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ABSTRACT

The effective mean free path for antinucleons in nuclear matter
is calculated at intermediate energies from the Fermi gas model, in terms
of the nucleon-antinucleon total and differential scattering cross sections.
The results are used to obtain the imaginary part of the optical-model
potential in the formalism of Riesenfeld and Watson. A comparison is
made with the nucleon-nucleon case.

EFFECTIVE MEAN FREE PATH OF ANTINUCLEONS IN NUCLEAR MATTER[*]

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I. INTRODUCTION

The antiproton beam from the Berkeley Bevatron is used in experiments with counters,[1] bubble chambers,[2] and photographic emulsions[3] to study the interaction of antinucleons with nucleons and nuclei.

Since the most successful theoretical approach to the problem of the nucleon-nucleus scattering has been made through the optical model of the nucleus,[4] Glassgold[5] has recently presented a detailed calculation of the antinucleon-nucleus interaction using this formalism. His work has shown that the most important parameter of the problem is the imaginary part of the central optical potential, since its value becomes very large as a result of the large antinucleon-nucleon cross section. Unfortunately, at the time Glassgold made his calculation, neither the $\bar{N}$-N differential scattering cross sections nor the total cross sections were known at the required energies, so that he could not obtain the actual value of the effective cross section. Therefore he chose for the imaginary part of the optical potential two extreme values: one corresponding to the total experimental cross section as measured in Reference 1a at 450 Mev, and the other corresponding to the annihilation part only of this cross section

Since, at the energies here considered, these two extreme values
differ by a factor of 2, we have considered it advisable to calculate
the effect of the Pauli principle in the scattering, using the now known
differential cross sections.[6]

In doing this we have chosen for the imaginary central optical
potential the standard definition,

$$V_{CI} = \frac{k}{M} \frac{1}{\bar{\lambda}_s} \quad , \tag{1}$$

where k is the antinucleon momentum in the $\bar{N}$-N barycentric system,
M the nucleon mass, and $\bar{\lambda}_s$ the "effective mean free path" defined by

$$\bar{\lambda}_s = \frac{1}{\rho \bar{\sigma}} = \frac{4\pi \lambda^3}{3 \bar{\sigma}} \quad , \tag{2}$$

where $\bar{\sigma}$ is defined below (Formula (4)), and ρ and λ as in Reference 4b.

Within this formalism our problem has been reduced to calculating
the "effective $\bar{N}$-N cross section," i.e., the part of the total $\bar{N}$-N cross
section not excluded by the Pauli principle.

In order to do that we have followed the ideas of Goldberger[7] and
Hayakawa, Kawai, and Kikuchi[8] in their calculations of the same effect in
the nucleon-nucleus system. However, there are two main differences
between the $\bar{N}$-nucleus and N-nucleus interaction. The first is that the
Pauli principle applies only to the nucleon inside the nucleus (and not to
the incoming antinucleon), and also only to the scattering part of the
cross section (the annihilation part is entirely unaffected). The second
is that the $\bar{N}$-N differential scattering cross section is strongly peaked

in the forward direction owing to diffraction from the annihilation
process, thus invalidating the assumption of isotropy of the angular
distribution. Also we take an energy dependence of the $\bar{N}$-N scattering
cross section as $1/k$ instead of $1/k^2$, as chosen by Hayakawa in the N-N
case. Therefore we have maintained the picture of the nucleus as a
mixture of two noninteracting Fermi gases at zero temperature, but we
have dropped the hypothesis of isotropy and have instead used an angular
distribution for $\bar{N}$-N scattering of the form

$$\sigma(\theta) = A(k) + B(k) \cos\theta + C(k) \cos^2\theta ,$$

which fits fairly well the theoretical and measured differential cross
sections for $\bar{p}$-p and $\bar{p}$-n scattering in the energy range between 100
and 250 Mev. [1b,6] It would be possible to have a better fit with higher
powers of $\cos\theta$, but the calculation becomes unreasonably complicated.
Considering the rough nature of the model, elaborate computations are
unjustified.

For example, a difficulty with the Fermi gas model that plays an
important part in antinucleon phenomena is the lack of any consideration
of the real shape of the nucleus. As we shall see, the interaction of
antinucleons with the nucleus is mainly on the nuclear surface, where the
density of nucleons is smaller and the Pauli principle less effective.
Some consideration of this effect can perhaps be accomplished by using a
small value of the Fermi energy. We have chosen 33 Mev for this parameter,
corresponding to $\lambda = 1.2 \times 10^{-13}$ cm.

The uniform k dependence of the coefficients of the $\cos\theta$
expansion of the differential cross section, although fairly good for the
total scattering cross section, does not represent the narrowing of the

forward diffraction-scattering peak with increasing energy, and therefore
underestimates the effect of the Pauli principle at the higher energies.
This error is not very important, however.

