Nucleon–Nucleon Physics at Intermediate Energies

The current status of nucleon–nucleon elastic and inelastic scattering up to 1 GeV is reviewed. Elastic data are now almost complete, but the physics interpretation lags behind. Data on $pp \to \pi^+ d$ are likewise almost complete, and have a simple interpretation. Data on the spin dependence of $NN \to NN\pi$ are just beginning to appear. They have an important bearing on the major outstanding issue of whether or not dibaryon resonances exist.

During the last ten years, a great deal of effort has been devoted to the spin dependence of nucleon–nucleon elastic and inelastic scattering by experimental groups at TRIUMF, SIN, LAMPF, and Gatchina. Where do we stand, and what have we learned so far? Where do we go now?

ELASTIC SCATTERING

Proton–proton phase shifts are now known well up to 800 MeV, and tentatively at 970 MeV, as a result of extensive measurements with polarized beams, polarized targets, and recoil proton polarimeters at SIN and LAMPF, with smaller contributions from TRIUMF, Saclay, and Gatchina. We have reached the point where further data do not improve the solutions appreciably, unless they are of extreme precision (< 1%) or at very forward angles (< 20°) or above 800 MeV. In the phase shift analysis, the only difficulty lies in determining inelasticities of low partial waves ($^1S_0$, $^3P_0$, and $^3P_1$), which cause little

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or no angular dependence in data, and can be confused with systematic errors (e.g., normalization). Fortunately, inelastic data now give some direct information on these elusive parameters. With this one reservation, $I = 1$ phase shifts of Arndt, the Geneva–Saclay group and I now agree closely up to 800 MeV; amplitudes agree even better, i.e., errors in the phase shifts are correlated.

The *np* data are not quite so complete. From 150 to 500 MeV, extensive data from TRIUMF, together with older data near 150 MeV, lead to secure phase shift solutions. Around 650 and 800 MeV the present data are limited in type and angular coverage. One can obtain rather shaky phase shift solutions at these energies, with $I = 0$ amplitudes very similar to those from 150 to 500 MeV. The crucial missing data are A_{SS} and A_{LL}, which are now being measured at LAMPF. In a year or so, we can be confident of having secure $I = 0$ phase shifts up to 800 MeV.

Below 150 MeV, the *np* data are incomplete, but amplitudes can be derived (with some uncertainty) from a judicious mixture of theory and extrapolation downward from higher energies. The Paris potential fits both the data from 150 to 425 MeV and the properties of the deuteron quite well. It probably gives the most reliable amplitudes at present from threshold to 150 MeV.

The physics interpretation is much less complete. The long-range part of the interaction is well understood in terms of π and 2π exchange, but there is no agreed understanding of short range forces. Long-range 2π exchange can be calculated reliably. The essential idea is that the *t* channel exchanges are given by $\langle N\bar{N}|\pi\pi\rangle\langle\pi\pi|N\bar{N}\rangle$ and each half of this expression is related by analyticity and crossing to $\pi N \rightarrow \pi N$ amplitudes, which are known from experiment. The calculations are tortuous, but there is reasonable agreement between several groups. Signell[1] has reviewed them recently. Results of the Paris group give good fits to tensor combinations of high partial waves, small disagreements with experiment for the spin-orbit combinations, and rather larger disagreements for central combinations.[2] The Paris group[3] treats the short range forces ($r < 0.8$ fm) phenomenologically.

An alternative approach is to apply dispersion relations to appropriate linear combinations of *s*-channel amplitudes in order to project out *t*-channel exchanges. The latter may then be interpreted as exchanges of π,η,ρ,ω, and A_1 mesons, supplemented by 2π, 3π, and $\rho + \pi$ exchanges. At present there is no widely agreed set of coupling constants. The problem is that there are strong cancellations between various exchanges (e.g., σ and ω) and one missing element can be accommodated to a considerable extent by changes in others. What is certain is that no single element dominates. The exchanges seem to be as complicated as they could be, with strong terms corresponding to almost every set of t-channel quantum numbers.

