RANGE OF THE SPIN-ORBIT FORCE BETWEEN TWO PROTONS*

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Gammel, Christian, and Thaler[1] were the first to carry through an extensive analysis of the two-nucleon scattering data up to 300 Mev on the basis of arbitrary combinations of central and tensor Yukawa-type forces. When this work failed to yield satisfactory agreement with experiment, two of the present authors[2] decided to try adding a phenomenological spin-orbit force to the particular combination of central and tensor forces defined by the meson-theoretic Gartenhaus potential. The rationale of this hybrid mixture has been discussed in the original papers[2] and in a paper by Okubo and one of the authors.[3] This so-called semiphenomenological SM potential gives a good fit to all of the two-nucleon data up to 150 Mev and becomes progressively worse as the energy is increased to 300 Mev. At least three questions must be raised: (1) How unique is the spin-orbit potential?[4] (2) How sensitive are the predictions to changes in the cores of the Gartenhaus potential?[5] (3) Can the scattering data at 300 Mev be explained by modifying the shape of the spin-orbit force and/or the cores of the Gartenhaus potential or must a higher-order velocity-dependent potential (e.g., the quadratic spin-orbit force[3]) be introduced? Some calculations giving partial answers to these three questions with regard to proton-proton scattering are reported in this note.

It was realized at the start that the Goldfarb-Feldman[6] parameters for the spin-orbit potential were not in accord with meson theory but they were at hand and gave such a good fit to the data that they were used. It was also recognized that the Gartenhaus potential would have to be modified at small distances for at least the triplet odd states since an unphysical bound $^3P_2$ state[2] resulted from the strongly attractive central part of the Gartenhaus potential in these states. We have now investigated the effect of decreasing the range of the spin-orbit potential from our initial value of 1.07×10^{-13} cm to the

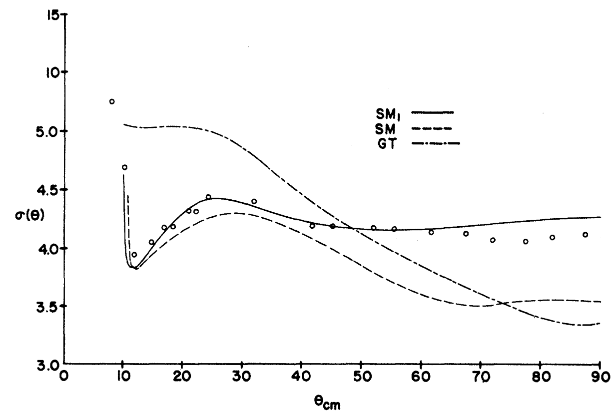

FIG 1. Comparison of 150-Mev proton-proton unpolarized cross section predictions with 147-Mev Harvard (8 and 14) experimental data.

"meson-theoretical" value of 0.7×10^{-13} cm; the spin-orbit potential is of the form

$$V_{LS}=(V_0/x)\frac{d}{dx}\left(\frac{e^{-2x}}{x}\right), \qquad (1)$$

where $x=\mu r$ and V_0(=21 Mev) is adjusted to fit[7] the p-p differential cross section at 45° (c.m.) and 150 Mev. In order to eliminate the bound $^3P_2$ state, we have modified the Gartenhaus triplet odd potential to include an infinitely repulsive core out to $x_c=0.37$. The resulting potential will be referred to as the SM1 potential.

The predictions of the SM1 potential for $\sigma(\theta)$, $P(\theta)$, and $D(\theta)$ at 150 Mev are shown in Figs. 1-3. Comparison is made with the predictions of the original SM and Gammel-Thaler[2] (GT) potential as well as with the experimental curves.[8] The SM and SM1 potentials make essentially the same predictions at energies lower than 150 Mev (e.g., 40 and 100 Mev [2]). At 300 Mev, it is interesting to compare the ^3P and ^3F phase shifts. In Table I we have listed these phase shifts corresponding to the SM1 and SM potentials and also the Stapp No. 1 set of phase shifts.[9]

From Figs. 1-3 and Table I, the following conclusions can be drawn: (1) At this stage, the spin-orbit force is not unique. Thus, a reduction in range — to match the "meson-theoretic" range — does not harm the agreement with the p-p scattering data at 150 Mev and even improves the agreement somewhat.[10] At 300 Mev, the reduced range of the spin-orbit potential yields phase shifts which constitute a distinct improvement over the previous ones. (2) Short-range repulsive cores can readily be introduced into the Gartenhaus potential to eliminate the unphysical bound states without adverse effects on the scattering.

