Physics Letters B 705 (2011) 235–239

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Antinucleus–nucleus cross sections implemented in Geant4

V. Uzhinsky [a,b,*,1], J. Apostolakis [a,1], A. Galoyan [c,1], G. Folger [a,1], V.M. Grichine [d,1], V.N. Ivanchenko [a,e,1], D.H. Wright [f,1]

[a] CERN, Geneva, Switzerland
[b] LIT, JINR, Dubna, Russia
[c] VBLHEP, JINR, Dubna, Russia
[d] Lebedev Physical Institute of RAS, Moscow, Russia
[e] Ecoanalytica, MSU, Moscow, Russia
[f] SLAC National Accelerator Laboratory, Stanford, CA, USA

ARTICLE INFO

Article history:
Received 20 June 2011
Received in revised form 29 September 2011
Accepted 6 October 2011
Available online 8 October 2011
Editor: V. Metag

ABSTRACT

Cross sections of antinucleus ($\bar{p}$, $\bar{d}$, $\bar{t}$, $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$) interactions with nuclei in the energy range 100 MeV/c to 1000 GeV/c per antinucleon are calculated in the Glauber approximation which provides good description of all known $\bar{p}A$ cross sections. The results were obtained using a new parameterization of the total and elastic $\bar{p}p$ cross sections. Simple parameterizations of the antinucleus–nucleus cross sections are proposed for use in estimating the efficiency of antinucleus detection and tracking in cosmic rays and accelerator experiments. These parameterizations are implemented in the Geant4 toolkit.

One of the most exciting puzzles in cosmology is connected with the question of the existence of antimatter in the Universe. Some cosmic ray experiments aim to search for antinuclei [1–4]. Antinuclei have also been observed in nucleus–nucleus and proton–proton collisions at accelerators by the RHIC [5–7] and LHC Collaborations [8]. The conventional point of view is that they are produced in high energy interactions due to the coalescence of antibaryons; thus their yields and properties reflect conditions at the freeze-out of the hot hadronic matter created in hadron–hadron and nucleus–nucleus collisions. The statistical model of multi-particle production predicts the creation of antinuclei [9] in the interactions assuming a hadro-chemical equilibrium at the freeze-out. It is possible, however, that systems containing many antiquarks (antinuclei) can be produced from the vacuum due to the fragmentation of partons.[2] One must should explore whether other possibilities exist as well. Thus, it is clear that the phenomenon has to be carefully studied both in experiment and theory.

An experimental study of antinucleus production requires a knowledge of antinucleus interaction cross sections with matter. The cross sections are needed to estimate various experimental corrections, especially those due to particle losses which reduce the detected rate. In practice, various phenomenological approaches are applied in order to estimate the antinucleus–nucleus cross sections [5,6,10–13]. Having no antinucleus beams and therefore no opportunity to measure the cross sections, it seems reasonable to calculate the cross sections using theoretical approaches. The aim of our Letter is to describe how these estimates were obtained using the Glauber approach, and how they were prepared for use as a part of the Geant4 toolkit [14].

Antiproton elastic scattering by deuterons was considered in the classic paper by V. Franco and R.J. Glauber [15]. O.D. Dalkarov and V.A. Karmanov [16] showed that elastic and inelastic (with excitation of nuclear levels) antiproton scattering by C, Ca, and Pb nuclei are described quite well for $\bar{p}$ kinetic energies above 46.8 MeV. The first calculations of the cross sections of antideuteron interactions with nuclei in the eikonal approximation were presented by Buck et al. [17] (see also [18]). Cross sections of antideuteron–deuteron interactions at $P_{\bar{d}} = 12.2$ GeV/c were calculated using the Glauber approach in [19]. They were in good agreement with the experimental data. Thus, it is natural to use the Glauber approach to calculate the antinucleus–nucleus cross sections.

The amplitude for an elastic scattering of an antinucleus containing B antibaryons on a target nucleus with mass number A is given as [20]:

* Corresponding author at: CERN, Geneva, Switzerland.
E-mail address: Vladimir.Uzhinskiy@cern.ch (V. Uzhinsky).
1 On behalf of the Geant4 Collaboration.
2 The authors are thankful to N. Kochelev for consideration of this subject, especially regarding the instanton mechanism of antinucleus production.