Grein and Kroll[4] applied dispersion relations to three forward pp and np amplitudes, with very revealing results. They took 2π eachanges from known $N\bar{N} \rightarrow \pi\pi$ amplitudes, and uncovered strong ω and 3π exchanges; they were able to interpret the latter sensibly in terms of $(\rho + \pi)$ and $(\sigma + \pi)$ exchanges. Unfortunately, the quantitative accuracy of these results is uncertain because their np forward amplitudes disagree substantially with the latest phase shift solutions at the higher energies. For example, at 800 MeV they predict $K_{LL}(180°) = -0.08$, compared with the experimental value -0.65 ± 0.11. One can have confidence in the large experimental value since polarized neutrons are made at LAMPF using just this polarization transfer, i.e., via the $\vec{p}n \rightarrow \vec{n}p$ reaction with longitudinally polarized protons. A fresh look at dispersion relations is needed. This analysis should examine all five amplitudes over the whole s–t plane and should incorporate what we know about $N\bar{N} \rightarrow \pi\pi$ amplitudes. This is a substantial undertaking, but if done thoroughly is likely to reveal a wealth of detail.

A strong feature of the phase shift solutions is the appearance of half-loops in the Argand diagrams of the dominant inelastic amplitudes $^1D_2$, $^3F_3$, and $^3P_2$ (Figure 1). These are directly associated with the well-known peaks in $\Delta\sigma_L$ and $\Delta\sigma_T$, which first led to the suggestion[5] that dibaryon resonances might exist. The major outstanding issue in nucleon–nucleon physics is whether these half-loops are due to highly inelastic resonances or can be explained purely as strong inelastic thresholds. Analyticity tells us that partial wave amplitudes f_l^J satisfy

$$\mathrm{Re}\, f_l^J(s) = \frac{1}{\pi}\int \frac{\mathrm{Im}\, f_l^J(s')\, ds'}{s' - s} + \text{constant},$$

where the integral is over the s channel and over the unphysical region. The latter integral varies slowly with s and can be approximated by a distant pole. Figure 2 illustrates the contributions to Re $f(s)$ from the s-channel integral for (a) a resonance, and (b) an inelastic threshold. The latter approximates the half-loops of Figure 1. On the other hand, many πN resonances resemble Figure 1. From elastic

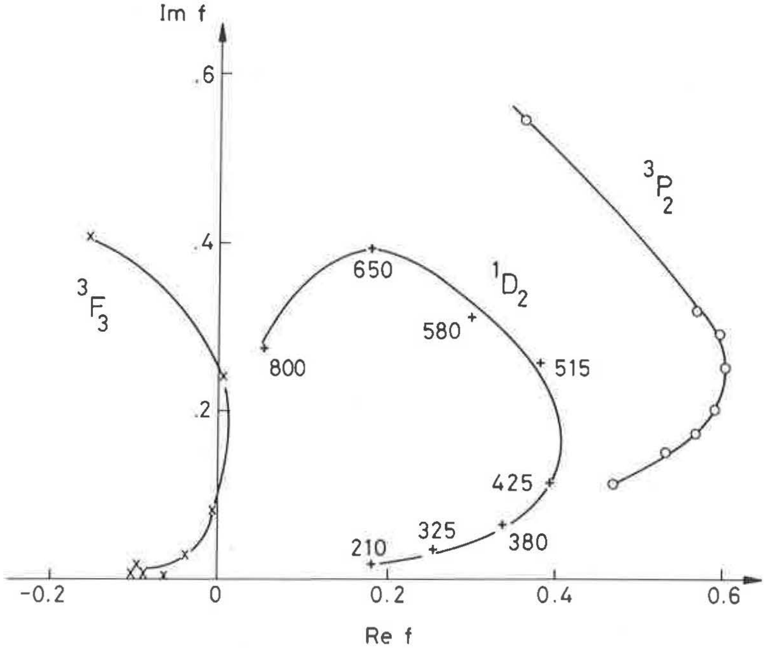

FIGURE 1 The Argand diagram of elastic ${}^1D_2$, ${}^3F_3$, and ${}^3P_2$ amplitudes. Figures indicate lab energies in millielectron volts.

data alone it is difficult to distinguish between a threshold and a threshold with a weak resonance superposed. From present data, it is agreed that the branching ratio of any resonance to the elastic channel is $\leqslant 10\%$. Obviously, one should look in inelastic channels.

