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Nucleon-nucleon scattering near 50 MeV. III. Analysis of new Davis *np* differential cross-section data*

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New Davis *np* differential cross-section data at 50 MeV are phase-shift-analyzed together with the other world *pp* and *np* data in the laboratory scattering energy range 47.5 to 60.9 MeV. Various combinations of the *np* $d\sigma/d\Omega$ data, taken by groups at Davis, Oak Ridge, and Harwell, are included in the analysis and are found to affect mainly just the phase parameter $\delta(^1P_1)$. We argue that the Harwell only, or Harwell + Oak Ridge + Davis data analyses call for a strong long-range potential such as might come from ABC (Abashian-Booth-Crowe) exchange, while the Davis only or Davis + Oak Ridge data analyses are compatible with ordinary (non-ABC) meson-theoretical models. We urge that more precise *np* absolute $d\sigma/d\Omega$ data be taken, to 1 or 2% accuracy, especially at far forward angles.

Recently the Davis group has reported on new 50-MeV neutron-proton differential cross-section data taken at both forward and backward scattering angles.[1] These new data are highly interesting in view of a recent phase-shift analysis of the world *pp* and *np* data falling in the scattering energy range of 47.5 to 60.9 MeV. This analysis, carried out by Arndt, Binstock, and Bryan[2] (henceforth referred to as paper I), included the new Davis backward *np* $d\sigma/d\Omega$ data (which were then available in preliminary form), but did not include the new forward scattering data. The phase shifts that resulted from this analysis were in good agreement with meson-theoretical models[3] at 50 MeV except for the phase parameter $\delta(^1P_1)$, which, being $-3.5°\pm 1.0°$, was five or more standard deviations above the meson-theoretically expected range of $-8.5°$ to $-11°$. (We comment below on theoretically expected values. See also Ref. 2.) The cause for the anomalous value of $\delta(^1P_1)$ was seen[4-6] to be the Harwell np $d\sigma/d\Omega$ data taken at 47.5, 52.5, and 57.5 MeV. (These data are shown in Fig. 3 of paper I and referenced in Table I of that paper.)

We were surprised to observe, however, that Reid's soft-core potential[7] fit this searched value of $\delta(^1P_1) = -3.5° \pm 1.0°$. Inspection of Reid's potential for the $^1P_1$ state reveals how this is possible. This potential is shown in Fig. 1 along with the one-pion-exchange potential (OPEP) and the Lomon-Feshbach potential[8] (to be discussed later). One may see that Reid's soft-core $^1P_1$ potential has a marked attraction extending from 2 to 5 F before finally going over to OPEP at larger distances. It is this attraction which gives the positive increment to $\delta(^1P_1)$ at 50 MeV. In paper I it was suggested that this long-range $^1P_1$ attraction in Reid's potential might be due to the exchange of a low-mass neutral ($I=0$) scalar ($J=0^+$) meson, possibly the ABC (Abashian-Booth-Crowe) effect.[9]

Thus it was with considerable interest that we viewed the new Davis forward-scattering $d\sigma/d\Omega$ data. We decided to analyze the world nucleon-nucleon data in the range 47.5 to 60.9 MeV as before, trying various combinations of the new and old np $d\sigma/d\Omega$ data. It may be recalled that in addition to the Harwell and the Davis measurements, there exist np $d\sigma/d\Omega$ data taken some years ago at Oak Ridge[10] at 60.9 MeV in the backward-angle region. We have listed these data in Table III of paper I with the kind permission of the authors. We show in Table I of the present paper the result of phase-shift-analyzing the data when Harwell only, Davis only, Oak Ridge only, Davis + Oak Ridge, and Davis + Oak Ridge + Harwell $d\sigma/d\Omega$ data are used together with the other kinds of world np data (σ_{tot} and P) and the world pp data. The value of $\delta(^1P_1)$ for each analysis is plotted with its error in Fig. 2. One will note from Table I that the pp (that is, $T=1$) phase parameters are remarkably stable from one analysis to the next, and hence need not be discussed further. The $T=0$ phase parameters, apart from $\delta(^1P_1)$, are rather stable also (once ϵ_1 is fixed at 2.78°; see Ref. 11). Thus the differences in the np data boil down rather neatly to differences in $\delta(^1P_1)$.

