Theoretical antideuteron-nucleus absorptive cross sections

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Antideuteron-nucleus absorptive cross sections for intermediate to high energies are calculated using an ion-ion optical model. Good agreement with experiment (within 15 percent) is obtained in this same model for $\bar{p}$-nucleus cross sections at laboratory energies up to 15 GeV. We describe a technique for estimating antinucleus-nucleus cross sections from $N\bar{N}$ data and suggest that further cosmic ray studies to search for antideuterons and other antinuclei be undertaken.

The search for antimatter in the form of cosmic ray antinuclei is an intriguing and speculative endeavor. Certainly, with present experimental capabilities, producing particles heavier than antiprotons in the laboratory is difficult at best. Indeed, the question as to whether or not one should even search for antinuclei in cosmic rays has been addressed from several different perspectives. One point of view,[1] for example, argues that theoretical abundances, estimated from empirical observations, of antinuclei with $Z \geq 3$ are negligible. Although the extreme rarity of antinuclei events may reflect nonconservation of baryon number in our universe, the purpose of this paper is not to address these issues but, rather, to provide a calculational procedure for determining whether or not an antinucleus has interacted with a nucleus. To do this we calculate antinucleus-nucleus total and absorptive cross sections utilizing an optical potential model[2,3] of nucleus-nucleus scattering as described below. Numerical results for $\bar{d}$ nucleus are presented to illustrate the predictions. Since experimental data for antinucleus-nucleus collisions are nonexistent, predictions for $\bar{p}$-nucleus cross sections are made, compared to available experimental data, and are found to be in good agreement (within 15 percent). Comprehensive tabulations of the predicted antinucleus-nucleus cross sections are published elsewhere.[4]

For the scattering of composite nuclei, a general multiple-scattering theory (neglecting three-body interactions) has been developed by Wilson.[5] The series reduces to the usual Watson form when the projectile is elementary. Through the use of the impulse and closure approximations, a simple, folded, optical model potential was derived[2] as

$$W(x)=A_P A_T \int d^3z\, \rho_T(z) \times \int d^3y\, \rho_P(x+y+z)\bar{t}(e,y) , \qquad (1)$$

where e is the $N\bar{N}$ kinetic energy in the c.m. frame, y is the $N\bar{N}$ relative separation, ρ_T and ρ_P are the target and projectile number density distributions normalized to unity, $\bar{t}(e,y)$ is the energy-dependent constituent-averaged two-nucleon transition amplitude obtained from scattering experiments, and A_P and A_T are the projectile and target atomic numbers, respectively. With no renormalization or parameter adjustments, this optical potential has been previously used in a Wentzel-Kramers-Brillouin (WKB) formulation to obtain excellent agreement with experimental elastic scattering differential, reaction, and total cross section data at energies lower than 25 MeV/nucleon.[6] More often, however, this optical potential approximation is used within the context of an eikonal formalism to predict nucleon-nucleus, deuteron-nucleus, and nucleus absorptive (inelastic) cross sections to within 3% for energies higher than 80 MeV/particle and to within 10% for lower energies.[2,3,7] From eikonal scattering theory, the absorption (reaction) cross section is

$$\sigma_{abs}=2\pi \int_0^\infty \{1-\exp[-2\,\mathrm{Im}\chi(b)]\}\, b\, db , \qquad (2)$$

where the complex phase function is (with $\hbar=1$)

$$\chi(b)=-(2k)^{-1}\int_{-\infty}^{\infty} U(b,z)dz , \qquad (3)$$

with k the projectile momentum wave number and b denoting the impact parameter. The reduced potential is then obtained from the optical potential as

$$U(x)=2mA_P A_T(A_P+A_T)^{-1}W(x) , \qquad (4)$$

where m is the nucleon mass. Within the eikonal context, this model is similar to the comparable, but alternative, Glauber theory formalism which has been extensively developed by Franco and collaborators.[8] Aside from the improved convergence to the exact multiple-scattering series by the Wilson approximation[5] (due to differences in higher order terms), the Wilson propagator[2] also includes target recoil and terms to order k^2.

