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Abstract

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 quasi-bound states of $NN\bar{N}$ 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 quasi-bound 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 $NN\bar{N}$ system using the Faddeev equations and concentrated their attention on the purely nuclear quasi-bound 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.

The purpose of the present paper is to develop an exact three-body description of the antiproton-deuteron inclusive annihilation process in the proton or neutron final channel, namely,

$$\bar{p} + D \rightarrow \begin{matrix} p + X \\ n \quad Y \end{matrix} \tag{1}$$

when X and Y represent anything. In developing the theory for the inclusive cross section of (1), we rely heavily on recent theoretical development of nuclear inclusive break-up reactions[3]. 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 energy 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

$$F(\vec{q}_p, f) = < \vec{q}_p f \mid V_{pn} + U_{p\bar{p}} \mid \psi^+ > \tag{3}$$

where we have denote 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

$$\frac{d^2\sigma_{inc}}{d\Omega_p dE_p} = \frac{2\pi}{\hbar v_p}\rho(E_p) \sum_f \mid F(\vec{q}_p, f) \mid^2 =$$

$$\sum_f \frac{2\pi}{\hbar v_p}\rho(E_p) < \psi^+ \mid U^\dagger_{p\bar{p}} + V_{pn} \mid \vec{q}_p f >< \vec{q}_p f \mid V_{pn} + U_{p\bar{p}} \mid \psi^+ > \delta(E - E_p - E_f) \tag{4}$$

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 *lab* system.

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

$$\frac{d^2\sigma_{inc}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_p}\rho(E_p) < \psi^+ \mid U^\dagger_{p\bar{p}} + V_{pn} \mid \vec{q}_p > ImG_{\bar{p}n}(E - \frac{3}{4}q_p^2) < \vec{q}_p \mid V_{pn} + U_{p\bar{p}} \mid \psi^+ > \tag{5}$$

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

$$ImG_{\bar{p}n} = (1 + G^\dagger_{\bar{p}n} U^\dagger_{\bar{p}n}) ImG_{0\bar{p}n}(1 + U_{\bar{p}n} G_{\bar{p}n}) + G^\dagger_{\bar{p}n} W_{\bar{p}n} G_{\bar{p}n} \tag{6}$$

where

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

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

The second term describes the fux 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

$$\frac{d^2\omega_{inc}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_p}\rho(E_p) < \psi^+ \mid (U^\dagger_{p\bar{p}} + V_{pn}) G^\dagger_{\bar{p}n} \mid \vec{q}_p > W_{\bar{p}n} < \vec{q}_p \mid G_{pn}(U_{p\bar{p}} + V_{pn}) \mid \psi^+ > \tag{8}$$

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

$$\mid \psi^+ > = G_{\bar{p}n}(U_{p\bar{p}} + V_{pn}) \mid \psi^+ > \tag{9}$$

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

$$\frac{d^2\sigma_{inc}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_p}\rho(E_p) < \psi^+ \mid \vec{q}_p > W_{\bar{p}n} < \vec{q}_p \mid \psi^+ > \tag{10}$$

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 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.[3)] The difference between the two is limited to the plane wave states here instead of the distorted waves obtained in the break-up fusion expression. This is entirely reasonable, however, as, after annihilation, there is simply nothing left to distort the final state wave fuction of the remaining nucleon.

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 subtration method of ref. 4 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 in Latta and Tandy, we neglect the Coulomb interaction.

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

$$\frac{d^2\sigma_{inc}}{d\Omega_p dE_p} = \frac{8\pi}{9}\frac{q}{k}\sum_{I,S} \mid C^{\frac{1}{2}\ \frac{1}{2}\ I}_{-\frac{1}{2}\ \frac{1}{2}\ M_I} \mid^2 \mid W_{IS} \mid \{\frac{2}{3} \mid \chi^{N\bar{N}}_{\frac{1}{2}IS}(\vec{q}) \mid^2 + \frac{1}{3} \mid \chi^{N\bar{N}}_{\frac{1}{2}IS}(\vec{q}) \mid^2\} \qquad (11)$$

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 strenght in the channel in which the annihilated pair have isospin I and S. The amplitudes are obtained as the overlap between the nucleon-antiproton separable potential form factor and the exact three body wave function.

$$\chi^{N\bar{N}}_{sIS}(\vec{q}) = \langle g_{IS} \mid \psi^+_s \rangle \qquad (12)$$

where s denotes the total channel spin, 1/2 or 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 $\delta(\vec{k} - \vec{k}')$.

In figure 1 we present our numerical results for the angle-integrated proton spectrum at two antiproton lab energies below the deuteron breakup theresiold, 1 and 3 MeV. The proton relative center-of-mass energy ($E_p = 3/4q^2$ was varied from zero to 20 MeV. 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 $\bar{p}$ lab 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. 3a the proton spectra at three fixed angles, $0^o, 20^o$ and 40^o. We see a clear minimum and a bump at 0^o ($E^{Lab}_{\bar{p}} = 3MeV$). This bump seems to be very sensitive to the binding energy of the target as indicated in fig. 3b.