We observe in Fig. 2 that $\delta(^1P_1)$ is most positive for Harwell-only $d\sigma/d\Omega$ data, most negative for Oak Ridge–only $d\sigma/d\Omega$ data, and in between for Harwell + Davis + Oak Ridge, Davis only, and Davis + Oak Ridge $d\sigma/d\Omega$ data. For comparison we show several theoretical calculations for $\delta(^1P_1)$ over the 0 to 160 MeV range. First, there is the one-pion-exchange contribution (OPEC), labeled "π," which is obtained by just setting $\delta(^1P_1)$ equal

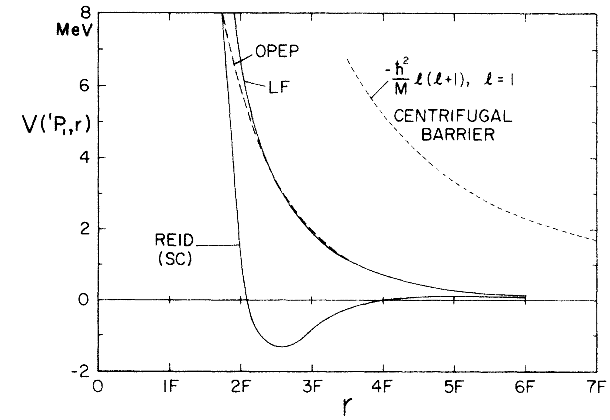

FIG. 1. Plots of nucleon-nucleon potentials acting in the $^1P_1$ state. Shown are the Reid (soft-core) potential, labeled "REID(SC)," the Lomon-Feshbach (5.202% D state) potential, labeled "LF," and the nonrelativistic one-pion-exchange potential, labeled "OPEP." Parameters for OPEP are $g_\pi^2 = 15$ and $m_\pi = 138.1$ MeV/c^2. The centrifugal potential for P waves is also shown.

to OPEC in the $^1P_1$ state (called geometric unitarization). Next, there is $\delta(^1P_1)$ predicted by a potential model due to Feshbach and Lomon[8] (LF), which potential includes one-pion exchange, two-pion exchange, and ρ, ω, and η exchange. Furthermore, boundary conditions are imposed on the wave functions at short distances. Then there is a model due to Binstock and Bryan[12] (BB) which includes one-pion exchange, two-pion exchange [with both nucleon and $\Delta(1236)$ intermediate baryon states] and ρ, ω, and ϵ exchange. [The ϵ is taken to be a wide ($\Gamma = 370$ MeV) scalar ($I=0$, $J=0^+$) meson centered at 715 MeV.] Binstock and Bryan arrive at a phase shift by setting the real part of the sum of diagrams equal to $\delta(^1P_1)$. (This is another form of geometric unitarization.) Finally, there is Reid's model[7] [Reid (SC)], a phenomenological potential with free parameters adjusted to fit each partial wave over the 0 to 350 MeV range, with, however, the built-in condition that the potential reduce to the one-pion-exchange potential (OPEP) at a sufficiently large distance.

Now one will observe that the Binstock-Bryan and the Lomon-Feshbach $\delta(^1P_1)$ phase shifts coalesce to OPEC at low energy, and fan out at higher energies. At 50 MeV these models' $\delta(^1P_1)$ span the range $-9°$ to $-10.4°$. We would guess that this range is typical for all meson-theoretical models,[2] especially if it is extended from, say, $-8.5°$ to $-11°$. Why we believe this to be so will be discussed shortly.

Unlike the meson-theoretical models, the Reid soft-core model predicts a $\delta(^1P_1)$ that falls right in the middle of the world-averaged prediction

