on rare occasions, be an essentially impenetrable barrier for low-energy cosmic-ray particles. It is quite possible these conditions at the source would change with solar activity cycle to account for the effect found by Firor[4] near the minimum of cycle.

Additional investigation of this problem during the approaching period of lower solar activity is required. In particular, it would be desirable to study the hard component as well as the nucleonic component of cosmic radiation so that the diurnal effects and flare effect may be more effectively separated.

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Nucleon-Antinucleon Scattering*

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By use of the model of the nucleon-antinucleon interaction proposed by Ball and Chew, a calculation of the complex phase shifts at 50 and 260 Mev has been made. The values of annihilation, elastic-scattering, and charge-exchange cross sections, and the angular distributions for $\bar{p}$-p and $\bar{p}$-n elastic scattering are obtained. A comparison with the experimental data shows reasonable agreement. Finally, the parameters of an optical-model potential for antinucleon interaction with complex nuclei are presented.

A MODEL of the nucleon-antinucleon interaction at intermediate energies has been presented recently by Ball and Chew[1] (hereafter referred to as I). They used the Gartenhaus[2] and Signell and Marshak[3] potentials, with a "black central hole" to account for the annihilation, and their WKB calculation of the cross sections and angular distributions[4] at 140 Mev has proved to be in good agreement with experiment.

In view of this success we have extended the calculation to 50 and 260 Mev, to cover the range where experimental data have become available.[5] We have assumed that these two energies are the extreme points between which the model should be reasonably valid. At higher energies the details of the annihilation boundary condition become more important and a partial penetration of the higher waves can be expected, increasing the annihilation cross section. At energies lower than 50 Mev the wavelength of the incident particle becomes of the same order as the wavelength associated with the barrier and the WKB method of calculation breaks down.

The transmission coefficients and the real phase shifts are given in Table I.

We have modified the singlet-isotopic-spin, singlet-spin potential by cutting off the large repulsive central region; since this potential produces an unphysical bound state in the N-N system.[3] For this reason, the

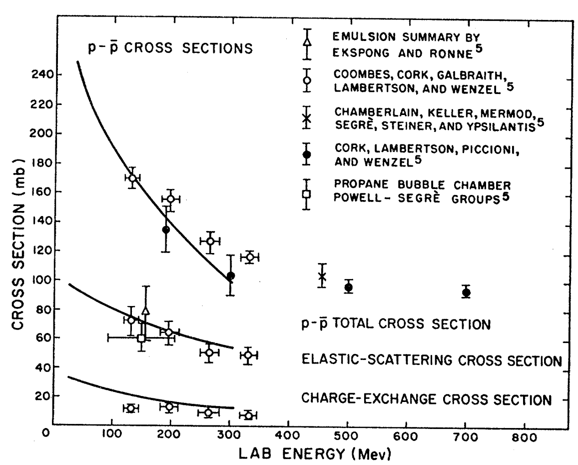

FIG. 1. $\bar{N}$-N cross sections as a function of energy. (The charge-exchange cross sections of Coombes, Cork, Galbraith, Lambertson, and Wenzel have been modified according to what it is proposed in their paper.)

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‡ Visitor from the Argentine Army.

[1] J. S. Ball and G. F. Chew, Phys. Rev. **109**, 1385 (1958).

[2] S. Gartenhaus, Phys. Rev. **100**, 900 (1955). The sign of the one-meson contribution has been changed to describe the nucleon-antinucleon system.

[3] P. Signell and A. Marshak, Phys. Rev. **109**, 1229 (1958).

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[5] Coombes, Cork, Galbraith, Lambertson, and Wenzel, Phys. Rev. **112**, 1303 (1958); Chamberlain, Keller, Mermod, Segrè, Steiner, and Ypsilantis, Phys. Rev. **108**, 1553 (1957); Cork, Lambertson, Piccioni, and Wenzel, Phys. Rev. **107**, 248 (1957); Agnew, Elioff, Fowler, Gilly, Lander, Oswald, Powell, Segrè, Steiner, White, Wiegand, and Ypsilantis, Phys. Rev. **110**, 994 (1958), and private communication; Goldhaber, Kalogeropoulos, and Silberberg, Phys. Rev. **110**, 1474 (1958); A. G. Ekspong and B. E. Ronne, Uppsala University, Institute of Physics, Technical note No. 1 (unpublished).

