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ISOBAR WIDTH EFFECTS IN THE COUPLING OF NUCLEON TO ISOBAR CHANNELS

P. Gonzalez and E. L. Lomon

ABSTRACT*

The investigation of the effects of isobar coupling to two-nucleon channels has been extended to include additional physical features. A new code discretizes the mass distribution of the isobar widths and treats each mass as a separate channel. This allows the treatment of width in the presence of coupling by transition potentials, in addition to the previously permitted boundary coupling. It also produces the S -matrix components required to describe the many-body final state distributions. When indicated by the OPE coupling strength new isobar channels are included. The new results for nucleon-nucleon scattering fit the data better, starting from more realistic models. The observed 1D_2 and 3F_3 structures are well understood as coupled channel effects, without exotic quark contributions. The existence of a structure in the 3P_0 channel depends on the amount of inelasticity, which differs among the phase shift solutions. The energy dependence seen in recent analyses, of the 3P_2 phase shift near $T_L = 800$ MeV, is shown to be a consequence of the isobar channel coupling. Improved models obtained for the 1S_0 and ${}^3S_1 - {}^3D_1$ channels are being developed. They are important to accurately extrapolate those phases to higher energies where six-quark effects are expected.

I. INTRODUCTION

Data from medium energy accelerators has provided important information about two-hadron systems, including new structures in nucleon-nucleon scattering and accurate deuteron form factors in an extended momentum transfer range. In nucleon-nucleon scattering the first isobar channel, the $N\Delta$, has a threshold at a laboratory beam energy $T_L = 630$ MeV (lower when the Δ width is included). Consequently, the coupling of isobar channels is of great importance for $T_L \geq 400$ MeV and must be considered in the present medium energy range of several GeV. The explicit treatment of the isobar channel effects is necessary to the understanding of the growing amount of pion production data.¹

For $T_L \geq 1.5$ GeV it is expected that quark degrees of freedom will have a significant role.² In order to distinguish their effects from conventional hadronic effects, the behavior of the coupled hadronic channels must be well understood. For instance, the 1D_2 and 3F_3 two-nucleon structures,³ which have been suggested to represent six-quark states,⁴ have been shown to be predicted by coupling to $N\Delta$ channels.⁵⁻⁸ Furthermore, the prediction of the size of observable effects of resonances caused by ex-

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otic quark states^{9, 10} requires a coupled channel model extrapolation of the background phase parameters.

Previous coupled channel calculations^{5–8} have been successful in predicting many of the features of intermediate energy nucleon-nucleon reactions, as well as of some meson-baryon reactions.^{11–15} However this extant work falls short of the realism demanded by the present data or the completeness required to satisfy the objectives mentioned above. In some cases the long range interaction is missing or inadequate,^{11–15} while in others the short range interaction is not sufficiently realistic.^{6–8} Sometimes the decay width of the isobars is neglected. In many cases some significant coupled channels are omitted. In Ref. [5] either the effect of the isobar decay width or of the transition potential is taken into account, but not both together. Also in Ref. [5], significant coupled channels are omitted from a few partial waves.

The present work is an extension of that of Ref. [5], for several of the most interesting nucleon-nucleon partial waves, which overcomes the width restriction and includes more significant channels. In Ref. [5] the short range interaction is described by an energy independent boundary condition at $r_0 \simeq \frac{1}{2}m_{\pi}^{-1}$:

$$r_0 \left(\frac{d\psi^\alpha}{dr} \right)_{r_0} = f \psi^\alpha(r_0) \quad (1)$$

where f is a square matrix of constant coefficients and $\psi^\alpha(r)$ is a column matrix of coupled channel wave functions with the strong quantum number list denoted by α (α denotes J, S, T , and P for the systems discussed in this article.). This boundary condition has been shown¹⁶ to represent the strong, non-local, short range interaction below the energy of states internal to r_0 . Furthermore, it is easily extended² to treat the effects of quark/gluon internal states by the addition of simple, real poles of positive residue to the energy independent f .

Outside of r_0 , the interaction in the nucleon-nucleon sector is taken to be the Feshbach-Lomon potential¹⁷ which includes the contribution of two-pion exchange as well as of single π, η, ρ and ω exchange. The transition potentials from the NN sector to the $N\Delta, \Delta\Delta$ and NN^* (1440) sectors are those determined from one-pion exchange and, sometimes, a phenomenological two-pion range potential (which may also simulate η, ρ and ω exchange).

When the transition potentials are neglected the coupled isobars channels can be eliminated, producing a complex, energy dependent, effective f -matrix in the NN sector. In Ref. [5] the width of an isobar is taken into account for this case by integrating f_{eff} over the Breit-Wigner mass distribution of the isobar. When width effects are important (near threshold) they are treated in this way, replacing the transition potential in that channel with a change of the corresponding f -matrix component. However, over the extended energy region being fitted, the energy dependence of a transition potential can differ significantly from that of boundary condition coupling. In Ref. [5] when both transition potential effects and width effects are important in the description of a specific coupled system, these aspects were examined separately, but could not be treated together.

The important technical feature of the present work is the use of a code which treats each physical channel, such as the $N\Delta$ system with a given J, L, S , and T , as

a large set of channels with distributed isobar masses. The coupling to these channels is weighted by the Breit-Wigner distribution, both for the transition potential and the off-diagonal f -matrix component. Widths and transition potentials are both taken into account appropriately and simultaneously. Of course, this is at the expense of much longer computation times. An added advantage to this approach is that the resulting amplitudes for production of isobars of distributed mass enables the prediction of the decay product distributions.

In some instances the computation of one-pion exchange transition potentials to states neglected in Ref. [5] have indicated their importance and we have included them here.

In Section II we describe the formalism and calculational methods. In Section III we present applications to the ${}^3P_0, {}^3P_2, {}^3F_2, {}^1D_2$ and 3F_3 channels, all of which may have resonances. We also discuss implications for the 1S_0 and ${}^3S_1 - {}^3D_1$ channels which have consequences for the lowest lying six-quark resonances. Section IV summarizes the implications of the results.