There is great interest in the possibility of accounting for short-range forces with quark models, but as yet only qualitative results have appeared. It would help if dispersion relations could isolate the *t*-channel spin dependence; a distinctive pattern would be a challenge to quark models and the specific spin dependence of QCD. An interesting approach is the boundary condition model of Lomon.[6] At long range, his wavefunctions are consistent with meson exchanges; they are joined at the surface of a spherical bag to wavefunctions corresponding to free quarks within the bag. However, it is by no means clear that for two interacting nucleons the bag should be spherical.

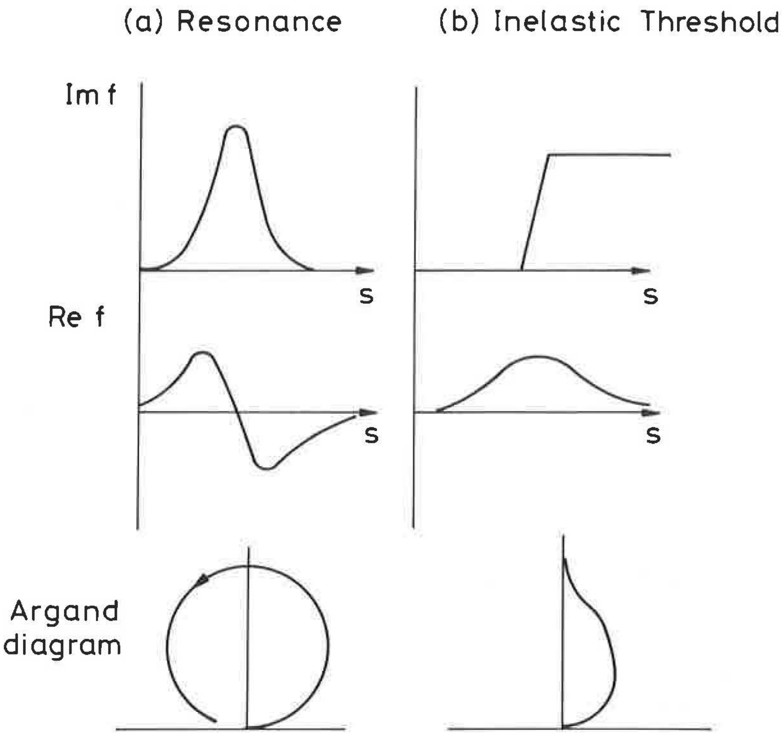

FIGURE 2 Real and imaginary parts of elastic amplitudes and the Argand diagram for (a) a resonance, and (b) an inelastic threshold.

pp → *dπ*

There are now extensive spin dependent data from SIN and LAMPF on this reaction from 445 to 800 MeV. With very mild theoretical input (high partial waves and some smoothing of the energy dependence of small amplitudes), they determine the magnitudes and phases of almost all of the low partial waves.[7]

Viewing this reaction in reverse, one expects it to be dominated by $\pi d \to \Delta N \to NN$, where the nucleon in the intermediate state is purely a spectator to the basic πN interaction on the other nucleon. Suppose the deuteron had zero binding energy, hence no Fermi momentum. The πN cross section would peak at a pion lab kinetic energy of 175 MeV; in the reaction $pp \to d\pi$, this corresponds to a proton lab kinetic energy $T_p = 637$ MeV. In the real deuteron, the mean Fermi momentum is about 70 MeV/c. This broadens the Δ peak (Doppler broadening). The Δ is further broadened by the deexcitation process $\Delta N \rightarrow NN$, which is not available to a free Δ (collision broadening).