The above feature of the proton spectrum seems to be a genuine three-body effect and it centainly 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 become more and more symmetrical about 90^0 indicating the complete loss of memory of the incident direction.

Finally a word about the formalism employed in the present work. 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 propose.

Further, corrections to the DWBA inclusive annihilation cross-section can be generated in a simple and consistent way using the method developed in Ref. 3c and 3d.

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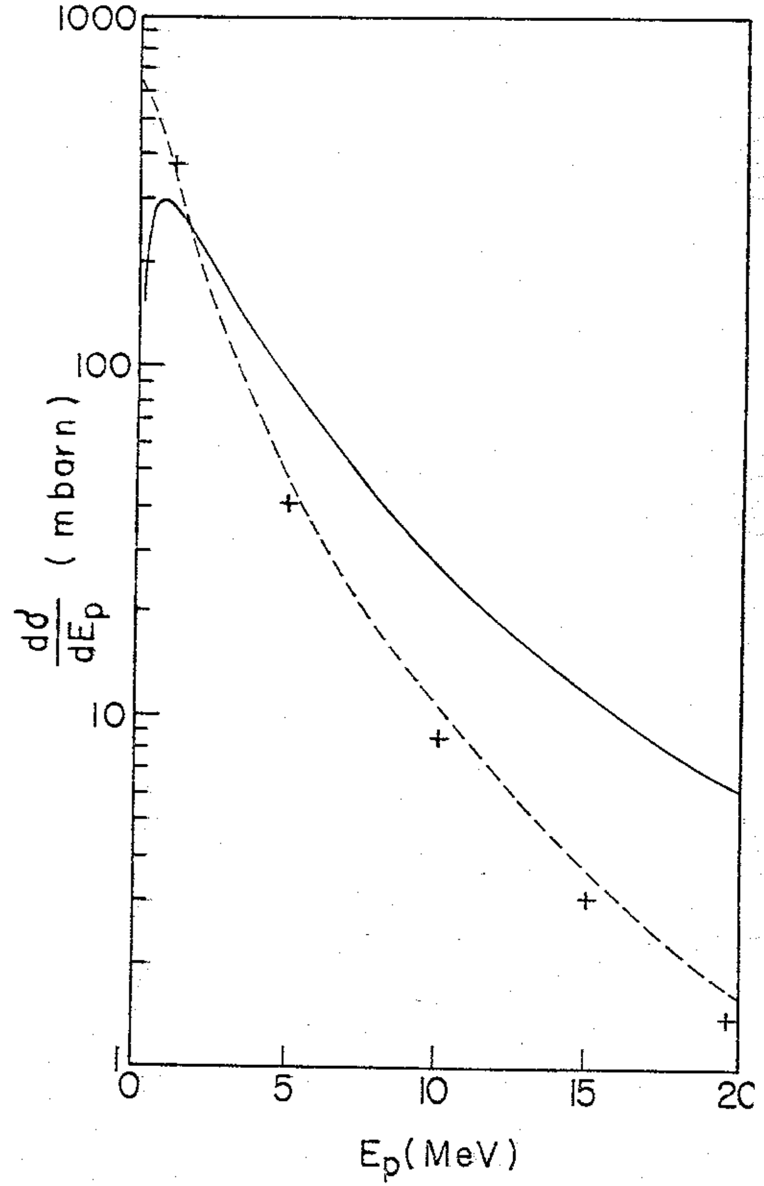
[4] S.K. Adhikari e L. Tomio, Phys. Rev. **C37**, 41 (1988), and references therein.

