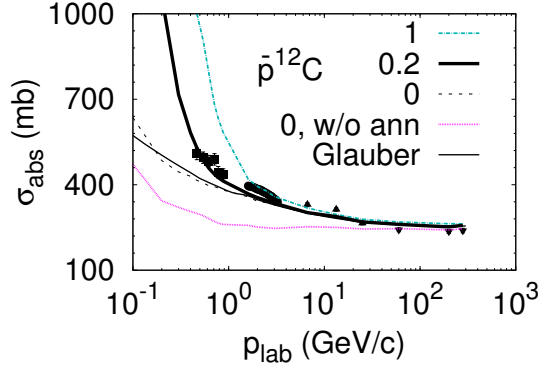


Fig. 1. (Color online) Beam momentum dependence of the antiproton absorption cross-section on ^{12}C . GiBUU calculations are represented by the curves denoted by the value of the scaling factor ξ of meson–antibaryon coupling constants. The results obtained using the Glauber model [13] are shown by thin solid line. The calculation with $\xi = 0$ without annihilation is shown by dotted line. Experimental data are from [2].

The attractive real part of an antiproton optical potential

$$\text{Re}(V_{\text{opt}}) = S_{\bar{p}} + V_{\bar{p}}^0 + \frac{S_{\bar{p}}^2 - (V_{\bar{p}}^0)^2}{2m_N} \quad (1)$$

bends the $\bar{p}$ trajectory towards the nuclear centre and increases the $\bar{p}$ absorption cross-section. One can see from Fig. 1, that the finite values of the scaling factor $\xi \simeq 0.2$ are needed to describe the antiproton absorption cross-section data at $p_{\text{lab}} = 470\text{--}880$ MeV/c measured at KEK [2]. The best fit of the data [2] on $\bar{p}$ absorption cross-sections on the ^{12}C , ^{27}Al and ^{64}Cu nuclei by GiBUU calculations is reached with $\xi \simeq 0.21 \pm 0.03$, which produces $\text{Re}(V_{\text{opt}}) \simeq -(150 \pm 30)$ MeV in the nuclear centre.

The imaginary part of the $\bar{p}$ optical potential can be calculated as

$$\text{Im}(V_{\text{opt}}) = -\frac{1}{2} \left\langle v_{\bar{p}N} \sigma_{\text{tot}}^{\text{med}} \right\rangle \rho_N, \quad (2)$$

where $v_{\bar{p}N}$ is the relative velocity of the antiproton and a nucleon; $\sigma_{\text{tot}}^{\text{med}}$ is the total $\bar{p}N$ cross-section including the in-medium effect of Pauli blocking for the final state nucleon in the $\bar{N}N \rightarrow \bar{N}N$ channel; ρ_N is the local nucleon density. The averaging in Eq. (2) is taken with respect to the nucleon Fermi distribution. Using (2), we obtain $\text{Im}(V_{\text{opt}}) \simeq -(105 \pm 5)$ MeV in the nuclear centre, where a small uncertainty is due to different considered nuclei. More details on the extraction of an antiproton optical potential by GiBUU calculations can be found in [12].

4. Dynamical compression of a nucleus by an antiproton

Fig. 2 shows the time evolution of nucleon and antiproton densities for the case of an antiproton initialized at the nuclear periphery with momentum of 0.3 GeV/ c directed towards the nuclear centre. The calculation has been done without the $\bar{N}N$ annihilation channel in the collision term, but allowing for the $\bar{N}N$ and NN scattering. We observe that the antiproton attracts surrounding nucleons catching them into a potential well of about 70–100 MeV depth. The nucleon density bump moves with the $\bar{p}$ or slightly behind it due to some delay in the reaction of the nucleon density on the perturbation created by the antiproton.