One thus expects the magnitudes and phases of $pp \rightarrow d\pi$ amplitudes to be dictated by those of $\pi N \rightarrow \Delta$. The data confirm this simple picture. Figure 3 sketches the magnitudes and phases of the largest amplitudes. The strongest is the one with ΔN having relative orbital angular momentum $L = 0$; this originates from the NN $^1D_2$ state. With $L = 1$, the NN channels are $^3P_1$, $^3P_2$, $^3F_2$, and $^3F_3$. Theory and experiment agree that the last of these dominates for $L = 1$. This is because π exchange favors the "stretched" configuration, where J takes its maximum allowed value.

An amusing point is that one can account readily for the energies at which $L = 0$ and $L = 1$ amplitudes peak. The full line of Figure 3 shows the energy variation of the πd total cross section (translated to the kinematics of the pp channel). The $L = 0$ peak is at about 560 MeV, well below the peak in the full line. The explanation is simple. For energy economy, and for $L = 0$, the spectator nucleon should be at rest in the *overall center of mass*. This implies that it runs away from the incident pion, while the struck nucleon moves toward the incident pion, enhancing the energy available for Δ formation and creating a Δ at rest in the πd center of mass system. A simple kinematic calculation reveals that the $^1D_2$ amplitude should peak 66 MeV below the πd total cross section. This is very close to observation. Why does the πd total cross section not move downward to enjoy the same kinematics? The reason is that only a small part of the deuteron wavefunction has the high required momentum $p =$ 113 MeV/c. One can likewise account sensibly for the $L = 1$ cross sections peaking at about 650 MeV. The requirement $L = 1$ for a ΔN final state corresponds to a mean impact parameter 0.9 fm between Δ and N. This value is consistent with the deexcitation process $\Delta N \rightarrow NN$ being dominated by π exchange with a little ρ exchange.

There is an interesting feature in one of the smaller amplitudes. Figure 4 shows that the $^3P_1$ amplitude is strongly repulsive near threshold and then develops a loop due to an attractive interaction involving intermediate Δ formation.

From an experimental point of view, the story is not quite closed. There are two small amplitudes, $^3F_2$ and NN $^3P_1 \rightarrow \pi d$ $l = 2$, which