II. FORMALISM AND CALCULATIONAL METHOD

The basic formalism for coupled channel scattering used here has been described in detail in the literature.⁵ However, the previous computer program was not able to simultaneously include the effects of the isobar widths and the transition potentials for the coupling of isobar channels to stable hadron channels. When widths effects were included, the coupling of these channels was restricted to that due to the off-diagonal f -matrix components at the boundary. We have modified the old program to overcome this deficiency. The price paid is an increase in computer time by an order of magnitude.

A. COUPLED CHANNEL EQUATIONS

We write the coupled channel equations of Ref. [5] in a form that explicitly represents the distribution of isobar masses as a distribution of channels. We ignore the coupling of the isobar channels to each other as such coupling has only an indirect effect on the observable results and introduces no new qualitative consequences.

We will use an index notation suitable for the two-nucleon reaction which will be the only application presented in this paper. The alteration for scattering of other stable hadron pairs is obvious. Let α, β be the two-nucleon channel indices ($\alpha, \beta = 1, 2$ for the tensor coupled channels and only 1 otherwise) and let i be the index for isobar channels (channels with either one isobar and one nucleon or with two isobars). We will use κ and λ indices for all the channels, collectively. For the modified partial waves $u_\lambda(r) = r\psi_\lambda(r)$

$$\begin{aligned} & -\frac{1}{M_\alpha^2} \frac{d^2 u_\alpha(r)}{dr^2} + \frac{L_\alpha(L_\alpha + 1)}{M_\alpha^2 r^2} u_\alpha(r) + \sum_\beta V_{\alpha\beta}(r) u_\beta(r) \\ & + \sum_i \tilde{V}_{\alpha i}(r) \int_{m+i}^\infty \varphi_i(M, r) dM^* = k_\alpha^2 u_\alpha(r) \end{aligned} \quad (2)$$

where

$$\varphi_i(M_*, \tau) \equiv [k_i \rho_i(M_*)]^{1/2} u_i(M_*, \tau) \quad (3)$$

and, for $M + \mu_i \leq M_* < \infty$

$$\begin{aligned} & -\frac{1}{M_*^{\mu_i}} \frac{d^2 u_i(M_*, \tau)}{d\tau^2} + \frac{L_i(L_i + 1)}{M_*^{\mu_i} r^2} u_i(M_*, \tau) + V_{ii} u_i(M_*, \tau) \\ & + \sum_{\alpha} \tilde{V}_{i\alpha}(\tau) [k_i \rho_i(M_*)]^{1/2} u_{\alpha}(\tau) = [k_i(M_*)]^2 u_i(M_*, \tau) \end{aligned} \quad (4)$$

M is the nucleon mass and μ_i is m_{π} or $2m_{\pi}$ when the isobar decays into a nucleon and one or two pions, respectively (the code also deals with the case of an isobar decaying partly to one pion and partly to two pions by using $\rho = \alpha\rho_{\pi} + \beta\rho_{\pi\pi}$ where α and β represent the probability of decay into one and two pions, respectively). These equations contain the Breit-Wigner distributions functions

$$\rho_i(M_*) = q_i^{2\ell_i+1} M_*^{-2\ell_i} \left[\left(\bar{M}_i^2 - M_*^2 \right)^2 + \Gamma_i^2 \frac{\bar{M}_i^4}{M_*^2} \left(\frac{q_i}{\bar{q}_i} \right)^{4\ell_i+2} \right]^{-1} \quad (5)$$

and their normalization

$$N_i^{-1} = \int_{M+\mu_i}^{\infty} \rho_i(M_*) dM_* \quad (6)$$

The k_{α} , $k_i(M_*)$ and the L_{λ} are the channel momenta and orbital angular momenta, respectively. The $q_i \equiv q(M_*)$ and the ℓ_i are the relative momenta and orbital angular momenta of the baryon-meson pair arising from the isobar decay (we assume the decay takes place through some two-body system). \bar{q}_i is the q_i corresponding to the central mass \bar{M}_i of the isobar and Γ_i is the total decay width. Eq. (4) is written in a form appropriate to an isobar-nucleon channel. If the channel has two isobars with non-zero width, Eq. (4) must be replaced by a convolution over the two distributions. In our $\Delta\Delta$ channel case we have found⁵ that the convolution can be replaced by a single ρ_i with an effective Γ_i and \bar{M}_i .

The M_{α} and M_{α}^* are the reduced masses appropriate to each channel. The $V_{\lambda\kappa}(\tau)$ are the potentials ($V_{\lambda\kappa} = V_{\kappa\lambda}$) and

$$\tilde{V}_{\lambda\kappa}(\tau) = \left(\frac{M_{\alpha}^*}{M_{\lambda}} \right)^{1/2} V_{\lambda\kappa}(\tau) \quad (7)$$

as required for unitarity^{15,18} (this factor was used in the calculations of Ref. [5] although not explicitly indicated in the notation).

Also required are the boundary conditions applied at core radius r_0 .

$$r_0 \frac{du_{\alpha}}{dr_0} = \sum_{\beta} f_{\alpha\beta} u_{\beta}(r_0) + \sum_{\dagger} f_{\alpha\dagger} \int_{M+\mu_i}^{\infty} \varphi_{\dagger}(M_*, \tau_0) dM_* \quad (8)$$

and

$$r_0 \frac{du_i(M_*)}{dr_0} = \sum_{\alpha} f_{i\alpha} [k_i \rho_i(M_*)]^{1/2} u_{\alpha}(r_0) + f_{ii} u_i(M_*, r_0) \quad (9)$$

with $f_{i\alpha} = f_{\alpha i}$.