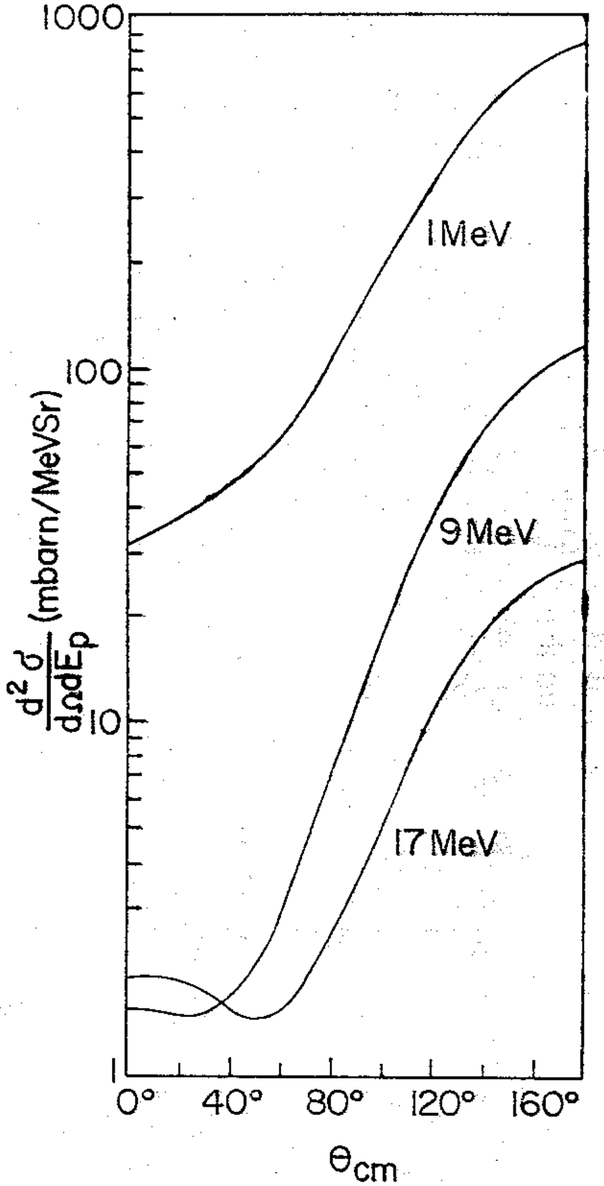
Figure Caption

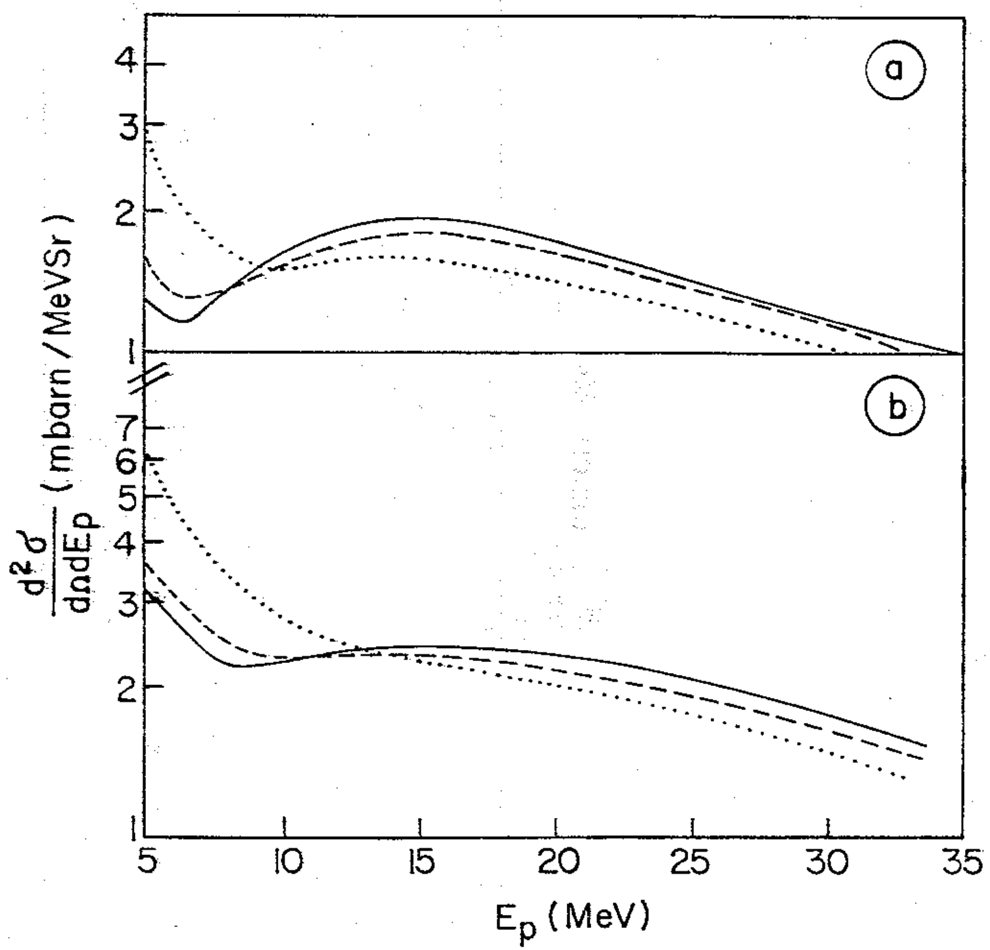
1. Angle integrated proton spectra as a function of the proton relative center of mass energy. Full line is for $E_{\bar{p}}^{Lab} = 3\ MeV$. Results for $\frac{k}{q}\frac{d\sigma}{dE_p}$ are showed by dashed line for $E_{\bar{p}}^{Lab} = 3\ MeV$ and the crosses for $E_{\bar{p}}^{Lab} = 1\ MeV$

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

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


1000
100
10
1
0
5
10
15
20
dσ/dEp (mbarn)
Ep(MeV)


1000
100
10
1
1MeV
9MeV
17MeV
0°
40°
80°
120°
160°
d²σ/dΩdEp (mbarn/MeVSr)
θcm


a
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25
30
35
$\frac{d^2\sigma}{d\Omega dE_p}$ (mbarn / MeVSr)
E_p (MeV)