II. CALCULATION OF THE "EFFECTIVE MEAN FREE PATH"

Let $\vec{P}_1$ and $\vec{P}_1{}'$ be the antinucleon momenta in the laboratory
system, before and after the collision respectively, and $\vec{P}_2$ and $\vec{P}_2{}'$
the corresponding momenta of the target nucleon. The Fermi model gives
rise to a uniform distribution of P_2 bounded by the Fermi momentum P_F,
which we assume to have the same value for neutrons and protons. The
Pauli principle requires $P_2{}' > P_F$. See Fig. 1.

If we write the differential scattering cross section in the
nucleon-antinucleon barycentric system as $\frac{d\sigma}{d\Omega} \left| \vec{P}_1 - \vec{P}_2 \right| = K + L \cos \theta + M \cos^2 \theta$,
we get for the effective cross section

$$\bar{\sigma}(P_1) = \frac{3P_1}{4\pi P_F{}^3} \int_0^\infty (J_1 + J_2 + J_3) dx , \qquad (3)$$

where

$$J_1 = 4 \pi^2 K x^2 \left[(1 + x^2 - 2\alpha^2) z_1 + z_2 \right] ,$$

$$J_2 = -2 \pi^2 L x^2 (1 - x^2) \left[z_1 - (1 + x^2 - 2\alpha^2)^2 z_3 \right] ,$$

$$J_3 = 2 \pi^2 M x^2 \left\{ \frac{2}{3} z_2 + (1 + x^2 - 2\alpha^2) z_1 + (1 - x^2)^2 (1 + x^2 - 2\alpha^2)^3 z_4 \right.$$

$$\left. - (1 + x^2 - 2\alpha^2) \left[\frac{4}{3} (1 + x^2 - \alpha^2)^2 - (1 - x^2)^2 \right] z_3 \right\} ,$$

$$x = \frac{P_2}{P_1} \quad , \qquad \alpha = \frac{P_F}{P_1} \quad ,$$

$$z_1 = \frac{1}{x} \sin^{-1} \frac{2x}{1 + x^2} \quad ,$$

$$z_2 = 2 \quad , \qquad\qquad z_3 = \frac{2}{(1 + x^2)^2 (1 - x^2)}$$

and

$$z_4 = \frac{2}{3} \frac{3(1 + x^2)^2 - 8x^2}{(1 + x^2)^4 (1 - x^2)^3} \quad .$$

We consider a nucleus with the same number of protons and neutrons and average over the $\bar{p}$-p and $\bar{p}$-n cross sections (the former including charge exchange), therefore defining

$$\bar{\sigma} = \left\langle \sigma_{annih} \right\rangle + \gamma \left\langle \sigma_{scat} \right\rangle \quad , \tag{4}$$

where

$$\left\langle \sigma_{\genfrac{}{}{0pt}{}{(annih)}{(scat)}} \right\rangle = \sum_{I=0}^{1} \frac{2I + 1}{4} \sigma^I_{\genfrac{}{}{0pt}{}{(annih)}{(scat)}} \quad (\text{I is the isotopic spin})$$

and γ is the factor that accounts for the Pauli principle. We now determine K, L, and M by fitting the averaged theoretical angular distributions of $\bar{p}$-p and $\bar{p}$-n scattering at different energies.[6]

The integration (3) has been made numerically and the results, expressed in terms of the mean free path $\bar{\lambda}_s$, are shown in Fig. 2. For

comparison the mean free paths obtained (a) from an isotropic angular
distribution (with the same k dependence) and (b) from $\gamma = 1$
(i e., complete neglect of the exclusion principle) are also plotted.

Finally, Table I shows the imaginary part of the central optical-
model potential, according to Formula (1), at several different energies,
together with the corresponding values for the case of $\gamma = 1$.

TABLE I

Optical potentials: V_{CI} in Mev ($\lambda = 1.2 \times 10^{-13}$ cm)				
E_{lab} (in Mev)				
50	100	140	200	260
γ calculated				
64[a]	73	77	80	84
$\gamma \cdot 1$				
90	103	106	108	108

[a] The value of λ_s has been extrapolated.

III. CONCLUSION

The large value of the nucleon-antinucleon cross section has long been known to imply a very short mean free path for antinucleons in nuclear matter. The exclusion-principle effect considered here increases somewhat the mean free path, but not enough to change the conclusion that nearly all antinucleon interactions occur on the nuclear surface.