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2011.10.010

$$F_{BA}(\vec{q}) = \frac{i}{2\pi}\int d^2b\, e^{i\vec{q}\vec{b}}\left\{1-\prod_{i=1}^{B}\prod_{j=1}^{A}\left[1-\gamma(\vec{b}+\vec{\tau}_i-\vec{s}_j)\right]\right\}$$
$$\times |\Psi_B|^2|\Psi_A|^2\left(\prod_{i=1}^{B}d^3t_i\right)\left(\prod_{j=1}^{A}d^3r_j\right)$$
$$= i\int_0^\infty b P_{BA}(b) J_0(qb)\,db, \quad (1)$$

where γ is the amplitude of an elastic antinucleon–nucleon scattering in the impact parameter representation, averaged over the spin and isospin degrees of freedom,

$$\gamma(\vec{b}) = \frac{1}{2\pi i}\int d^2q\, e^{i\vec{q}\vec{b}} F_{\bar{N}N}(\vec{q}).$$

Ψ_A (Ψ_B) is the wave function of the nucleus (antinucleus) in the ground state. Taking the origins of the coordinate systems to coincide with the centers of the nuclei, the nucleon coordinates ($\{\vec{r}_A\}$, $\{\vec{t}_B\}$) are decomposed into longitudinal ($\{z_i\}$) and transverse ($\{\vec{s}_j\}$, $\{\vec{\tau}_i\}$) components. The z-axis is directed along the projectile momentum. $\vec{b}$ is the impact parameter vector orthogonal to the momentum. $P_{BA}(b)$ is the profile function and J_0 is the Bessel function of zero order.

The amplitude is normalized so that the differential elastic scattering cross section can be written as:

$$d^2\sigma/dq^2 = \left|F_{BA}(\vec{q})\right|^2,$$

where $\vec{q}$ is the momentum transfer ($t=-\vec{q}^2$). The corresponding total cross section is $\sigma_{BA}^{tot} = 4\pi\,\mathrm{Im}\,F_{BA}(0)$.

Quite often γ is parameterized as[3]:

$$\gamma(\vec{b}) = \frac{\sigma_{\bar{N}N}^{tot}(1-i\rho)}{4\pi\beta}e^{-\vec{b}^2/2\beta}, \quad (2)$$

where $\sigma_{\bar{N}N}^{tot}$ is the total cross section of the antinucleon–nucleon interactions, ρ is the ratio of the real to imaginary parts of the $\bar{N}N$ elastic scattering amplitude at zero momentum transfer, and β is the slope parameter of the $\bar{N}N$ differential elastic scattering cross section. Then

$$F_{\bar{N}N}(\vec{q}) = \frac{i}{4\pi}\sigma_{\bar{N}N}^{tot}(1-i\rho)e^{-\beta\vec{q}^2/2}, \quad (3)$$

where β is:

$$\beta = \left(\sigma_{\bar{N}N}^{tot}\right)^2\left(1+|\rho|^2\right)/\left(16\pi\sigma_{\bar{N}N}^{el}0.3897\right).$$

Here, $\sigma_{\bar{N}N}^{el}$ is the $\bar{N}N$ elastic cross section and 0.3897 is a coefficient required in order to express β in units of $(\mathrm{GeV}/c)^{-2}$, if the cross sections are given in millibarns.

The squared modulus of the wave function is usually written as:

$$|\Psi_A|^2 = \delta\left(\sum_{i=1}^{A}\vec{r}_i/A\right)\prod_{i=1}^{A}\rho_A(\vec{r}_i). \quad (4)$$

ρ_A coincides with the one-particle density of the nucleus if one neglects the center-of-mass correlation connected with the δ-function. The densities for heavy nuclei were chosen to have the standard Woods–Saxon distribution with the parameters given in [21]. The correlations were accounted for according to [22]. We use the Gaussian parameterization for light (t, ^{3}He, ^{4}He) nuclei and for the corresponding antinuclei:

$$\rho_A(\vec{r}_i) = \frac{1}{(\pi R_A)^{3/2}}e^{-\vec{r}^2/R_A^2},$$
$$R_{^3\mathrm{H}} = R_{^3\mathrm{He}} = 1.81\ (\mathrm{fm}), \qquad R_{^4\mathrm{He}} = 1.37\ (\mathrm{fm}).$$

The squared modulus of the (anti) deuteron wave function was chosen as the sum of three gaussians [23].