We note, as in Ref. [5], that when the transition potentials are neglected, one can drop the terms proportional to $\tilde{V}_{\alpha i}$ and $V_{i\alpha}$ in Eqs. (2) and (4), solve Eq. (4) for the outgoing wave functions $u_i^{\dagger}(M_*, \tau)$ and insert the result in Eqs. (8) and (9) to obtain

$$r_0 \frac{du_{\alpha}}{dr_0} = \sum_{\beta} f_{\alpha\beta}^{\text{eff}} u_{\beta} \quad (10)$$

where

$$f_{\alpha\beta}^{\text{eff}} = f_{\alpha\beta} - \sum_{\dagger} f_{\alpha\dagger} f_{\dagger\beta} \int_{M+\mu_i}^{\infty} dM_* \frac{k_i \rho_i(M_*)}{[f_{ii} + \theta_i^{\dagger}(M_*)]} \quad (11)$$

with

$$\theta_i^{\dagger}(M_*) = -\frac{r_0}{u_i^{\dagger}(M_*, r_0)} \frac{du_i^{\dagger}(M_*, \tau)}{dr_0} \quad (12)$$

This considerably simplifies the calculations, but the quadrature in Eq. (11) still takes substantial computer time as the θ_i^{\dagger} must be calculated for each M_* used in the integration.

B. DISCRETIZATION OF THE WIDTH

To solve the above equations numerically without neglect of the $\tilde{V}_{\alpha i}$ and $V_{i\alpha}$, we discretize the width to obtain a finite number of coupled differential equations. In order to discretize the width we substitute for the integration over $\varphi_i(M_*, \tau)$ in Eqs. (2) and (8), a sum over a distribution of masses. The trapezoidal rule is used for a reason which will become clear

$$\int_{M+\mu_i}^{\infty} \varphi_i(M_*, \tau) dM_* \rightarrow \sum_{j=1}^{n_i} \frac{h_j}{2} [\varphi_i(M_{*j}, \tau) + \varphi_i(M_{*(j+1)}, \tau)] \quad (13)$$

where $h_j = M_{*(j+1)} - M_{*j}$. As a cut-off for the top limit of integration, we use the kinematical restriction $M_* \leq (s + M^2)^{1/2}$, with s the invariant mass, which ignores only a negligible portion of the integral. We can then compactly rewrite Eqs. (2), (4), (8) and (9) as

$$-\frac{d^2 \bar{u}_{\lambda}(r)}{dr^2} + \frac{L_{\lambda}(L_{\lambda} + 1)}{r^2} \bar{u}_{\lambda}(r) + \sum_{\kappa=1}^n \tilde{V}_{\lambda\kappa} \bar{u}_{\kappa}(r) = k_{\lambda}^2 \bar{u}_{\lambda}(r) \quad (14)$$

and

$$r_0 \frac{d\bar{u}_{\lambda}(r)}{dr_0} = \sum_{\kappa=1}^n \tilde{f}_{\lambda\kappa} \bar{u}_{\kappa}(r_0) \quad (15)$$

where the λ, κ indices now run over the two-nucleon and all the discretized channels $j_i = 1, 2, \dots, n_i + 1$ of the m isobar channels labelled by i . Therefore, $n = n_0 + \sum_{i=1}^m (n_i + 1)$ where $n_0 = 1$ or 2 depending on whether the two-nucleon channel is not or is tensor coupled. We have defined

$$\bar{u}_\alpha(r) = u_\alpha(r) \quad (16a)$$

$$\bar{u}_{\lambda(i),j} = u_i(M_{\lambda,j}, r) \sqrt{\frac{H_i}{2}} \quad (16b)$$

where

$$H_1 = M_{\lambda 2} - M_{\lambda 1}, \quad H_{n_i+1} = M_{\lambda(n_i+1)} - M_{\lambda n_i} \quad (17a)$$

$$H_j = M_{\lambda(j+1)} - M_{\lambda(j-1)}, \quad j = 2, \dots, n_i \quad (17b)$$

$$\bar{V}_{\lambda, \kappa} = 0 \text{ and } \bar{f}_{\lambda, \kappa} = 0 \text{ unless } \lambda = \alpha, \beta \text{ or } \kappa = \alpha, \beta \text{ or } \lambda = \kappa \quad (18)$$

$$\bar{V}_{\alpha, \beta} = M V_{\alpha, \beta} \quad \bar{f}_{\alpha, \beta} = f_{\alpha\beta} \quad (19)$$

$$\bar{V}_{\alpha, \lambda(i), j} = (M M_{\lambda, j})^{1/2} [M_i \rho_i(M_{\lambda, j})]^{1/2} \sqrt{\frac{H_i}{2}} V_{\alpha i} = \bar{V}_{\lambda(i), j}, \quad \alpha \quad (20)$$

$$\bar{f}_{\alpha, \lambda(i), j} = [M_i \rho_i(M_{\lambda, j})]^{1/2} \sqrt{\frac{H_i}{2}} f_{\alpha, i} = \bar{f}_{\lambda(i), j}, \quad \alpha \quad (21)$$

and

$$\bar{V}_{\lambda(i), j}, \lambda(i), j = M_{\lambda, j} V_{\lambda, i} \quad \bar{f}_{\lambda(i), j}, \lambda(i), j = f_{\lambda, i}$$

In the limit $n \rightarrow \infty$, Eqs. (14) and (15) reproduce the results of Eqs. (2), (4), (8) and (9). To minimize the number of coupled channels, n , for a given accuracy, the $M_{\lambda, j}$ are concentrated where the $\rho_i(M_{\lambda, j})$ is large. In practice, this is accomplished by using about 15 equally spaced $M_{\lambda, j}$ between M_i and $\bar{M}_i + \Gamma_i$ and two $M_{\lambda, j}$ for $M_{\lambda, j} > \bar{M}_i + \Gamma_i$. It is important to note that each $M_{\lambda, j}$ produces a discrete threshold at the corresponding two-nucleon energy, which produces cusps of magnitude $\propto H_j$ in the phase parameters at these energies. Thus, the phase parameters at these threshold energies have the largest errors, mid-way between thresholds the phase parameters have errors of the opposite sign and at some off-set from these thresholds the phase parameters are exact. The approximate value of this off-set is determined by comparison with the results of the old code (see Eqs. (10) – (12)) for the case of vanishing transition potential. In this way, we have obtained accurate results for most of the results in this paper (less than 0.1° in the phase shift difference and 0.05 in the inelasticity difference from the old code) by using 17 channels to decompose the width of one physical isobar channel. On a VAX 780 the CPU time is about 20 minutes per energy when the width of one physical channel is included.