TABLE I. Phase shifts (δ) and transmission coefficients ($T=1-R^2$).

State	50 Mev T	50 Mev δ	140 Mev T	140 Mev δ	260 Mev T	260 Mev δ
$^3P_0{}^1$	1	...	1	...	1	...
$^3S_1{}^1$	1	...	1	...	1	...
$^3P_1{}^1$	0	−19°	0	−41°	0	−54°
$^3D_1{}^1$	0	0	0	0	0	−15°
$^3P_2{}^1$	1	...	1	...	1	...
$^3D_2{}^1$	0	0	0	−17°	0	−23°
$^3F_2{}^1$	0	0	0	0	0	−18°
$^3D_3{}^1$	0	0	1	...	1	...
$^3F_3{}^1$	0	0	0	0	0	−12°
$^3F_4{}^1$	0	0	0	0	0	10°
$^3P_0{}^3$	0	−10°	0	−33°	0	−47°
$^3S_1{}^3$	1	...	1	...	1	...
$^3P_1{}^3$	1	...	1	...	1	...
$^3D_1{}^3$	0	0	0	−13°	0	−29°
$^3P_2{}^3$	0	3°	1	...	1	...
$^3D_2{}^3$	0	0	0	6°	0	11°
$^3F_2{}^3$	0	0	0	0	0	−28°
$^3D_3{}^3$	0	0	0	2°	0	8°
$^3F_3{}^3$	0	0	0	0	0	3°
$^3F_4{}^3$	0	0	0	0	0	0
$^1S_0{}^1$	1	...	1	...	1	...
$^1P_1{}^1$	0	11°	0	6°	0	−10°
$^1D_2{}^1$	0	0	0	6°	0	6°
$^1F_3{}^1$	0	0	0	0	0	3°
$^1S_0{}^3$	1	...	1	...	1	...
$^1P_1{}^3$	0	−1°	1	...	1	...
$^1D_2{}^3$	0	0	0	0	0	3°
$^1F_3{}^3$	0	0	0	0	0	−1°

$^1S_0{}^1$ transmission coefficient at 140 Mev has been changed from that given in I, and is now consistent with the values at 50 and 260 Mev. This state is of such a small statistical weight that the change in the cross sections is negligible.

The total annihilation and scattering cross sections are given in Table II.

TABLE II. Cross sections (mb) for nucleon-antinucleon interactions at different energies.

	50 Mev p-$\bar{p}$	50 Mev $\bar{p}$-n	140 Mev p-$\bar{p}$	140 Mev $\bar{p}$-n	260 Mev p-$\bar{p}$	260 Mev $\bar{p}$-n
σ_{total}	232	184	168	148	113	101
$\sigma_{\text{elastic scattering}}$	91	93	73	79	58	64
$\sigma_{\text{absorption}}$	110	91	74	69	40	37
$\sigma_{\text{charge exchange}}$	31	...	21	...	15	...

TABLE III. The effect of partial transmission on p-$\bar{p}$ scattering at 260 Mev.

States modified $^3D_3{}^3$	States modified $^3F_4{}^1$	Cross sections (mb) σ_{total}	σ_{elastic}	$\sigma_{\text{abs.}}$	$\sigma_{\text{exch.}}$
$T=0.5$	$T=0$	118	61	44	13
$T=0$	$T=0.5$	118	56	45	17
$T=0.5$	$T=0.5$	123	58	50	15

A comparison with the experimental data available up to now is shown in Fig. 1. The agreement is fairly good, except for the value of the theoretical annihilation cross section at 260 Mev, which seems to be too small. However, by allowing partial transmission of the most strongly attractive effective potentials one may obtain larger values of this cross section. Various possible modifications and their results are shown in Table III.

The angular distributions are plotted in Figs. 2 to 7. For their calculation we have used the method described in reference 4. A comparison with the experimental data at 133 and 265 Mev is also given.