Many approximations have been proposed in order to simplify the calculation of P_{hA} and P_{BA}. Most effective is a method proposed in [24], in which the amplitude is found as an average over various samples of the nucleon coordinates:

$$P_{BA}(\vec{b}) \simeq \frac{1}{N}\sum_{\alpha=1}^{N}\left\{1-\prod_{i=1}^{B}\prod_{j=1}^{A}\left[1-\gamma\left(\vec{b}+\vec{\tau}_j^{\alpha}-\vec{s}_i^{\alpha}\right)\right]\right\}, \quad (5)$$

where N is the volume of the samples. The nucleon coordinates are sampled according to the measure $|\Psi_B|^2|\Psi_A|^2$. The method consists of multiple sampling of the nucleon coordinates according to the function $|\Psi_B|^2|\Psi_A|^2$, calculation of the expression in braces of Eq. (5) for each sampling, and an averaging of the calculation results over the samples. This method is implemented in the DIAGEN code [24].

To run the code, the total and elastic $\bar{N}N$ cross sections $\sigma_{\bar{N}N}^{tot}$ and $\sigma_{\bar{N}N}^{el}$ should be provided. Following [25–27], we have parameterized $\sigma_{\bar{p}p}^{tot}$ as:

$$\sigma_{\bar{p}p}^{tot} = \sigma_{asymp}^{tot}\left[1+\frac{C}{\sqrt{s-4m_N^2}}\frac{1}{R_0^3}\left(1+\frac{d_1}{s^{1/2}}+\frac{d_2}{s^2}+\frac{d_3}{s^{3/2}}\right)\right],$$
$$\sigma_{asymp}^{tot} = 36.04+0.304\left[\ln(s/33.1)\right]^2 \quad [26]. \quad (6)$$

Here m_N is the nucleon mass (GeV); s (GeV^2) is the square of the collision energy in the center of mass system (CMS); C, d_1, d_2, d_3 are the parameters used by Arkhipov [27]. We determined the parameters C, d_1, d_2 and d_3, using a fit to experimental data [28], to be

$$C = 13.55 \pm 0.09\ \mathrm{GeV}^{-2},$$
$$d_1 = -4.47 \pm 0.02\ \mathrm{GeV},$$
$$d_2 = 12.38 \pm 0.05\ \mathrm{GeV}^2,$$
$$d_3 = -12.43 \pm 0.05\ \mathrm{GeV}^3.$$

Also,

$$R_0^2 = 0.40874044\sigma_{asymp}^{tot} - B(s)\ \mathrm{GeV}^{-2} \quad [27],$$
$$B(s) = b_0 + b_1\left[\ln(\sqrt{s}/20.74)\right]^2\ \mathrm{GeV}^{-2},$$
$$b_0 = 11.92 \pm 0.15\ \mathrm{GeV}^{-2},$$
$$b_2 = 0.3036 \pm 0.0185\ \mathrm{GeV}^{-2} \quad [27].$$

Fig. 1 shows that the total $\bar{p}p$-interaction cross sections are described over a wide energy range. We note that there are many parameterizations of the total cross section, most of which are applicable at high energies ($\sqrt{s} > 5$ GeV). The expression for σ_{asymp}^{tot} from [26] is in agreement with them. At low energies there are few parameterizations only. A very interesting one was proposed by A.A. Arkhipov in [27] where a combination of the parameterizations was also considered. We used the high energy part of the cross sections from [26]. The method of connecting the high and

[3] The amplitude has to be corrected at low energies in order to take into account the unitarity requirement ($\mathrm{Re}\,\gamma(0) \leqslant 1$) and a restriction of the phase space.

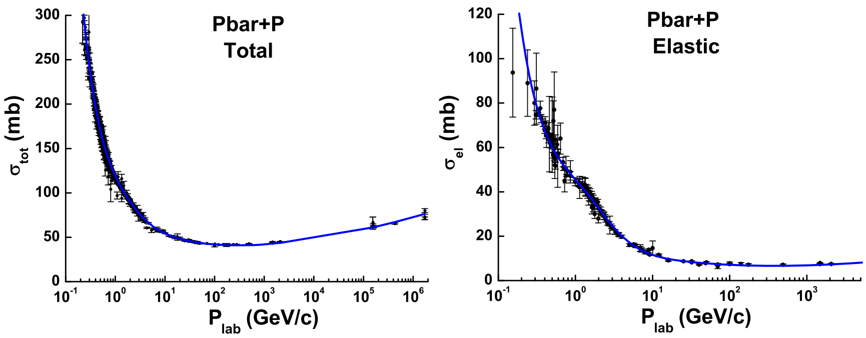

Fig. 1. Total and elastic cross sections of $\bar{p}p$-interactions. The points are experimental data from the PDG data base [28]. The lines are our parameterizations.

