Inclusive annihilation of antiprotons on deuterium

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The inclusive annihilation of antiprotons on deuterium is calculated within a three-body model. At very low antiproton energies ($E_{\bar{p}} < 2.2$ MeV), structure is observed in the energy spectra of emerging protons at forward angles. The theory can be easily extended to higher antiproton energies.

In a recent paper, Latta and Tandy[1] discussed the nuclear quasibound $NN\bar{N}$ systems and assessed their importance in antinucleon-nucleus dynamics. In particular, the relevance of three-body effects was emphasized in connection with the theoretical possibility that some $\bar{N}$-nucleus quasibound states could be of sufficiently small decay width to be observable.[2] Latta and Tandy investigated the relevance of an explicit three-body description of the $NN\bar{N}$ systems using the Faddeev equations and concentrated their attention on the purely nuclear quasibound states. No attempt was made to calculate scattering observables, which may be of great importance in assessing the effect of NN correlations in $\bar{N}$-nucleus scattering.

Scattering observables may also provide an important test of the $N\bar{N}$ interaction, since the presence of the third nucleon can reveal aspects of this potential not accessible through the two-body data. An interesting example of such an observable is the spectator nucleon spectrum which carries information about the off-energy shell annihilation process occurring at energies below the $N\bar{N}$ free mass. To gain access to this information however, one needs a consistent formalism for describing the $N\bar{N}$ annihilation in the $\bar{N}$-NN system.

At energies around 1 GeV/c the measured spectra[3,4] of the spectator proton in the antiproton-deuteron annihilation show two peaks. The low-energy peak is related to the initial state interaction,[4,5] which at these energies is dominated by the deuteron wave function. The other peak appears above 0.2 GeV/c, and can be attributed to the dominance of meson rescattering.[3-5] This feature is clearly shown in the lambda spectra obtained in antiproton-deuteron experiments.[6-8] Another approach[9] indicates that the high-energy tail of the proton spectra can be associated with annihilation of two nucleons.

Our aim is to study the initial state interaction in the antiproton-deuteron low-energy interaction, and for that purpose we develop in this paper an exact three-body formalism for the description of the antiproton-deuteron inclusive annihilation process in the proton or neutron final channel, that is,

$$\begin{aligned} \bar{p}+D &\to p+X \\ &\to n+Y\ , \end{aligned} \tag{1}$$

where X and Y represent anything. We apply this formalism in a model calculation with simple separable potentials.[1] In developing the theory for the inclusive cross section of (1), we rely heavily on recent theoretical developments of nuclear inclusive breakup reactions.[10] For the purpose of completeness, we present below the derivation of the cross section.

We use a nonrelativistic description of the three-body $\bar{N}$ system and denote the Hamiltonian by H,

$$H = T + U_{\bar{p}n} + U_{\bar{p}p} + V_{pn}\ , \tag{2}$$

where T is the kinetic operator, $U_{\bar{p}n}$ is the $\bar{p}$-n optical potential, $U_{\bar{p}p}$ the $\bar{p}$-p optical potential, and V_{pn} the (real) p-n potential. The antiproton-nucleon optical potentials have an imaginary part to take into account the flux lost to annihilation.

Within the three-body formalism, we can write the matrix element containing an asymptotic proton in the final state as

$$F(\mathbf{q}_p,f) = \langle \mathbf{q}_p f | V_{pn} + U_{p\bar{p}} | \Psi^+ \rangle\ , \tag{3}$$

where we have denoted by f all antiproton-neutron final states, including those in which they have annihilated. We can then immediately write the inclusive proton cross section as

$$\frac{d^2\sigma_{\rm inc}}{d\Omega_p dE_p} = \frac{2\pi}{\hbar v_p}\rho(E_p)\sum_f |F(\mathbf{q}_p,f)|^2 = \sum_f \frac{2\pi}{\hbar v_p}\rho(E_p)\langle \psi^+ | U_{p\bar{p}}^\dagger + V_{pn} | \mathbf{q}_p f\rangle \langle \mathbf{q}_p f | V_{pn} + U_{p\bar{p}} | \psi^+ \rangle \delta(e - E_p - E_f)\ , \tag{4}$$

where E_p (E_f) is the proton (antiproton-neutron) final energy, E is the initial energy, $\rho(E_p)$ is the proton density of states, and $v_{\bar{p}}$ is the initial velocity of the antiproton in the laboratory system.