TABLE I. Phase-shift analyses of $pp+np$ data falling in the 47.5- to 60.9-MeV laboratory scattering range; pp data used in analyses are those data listed in Table V of MacGregor, Arndt, and Wright (Ref. 20) falling in this energy range; np data used are those σ_{tot} and P data listed in Table I of paper I, plus those np $d\sigma/d\Omega$ data identified at the top of each of the five columns: Harwell stands for Harwell $d\sigma/d\Omega$ data at 47.5, 52.5, and 57.5 MeV, referred to in Table I of paper I; Davis stands for the Davis $d\sigma/d\Omega$ data at 50 MeV (Ref. 1); Oak Ridge stands for the unpublished Oak Ridge $d\sigma/d\Omega$ data at 60.9 MeV, listed in Table III of paper I through the kind permission of the authors; Davis + Oak Ridge means that the combined Davis and Oak Ridge $d\sigma/d\Omega$ data were used in the analysis; Harwell + Davis + Oak Ridge means that the combined Harwell, Davis, and Oak Ridge $d\sigma/d\Omega$ data were used in the analysis. Because of insufficient np data to determine ϵ_1, this phase parameter was set to the value predicted by a potential model due to Bryan and Gersten (Ref. 11, fit C) at 50 MeV, namely, 2.78°. A slope $d\delta/dT_{lab}$ was assigned to each phase parameter searched, with the value taken from the potential model of Bryan and Gersten (Ref. 11). The phase shift $\delta(^1S_0)_{np}$ was not separately searched, but rather set to 40.38° as in Table IV of paper I. Higher partial-wave phase parameters not appearing in this table were set to the one-pion-exchange contribution value, with $g_\pi^2=14.43$, $m_\pi=135.04$ MeV/c^2, and nucleon mass = 938.211 MeV/c^2.

	Harwell	Davis	Oak Ridge	Davis +Oak Ridge	Harwell +Davis +Oak Ridge
			$I=1$ phase parameters		
$\delta(^1S_0)pp$	38.9° ± 0.3°	38.8° ± 0.3°	38.9° ± 0.3°	39.0° ± 0.3°	39.0° ± 0.3°
$\delta(^3P_0)$	11.7° ± 0.3°	11.6° ± 0.3°	11.6° ± 0.4°	11.7° ± 0.3°	11.7° ± 0.3°
$\delta(^3P_1)$	−8.3° ± 0.2°	−8.2° ± 0.2°	−8.3° ± 0.2°	−8.3° ± 0.2°	−8.3° ± 0.2°
$\delta(^3P_2)$	5.9° ± 0.1°	5.9° ± 0.1°	5.9° ± 0.1°	5.9° ± 0.1°	5.9° ± 0.1°
$\delta(^1D_2)$	1.7° ± 0.1°	1.7° ± 0.1°	1.7° ± 0.1°	1.7° ± 0.1°	1.7° ± 0.1°
ϵ_2	−1.7° ± 0.1°	−1.8° ± 0.1°	−1.7° ± 0.1°	−1.7° ± 0.1°	−1.7° ± 0.1°
			$I=0$ phase parameters [a]		
$\delta(^3S_1)$	62.4° ± 1.3°	62.2° ± 1.2°	60.2° ± 1.6°	62.4° ± 1.1°	62.4° ± 1.1°
$\delta(^1P_1)$	0.3° ± 1.3°	−7.0° ± 1.8°	−15.7° ± 3.6°	−7.5° ± 1.8°	−4.1° ± 1.0°
$\delta(^3D_1)$	−6.9° ± 1.1°	−6.5° ± 1.1°	−7.3° ± 1.2°	−6.3° ± 1.0°	−6.3° ± 0.9°
$\delta(^3D_2)$	11.2° ± 1.1°	9.9° ± 1.5°	6.8° ± 2.3°	9.8° ± 1.4°	10.9° ± 1.1°
$\delta(^3D_3)$	0.7° ± 0.6°	0.4° ± 0.6°	−1.1° ± 1.0°	0.6° ± 0.6°	1.0° ± 0.5°
χ^2	181	139	138	152	217
No. data	204	156	145	165	233
χ^2/datum	0.89	0.89	0.95	0.92	0.93

[a] The errors quoted for the $I=0$ phase shifts are considerably less than would pertain if ϵ_1 were not fixed at 2.78°, but allowed to vary over the entire range allowed by a χ^2 increase of only 1 (approximately from −8° to 0°) as discussed in Ref. 3. However, for the $I=1$ phase parameters, the errors and values quoted are hardly affected by the constraint on ϵ_1.

(Harwell + Oak Ridge + Davis np $d\sigma/d\Omega$ data). The Reid soft-core $\delta(^1P_1)$ is headed toward the OPEC value for decreasing energy but achieves it only at very low energy. Why this potential model gives a $\delta(^1P_1)$ so much more positive than the meson-theoretical models is perhaps best illustrated by means of Fig. 1. As mentioned earlier, there is a deep attraction extending out to 5 F before the $^1P_1$ potential finally goes over the OPEP. This attraction is atypical of meson-theoretical models (e.g., the Lomon-Feshbach potential shown in the same figure) and occurs because of a term in Reid's potential which goes as $[\exp(-2m_\pi r)]/r$, characteristic of the exchange of a meson (or narrow resonance) of mass $2m_\pi$.