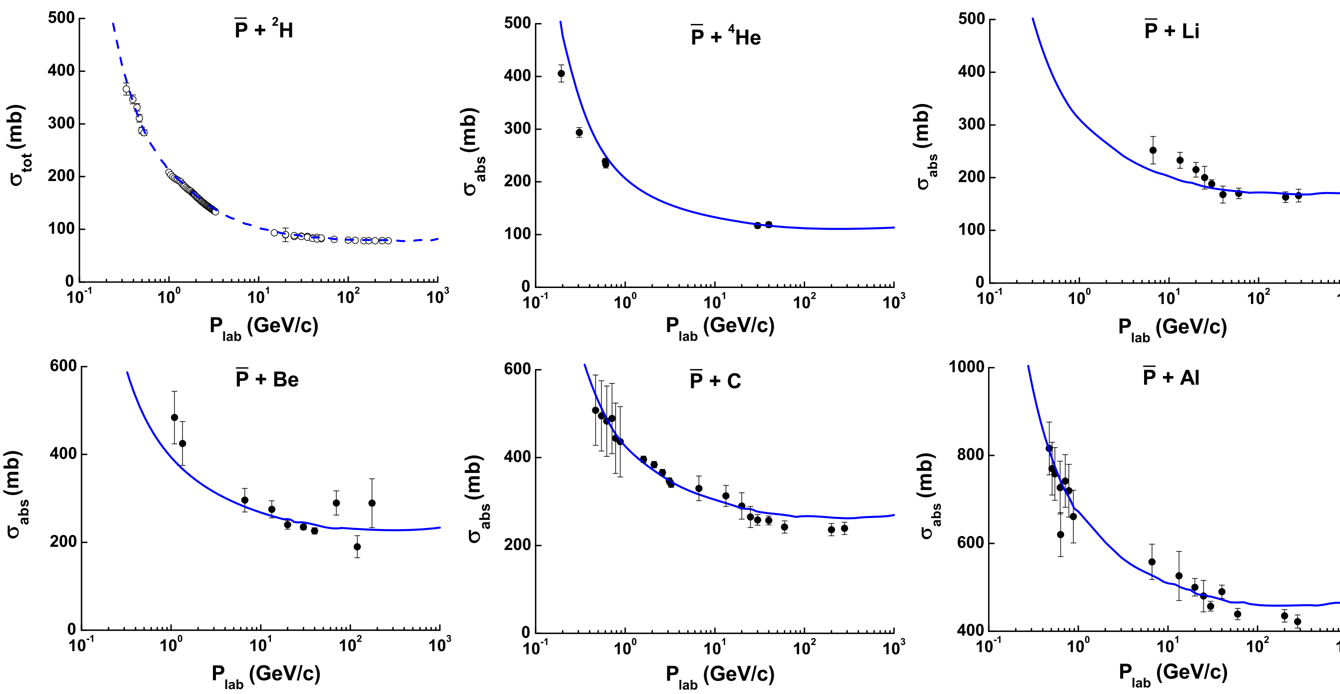

Fig. 2. Cross sections of antiproton interactions with light nuclei. The points are experimental data [31], the lines are our calculations.

low energy parts was taken from [27], but we refitted the parameters C, d_1, d_2 and d_3.

A more complicated situation occurs with the elastic cross section. There are essentially no good parameterizations available. Thus, we had to combine the approach given above with the quasi-eikonal approximation of the reggeon field theory [29], setting $\sigma^{el}_{asymp} = \sigma^{tot}_{asymp}/1.5$.

We determined the parameters for the elastic cross section, C, d_1, d_2 and d_3, using a fit to experimental data [28].

$$C = 59.3 \pm 2.0\ \mathrm{GeV}^{-2},$$

$$d_1 = -6.95 \pm 0.09\ \mathrm{GeV},$$

$$d_2 = 23.54 \pm 0.29\ \mathrm{GeV}^2,$$

$$d_3 = -25.34 \pm 0.36\ \mathrm{GeV}^3.$$

This parameterization is valid from 100 MeV/c up to 1000 GeV/c.