In order to apply Eqs. (1)–(4) to antinucleus-nucleus collisions, several assumptions, other than the applicability of the underlying composite-particle multiple-scattering formalism, are necessary. First, we assume that the num-

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ber density distribution for an antinucleus is identical to that of its "normal" nucleus counterpart. Hence, aside from the overall sign of the charge distribution, the antinuclei charge distribution parameters and functional forms are assumed to be identical to those of the corresponding nuclear species. We then extract the number densities ρ_A from the corresponding charge densities ρ_C obtained from electron scattering experiments, by assuming that

$$\rho_C(r)=\int \rho_N(r')\rho_A(r+r')d^3r' , \qquad (5)$$

where the nucleon charge distribution is taken to be the usual Gaussian form

$$\rho_N(r)=(3/2\pi r_N^2)^{3/2}\exp(-3r^2/2r_N^2) , \qquad (6)$$

with a nucleon root mean-square charge radius set equal to the proton value[9] of 0.87 fm.

For elementary projectiles, substitution of (6) into (5) yields a delta function for ρ_A. For nuclei or antinuclei with $A<20$ we use an harmonic oscillator form for ρ_C as

$$\rho_C(r)=\rho_0\left[1+\gamma\left[\frac{r}{a}\right]^2\right]\exp(-r^2/a^2) , \qquad (7)$$

where the charge distribution parameters γ and a are listed in Table I. Inserting (6) and (7) into (5) yields

$$\rho_A(r)=(\rho_0 a^3/8s^3)[1+(3\gamma/2)-(3\gamma a^2/8s^2)$$
$$+(\gamma a^2 r^2/16s^4)]\exp(-r^2/4s^2) , \qquad (8)$$

where

$$s^2=(a^2/4)-(r_N^2/6) . \qquad (9)$$

For nuclei or antinuclei with $A\geq 20$ we choose a Woods-Saxon form

TABLE I. Nuclear charge distribution parameters from electron scattering data.

Nucleus	Distribution[a]	γ (HW) or t (fm)(WS)	a (HW) or R (fm)(WS)
^{3}H	HW	0	1.71
^{4}He	HW	0	1.33
^{7}Li	HW	0.327	1.77
^{9}Be	HW	0.611	1.791
^{11}B	HW	0.811	1.69
^{12}C	HW	1.247	1.649
^{14}N	HW	1.291	1.729
^{16}O	HW	1.544	1.833
^{20}Ne	WS	2.517	2.74
^{27}Al	WS	2.504	3.05
^{40}Ar	WS	2.693	3.47
^{56}Fe	WS	2.611	3.971
^{64}Cu	WS	2.504	4.20
^{80}Br	WS	2.306	4.604
^{108}Ag	WS	2.354	5.139
^{120}Sn	WS	2.621	5.618
^{208}Pb	WS	2.416	6.624

[a]The harmonic well (HW) distribution is used for $A<20$ and the Woods-Saxon (WS) distribution for $A\geq 20$.

$$\rho_C=\rho_0[1+\exp[(r-R)/c]]^{-1} , \qquad (10)$$

where R is the half-density radius, and the surface diffuseness c is related to the charge skin thickness t_c through

$$t_c=4.4c . \qquad (11)$$

Values for R and t_c are also listed in Table I. Inserting (6) and (10) into (5) yields, after some simplification,[2] a number density ρ_A that is of the Woods-Saxon form with the same R, but different overall normalization ρ_0 and surface thickness. The latter is given (in fm) by

$$t_A=5.08r_N\{\ln[(3\beta-1)/(3-\beta)]\}^{-1} , \qquad (12)$$

where

$$\beta=\exp[2.54r_N/t_c] . \qquad (13)$$

In all cases the densities are normalized to unity.

For the antinucleon-nucleon ($N\bar{N}$) transition amplitude, $\tilde{t}$, we assume a form

$$\tilde{t}(e,y)=\left[\frac{e}{m}\right]^{1/2}\sigma_{tot}(e)[\alpha(e)+i][2\pi B(e)]^{-3/2}$$
$$\times\exp[-y^2/2B(e)] , \qquad (14)$$

which is obtained by taking the Fourier transform of the usual nuclear amplitude.[10] In Eq. (14) σ_{tot} is the $N\bar{N}$ total cross section, $\alpha(e)$ is the real-to-imaginary ratio of the forward amplitude, and $B(e)$ is the $N\bar{N}$ slope parameter. With this choice for the two-body amplitude we effectively treat antinucleus-nucleus scattering as a purely complementary system to nucleus-nucleus scattering. Values for σ_{tot} are parametrized in terms of the incident particle momentum P by