When the scattering energy is far from the physical threshold region, the influence of the width is small and accurate results are provided by the version of the old code which neglects the width but includes transition potentials. This code only requires

about 20 seconds of VAX 780 CPU time per energy. It is used where appropriate to save computing time.

III. NUCLEON-NUCLEON SCATTERING RESULTS

A. THE 1D_2 CHANNEL

As shown in Ref. [5], when the Δ width is ignored the strong coupling of the 1D_2 NN channel to the $L' = 0, {}^5S_2$ $N\Delta$ channel produces a large cusp in the phase shift at inelastic threshold, $T_L = 630$ MeV (in general, there is a discontinuity in the $(L' + 1)$ th derivative at inelastic threshold). It was also shown that the cusp becomes a broad smooth maximum when the width is included. Although the transition potential then had to be omitted in that work, an adequate fit was obtained within the uncertainty of the experimental phase shifts at that time. Since then there has been new data and the experimental phase shifts have changed significantly for $T_L > 500$ MeV. Also, the results of different phase shift analyses are now much closer than before. 10–21 Consequently, the fitting requirements are now different and more stringent than they were in Ref. [5].

Apart from using the new code, which allows transition potentials when the isobar widths are taken into account, the present model is more realistic because of the inclusion of the 3D_2 $N\Delta$ state. This was omitted in Ref. [5] because of the higher effective threshold due to the angular momentum barrier. However, the one-pion exchange coupling strength to the two nucleon system is stronger than that of the 5S_2 partial wave. Its contribution turns out to be crucial to obtaining the correct fit at $T_L = 800$ MeV, as this is the region of the effective threshold for the $N\Delta$ system in a D -wave.

The fit to experimental data requires the introduction of two-pion exchange range transition potentials, to reduce the effect of the one-pion exchange transition potentials. The potentials resulting from one-pion exchange and the fitted two-pion range terms are

$$V [NN({}^1D_2) - N\Delta({}^5S_2)] = -0.098 m_\pi V_2(m_\pi r) + 0.335 r^{-1} e^{-2m_\pi r}$$

$$V [NN({}^1D_2) - N\Delta({}^3D_2)] = 0.1176 m_\pi V_2(m_\pi r) - 1.25 r^{-1} e^{-2m_\pi r}$$

$$V [N\Delta({}^5S_2) - N\Delta({}^3S_2)] = -0.079 m_\pi V_0(m_\pi r)$$

where

$$V_0(x) = x^{-1} e^{-x} \quad \text{and} \quad V_2(x) = (x^{-1} + 3x^{-2} + 3x^{-3}) e^{-x}$$

We note that the effect of the diagonal $N\Delta({}^5S_2)$ potential on the 1D_2 amplitude is negligible and has been included only for completeness. Other possible coupled channels are unimportant because of high thresholds and weak coupling.

The fit obtained for the phase shift and inelasticity is shown in Figs. 1a and 1b. The curve of $\eta({}^1D_2)$ shows the effect of the coupling to the $N\Delta({}^5D_2)$ channel. The value continues to decrease sharply after 600 MeV instead of levelling shortly after the 630 MeV threshold. The 5D_2 coupling also causes the steep descent of $\delta({}^1D_2)$

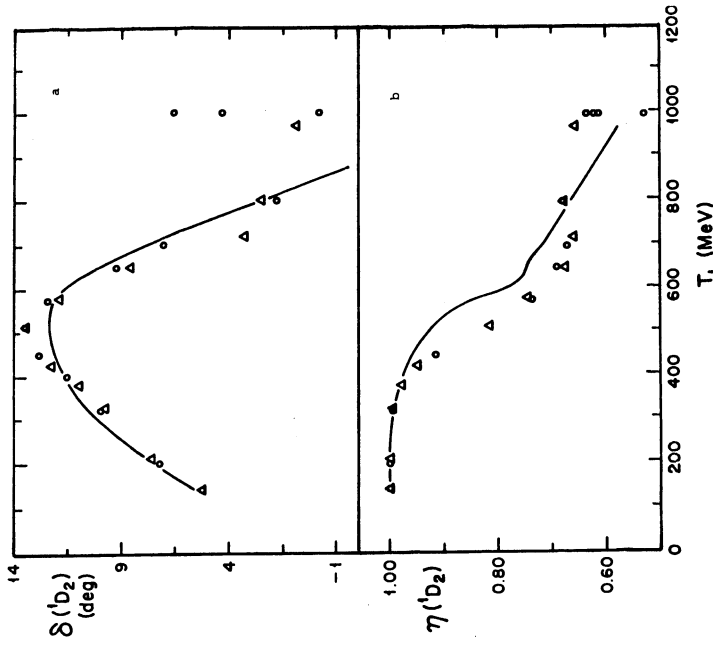


Fig. 1: (a) The 1D_2 phase shift. The open triangles denote the phase shift analysis of Ref. [19]. The open circles denote the analysis of Ref. [21]. The solid curve is the model prediction for $NN({}^1D_2)$ coupled to $N\Delta({}^5S_2)$ and $N\Delta({}^5D_2)$ with f matrix elements $f_{NN,NN} = 19.3$, $f_{NN,N\Delta(S)} = 0.2$, $f_{NN,N\Delta(D)} = 1.5$, $f_{N\Delta(S),N\Delta(S)} = 1.0$, $f_{N\Delta(S),N\Delta(D)} = f_{N\Delta(D),N\Delta(D)} = 0.0$; (b) The 1D_2 inelasticity. The points and curve denote phase-shift solutions and model prediction as in Fig. 1a.

to continue. These features conform to the data. As shown in Figs. 1a and 1b, the phase shift does not peak as much, nor the inelasticity decrease as rapidly, near $T_L = 500$ MeV as the experimental values. If the phase shift analyses are accurate this may indicate that there is some continuum, non-isobaric, pion-production contributing significantly below the $N - \Delta$ threshold.