Fig. 1 shows that we describe the total and elastic $\bar{p}p$-interaction cross sections quite well. The slope parameter (β) is also reproduced. To estimate the quality of fit the χ^2-test is often used. For the elastic cross section fit, we have $\chi^2/NoF = 149/137$ and for the total cross section fit of selected data[4] we get $\chi^2/NoF = 1190/308$. At this, 396 data out of 444 points are in $\pm 5\%$ band around corresponding fitted values. We therefore estimate the accuracy of the parameterizations to be a 5%.

We believe that the quality of our parameterizations is sufficient for most experiments. However, problems may arise in the treatment of low energy interactions (below 50 MeV per antibaryon) which may be important when considering the contact of matter with antimatter.

Many tracking detectors consist of heavy materials. Thus, we have to estimate the antinucleus–nucleus cross sections over a broad range of elements. Before doing this, the approach used should be checked applying it to antiproton–nucleus cross sections. Our calculations of the antiproton–nucleus cross sections together with experimental data [31] are presented in Figs. 2 and 3. We assumed in the calculations that $\rho = 0$. In the figures, we denote the

[4] The fitting process considered only statistical errors of the data points. Systematical errors were ignored. Some data points have small statistical errors, but undefined systematical ones. Some of such points do not follow the trend of the majority of the data points. We remove these 136 points from the total sample each of them added at least 10 to χ^2. A detailed consideration of the data reduction see in [25,30].

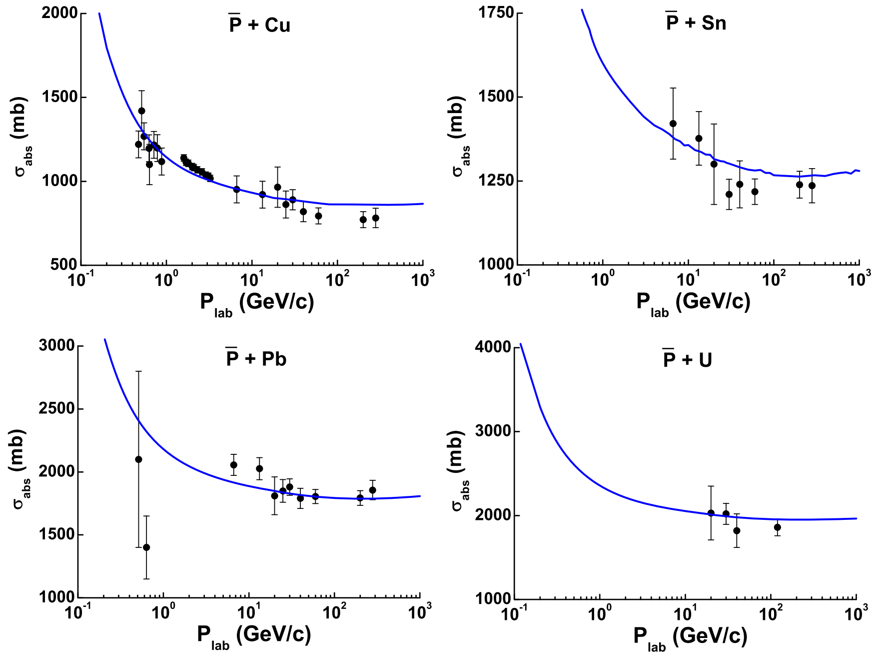

Fig. 3. Absorption cross sections of antiproton interactions with heavy nuclei. The points are experimental data [31], the lines are our calculations.

absorption cross sections, $\sigma^{tot}_{\bar{p}A} - \sigma^{el}_{\bar{p}A}$, by the solid lines. The dotted line gives the total cross sections for $\bar{p}d$-interactions. The points correspond to various experimental data [31].