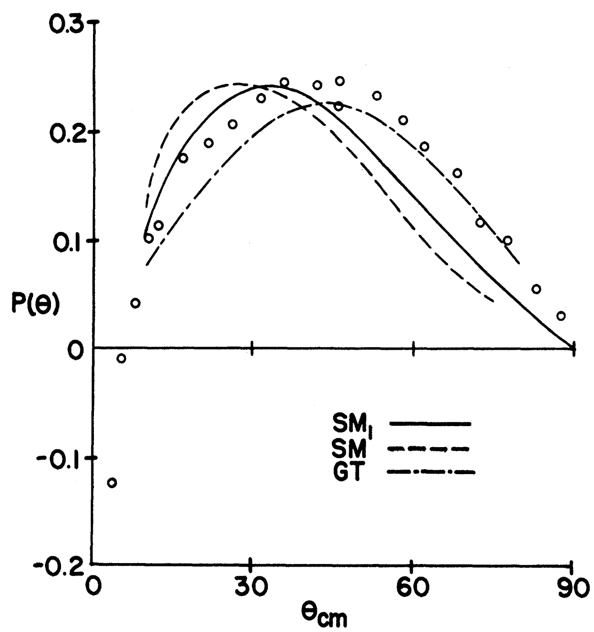

FIG. 2. Comparison of 150-Mev proton-proton polarization predictions with 147-Mev Harvard experimental data.

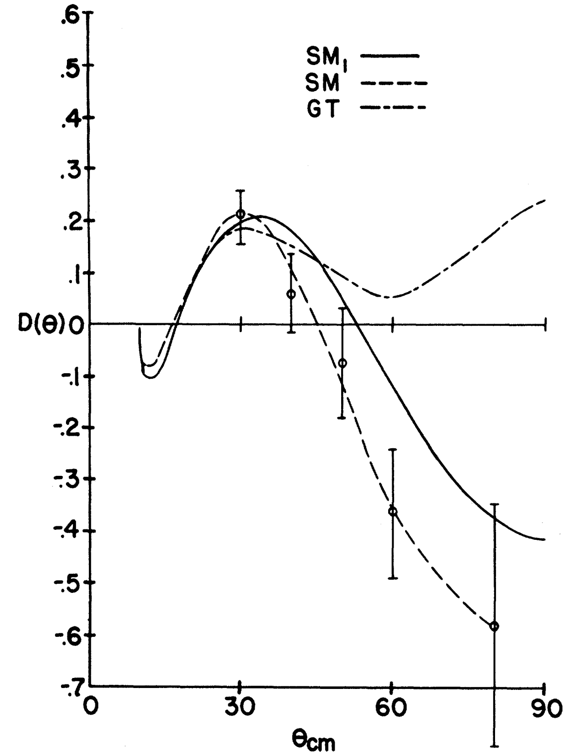

FIG. 3. Comparison of predictions for the triple scattering parameter $D(\theta)$ at 150 Mev.

(3) It is not excluded that a more exotic combination of spin-orbit and modified Gartenhaus potentials can explain the present p-p scattering data up to 300 Mev. A final decision as to whether the p-p interaction is more than linearly velocity-dependent in this energy region will probably require a complete determination of the experimental scattering matrix.[11]

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[1]Gammel, Christian, and Thaler, Phys. Rev. 105, 311 (1957).

[2]P. S. Signell and R. E. Marshak, Phys. Rev. 106, 832 (1957), and 109, 1229 (1958); this potential will be referred to as the SM potential. Independent calculations utilizing the spin-orbit force were carried out by J. Gammel and R. Thaler, Phys. Rev. 107, 291 (1957), and G. Breit, Phys. Rev. 111, 652 (1958).

[3]S. Okubo and R. E. Marshak, Ann. Phys. 4, 166 (1958).

[4]The meson-theoretic status of the spin-orbit potential is still obscure. It was shown in reference 3 that "p-wave" perturbation theory predicts an attractive spin-orbit potential (in the $I = 1$ state) with range $(1/2\mu)$ (μ is the pion mass) but with somewhat too small a magnitude. Recent dispersion-theoretic calculations by S. Okubo and S. Sato (private communication) have not improved the situation and have led the Japanese workers to question the necessity for introducing a spin-orbit force at all [S. Otsuki, Progr. Theoret. Phys. (Japan) 20, 171 (1958), and W. Watari, Progr. Theoret. Phys. (Japan) 20, 181 (1958)]. It is our belief that the present weight of evidence is strongly in favor of a significant spin-orbit force in the $I = 1$ (I is isotopic spin) state of the two-nucleon system; the evidence on the $I = 0$ state is at present inconclu-

Table I. Comparison of SM, SM1, and Stapp No. 1 nuclear (Blatt-Biedenharn) phase shifts in degrees.

300 Mev	$^3P_0$	$^3P_1$	$^3P_2$	ϵ_2	$^3F_2$	$^3F_3$	$^3F_4$
SM	9.8	-20.0	8.9	-20.8	-4.8	-4.9	7.4
SM1	- 1.2	-27.5	10.1	-20.1	-3.7	-4.7	6.5
Stapp No. 1 (310 Mev)	-14.3	-26.7	16.1	- 1.0	0.8	-4.4	3.1

sive [de Swart, Marshak, and Signell, Nuovo cimento 6, 1189 (1957)].