We now identify the sum over $\bar{p}$-n final states with the imaginary part of the $\bar{p}$-n propagator to obtain

$$\frac{d^2\sigma_{\rm inc}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_p}\rho(E_p)\langle\psi^+|U^\dagger_{p\bar{p}}+V_{pn}|\mathbf{q}_p\rangle \times {\rm Im}G_{\bar{p}n}(E-\tfrac{3}{4}q_p^2)\langle\mathbf{q}_p|V_{pn}+U_{p\bar{p}}|\psi^+\rangle \ . \quad (5)$$

Standard two-body manipulations now permit us to rewrite ${\rm Im}G_{\bar{p}n}$ as

$$ {\rm Im}G_{\bar{p}n} = (1+G^\dagger_{\bar{p}n}U^\dagger_{\bar{p}n}){\rm Im}G_{0\bar{p}n}(1+U_{\bar{p}n}G_{\bar{p}n}) + G^\dagger_{\bar{p}n}W_{\bar{p}n}G_{\bar{p}n} \ , \quad (6)$$

where

$$W_{\bar{p}n} = \frac{U_{\bar{p}n}-U^\dagger_{\bar{p}n}}{2i} \quad (7)$$

is the imaginary part of the antiproton-neutron optical potential. The first term in Eq. (6) describes scattering in which both the antiproton and neutron continue to exist in the final state.

The second term describes the flux lost from the incoming channel which here corresponds solely to annihilation. We can thus identify the inclusive antiproton-neutron annihilation cross section with the contribution of this term to the inclusive proton cross section. We have

$$\frac{d^2\sigma_{\rm inc}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_p}\rho(E_p)\langle\psi^+|(U^\dagger_{p\bar{p}}+V_{pn})G^\dagger_{\bar{p}n}|\mathbf{q}_p\rangle \times W_{\bar{p}n}\langle\mathbf{q}_p|G_{pn}(U_{p\bar{p}}+V_{pn})|\psi^+\rangle \ . \quad (8)$$

As the entrance channel is that of the antiproton and deuteron, the exact three-body wave function satisfies the homogeneous Lippmann-Schwinger equation

$$|\psi^+\rangle = G_{\bar{p}n}(U_{p\bar{p}}+V_{pn})|\psi^+\rangle \ . \quad (9)$$

We can thus reduce the expression for the antiproton-neutron annihilation cross section to

$$\frac{d^2\sigma_{\rm inc}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_p}\rho(E_p)\langle\psi^+|\mathbf{q}_p\rangle W_{\bar{p}n}\langle\mathbf{q}_p|\psi^+\rangle \ . \quad (10)$$

A similar expression can be derived for the inclusive neutron cross section due to proton-antiproton annihilation.

The sum of the two annihilation cross sections obviously satisfies the optical theorem for the three-body system, as annihilation is the only mechanism for flux absorption which enters. In this respect, we remind the reader that the breakup channel is contained in the three-body formalism and thus does not absorb flux. We note that the formal expression obtained for the cross section is very similar to that obtained for the heavy-ion breakup-fusion one.[10]