As seen, our calculations agree with previous ones [15] for the total cross sections of the $\bar{p}d$-interactions. We also describe $\bar{p}d$ annihilation as well as elastic and quasi-elastic cross sections (not shown). For another light nucleus, ^{4}He, our results agree with the total and inelastic ($\sigma^{tot} - \sigma^{el}$) cross sections (only inelastic cross sections are shown). More detailed Glauber calculations for this nucleus are presented in [32]. The description of other experimental data for light and heavy target nuclei is sufficiently good, with $\chi^2/NoF = 258/112$ for the presented absorption cross sections, which corresponds to an accuracy of ~8%. We have analyzed nearly all available experimental data and no drastic discrepancy was found. Existing discrepancies can be explained by peculiarities in experimental conditions. For example, the so-called "annihilation" cross section quite often includes a part of the quasi-elastic scattering without multi-particle production and change of the projectile. In general, we believe that the precision of the calculations is sufficient for the simulation of transportation in matter.[5]

Corrections to the Glauber approach would be needed at low and very high energies. The most important ones at high energies are connected with the inelastic intermediate states (IIS) in hadron penetration through a nucleus [33]. They give 5–7% corrections to the nucleon–nucleus total cross sections (see, for example, [34–36]). They have a minor effect on the inelastic cross sections. We have verified that this is also true for nucleus–nucleus interactions. An extension of the approach to the very high energy domain can be found in [37].

Various corrections to the Glauber approximation are considered at low and intermediate energies ($P_{lab} < 1$ GeV/c). Interesting ones are due to the modification of the NN-scattering amplitude in the nuclear medium [38]. Another is the deviation in the projectile trajectories due to strong Coulomb fields [39,40]. These can be important when considering elastic antinucleus–nucleus scattering. For a short review of the possibilities in the low energy domain see [41].

Our predictions for antinucleus–nucleus cross sections are presented in Fig. 4. From many possible materials, we have chosen iron and lead as the materials most often used in calorimetric studies.

Direct application of the Glauber approach in software packages like GEANT4 [14] in a run-time mode is ineffective due to the large number of numerical integrations. Thus, a parameterization of the calculated results should be used. In papers [42,43], the following expressions for the total and inelastic hadron–nucleus and nucleus–nucleus cross sections were proposed:

$$\sigma^{tot}_{hA} = 2\pi R_A^2 \ln\left[1 + \frac{A\sigma^{tot}_{hN}}{2\pi R_A^2}\right],$$

$$\sigma^{in}_{hA} = \pi R_A^2 \ln\left[1 + \frac{A\sigma^{tot}_{hN}}{\pi R_A^2}\right], \tag{7}$$

$$\sigma^{tot}_{BA} = 2\pi\left(R_B^2 + R_A^2\right) \ln\left[1 + \frac{BA\sigma^{tot}_{NN}}{2\pi(R_B^2 + R_A^2)}\right],$$

$$\sigma^{in}_{BA} = \pi\left(R_B^2 + R_A^2\right) \ln\left[1 + \frac{BA\sigma^{tot}_{hN}}{\pi(R_B^2 + R_A^2)}\right], \tag{8}$$

where R_A and R_B are the nucleus radii. Due to simplifications made in [42,43] the radii cannot be directly connected with known values. Thus, we consider the expressions (7) and (8) as equations for the determination of R_A, having calculated $\sigma_{\bar{p}A}$ and $\sigma_{\bar{B}A}$ in the Glauber approach for given projectile and target nuclei. The following parameterizations for R_A were obtained for the total cross sections:

$$\bar{p}A \; R_A = 1.34A^{0.23} + 1.35/A^{1/3} \text{ (fm)}, \tag{9}$$

$$\bar{d}A \; R_A = 1.46A^{0.21} + 1.45/A^{1/3} \text{ (fm)}, \tag{10}$$

$$\bar{t}A \; R_A = 1.40A^{0.21} + 1.63/A^{1/3} \text{ (fm)}, \tag{11}$$

$$\bar{\alpha}A \; R_A = 1.35A^{0.21} + 1.10/A^{1/3} \text{ (fm)}. \tag{12}$$

[5] A study of the structure of exotic nuclei (^{6}He, ^{11}Li and so on) may require more precise calculations if one assumes that the usage of antiproton beams would be helpful.

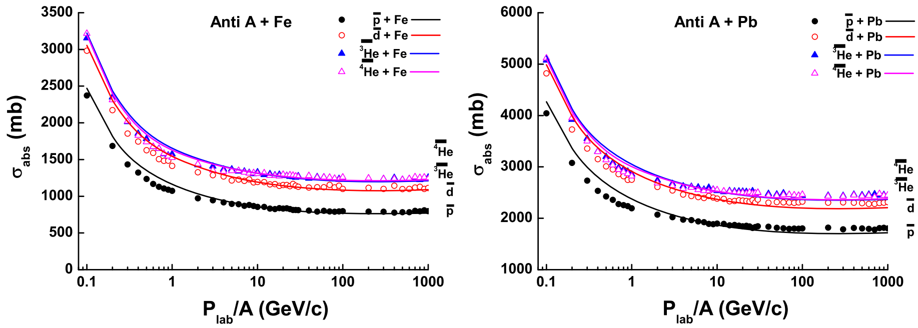

Fig. 4. Antinucleus–nucleus cross sections. The points are the Glauber calculations and the lines are our parameterizations of the cross sections (see text).