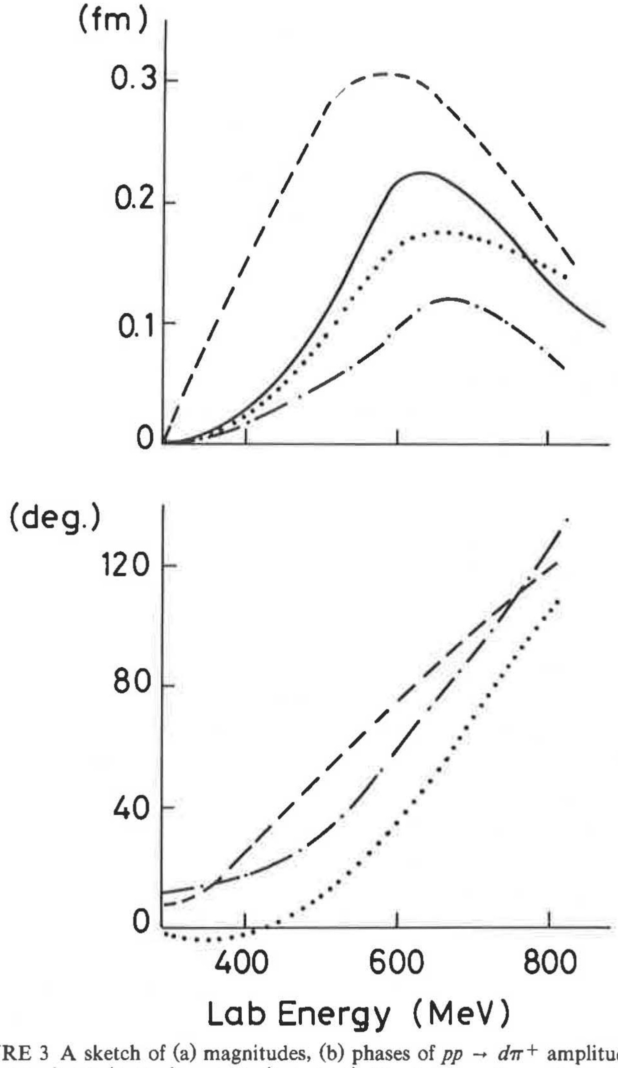

FIGURE 3 A sketch of (a) magnitudes, (b) phases of $pp \rightarrow d\pi^+$ amplitudes for $^1D_2$ (dashed line), $^3F_3$ (dotted), and $^3P_2$ (dot–dash). The full line shows the πd total cross section, translated to the kinematics of the pp channel.

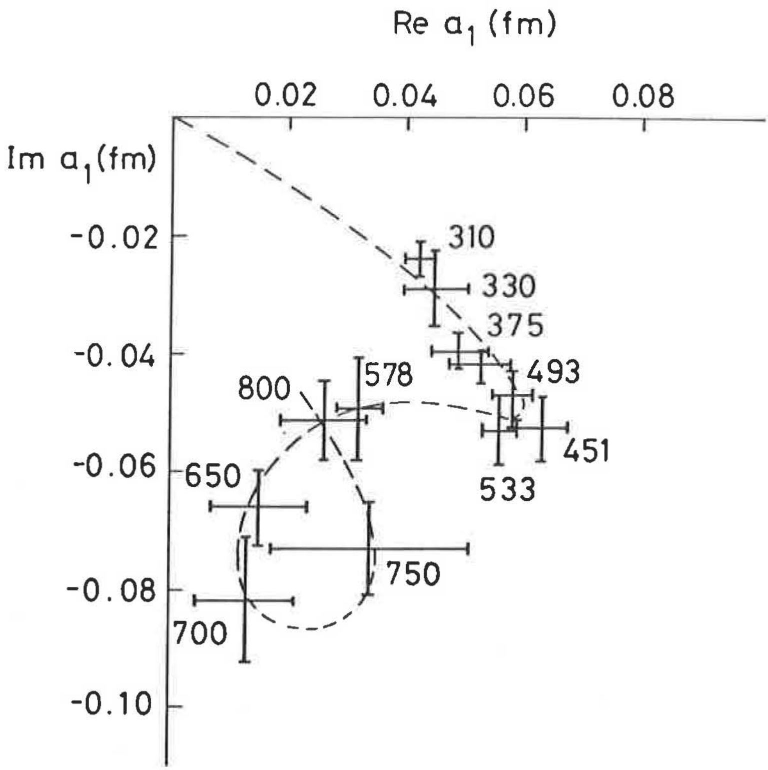

FIGURE 4 The Argand diagram for the $^3P_1$ $pp \rightarrow d\pi^+$ ($I = 0$) amplitude. Figures indicate values of T_p in MeV. The dashed curve is to guide the eye.

are presently poorly determined, if at all. The remedy lies in precise measurements K_{SS}, the polarization transfer from a proton polarized sideways in the plane of scattering to deuteron vector polarization (iT_{11}) in the sideways direction. Below 600 MeV, iT_{11} itself is needed to determine the $^1S_0$ amplitude. Below 450 MeV, there are at present only $d\sigma/d\Omega$ and P data; measurements of A_{SL} would greatly improve the accuracy of amplitudes at these low energies.