In the same energy range the nucleon effective mean free path is larger than 5×10^{-13} cm, showing a striking difference between the nucleon-nucleus and antinucleon-nucleus interaction.
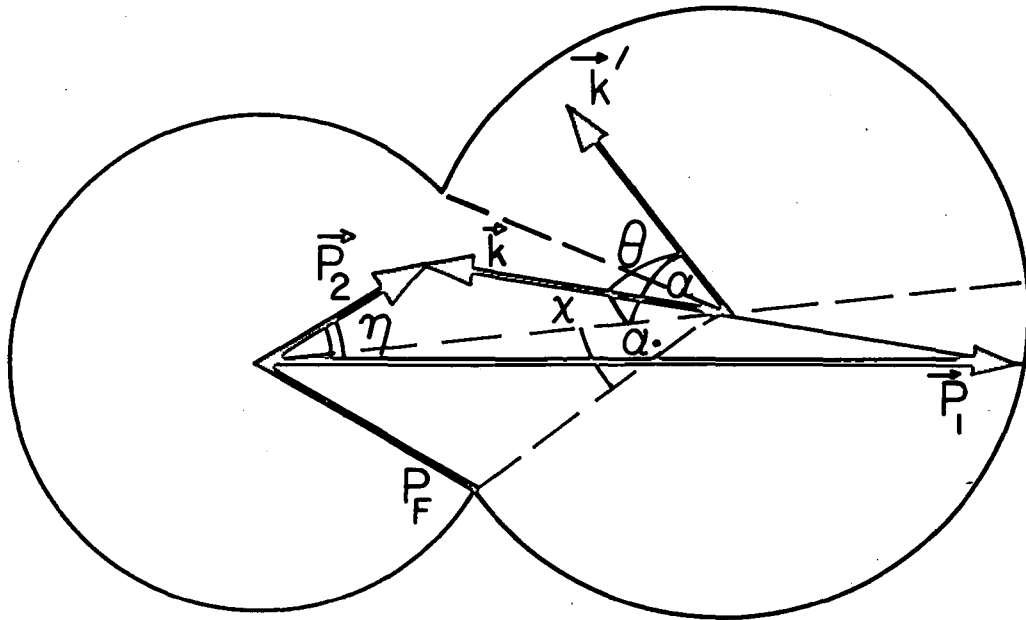
ACKNOWLEDGMENTS

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FIGURE CAPTIONS

1.   Coordinate systems and limits of integration.

2.   Mean free path of antinucleon in nuclear matter.

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Fig. 1.
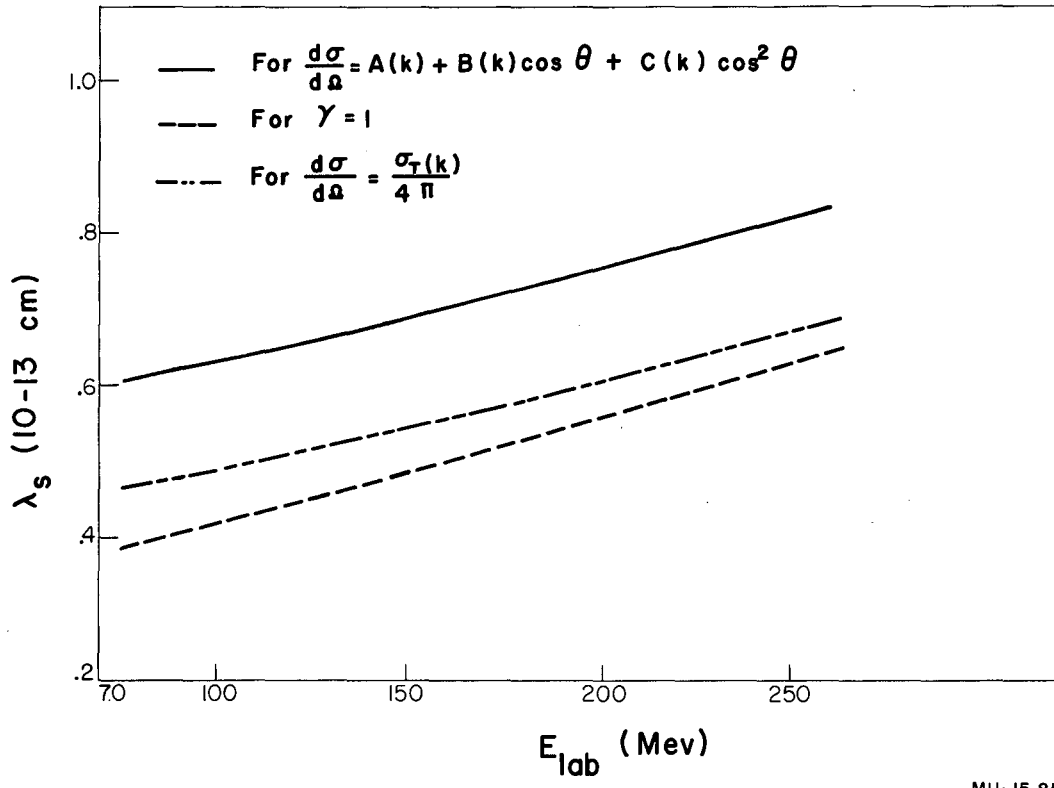
Fig. 2.