$$\sigma_{tot}=(61.2\text{ mb})+(53.4\text{ mb GeV}/c)/P$$
$$-P(\text{mb GeV}/c) , \qquad (15)$$

which is a modification of the expression given in Ashford *et al.*[11] to extend the cross sections to 15 GeV. Values for the slope parameter, displayed in Fig. 1, were taken from the Paris $N\bar{N}$ potential[12] and from Block and Cahn.[13] Values of the parameter α are not presented for these results since only the imaginary part of the transition amplitude is used to calculate absorption cross sections. Details of the values used for the total cross section estimates are found in Ref. 4.

Predictions for $\bar{p}$-nucleus and $\bar{d}$-nucleus absorption cross sections are displayed in Figs. 2–4. Also plotted in Figs. 2 and 3, for comparison, are data from various experimental measurements.[14–16] Clearly the agreement between theory and experiment is good since the maximum cross section difference for any of these results is less than 15 percent. Typical differences between theory and experiment are 5 percent. Figure 4 displays predicted $\bar{d}$-nucleus absorptive cross sections for the range from 50 MeV/nucleon to 15 GeV/nucleon. These are provided in the event that techniques for producing antideuterons in the laboratory may become available in the future. Simi-

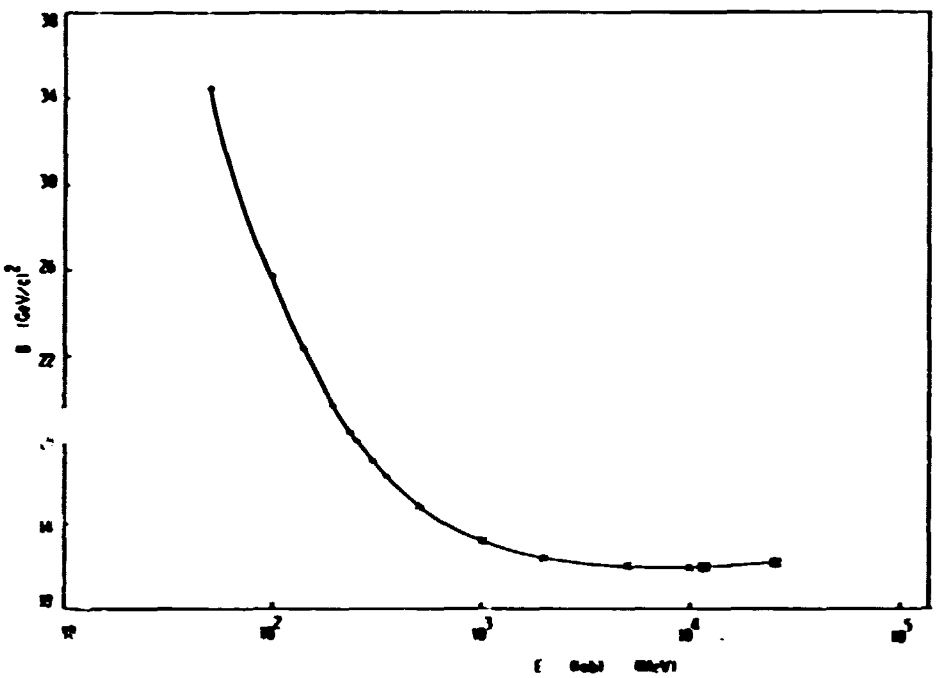

FIG. 1. $N\bar{N}$ slope parameter values used in the present work. The crosses are our interpolation.

larly, the possibility of observing antinuclei in cosmic rays may also contribute to the usefulness of this collision model. Indeed a primary cosmic antitriton event was reported at the 18th International Cosmic Ray Conference.[17] Cross sections for antinucleus-nucleus collisions up to $\overline{\mathrm{Fe}}$-Pb are tabulated in Ref. 4. For all collision pairs, the cross sections, as in Fig. 4, are smooth curves displaying no complicated structure. For optical model calculations, however, this is not entirely unexpected since it merely reflects the averaging nature of the calculation and the smooth functional dependencies of the input $N\bar{N}$ data.

