Experimentally[1,2] $\epsilon G \gtrsim 0.012$ so, from (10) and (12),

$$A_{\pi^- e^+ \nu} \lesssim 8.5\%. \tag{13}$$

Probably it will be some time before experiments are performed which are capable of detecting such small charge asymmetries.

I wish to thank Professor N. M. Kroll, Professor L. M. Lederman, Professor T. D. Lee, and Professor J. Steinberger for a number of valuable discussions concerning this work.

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Theoretical Angular Distribution of Nucleon-Antinucleon Scattering at 140 Mev*

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A POSSIBLE explanation of the "large" value of the nucleon-antinucleon ($N-\bar{N}$) cross section,[1] in the intermediate energy range, has been given by the work of Ball and Chew[2] on the basis of the Yukawa interaction with a "black central hole" to account for the annihilation. Using the Gartenhaus potential,[3] with the spin-orbit term added by Signell and Marshak,[4] in the WKB approximation, they obtained results in satisfactory agreement with the experimental data available at the time.

In recent months, experiments both with bubble chambers and with emulsions have been planned and are now being carried out in order to obtain a more complete knowledge of the $p-\bar{p}$ interaction. In connection with this program it has seemed worthwhile to perform the calculation of the angular distribution of antinucleon-nucleon scattering, using the transmission coefficients and the phase shifts given in reference 2. This is a report of the results of the calculation.

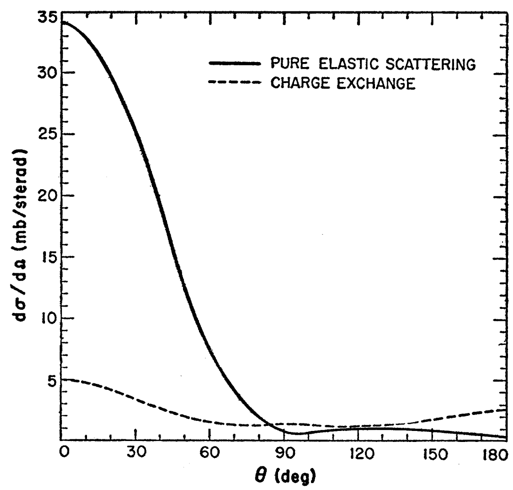

FIG. 1. Scattering cross section of $\bar{p}$-p (neglecting Coulomb scattering) and $\bar{n}$-n, at $E_{\text{lab}}=140$ Mev (in the c.m. system).

There are two important differences between the $N-N$ and $N-\bar{N}$ interactions. One is the annihilation process and the other the possibility of charge exchange: $p+\bar{p}\leftrightarrow n+\bar{n}$. The first is easily considered by using diagonal scattering matrix elements of the form $S_\alpha = R_\alpha e^{2i\delta_\alpha}$, where R_α are the reflection coefficients and δ_α the real scattering phase shifts for the α eigenstate. The second involves isotopic-spin considerations.[5] If the amplitudes for scattering in isotopic-spin singlet and triplet states are represented by f^1 and f^3, respectively, then the amplitudes for ordinary (o) and exchange (e) $p-\bar{p}$ and $n-\bar{n}$ scattering are given by

$$f^o = \tfrac{1}{2}(f^1+f^3), \quad f^e = \tfrac{1}{2}(f^1-f^3).$$

For the $p-\bar{n}$ and $n-\bar{p}$ systems, which are pure isotopic triplets, there is no exchange scattering and the ordinary scattering amplitude is simply f^3. Once these complications are recognized, the formalism developed by Blatt and Biedenharn[6] can be consistently used.

Since in the WKB approximation there is no way to calculate "mixture parameters," interchange between waves with the same total angular momentum and parity but with different orbital angular momentum has not been considered in reference 2. Therefore it must be assumed that the mixture parameters are small if this method is expected to give good accuracy. With mixing neglected, the scattering cross sections were calculated; the results are plotted in Figs. 1 and 2.

The forward peak in the ordinary scattering is largely a diffraction effect, since the S and P waves are mostly absorbed, leading to annihilation. The forward peak in the exchange scattering is much weaker.