Such a long-range term is absent in meson-theoretical models and explains why these models cannot fit $\delta(^1P_1)=-4°$ predicted by the combined Harwell, Oak Ridge, and Davis (H + D + OR) np $d\sigma/d\Omega$ data. In meson-theoretical models, the longest-range term after single-pion exchange goes approximately as $(3m_\pi)^{-1}$ and not $(2m_\pi)^{-1}$. This next-to-longest-range term is due, of course, to two-pion exchange and goes $\approx(3m_\pi)^{-1}$ because the amplitude goes as

$$\int_{t'=4m_\pi^2}^{t'=\infty} dt'\rho(s,t')/(t-t'),$$

and in the absence of a sharp peaking of $\rho(s,t')$ for t' near $(2m_\pi)^2$, gives an effective long-range force necessarily shorter than $(2m_\pi)^{-1}$. Here t is the square of the four-momentum transfer and s is the square of the center-of-mass energy.

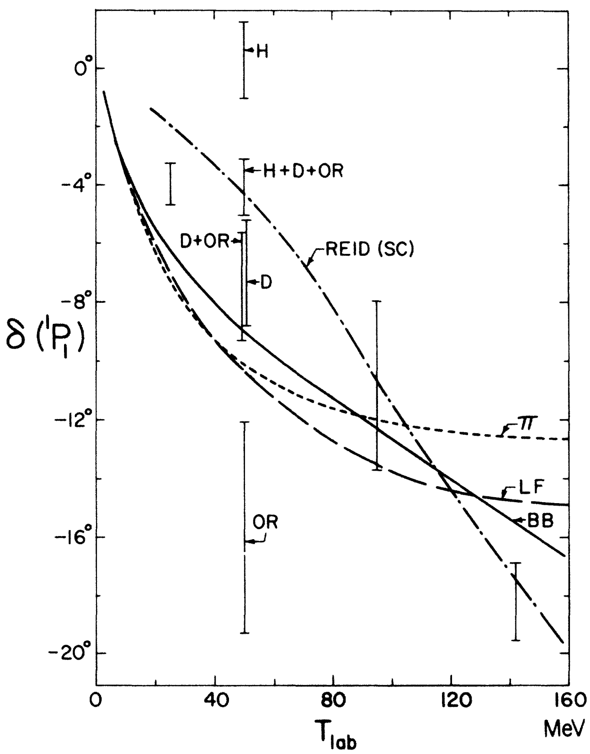

FIG. 2. Plots of $\delta(^1P_1)$ vs energy over the 0- to 160-MeV laboratory scattering energy range. Several experimental values for $\delta(^1P_1)$ are shown at 50 MeV. These result from phase-shift-analyzing the world pp data, the world np P and σ_{tot} data, and selected np $d\sigma/d\Omega$ data: H corresponds to including only the Harwell np $d\sigma/d\Omega$ data, D to including only the Davis $d\sigma/d\Omega$ data, OR to including only the Oak Ridge $d\sigma/d\Omega$ data, D + OR to including only the Davis + Oak Ridge $d\sigma/d\Omega$ data, and H + D + OR to including all the np $d\sigma/d\Omega$ data. Also shown are the experimental values for $\delta(^1P_1)$ at 25, 95, and 142 MeV predicted by the Livermore group (Ref. 20). Several theoretical curves are shown. These include the one-pion-exchange contribution (OPEC), labeled "π," where $\delta(^1P_1)$ is set equal to OPEC with $g_\pi^2 = 14.9$ and $m_\pi = 135.04$ MeV/c^2, the Lomon-Feshbach model (5.202% D state), Ref. 8, labeled LF, the Binstock-Bryan model, Ref. 12, labeled "BB," and the Reid soft-core model, labeled REID(SC), Ref. 7.