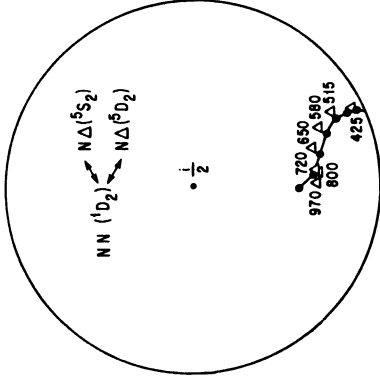


Fig. 2: Argand plot for the 1D_2 amplitude. The points and solid curve are denoted as in Fig. 1a. The filled circles on the model denote the same energies as the open triangles. The laboratory energies T_L are indicated in MeV.

In the Argand plot, Fig. 2, it is seen that the model and data both indicate the rapid anti-clockwise motion typical of an inelastic resonance.

B. THE 3F_3 CHANNEL

The 3F_3 channel can couple to $N\Delta$ in $P(L' = 1)$ and $F(L' = 3)$ waves, to $\Delta\Delta$ in P, F and $H(L' = 5)$ waves and to NN^* in an F wave. However, all the other one-pion exchange interactions are relatively small compared to the coupling to $N\Delta({}^5P_3)$. Furthermore, the other effective thresholds are also higher so that one expects the dominant effects to come from the $N\Delta({}^5P_3)$ coupling. However, for the higher energies in the range considered, i.e., say, $T_L > 700$ MeV, and as confirmed below by our fit, the influence of extra channels can start to be important. We only use the one-pion exchange interactions:

$$V [NN({}^3F_3) - N\Delta({}^5P_3)] = -0.1288 m_\pi V_2(m_\pi r)$$

$$V [N\Delta({}^5P_3) - N\Delta({}^5P_3)] = -0.079 m_\pi V_0(m_\pi r) + 0.0063 m_\pi V_2(m_\pi r)$$

As in the 1D_2 case, the diagonal potential has no influence whatsoever. No two pion exchange interaction is needed. The fit to new phase shifts, Fig. 3a, is very good, a much better fit than that of Ref. [5] or [22] at the peak and beyond. For the inelasticity, Fig. 3b, our result is too elastic above 700 MeV, in the region at which there can be some effect from higher-mass coupled channels. It is difficult at this point to predict which of these extra channels are going to be most important until we have

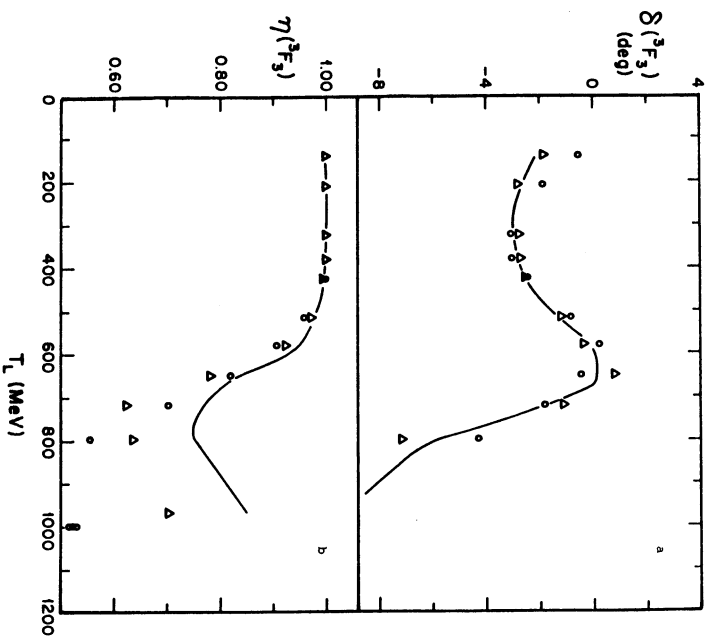


Fig. 3. (a) The 3F_3 phase shift. The phase-shift analysis points and solid curve are denoted as in Fig. 1a. The model curve corresponds to $N'N'({}^3F_3)$ coupled to $N\Delta({}^5P_3)$ and $f_{N'N',N'N} = 5.4$, $f_{N'N',N\Delta} = 2.72$, $f_{N\Delta,N\Delta} = 0.3$. (b) The 3F_3 inelasticity. Points and curve are denoted as in Fig. 3a.

more inelastic experimental data available for these energies and beyond. However, one is tempted to some speculation. Looking at the different couplings, it turns out that the most favored channels are $N\Delta({}^5F_3)$ and $N\Delta({}^3F_3)$. Their couplings to $N'N'({}^3F_3)$ are only one half to one third of that to $N\Delta({}^5F_3)$, but their influence increases with energy since their thresholds are higher.

We make a technical remark concerning this case. In the region around $T_L = 500$ MeV, the instability of the numerical results with respect to the mass offset chosen has made it necessary to increase the number of channels and consequently the computing time to obtain enough accuracy.

The Argand plot, Fig. 4, shows the anti-clockwise rotation of an inelastic resonance beginning at $T_L = 425$ MeV although it is not as strong as that of the 1D_2 case.

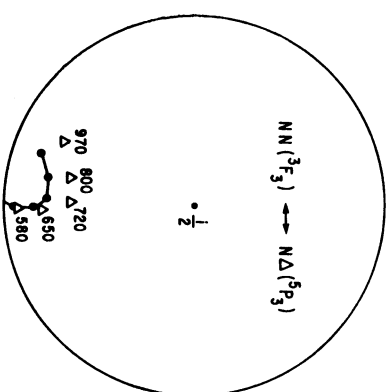


Fig. 4: Argand plot for the 3F_3 amplitude. Notation as in Fig. 2. f -matrix parameters as in Fig. 3a.