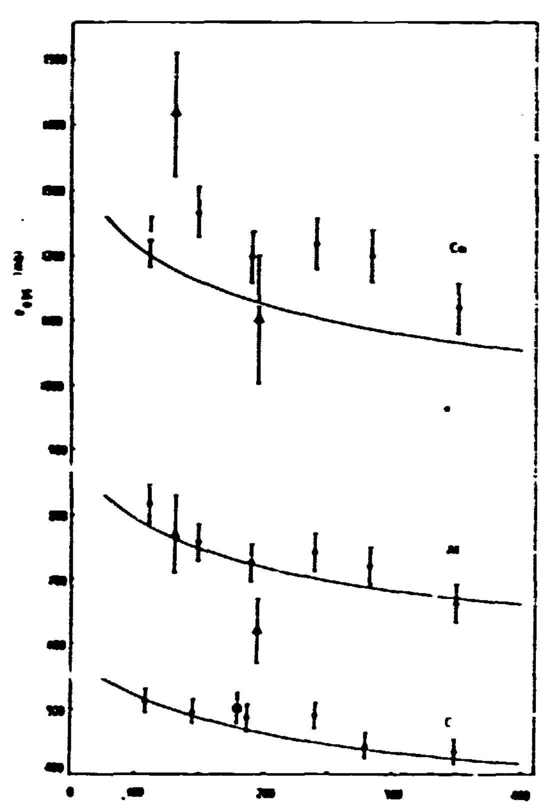

FIG. 2. Theoretical $\bar{p}$-nucleus absorption cross sections as a function of incident kinetic energy. Experimental values were obtained from Refs. 14–16.

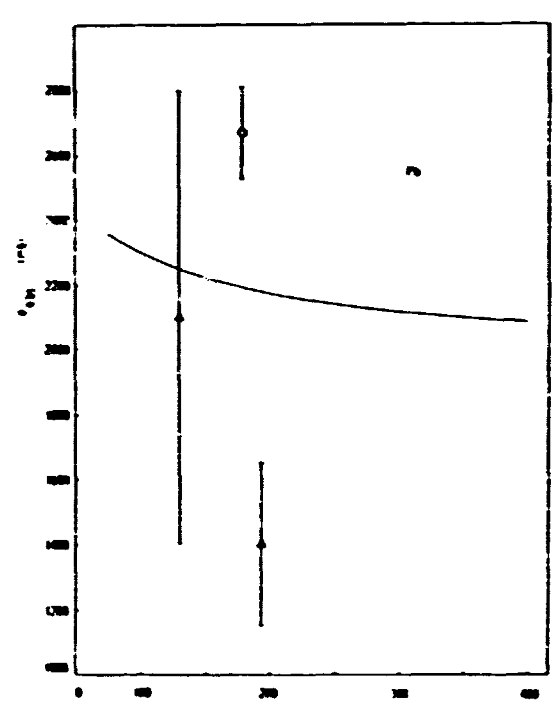

FIG. 3. Theoretical $\bar{p}$-Pb absorption cross sections as a function of incident kinetic energy. Experimental values are taken from Refs. 15 and 16.

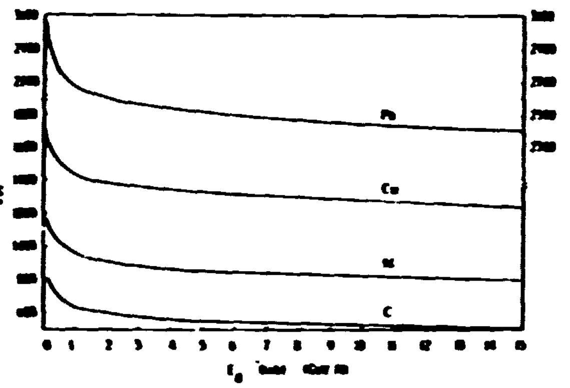

FIG. 4. Theoretical predictions for $\bar{d}$-nucleus absorptive cross sections as a function of incident kinetic energy.