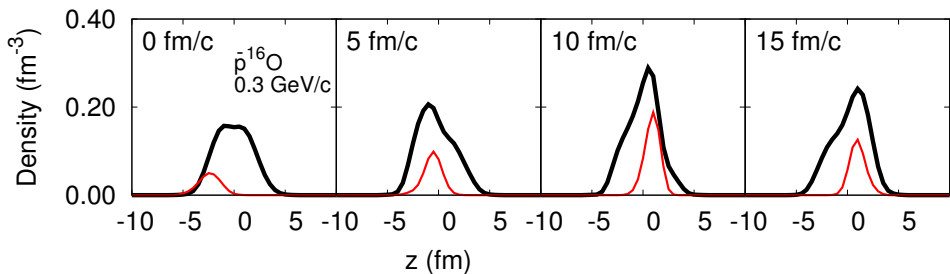


Fig. 2. (Color online) Nucleon (thick solid lines) and antiproton (thin solid lines) densities along the z -axis passing through the nuclear centre $(x, y, z) = (0, 0, 0)$ for the $\bar{p}^{16}\text{O}$ system at different times. The antiproton has been initialized at the coordinates $(0, 0, -2.5)$ fm with momentum components $(0, 0, 0.3)$ GeV/ c . The scaling factor of the antiproton–meson coupling constants $\xi = 0.22$ is used. Annihilation is switched-off.

The compression process of Fig. 2 has to be complemented with the calculation of an antiproton survival probability

$$P_{\text{surv}}(t) = \exp \left\{ - \int_0^t dt' \Gamma_{\text{ann}}(t') \right\}, \quad (3)$$

where $\Gamma_{\text{ann}} = \rho_N \langle v_{\bar{p}N} \sigma_{\text{ann}} \rangle$ is the antiproton annihilation width and σ_{ann} is the $\bar{p}N$ annihilation cross-section (other notations are the same as in Eq. (2)). In the case of the process shown in Fig. 2, the antiproton survives with the probability $P_{\text{surv}} \sim 10^{-3}$ at the time 10 fm/ c when the nucleon density maximum is reached. The experimental detection of the nuclear compression by the antiproton is only possible, if $\bar{p}$ annihilates in the compressed zone of a nucleus. The corresponding probability is $P_{\text{compr}}(\rho_c) = P_{\text{surv}}(t_1) - P_{\text{surv}}(t_2)$, where $t_1 < t_2$ are the times delimiting

the time interval, when the maximum density of a nuclear system exceeds some preselected value ρ_c . In concrete calculations, we set $\rho_c = 2\rho_0$ with $\rho_0 = 0.148 \text{ fm}^{-3}$ being the nuclear saturation density.

In the case of a real antiproton–nucleus collision, we apply, first, the GiBUU model in the standard parallel ensemble mode to determine the coordinates $\mathbf{r}$ and momentum $\mathbf{p}$ of the antiproton at its annihilation time moment event-by-event. Next, we initialize $\bar{p}$ at $(\mathbf{r}, \mathbf{p})$ and run GiBUU without annihilation. This allows us to compute P_{compr} for a given annihilation event, *i.e.* to determine the probability that this event will take place in a compressed nuclear zone. Finally, we calculate the cross-section of a $\bar{p}$ annihilation in the compressed zone by weighting with the impact parameter as $\sigma_{\text{compr}} = \int_0^\infty db 2\pi b \bar{P}_{\text{compr}}(\rho_c, b)$, where the upper line denotes averaging over annihilation events with a given impact parameter b .

In Fig. 3, we present the probability of $\bar{p}$ annihilation in a compressed zone given by the ratio $\sigma_{\text{compr}}/\sigma_{\text{ann}}$, where σ_{ann} is the total annihilation cross-section of $\bar{p}$ on the oxygen nucleus. The rise of the ratio with the beam momentum between about 1 and 3 GeV/c is caused by opening the pion production channels $\bar{N}N \rightarrow \bar{N}N\pi(\pi\dots)$, which leads to more intensive stopping of an antibaryon before annihilation, and, therefore, to larger compression probabilities.