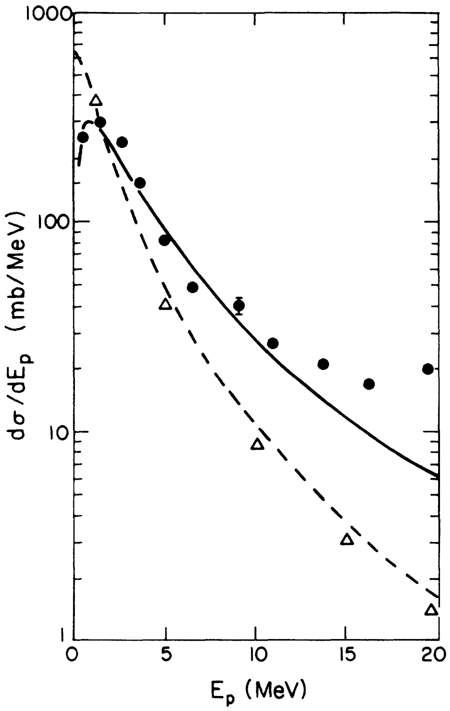

FIG. 1. Angle-integrated proton spectra as a function of the proton relative center-of-mass energy. Solid line is for $E_{\bar{p}}^{\rm lab}=3$ MeV. Results for $k/q\, d\sigma/dE_p$ are showed by a dashed line for $E_{\bar{p}}^{\rm lab}=3$ MeV and by the triangles for $E_{\bar{p}}^{\rm lab}=1$ MeV. The dots are the experimental data from Ref. 3.

In the following, we will use our formalism to perform a schematic calculation of the inclusive proton cross section due to the antiproton-neutron annihilation. For this purpose, we will employ the simple s-wave one-term separable potentials used by Latta and Tandy[1] and solve the inhomogeneous Faddeev equations corresponding to the antiproton-deuteron entrance channel to obtain the exact three-body wave function.

We use the kernel subtraction method of Ref. 11 to solve the integral equations numerically, and restrict our attention to energies below the deuteron breakup threshold to avoid the numerical complications which the breakup channel introduces. As did Latta and Tandy, we neglect the Coulomb interaction.

After lengthy but straightforward algebraic manipulations, we obtain for the double differential cross section

$$\frac{d^2\sigma_{\rm inc}}{d\Omega_p dE_p} = \frac{8\pi}{9}\frac{q}{k}\sum_{I,S}|\mathcal{C}^{1/2\,1/2\,I}_{-1/2\,1/2\,M_I}|^2|W_{IS}|\{\tfrac{2}{3}|\chi^{N\bar{N}}_{3/2\,IS}(\mathbf{q})|^2+\tfrac{1}{3}|\chi^{N\bar{N}}_{1/2\,IS}(\mathbf{q})|^2\} \ , \quad (11)$$

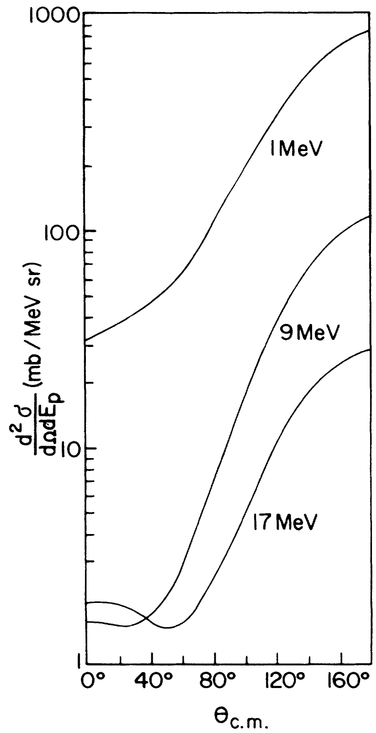

FIG. 2. Angular distributions of the spectator proton for the proton relative center-of-mass energies of 1, 9, and 17 MeV at $E_{\bar{p}}^{\rm lab}=3$ MeV.