$NN \rightarrow NN\pi$

The dominant inelastic channel is $pp \rightarrow pn\pi^+$, which is largely $N\Delta$. This is the obvious place to look for dibaryons, since, if they exist, they must have a branching ratio $\geqslant 80\%$ into this channel. This signature of a dibaryon would be a large and rapid variation of the $N\Delta$ phase shift with lab energy. This point is worth discussion, since there is some confusion in the literature about what phase is of interest.

Suppose, for a start, that there is no dibaryon, and that the Δ is produced purely by single pion exchange. In the absence of initial and final state interactions, the amplitude is

$$f \alpha \frac{g_{\pi NN}\,\boldsymbol{\sigma}\cdot\mathbf{q}}{t-\mu^2}\,\frac{M\Gamma_{EL}}{M_\Delta^2 - w^2 - iM\Gamma_\Delta}. \qquad (1)$$

Here w is the πN mass, M_Δ the mass of the Δ, Γ_{EL} and Γ_Δ its elastic and total widths, and M the mass of the nucleon. The phase dependence of w has nothing to do with a dibaryon, and is therefore not the phase dependence of fundamental interest. This w dependence is the origin of the energy dependence of $\pi d \rightarrow pp$ amplitudes (as far as we presently know); many authors have confused this phase dependence with a dibaryon.

Next, suppose there are initial and final state interactions in the NN and $N\Delta$ channels. In the first approximation, they will multiply f by a phase factor

$$g = \exp i\{\delta_{NN}(s) + \delta_{N\Delta}(s)\}.$$

If these interactions are sufficiently attractive to generate a resonance, the multiplying factor becomes a Breit–Wigner propagator:

$$g = \frac{M\gamma_{EL}(s)}{s_0 - s - iM\gamma_{Tot}}.$$

It is the pole in the s variable that signifies the dibaryon, and creates rapid variation with s of $\delta_{N\Delta}$.

A final point is whether $\delta_{N\Delta}$ has a value independent of w, the πN mass. To answer this, one should remember that the propagator

$(M_\Delta^2 - w^2 - i\,M\Gamma_\Delta)^{-1}$ in (1) accounts for the lifetime of the Δ. If the Δ were long-lived, $\delta_{N\Delta}$ would depend purely on s. If there is a dibaryon resonance between N and Δ, there will undoubtedly be some effect on the lifetime of the Δ, but one expects the general form cf the propagator to be unchanged, and therefore $\delta_{N\Delta}$ to be approximately independent of w.

Experimental data on the spin dependence of $NN \rightarrow NN\pi$ have appeared only recently. At LAMPF, there have been measurements at 650 and 800 MeV of several parameters, but only at a limited number of points in phase space. At TRIUMF, there have been measurements of A_{NO}, A_{NN}, A_{LL}, A_{SS}, and A_{SL} over quite a wide geometry (as large as the aperture of a conventional polarized target allows), but only at 425, 465, and 510 MeV below the energy of