For inelastic cross sections, the parameterizations are as follows:

$$\bar{p}A \; R_A = 1.31A^{0.22} + 0.90/A^{1/3} \text{ (fm)}, \tag{13}$$

$$\bar{d}A \; R_A = 1.38A^{0.21} + 1.55/A^{1/3} \text{ (fm)}, \tag{14}$$

$$\bar{t}A \; R_A = 1.34A^{0.21} + 1.51/A^{1/3} \text{ (fm)}, \tag{15}$$

$$\bar{\alpha}A \; R_A = 1.30A^{0.21} + 1.05/A^{1/3} \text{ (fm)}. \tag{16}$$

These parameterizations result in the curves presented in Fig. 4.

Using the described approach we have developed in the GEANT4 framework parameterized elastic and inelastic antinucleus–nucleus cross sections for the projectiles $\bar{p}$, $\bar{d}$, $\bar{t}$, $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$, which are valid between 100 MeV/c and 1 TeV/c per antinucleon. A comparison of the parameterizations to data shows agreement to within ∼8%, sufficient for most applications in large HEP experiments including those at the LHC and RHIC.

In conclusion, we would like to emphasize that using the Glauber approach and the data for cross sections on protons the realistic parameterizations have been proposed for the antinucleus–nucleus interactions. As a result, the GEANT4 toolkit is now able to simulate the antinucleus–nucleus interactions for all target nuclei since version 9.4.p01.

Acknowledgements

The authors are thankful to M. Kelsey for stimulating discussions and interest in the work.