Notwithstanding the very limited experimental data available up to now,[7] a crude test of the theory can already be made by integrating the $p-\bar{p}$ elastic differential cross section of Fig. 1 over the forward

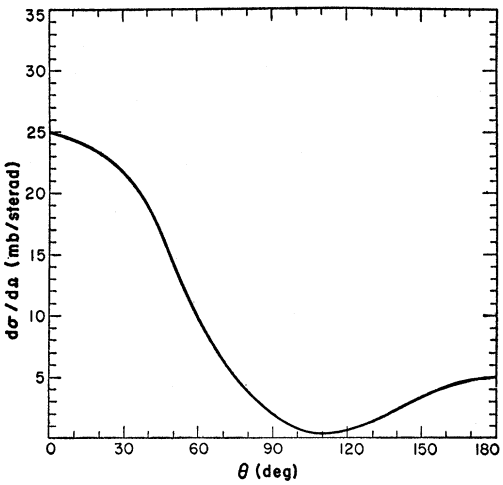

FIG. 2. Scattering cross section of $\bar{p}$-n and $\bar{n}$-p at $E_{\text{lab}}=140$ Mev (in the c.m. system).

and backward hemispheres separately to obtain 70 mb in the forward direction and 5 mb in the backward. The six emulsion events found at Berkeley in the energy range between 40 and 200 Mev[7] are all in the forward direction.

Further work is being done to extend the scope of this paper.

The author wishes to thank Professor Geoffrey F. Chew for his guidance and help throughout the work.

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† A visitor from the Argentine Army.

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Spin-Orbit Contributions in the Low-Energy n-p Triplet Potentials

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IT was recently pointed out by Feshbach[1] that some of the spin-orbit forces lately proposed for the neutron-proton system lead to unacceptably large modifications of the magnetic moment of the deuteron. The same objection applies also to the spin-orbit coupling obtained by Newton and Fulton.[2]

In the presence of a spin-orbit potential,

$$V_0(r)\mathbf{S}\cdot\mathbf{L},$$

the difference between the magnetic moment of the deuteron and the sum of the neutron and proton moments becomes, in nuclear magnetons,[1]

$$\Delta\mu\equiv\mu_d-(\mu_p+\mu_n)=-\tfrac{3}{2}(\mu_p+\mu_n-\tfrac{1}{2})p_D+(\Delta\mu)_{SL}, \quad (1)$$

where

$$(\Delta\mu)_{SL}=\tfrac{1}{6}[\langle S|r^2V_0|S\rangle-\tfrac{1}{2}\sqrt{2}\langle S|r^2V_0|D\rangle +\tfrac{1}{2}\langle D|r^2V_0|D\rangle], \quad (2)$$

if V_0 is measured in units of the rest mass of the nucleon and r in units of the Compton wavelength of the nucleon. The experimental value is

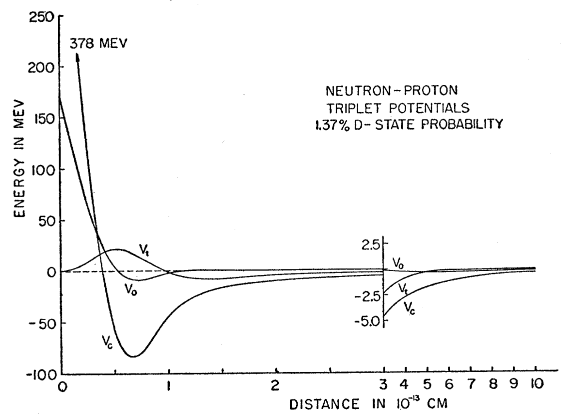

FIG. 1. Neutron-proton triplet potentials for a D-state probability of 1.37%. V_c is the central, V_t, the tensor, and V_0, the spin-orbit potential. There is a change in vertical and horizontal scale at 3×10^{-13} cm.

$$\Delta\mu=-0.0224 \text{ nm}. \quad (3)$$

For the potentials of reference 2, with a D-state probability of 2.09%, we have

$$-\tfrac{3}{2}(\mu_p+\mu_n-\tfrac{1}{2})p_D=-0.012 \text{ nm},$$
$$(\Delta\mu)_{SL}=+0.034 \text{ nm},$$

and therefore

$$\Delta\mu=+0.022 \text{ nm}. \quad (4)$$

The discrepancy between (3) and (4) is too large to be accounted for by relativistic and other effects. We have, therefore, changed the parameters in the potentials to obtain a better fit.

If, in the notation of reference 2, we put $\chi=2.20\times10^{13}$ cm^{-1} and $d=1.12$, then a set of central, tensor, and spin-orbit potentials is obtained for which the deuteron D-state probability is

$$p_D=1.37\%$$