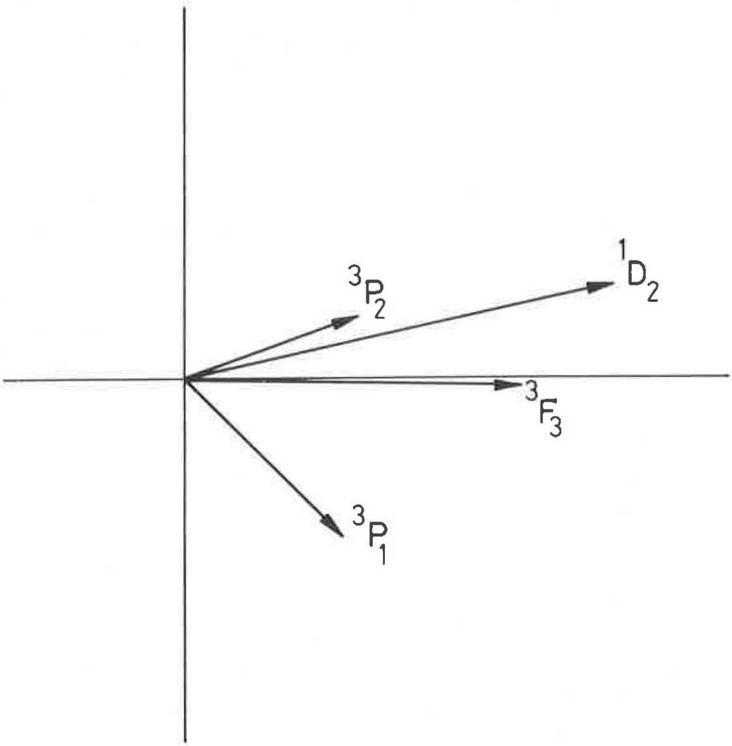

FIGURE 5 The Argand diagram for $NN \rightarrow N\Delta$ amplitudes at 510 MeV, assuming phases are given by the NN initial state interaction, i.e., $\delta_{N\Delta} = 0$.

postulated dibaryons. Calculations of Dubach, Kloet, and Silbar,[8] based on π exchange, predict dominant $^1D_2$ and $^3F_3$ amplitudes. The TRIUMF data confirm this,[9] but also indicate a strong $NN(^3P_1) \rightarrow NZ$ amplitude, where Z denotes a $\pi N\, S_{1/2}$ state. Interference between the $^1D_2$ amplitude and these triplet waves creates large polarization.

There is one particularly interesting feature of the TRIUMF data. This is that the parameter A_{SL} is close to zero everywhere. This is quite different from $pp \rightarrow \pi d$, where large negative values of A_{SL} arise from interference between $^1D_2$, $^3F_3$, and $^3P_2$. The vector diagram for $NN \rightarrow N\Delta$ amplitudes is illustrated on Figure 5, assuming phases are given *only* by the NN initial state interaction. Now σA_{NO} is given by the imaginary part of interference between $^1D_2$ and triplet waves (largely $^3F_3$ and $^3P_1$), while σA_{SL} is given by the real part of exactly the same interference terms. The fact that the observed polarization is large and $A_{SL} \simeq 0$ indicates that the $^1D_2$ amplitude must be roughly orthogonal to the vector sum of $^3F_3$ and $^3P_1$ amplitudes. This requires that the $^1D_2$ amplitude shown on Figure 5 must be rotated by about $+\ 50°$, i.e., it requires $\delta_{N\Delta}(^1D_2) \simeq 50°$ at all three energies. It is not surprising that the $N\Delta$ S wave interaction should be strongly attractive. The question is whether this is a threshold effect or whether $\delta_{N\Delta}(^1D_2)$ resonates at somewhat higher energies. This can be resolved by measurements of A_{NO} and A_{SL} over the energy range 500–800 MeV.

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References

1. P. Signell, in *Proceedings of the Telluride Conference on the* (p,n) *reaction and the Nucleon–Nucleon Force,* edited by C. D. Goodman *et al.* (Plenum, New York, 1979), p. 1.
2. R. Dubois *et al.*, Nucl. Phys. **A377,** 554 (1982).
3. R. Vinh Mau, in *Mesons in Nuclei,* edited by M. Rho and D. H. Wilkinson (North-Holland, Amsterdam, 1979), Vol. 1, p. 151.
4. M. Grein and P. Kroll, Nucl. Phys. **A338,** 332 (1980).
5. K. Hidaka *et al.*, Phys. Lett. **70B,** 479 (1977).
6. E. Lomon, *AIP Conference Proceedings* edited by H. O. Meyer (American Institute of Physics, New York, 1983), Vol. 97, p. 78.
7. D. V. Bugg, QMC preprint HEP-84-1, submitted to J. Phys. *G.*
8. J. Dubach, W. M. Kloet, and R. R. Silbar, J. Phys. G. Nucl. Phys. **8,** 475 (1982).
9. D. V. Bugg, in *Proceedings of the 10th International Conference on Few Body Problems in Physics, Karlsruhe,* edited by B. Zeitnitz (to be published).