The general agreement of the theory with experiment in this energy range seems reasonably good in view of the crude nature of the potential description of the N-$\bar{N}$ interaction and the approximations made in our

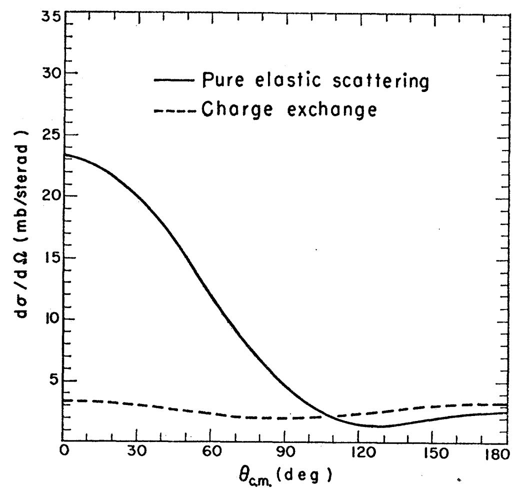

FIG. 2. Differential scattering cross sections in the c.m. system for $\bar{p}$-p (neglecting Coulomb scattering) and $\bar{n}$-n at $E_{\text{lab}}=50$ Mev.

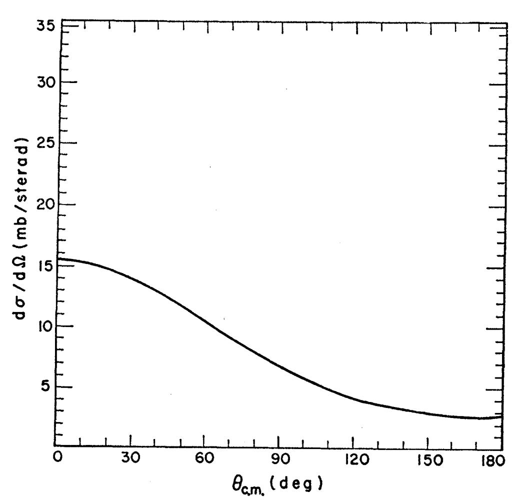

FIG. 3. Differential scattering cross sections (in the c.m. system) of $\bar{p}$-n and $\bar{n}$-p at $E_{\text{lab}}=50$ Mev.

calculations. Our main conclusion is that no long-range annihilation interaction is required by the existing experimental facts; the ordinary pion-exchange force appears to be sufficiently attractive on the average to produce the observed annihilation cross sections at intermediate energies. It is also reassuring that this model leads to only a small charge-exchange cross section, as required by experiment. In fact, one may say that in its predictions our model behaves not too differently from a black absorbing sphere of radius approximately equal to the pion Compton wavelength. That it should do so, however, appears to be an accident, following from the detailed nature of the pion-exchange force.

OPTICAL-MODEL POTENTIAL

An optical model for the scattering of nucleons by nuclei has been proposed and developed by many authors.[6,7] To apply it to the antinucleon-nucleus system we have followed the method of Riesenfeld and Watson,[7] suitably modified to account for the annihilation process.

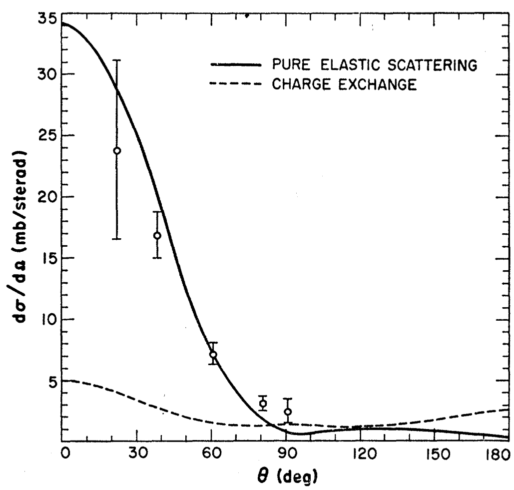

FIG. 4. Differential scattering cross section (in the c.m. system) of $\bar{p}$-p (neglecting Coulomb scattering) and $\bar{n}$-n at $E_{\text{lab}}=140$ Mev. Experimental data obtained by Coombes, Cork, Galbraith, Lambertson, and Wenzel.