C. THE 3P_0 CHANNEL

The 3P_0 nucleon-nucleon channel is of interest because both the experimental data^{21,23} and some models^{6,22} indicate that it, like the 1D_2 and 3F_3 channels, may be resonant at low energies. The uncertainty is due to the inelasticity which varies greatly in the phase shift analyses and depends on short range coupling in the model. The subject is discussed in Ref. [22] in which a model that has a slight anti-clockwise rotation in the Argand plot is compared with data. But that model, using the old code, did not include the effect of transition potentials. The width had to be taken into account as the inelastic structure, if it exists, is at $T_L < 630$ MeV.

We first remark that in the fits of Refs. [5], and [22], $6({}^3P_0)$ is somewhat too large for $T_L < 210$ MeV. This is not sensitive to the channel coupling but represents a deficiency in the Feshbach-Lomon nucleon-nucleon potential. This is rectified here by using $g_{N'N'}^2/4\pi = 13.0$ but may represent a deficiency of the semi-relativistic two-pion potential of Ref. [17].

The $N\Delta({}^3P_0)$ channel is the only channel to which the $N'N'({}^3P_0)$ can couple which has both the lowest threshold energy and the lowest L' available. The one-pion transition potential has moderate strength:

$$V [N'N'({}^3P_0) - N\Delta({}^3P_0)] = 0.1467 m_\pi V_0(m_\pi r) - 0.0733 m_\pi V_2(m_\pi r)$$

We do not use a two-pion range potential for this case. No other $N\Delta$ channel can couple. Therefore, all the remaining coupled channels have a higher threshold energy. We present, in Figs. 5a and 5b, two fits which differ only in the strength of coupling

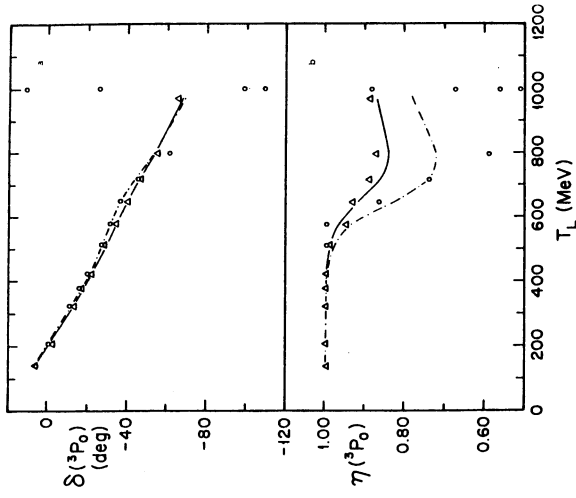


Fig. 5: (a) The 3P_0 phase shift. The points denote phase-shift solutions as in Fig. 1a. The solid and dash-dot curves are the model predictions for $NN({}^3P_0)$ coupled to $N\Delta({}^3P_0)$. The solid curve corresponds to $f_{NN,NN} = 25.0$, $f_{N\Delta,N\Delta} = -0.3$, $f_{N\Delta,N\Delta} = -0.2$. The dash-dot curve corresponds to $f_{NN,NN} = 26.0$, $f_{N\Delta,N\Delta} = -2.0$, $f_{N\Delta,N\Delta} = -0.2$; (b) The 3P_0 inelasticity. Points and curves are denoted as in Fig. 5a.

at the boundary. The less strongly coupled, $f_{NN,N\Delta} = 0.3$, fits the phase parameters of Ref. [19] well, and the other, $f_{NN,N\Delta} = 2.0$, fits the phase parameters of Ref. [21] (except for η at $T_L \geq 800$ MeV which would require an assist from the $\Delta\Delta({}^3P_0)$ and $NN^*({}^3P_0)$ coupling).

Examining the Argand plots (Figs. 6a and 6b) we see that the slope of the amplitude is significantly different when the two different couplings are used. For the less strongly coupled case it clearly rotates clockwise. However, for the more strongly coupled case between $T_L = 580$ MeV and 800 MeV, the Argand plot is nearly straight and may have a slightly anti-clockwise rotation. The confirmation of a possible structure in this partial wave awaits data for $T_L > 600$ MeV which is sensitive to $\eta({}^3P_0)$. This could be $\frac{d\delta}{dT_L}$ (absolute) together with A_{xx} , A_{zz} and D in the elastic data, or detailed single pion production data.

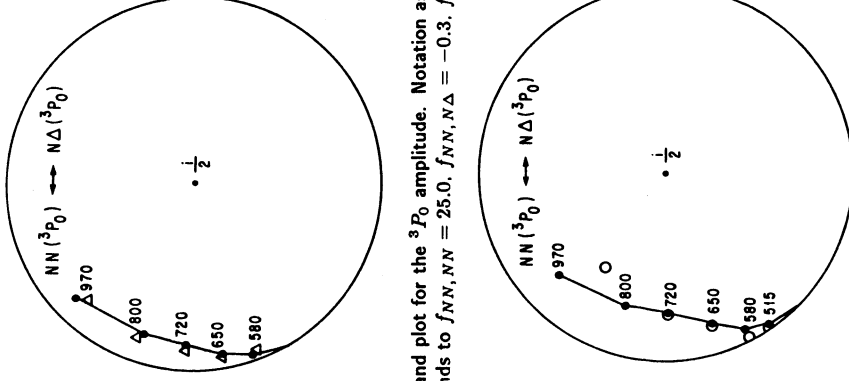


Fig. 6a: Argand plot for the 3P_0 amplitude. Notation as in Fig. 2. The model corresponds to $f_{NN,NN} = 25.0$, $f_{N\Delta,N\Delta} = -0.3$, $f_{N\Delta,N\Delta} = -0.2$.

Fig. 6b: Argand plot for the 3P_0 amplitude. Notation as in Fig. 2. The model corresponds to $f_{NN,NN} = 26.0$, $f_{N\Delta,N\Delta} = -2.0$, $f_{N\Delta,N\Delta} = -0.2$.