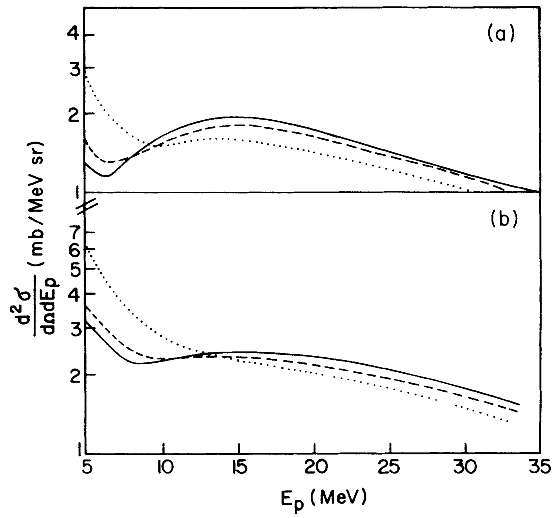

FIG. 3. Energy spectra of the spectator proton for $E_{\bar{p}}^{\rm lab}=3$ MeV. The solid line is for 0°, the dashed line for 20°, and the dotted line for 40°. In case (a) the deuteron binding energy is 2.22 MeV and in case (b), 4.4 MeV.

where k is the relative momentum of the initial antiproton, q is the relative momentum of the final nucleon, and W_{IS} is the annihilation strength in the channel in which the annihilated pair have isospin I and spin S. The amplitudes are obtained as the overlap between the nucleon-antiproton separable potential form factor and the exact three-body wave function,

$$\chi_{sIS}^{N\bar{N}}(\mathbf{q})=\langle g_{IS}|\psi_s^+\rangle \ , \tag{12}$$

where s denotes the total channel spin, $\frac{1}{2}$ or $\frac{3}{2}$.

The wave function normalization is determined by the entrance channel where the deuteron wave function is normalized to unity, while the antiproton plane wave is normalized to $\delta(\mathbf{k}-\mathbf{k}')$.

In Fig. 1 we present our numerical results for the angle-integrated proton spectrum at two antiproton laboratory energies below the deuteron breakup threshold, 1 and 3 MeV. The proton relative center-of-mass energy ($E_p=3/4q^2$) was varied from 0 to 20 MeV. This calculation is in good agreement with the data taken by Oh *et al.*[3]

The angular distribution of the emitted proton is shown in Fig. 2 at three proton relative center-of-mass energies, 1, 9, and 17 MeV, for an incident $\bar{p}$ laboratory energy of 3 MeV. The back-angle enhancement of the cross- section is a clear indication of the spectator nature of the emitted proton. Further, there is a clear structure at small angles (notice that small angle in the present context represents large momentum transfer) observable in the energy range $E_p\sim 10-17$ MeV. In order to exhibit this structure more clearly, we present in Fig. 3(a) the proton spectra at three fixed angles, 0°, 20°, and 40°. We see a clear minimum and bump at 0° ($E_{\bar{p}}^{\rm lab}=3$ MeV). This bump seems to be very sensitive to the binding energy of the target, as indicated in Fig. 3(b).

The above feature of the proton spectrum seems to be a genuine three-body effect, and it certainly merits further investigation. We believe that this effect may also be present in antiproton-nucleus scattering at low energies. We have calculated the angular distribution of the protons at higher energies (100 MeV) as well (fixing the antiproton energy at 3 MeV). At these higher energies, the distribution becomes more and more symmetrical about 90°, indicating the complete loss of memory of the incident direction.

In conclusion, we want to reiterate that the simple but precise formalism developed here could prove to be a powerful tool in a stringent study of the N-$\bar{N}$ interaction using the low-energy $\bar{p}$-d data. Although we concentrated our discussion at very low antiproton energies where an exact treatment of the three-body problem is required, at higher energies, a more convenient way of calculating the cross section would proceed through a DWBA treatment of the incident channel. Antiproton nuclear (including deuteron) optical potentials are available for this purpose.

Further corrections to the DWBA inclusive annihilation cross section can be generated in a simple and consistent way using the method developed in the third and fourth listings of Ref. 10.

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