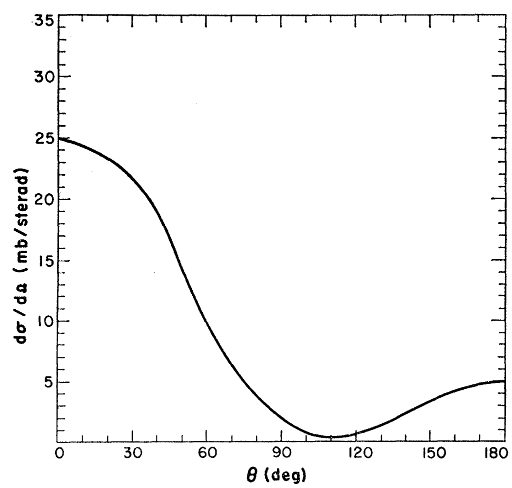

FIG. 5. Differential scattering cross sections (in the c.m. system) of $\bar{p}$-n and $\bar{n}$-p at $E_{\text{lab}}=140$ Mev.

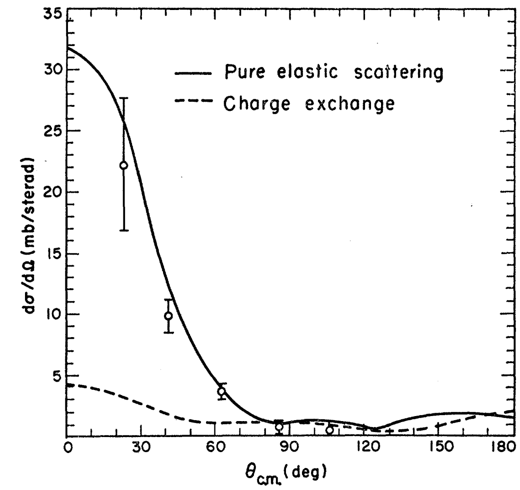

FIG. 6. Differential scattering cross section (in the c.m. system) of $\bar{p}$-p (neglecting Coulomb scattering) and $\bar{n}$-n at $E_{\text{lab}}=260$ Mev. Experimental data obtained by Coombes, Cork, Galbraith, Lambertson, and Wenzel.

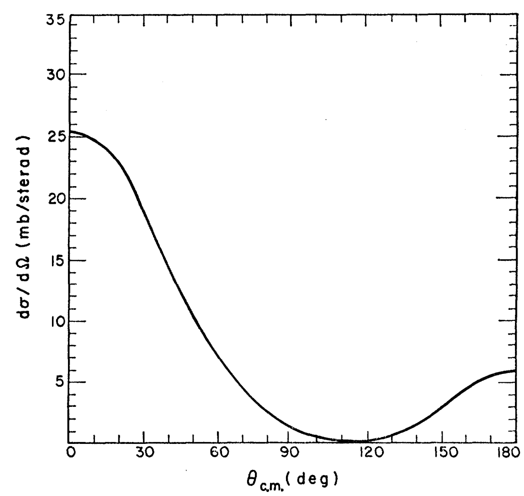

FIG. 7. Differential scattering cross sections (in the c.m. system) of $\bar{p}$-n and $\bar{n}$-p at $E_{\text{lab}}=260$ Mev.

The optical-model potential is then given (in units where $\hbar=c=\mu=1$, and μ is the π-meson mass) by

$$V_{\text{opt}}(x)=-[V_{CR}+iV_{CI}]\rho(x)+[V_{SR}+iV_{SI}]\frac{1}{x}\frac{d\rho}{dx}(\boldsymbol{\sigma}\cdot\mathbf{l}),$$

where

$$V_{CR}=\frac{3}{M\lambda^3}\,\mathrm{Re}[f(0)],$$

[6] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

[7] W. B. Riesenfeld and K. M. Watson, Phys. Rev. **102**, 1157 (1956). This paper contains a more complete list of references about the optical model.

TABLE IV. Optical-model potential depths for $\lambda=0.8571$.