D. THE ${}^3P_2 - {}^3F_2$ CHANNEL

While the older phase shift analysis of this channel gave no indication of structure (see Ref. [5]), recent analyses¹⁹⁻²¹ have indicated a rapid drop in $\eta({}^3P_2)$ for $T_L > 600$ MeV and a decreasing $\delta({}^3P_2)$ for $T_L > 800$ MeV^{19,21} or even for $T_L > 600$ MeV.²⁰

We note that the model of Ref. [5] was forced to produce these features for $T_L > 650$ MeV in order to fit the lower energy data. We now show that these features persist with our more realistic model and that a resonance is predicted in the vicinity of 1000 MeV.

First, we realize that, apart from the $N\Delta(^3P_2)$ channel considered in Ref. [5], other channels have important one-pion exchange transition potentials to the $^3P_2 - ^3F_2$ NN channel. In particular, $N\Delta(^3P_2)$, $N\Delta(^5F_2)$, and $N\Delta(^3F_2)$ are of some significance. It is possible to combine the effects of the two P -wave or the two F -wave isobar channels using Eq. (31) of Ref. [5]. It turns out that the resulting potentials provide too much coupling. As the boundary coupling has little effect on P -waves at low energy, the way to get a fit to experimental data is to cancel some of the one-pion exchange effect with two-pion exchange contributions of opposite sign. We have found as the adequate final potentials, including the one-pion exchange terms obtained as indicated above:

$$\begin{aligned} V [N\Delta(^3P_2) - N\Delta(P)] &= -0.068 m_\pi V_2(m_\pi r) + 1.65 r^{-1} e^{-2m_\pi r} \\ V [N\Delta(^3F_2) - N\Delta(P)] &= -0.0762 m_\pi V_2(m_\pi r) + 1.3 r^{-1} e^{-2m_\pi r} \\ V [N\Delta(^3F_2) - N\Delta(F)] &= 0.154 m_\pi V_2(m_\pi r) - 3.5 r^{-1} e^{-2m_\pi r} \\ V [N\Delta(^3F_2) - N\Delta(F)] &= 0.116 m_\pi V_2(m_\pi r) - 2.0 r^{-1} e^{-2m_\pi r} . \end{aligned}$$

With this choice we get a good fit to $\delta(^3P_2)$, $\eta(^3P_2)$, by tuning $f_{NN(^3P_2)-N\Delta(P)}$, with $f_{NN(^3P_2)-N\Delta(P)}$ correlated, to give the low energy $\delta(^3P_2)$ values. The results are shown in Figs. 7a, 7b, 8a, and 8b. As in Ref. [5], the $\delta(^3P_2)$ fit is poor and is insensitive to the coupling. This is a problem with the Feshbach-Lomon nucleon-nucleon potential,¹⁷ which may be due to its ignoring the linear and quadratic spin orbit parts, which can be significant for $L = 3$. In Figs. 9a and 9b we represent the coupling parameter ϵ_2 and the mixing angle ϕ_2 given by the model. The fit for ϵ_2 is reasonable but the model produces an oscillation in the value around $T_L = 720$ MeV. This may be ascribable to the rapid onset of inelasticity at $T_L = 600$ MeV, followed by a drop in $\delta(^3P_2)$ starting near $T_L = 800$ MeV.

The Argand plot for the 3P_2 complex phase, Fig. 10, shows the anti-clockwise behavior of an inelastic resonance from $T_L > 800$ MeV.

E. COMMENTS ON THE 1S_0 AND $^3S_1 - ^3D_1$ CHANNELS

The complex models required for the 1S_0 and $^3S_1 - ^3D_1$ channels will be the subject of a forthcoming paper,²⁴ which will also consider the effect of interior quark states.^{2,9,10} However, a few remarks of interest may be made now.

Because the $NN(^1S_0)$ couples only to the $N\Delta$ system in the 5D_0 channel, it is important to consider the coupling to the $\Delta\Delta$ and $NN^*(1440)$ systems in spite of their greater threshold energy. In both of the latter systems there is coupling to the 1S_0 state whose effective threshold is not far above that of the $N\Delta(^5D_0)$ channel.