[5]It is to be recalled that the Gartenhaus potential [S. Garthenhaus, Phys. Rev. 100, 900 (1955)] is based on a static-nucleon source theory so that it cannot be trusted at short distances.

[6]L. Goldfarb and D. Feldman [Phys. Rev. 88, 1099 (1952)] took over the "Thomas-Yukawa" shape of the spin-orbit potential for which K. Case and A. Pais [Phys. Rev. 80, 203 (1950)] had previously given arguments.

[7]The fit is fairly sensitive to V_0: e.g., if $V_0 = 17.7$ Mev, $\sigma(45°) = 3.75$ mb/sterad and $P(37°) = 0.19$ mb/sterad at 150 Mev. For $V_0 = 23$ Mev, $\sigma(45°) = 4.51$ mb/sterad at 150 Mev.

[8]The experimental cross-section and polarization curves are taken from Palmieri, Cormack, and Wilson, Ann. Phys. (to be published). The D curve is from A. E. Taylor (private communication).

[9]The Stapp No. 1 phase shifts [Stapp, Ypsilantis, and Metropolis, Phys. Rev. 105, 302 (1957)] yield an excellent fit of all the p-p measurements at 310 Mev.

[10]It is interesting to note that the shorter range is also preferable if one relates the spin-orbit force in nuclei to the two-nucleon spin-orbit force; for example a range of $\approx 0.7 \times 10^{-13}$cm is needed to explain the $p_{3/2} - p_{1/2}$ splitting in He^5 [J. P. Elliot (private communication)].

[11]This requires the measurement of five independent quantities [see Puzikov, Ryndin, and Smorodinski, J. Exptl. Theoret. Phys. (U.S.S.R.) 5, 489 (1957), and reference 3].

PARITY AND OTHER SYMMETRIES IN STRONG INTERACTIONS

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In recent times, the question whether the high degree of P-conservation in nuclear phenomena precludes any P-violation in strong interactions has been on many peoples minds. In this respect one has especially thought of the virtual role of the new particles in nuclear interactions. We do not as yet have the theoretical tools to tackle such problems quantitatively. However, qualitative tests have been devised[1] to check P-conservation directly in hyperon reactions. A first application[2] to

$$\pi^- + p \to \Lambda + K^0 \qquad (1)$$

yields no evidence of appreciable P-violation in this strong production reaction. Of course, this valuable information does not settle all issues quite definitely. Here we wish to comment further on this problem. Briefly the idea is the following: it has been shown previously[3] how possible deviations from invariance laws for nucleon and pion systems could be masked to a large extent if the baryon meson system can approximately be assigned a rather high symmetry, the doublet approximation (DA). In this note we shall explore the question of P-violation from the same viewpoint. This will lead to two qualitative questions which can be put to many tests.

In the DA the S-number splits[4] into two parts S_1, S_2 which are separately conserved. Thus in the DA we have one more selection rule. This added constraint forbids a small number of reactions, notably

$$\pi^+ + p \to \Sigma^+ + K^+,\ K^- + p \to \Sigma^+ + \pi^-,$$
$$\pi^- + n \to \Sigma^- + K^0,\ \bar{K}^0 + n \to \Sigma^- + \pi^+; \qquad (2)$$

but π-nucleon transitions and reactions like (1) are not forbidden. Thus as long as the DA is P-conserving[5] we have to this approximation neither P-violation in π-nucleon systems, not even due to virtual K-effects, nor in reactions like (1). But what about the reactions (2)?

As has been noted before[3,4] the very fact that the reactions (2) are so inhibited in a DA means either than a DA is just no approximation at all, or else that a "doublet perturbation" (DP) is needed to break the (S_1, S_2)-rules. What would happen if the latter alternative were true and if the DP would break the P-conservation of the DA? If the DP would only feed the channels (2) we would say that the DP leads to P-violations in those and only those reactions. But the DP may also contribute to (S_1, S_2)-allowed reactions of type (1) and may therefore add P-violating to the P-conserving contributions of the DA. Nevertheless, it seems reasonable to raise two questions.

(I) Are the production and absorption reactions which would be blocked by the (S_1, S_2)-rules[6] P-conserving to the same extent as the other channels? A marked difference would indicate that a DA is useful.

It should be emphasized that, even so, the applicability of a DA would be worse where the (Σ, Λ) mass difference can least be neglected. This is most prominently the case for Σ + nucleon $\to \Lambda$ + nucleon exchange at low Σ energies: these reactions are not forbidden by the (S_1, S_2)-rules but may be strongly distorted by the DP, just as $\pi^- + p \to \pi^0 + n$ at zero π^- momentum is not for-