$V \backslash E$ (Mev)	50	140	260
V_{CR} (Mev)	−0.66	−12.1	−14.8
V_{SR} (Mev)	3.5	2.9	5.4
V_{SI} (Mev)	−4.2	1.7	−1.2
V_{CI} (Mev)	64	77	84

$$\mathrm{Re}[f(0)]=\frac{1}{32k}\sum_{I=0}^{1}\sum_{S=0}^{1}\sum_{J,l}(2I+1)\times(2J+1)\,{}^SR_{J,l}{}^I\sin(2\,{}^S\delta_{J,l}{}^I),$$

$$V_{CI}=\frac{3}{M\lambda^3}\mathrm{Im}[f(0)]=\frac{k}{M}\frac{3\bar{\sigma}}{4\pi\lambda^3},$$

$$[V_{SR}+iV_{SI}]=\frac{3}{M\lambda^3}\frac{1}{4k^2}f_1(0),$$

$$f_1(0)=\frac{1}{32ik}\sum_{I=0}^{1}\sum_{j,l,S=1}(2I+1)(2J+1)\times\{[1-{}^1R_{J,l=J}{}^I\exp(2i\,{}^1\delta_{J,l=J}{}^I)]-(J-1)[1-{}^1R_{J,l=J-1}{}^I\exp(2i\,{}^1\delta_{J;l=J-1}{}^I)]+(J+2)[1-{}^1R_{J,l=J+1}{}^I\exp(2i\,{}^1\delta_{J;l=J+1}{}^I)]\},$$

k being the antinucleon momentum in the center-of-mass system; λ and $\rho(x)$ are defined in reference 7, and R is the amplitude of the reflected partial wave $[R=(1-T)^{\frac{1}{2}}]$.

In these expressions $\bar{\sigma}$ is the effective antinucleon-nucleon cross section given by

$$\bar{\sigma}=\tfrac{1}{2}[\sigma_{\bar{p}-n}{}^{\mathrm{abs}}+\sigma_{\bar{p}-p}{}^{\mathrm{abs}}]+\tfrac{1}{2}\gamma[\sigma_{\bar{p}-n}{}^{\mathrm{sc}}+\sigma_{\bar{p}-p}{}^{\mathrm{sc}}],$$

where γ is a factor that takes into account the effect of the Pauli principle upon nucleons inside the nucleus. This effect tends to forbid collisions with small momentum transfer, thereby decreasing the scattering in the forward direction.

A calculation of the γ factor has been performed considering a Fermi gas model of the nucleus and an N-$\bar{N}$ differential scattering cross section of the form $k[d\sigma(\theta)/d\Omega]=K+L\cos\theta+M\cos^2\theta$ which fits the measured angular distributions fairly well in the energy range considered here.[8] The results are shown in Table IV. Using these potentials, Fernbach *et al.* are now carrying out an optical-model calculation of the scattering of antiprotons from several light nuclei.

ACKNOWLEDGMENTS

We are indebted to Professor Geoffrey F. Chew for his invaluable advice and to Dr. Kenneth M. Watson for his help with the optical model.

[8] J. R. Fulco, University of California Radiation Laboratory Report UCRL-8416 (unpublished).

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p-n Asymmetries at 143 Mev*

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The asymmetry of neutrons produced by bombardment of C, Al, Cu, and Pb by 143-Mev polarized protons, at angles 20° to 70°, has been measured. The asymmetry is almost independent of target element but is inconsistent with that from a free *p-n* collision. The mechanism for the process is discussed.

INTRODUCTION

THE (p,n) reaction producing neutrons by proton bombardment of nuclei is primarily of interest as a source of neutrons from high-energy cyclotrons. It has usually been assumed that the process is an elementary collision with a neutron inside the nucleus. Early work on the polarization of the neutron[1] was consistent with this view. If this is indeed the case then the relation, which holds for elastic scattering, connecting the asymmetry of the outgoing neutrons from a polarized proton beam to the polarization of the neutrons from an unpolarized beam should still hold; this relation is $e=P_1P_2$. Thus it should be possible to compare directly the polarizations previously measured[1–3] with asymmetries. Roberts, Tinlot, and Hafner[3] and later Bradner and Donaldson[4] showed a deviation from the simple picture. They found a large asymmetry in the (n,p) reaction on carbon by polarized neutrons at 150 Mev, at 45° lab, of a sign opposite to the free *n-p* scattering. Stafford, Tournabene, and Whitehead[2] confirmed this by measuring the polarization of neutrons produced in the (p,n) reaction at 160 Mev. It is the purpose of this paper to extend this work by

* Supported by the Office of Naval Research.
† Now at Atomics International, Canoga Park, California.
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