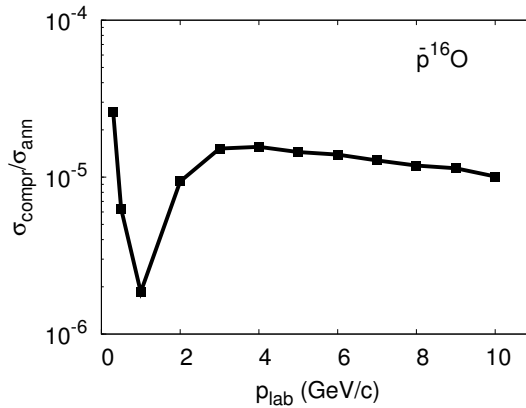


Fig. 3. The probability of antiproton annihilation at the nucleon density exceeding $2\rho_0$ as a function of the beam momentum for $\bar{p}^{16}\text{O}$ collisions.

5. Summary and conclusions

We have performed the microscopic transport GiBUU simulations of $\bar{p}$ -nucleus collisions. The antiproton mean field potential has been described applying the non-linear Walecka model supplemented by appropriate scaling of the meson–antinucleon coupling constants.

The extracted antiproton optical potential from comparison with the KEK data on $\bar{p}$ absorption cross-section below 1 GeV/ c is $V_{\text{opt}} = -(150 \pm 30) - i(105 \pm 5)$ MeV in the nuclear centre, which is comparable with the well known phenomenological values [2,3]. However, the BNL and Serpukhov data on $\bar{p}$ absorption above 1 GeV/ c require much deeper real part of about -660 MeV, close to the G -parity value. It is important, therefore, to perform the new measurements of the $\bar{p}$ absorption cross-section on nuclei above 1 GeV/ c at FAIR.

The probability of the antiproton annihilation in a compressed nuclear zone is maximal at the beam momenta below 0.5 GeV/ c . However, it is also big enough ($\sim 10^{-5}$) at the beam momenta from 3 to 10 GeV/ c . The possibility of additional triggering, *e.g.* on a high-momentum proton, would prefer this beam momentum range with respect to the low beam momenta for the study of annihilation events in the compressed nuclear zone.

This work was (financially) supported by the Helmholtz International Center for FAIR within the framework of the LOEWE program (Landesoffensive zur Entwicklung Wissenschaftlich-Ökonomischer Exzellenz) launched by the State of Hesse, by the DFG Grant 436 RUS 113/957/0-1 (Germany), and by the Grants NS-3004.2008.2 and RFBR-09-02-91331 (Russia).

REFERENCES

- [1] E. Friedman, A. Gal, *Phys. Rep.* **452**, 89 (2007).
- [2] K. Nakamura *et al.*, *Phys. Rev. Lett.* **52**, 731 (1984).
- [3] E. Friedman, A. Gal, J. Mareš, *Nucl. Phys.* **A761**, 283 (2005).
- [4] T. Bürvenich, I.N. Mishustin, L.M. Satarov, J.A. Maruhn, H. Stöcker, W. Greiner, *Phys. Lett.* **B542**, 261 (2002).
- [5] I.N. Mishustin, L.M. Satarov, T.J. Bürvenich, H. Stöcker, W. Greiner, *Phys. Rev.* **C71**, 035201 (2005).
- [6] A.B. Larionov, I.N. Mishustin, L.M. Satarov, W. Greiner, *Phys. Rev.* **C78**, 014604 (2008).
- [7] I.N. Mishustin, A.B. Larionov, *Hyperfine Interact.* **194**, 263 (2009).
- [8] <http://gibuu.physik.uni-giessen.de/GiBUU>
- [9] G.A. Lalazissis, J. König, P. Ring, *Phys. Rev.* **C55**, 540 (1997).
- [10] B. Blättel, V. Koch, U. Mosel, *Rep. Prog. Phys.* **56**, 1 (1993).
- [11] T. Gaitanos, H. Lenske, U. Mosel, *Phys. Lett.* **B675**, 297 (2009).
- [12] A.B. Larionov, I.A. Pshenichnov, I.N. Mishustin, W. Greiner, *Phys. Rev.* **C80**, 021601(R) (2009).
- [13] R.J. Glauber, G. Matthiae, *Nucl. Phys.* **B21**, 135 (1970).