References

[1] http://pamela.roma2.infn.it/index.php.
[2] http://www.universe.nasa.gov/astroparticles/programs/bess/.
[3] http://ams.cern.ch/.
[4] http://ida1.physik.uni-siegen.de/caprice.html.
[5] H. Agakishiev, et al., STAR Collaboration, arXiv:1103.3312 [nucl-ex], 2011; B.I. Abelev, et al., STAR Collaboration, Science 328 (2010) 58; C. Adler, et al., STAR Collaboration, Phys. Rev. Lett. 87 (2001) 262301; B.I. Abelev, et al., STAR Collaboration, arXiv:0909.0566 [nucl-exp].
[6] S. Afanasiev, et al., PHENIX Collaboration, Phys. Rev. Lett. 99 (2007) 052301; S.S. Adler, et al., PHENIX Collaboration, Phys. Rev. Lett. 94 (2005) 122302.
[7] B. Alver, et al., PHOBOS Collaboration, Phys. Rev. C 77 (2008) 061901(R).
[8] P. Antonioli, arXiv:1010.3735 [hep-ex], 2010.
[9] A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoker, Phys. Lett. B 697 (2011) 203.
[10] S. Schael, et al., ALEPH Collaboration, Phys. Lett. 639 (2006) 192.
[11] A. Moiseev, et al., BESS Collaboration, Astropart. J. 474 (1997) 479.
[12] A.A. Moiseev, J.F. Ormes, Astropart. J. 6 (1997) 379.
[13] R. Duperray, et al., Phys. Rev. D 71 (2005) 083013.
[14] S. Agostinelli, Geant4 Collaboration, Nucl. Instrum. Methods A 506 (2003) 250; J. Allison, Geant4 Collaboration, IEEE Trans. Nucl. Sci. 53 (2006) 270.
[15] V. Franco, R.J. Glauber, Phys. Rev. 142 (1966) 142.
[16] O.D. Dalkarov, V.A. Karmanov, Nucl. Phys. A 445 (1985) 579.
[17] W.W. Buck, J.W. Norbury, L.W. Townsend, J.W. Wilson, Phys. Rev. C 33 (1986) 234.
[18] Z. Yu-shun, L. Ji-feng, B.A. Robson, L. Yang-guo, Phys. Rev. C 54 (1996) 332.
[19] B.V. Batyunya, et al., JINR preprint P1-87-523, 1987.
[20] V. Franco, Phys. Rev. 175 (1968) 1376.
[21] W. Broniowski, M. Rybczynski, P. Bozek, Comp. Phys. Commun. 180 (2009) 69.
[22] V.V. Uzhinsky, S.Yu. Shmakov, Phys. Atom. Nucl. 57 (1994) 1459; V.V. Uzhinsky, S.Yu. Shmakov, Yad. Fiz. 57 (1994) 1532.
[23] L.S. Azhgirei, et al., Nucl. Phys. A 305 (1978) 397.
[24] S.Yu. Shmakov, V.V. Uzhinskii, A.M. Zadorozhny, Comput. Phys. Commun. 54 (1989) 125.
[25] J.R. Cudell, et al., COMPLETE Collaboration, Phys. Rev. D 65 (2002) 074024.
[26] M. Ishida, K. Igi, Phys. Rev. D 79 (2009) 096003.
[27] A.A. Arkhipov, hep-ph/9909531, 1999; A.A. Arkhipov, hep-ph/9911533, 1999.
[28] K. Nakamura, et al., Particle Data Group, J. Phys. G 37 (2010) 075021, http://pdg.lbl.gov/2010/hadronic-xsections/hadron.html.
[29] K.A. Ter-Martirosyan, JETP Lett. 15 (1972) 734.
[30] R. Timmermans, Th.A. Rijken, J.J. de Swart, Phys. Rev. C 50 (1994) 48.
[31] J.V. Allaby, et al., Yad. Fiz. 12 (1970) 538; R.J. Abrams, et al., Phys. Rev. D 1 (1970) 1917; R.J. Abrams, et al., Phys. Rev. D 4 (1971) 3235; S.P. Denisov, et al., Nucl. Phys. B 61 (1973) 62; T. Kalogeropoulos, G.S. Tzakanos, Phys. Rev. D 22 (1980) 2585; R. Bizzari, et al., Nuovo Cim. 22A (1974) 225; F. Balestra, et al., Nucl. Phys. A 526 (1991) 415; Ya.A. Batusov, et al., Yad. Fiz. 52 (1990) 1222; A.S. Carroll, et al., Phys. Lett. B 80 (1979) 319; A.M. Schiz, FERMILAB-THESIS-1979-17, UMI-80-12109, 1979; Yu.P. Gorin, et al., Yad. Fiz. 18 (1973) 336; P. Cork, et al., Phys. Rev. 107 (1957) 248; R. Bailey, et al., Z. Phys. C 29 (1985) 1; K. Nakamura, et al., Phys. Rev. Lett. 52 (1984) 731; V. Ashford, et al., Phys. Rev. C 31 (1985) 663.
[32] F. Balestra, et al., Nucl. Phys. A 452 (1986) 573; G. Bendiscioli, A. Rotondi, A. Zenoni, Nuovo Cim. A 104 (1991) 59; F. Balestra, et al., Phys. Lett. B 305 (1993) 18; V.F. Kuzichev, Yu.B. Lepikhin, V.A. Smirnitsky, Nucl. Phys. A 576 (1994) 581.
[33] V.N. Gribov, Sov. Phys. JETP 29 (1969) 483; V.N. Gribov, Zh. Eksp. Teor. Fiz. 56 (1969) 892.
[34] V. Karmanov, L. Kondratyuk, Sov. Phys. JETP Lett. 18 (1975) 266.
[35] P.V.R. Murthy, et al., Nucl. Phys. B 92 (1975) 269.
[36] G. Goggi, et al., Nucl. Phys. B 149 (1979) 381.
[37] S. Bondarenko, E. Gotsman, E. Levin, U. Maor, Nucl. Phys. A 683 (2001) 649.
[38] M. Yahiro, et al., Prog. Theor. Phys. 120 (2008) 767.
[39] G. Faldt, H. Pilkuhn, Phys. Lett. B 46 (1973) 337.
[40] A. Vitturi, F. Zardi, Phys. Rev. C 36 (1987) 1404.
[41] Deeksha Chaunhan, Z.A. Khan, Eur. Phys. J. A 47 (2011) 31.
[42] V.M. Grichine, Eur. Phys. J. C 62 (2009) 399.
[43] V.M. Grichine, Nucl. Instrum. Methods B 267 (2009) 2460.