It has been argued that uncorrelated two-pion exchange nonetheless gives a strong contribution to the $^1P_1$ state at 50 MeV, and perhaps ought to be able to give a strong enough positive increment to $\delta(^1P_1)$ at 50 MeV to fit the world data prediction even in the absence of a strong 2π resonance near 280 MeV. It is true that uncorrelated 2π exchange gives a large contribution to $\delta(^1P_1)$ at 50 MeV, and furthermore even of the right sign; we show this in Fig. 3. There the contribution of single-pion exchange plus two-pion exchange as represented in the Binstock-Bryan model[12] can be seen and compared with the contribution of single-pion exchange alone in the $^1P_1$ state. At 50 MeV the 2π contribution is + 4°, a non-negligible amount. What we emphasize, however, is that when the $\pi+2\pi$ contribution is supplemented by short-range processes to make $\delta(^1P_1)$ fit the data at *higher* energies (330 MeV, 425 MeV, and even 142 MeV), then $\delta(^1P_1)$ comes down markedly at 50 MeV as well. Thus the Binstock-Bryan $\delta(^1P_1)$ is seen to

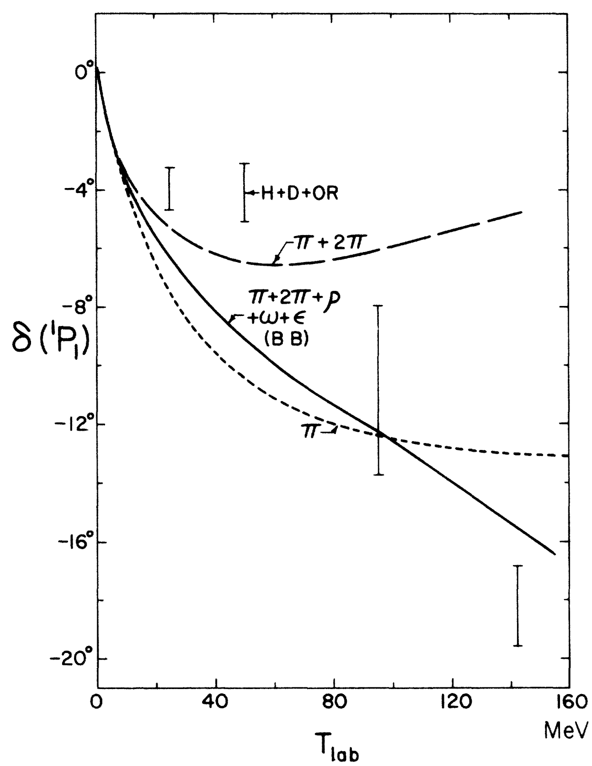

FIG. 3. Plots of $\delta(^1P_1)$ vs energy. Experimental phase shifts as described in the caption of Fig. 2. The theoretical curves include one-pion-exchange contribution for $\delta(^1P_1)$, explained in the caption of Fig. 2 and labeled π, the one-pion- plus two-pion-exchange contribution, labeled $\pi+2\pi$ and described in Ref. 12, and the $\pi+2\pi+\rho+\omega+\epsilon$ contribution, labeled as such and also as BB here and in Fig. 2 and described also in Ref. 12.

come down to $-9.0°$ at 50 MeV when the short-range ρ, ω, and ϵ exchange forces are added to achieve a fit to the data (curve BB in Fig. 3). The reason that the 2π continuum contribution is considerably reduced by the short-range forces is that the 2π continuum forces are not *that* much more long-ranged than the ρ, ω, and ϵ forces—perhaps $(3m_\pi)^{-1}$ compared with $(5.5m_\pi)^{-1}$. The only way to raise $\delta(^1P_1)$ well above OPEC at 50 MeV and keep it there after adding strong short-range forces to bring $\delta(^1P_1)$ down at 425 MeV is to add an attraction of such long range that the ω, ρ, etc. repulsive potentials cannot touch it (cancel it). This is just what Reid has done in the case of his soft-core potential model. The $(2m_\pi)^{-1}$ potential, evident in Fig. 1, is strong beyond the range of the ρ and ω repulsive potentials. These latter potentials extend at most out to 2.0 F, as shown, for example, in Fig. 1 of Ref. 13, or better yet, Fig. 3(a) of Ref. 14.

Thus if $\delta(^1P_1)$ really falls in the range $-8.5°$ to $-11°$, we argue that the existing (non-ABC) meson-theoretical models are correct (at least roughly), whereas if $\delta(^1P_1)$ is really $-4°$ or even more positive, then we argue that a strong 2π enhancement or resonance with a mass near $2m_\pi$ is called for.

It happens that the ABC effect is just what is required to fit the H + D + OR data, and would be a reasonable supposition if it were verified, for the ABC effect represents two pions resonating (or at least interacting strongly) in the S state, with $I=0$, and such a resonance gives rise to an attraction. The ABC mass is about $2m_\pi$ and so, to lowest order, gives rise to a Yukawa attraction $-g_{ABC}^2[\exp(-2m_\pi r)]/r$, just as required by Reid's soft-core $^1P_1$ potential. The ABC effect also has the right isospin, for had it been 2 (the other isospin allowed for S waves) it could not be emitted or absorbed by nucleons.