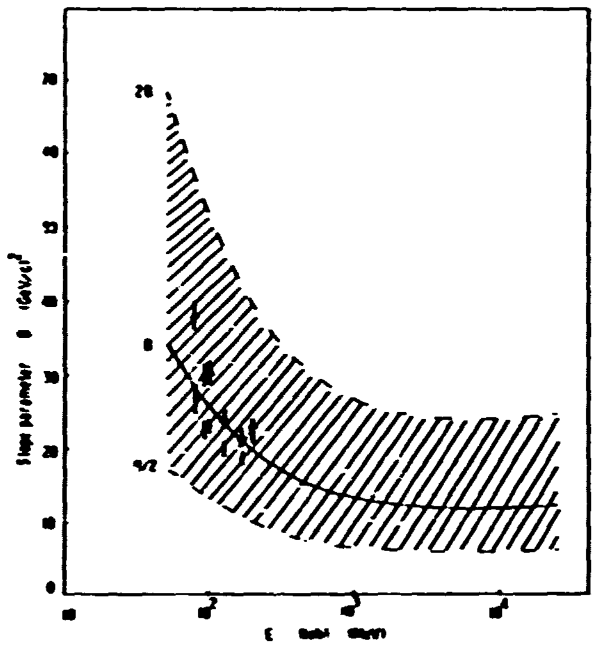

FIG. 5. Range of $N\bar{N}$ slope parameters used in the cross section sensitivity studies. The experimental values are taken from Brookhaven measurements (Ref. 11).

We have also performed an analysis to investigate the sensitivity of our predictions to the magnitude of the slope parameter. This was done by recalculating antiproton- and $\overline{\text{Fe}}$-nucleus cross sections for the cases where the $N\bar{N}$ slope parameters are taken in a rather *ad hoc* fashion as $2B(e)$ and $B(e)/2$. These slope parameter ranges are displayed in Fig. 5 along with the Brookhaven measurements.[11] As anticipated, we found that collisions involving light nuclei are far more sensitive to changes in the slope parameter than collisions involving heavy nuclei, especially at lower energies. For instance, with an assumed slope parameter of $2B$, we find that $\sigma_{\rm abs}$ at 100 MeV/nucleon, increases by 21% for $\bar{p}$-C (629 mb vs 520 mb), but only by 10% for $\bar{p}$-Pb (2528 mb vs 2303 mb). For $\overline{\text{Fe}}$-Pb at 100 MeV/nucleon, the increase is 6% (5886 mb vs 5542 mb). At 15 Gev/nucleon, the increases for these same collision pairs are 13%, 7%, and 4%, respectively. If the slope parameter is halved (to $0.5B$), we find that $\sigma_{\rm abs}$ for the same three collision pairs decreases by 13%, 6%, and 4% at 100 MeV/nucleon, and by 9%, 4%, and 3% at 15 GeV/nucleon. Clearly these absorption cross sections are not very sensitive to large changes in the slope parameter.

In summary, we have employed a simple optical model[2] from nucleus-nucleus scattering theory to intermediate energy antinucleus-nucleus collisions. The only new inputs required to complete the calculations are the experimental $N\bar{N}$ elastic scattering parameters (total cross section, elastic slope parameters, and real-to-imaginary ratio of the forward scattering amplitudes). For the energy range considered herein (100 MeV/nucleon to 15 GeV/nucleon), the eikonal formalism is certainly adequate. Although these methods could be extended to even lower energies,[7] other more suitable methods[18] are currently being implemented elsewhere. We have included charge exchange only as it is included in the determination of the Paris $N\bar{N}$ slope parameters. We have not considered pion propagation effects in the target nucleus, two-body correlation functions, and have ignored possibly important spin and isospin excitations of the target.[19] Nevertheless, we find that the model gives rather good agreement with available $\bar{p}$-nucleus data at intermediate energies and expect that the predicted $\bar{d}$-nucleus absorption cross sections are reasonably accurate (certainly within 15 percent). While we realize that the production of enough antideuterons in the laboratory (LEAR for example) to produce a beam is in the distant future, the production of such a beam could open up new areas of research since, for example, high temperatures in nuclear matter, may be achievable[20] with antideuterons of momentum greater than 2 GeV/c. For now, cosmic ray studies appear to offer the best chance for detecting and studying $\bar{d}$ and antinuclei interactions such as the reported antitriton event.[17]

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