A glance at Fig. 2 shows that the Davis + Oak Ridge np $d\sigma/d\Omega$ data favor the non-ABC meson-theoretical models somewhat more than the Reid model, but the error bar is very wide.[15] The Harwell data favor a long-range force of even greater strength than that of Reid's soft-core $^1P_1$ potential, and presumably call for an S-wave resonance of mass $2m_\pi$ and moderately strong coupling to the nucleon.

Which is correct? One way to find out is to search for a low-mass $I=0$ S-wave $\pi\pi$ resonance. This has been done, and is being done. Some authors claim to have seen such a low-mass resonance or enhancement, but only in complicated systems[16-18] (baryon number 2 or 3). In the simpler reaction $\pi + N \to \pi + \pi + N$, where it should definitely show up, no S-wave resonance has been seen at low dipion masses. Such a resonance *has* shown up near 700 MeV (it is the ϵ), but this is much too high an energy to account for the $\delta(^1P_1)$ phenomenon at 50 MeV. Thus current particle data[19] would not favor a $\delta(^1P_1)$ as high as $-4°$. [The fact that a long-range attraction has not shown up in the other P-wave phase shifts, the $I=1$ $\delta(^3P_0)$, $\delta(^3P_1)$, and $\delta(^3P_2)$, does not speak for the existence of a low-mass dipion either, as such a meson should give somewhat equal attraction in all P states.]

It is worth noting that the trend to a more positive $\delta(^1P_1)$ than predicted by non-ABC meson theories is also evident at 25 MeV. We have plotted $\delta(^1P_1)$ at that energy in Figs. 2 and 3, along with this phase shift at 95 and 142 MeV. These phase shifts have been found by the Livermore group[20] and agree with other groups' determinations.[21] Are the np $d\sigma/d\Omega$ measurements at 25 MeV also somewhat in error?

Clearly a new and more precise measurement of np $d\sigma/d\Omega$ is called for at 50 MeV, and probably at 25 MeV as well. Absolute measurement of $d\sigma/d\Omega$ at far forward angles to 1 or 2% accuracy would be highly desirable, as explained in papers I and II. It may also be possible to refine some of the existing $d\sigma/d\Omega$ data.[22,23]

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quoted for the constrained ($\epsilon_1 = 2.78°$) solution. Thus, preassigning ϵ_1 to 2.78° has little or no effect on the $I = 1$ errors.

It is fortunate for the purpose of this paper that $\delta(^1P_1)$ varies only slightly as ϵ_1 varies, as we wish to compare the searched value of $\delta(^1P_1)$ with theory. Thus, if ϵ_1 ought really to be, say, 2.0° and not 2.78°, $\delta(^1P_1)$ will not be thrown very far off.

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[22]It is possible that the errors in the Davis forward *np* $d\sigma/d\Omega$ data may be reduced through more accurate calibration with energy of the neutron detector efficiency (private communication from B. E. Bonner). Signell has also mentioned possible systematic error in the calibration of the neutron detector used in taking the Harwell data (P. S. Signell, private communication).

[23]It would not be correct to fail to mention that we have assumed that the P, D, F, ... wave phase shifts in the $I = 1$ state are identical in *pp* and *np* scattering. [Some $\delta(^1S_0)$ *pp*-*np* splitting is assumed, as noted in the caption of Table I.] Now, we have found (Ref. 2) that a moderate splitting of the *pp* and *np* values for $\delta(^3P_0)$, $\delta(^3P_1)$, and $\delta(^3P_2)$, say, *np* phase shifts uniformly 2° more positive than the *pp* phase shifts, permits $\delta(^1P_1)$ to search to a value about 6° more negative. This, then, puts $\delta(^1P_1)$ in accord with the non-ABC theoretical models. $\delta(^1P_1)$ at 25 MeV could be lowered similarly. But is 2° a reasonable splitting for triplet P waves? Also why is there no need for splitting at 95 and 142 MeV, where $\delta(^1P_1)$ is more in accord with non-ABC theoretical models? Certainly the amount of *pp*-*np* splitting to be reasonably expected for P waves needs additional investigation.