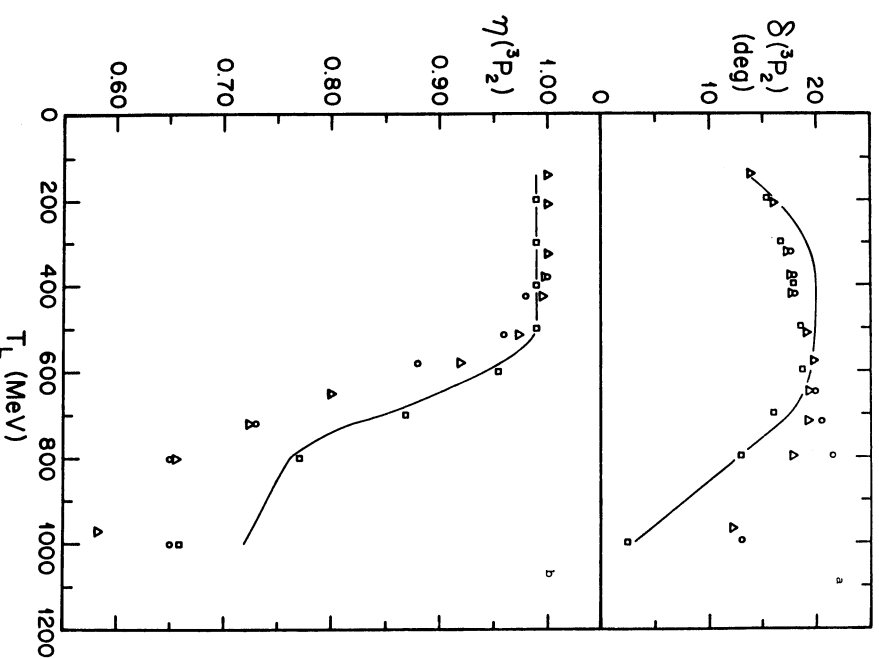


Fig. 7: (a) The 3P_2 phase shift. The points and curve denote phase-shift solutions as in Fig. 1a. The open squares denote the single energy phase shift analysis SP85 of Ref. [20]. The solid curve is the model prediction for $NN(^3P_2)$ coupled to $NN(^3F_2)$ (via the NN tensor potential) and to $N\Delta(^3,5F_2)$ and $N\Delta(^3,5P_2)$. $f_{PP} = 1.73$, $f_{PP} = -0.9$, $f_{P,N\Delta(P)} = -2.12$, $f_{P,N\Delta(P)} = 0.8$, $f_{PP} = 40.0$, $f_{P,N\Delta(P)} = f_{P,N\Delta(P)} = f_{N\Delta(P),N\Delta(P)} = 0.1$; (b) The 3P_2 inelasticity. The points and curve denoted as in Fig. 7a.

The resultant fit to the elastic nucleon-nucleon scattering data presented in Ref. [5] is quite good.

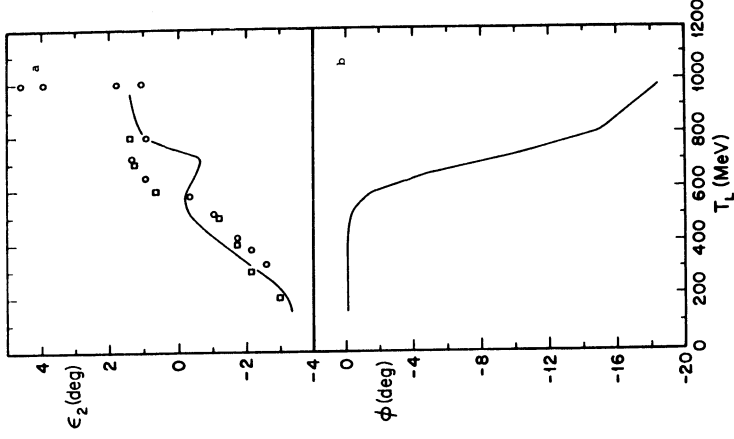


Fig. 9: (a) The $J = 2$ coupling parameter ϵ_2 . Notation as in Fig. 7a; (b) The mixing angle ϕ_2 predicted by the model as a function of the energy.

MeV were made later²⁵ by ignoring the transition potentials and suitably modifying the boundary coupling. This showed that the two-pion production generated by these channels exceeded the data²⁶ by two orders of magnitude. Subsequent work with the old code²⁵ showed that one could modify the short range coupling to the two-pion channels so as to agree with the experimental production limit.

We now find similar effects with the new code, in which the comparison with both the low energy pion production and the elastic scattering phase shifts can be made consistently. The distortion of the phase shifts by the width of the higher mass channels is substantial, in addition to the effect on the inelasticity parameter. In the forthcoming paper²⁴ we will consider the sensitivity of the projections to higher energy (and the six-quark resonances) to the choice of boundary couplings and of QCD models.

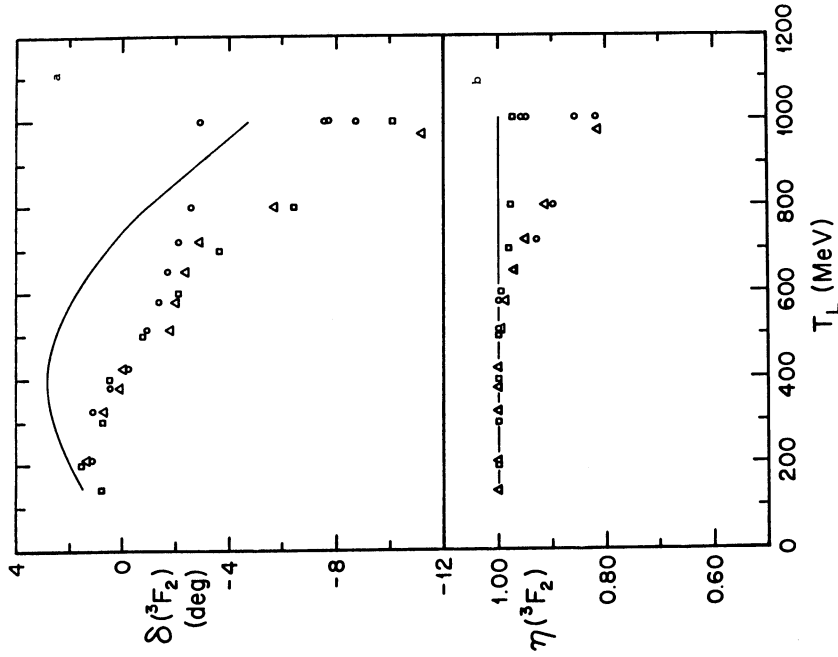


Fig. 8: The (a) 3F_2 phase shift. The points and curve are denoted as in Fig. 7a; (b) The 3F_2 inelasticity. The points and curve are denoted as in Fig. 7a.

In that fit the Δ -width is included in the $N\Delta({}^5D_0)$ channel (whose threshold is in the experimental region) and consequently the transition potential to that channel is ignored. The transition potentials to the $\Delta\Delta({}^1S_0)$ and $NN^*({}^1S_0)$ channels are included. Estimates of the inelasticity to the latter two channels near $T_L = 800$

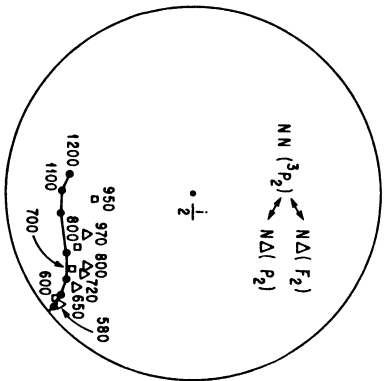


Fig. 10: Argand plot for the 3P_2 amplitude. Notation as in Figs. 2 and 7a. The corresponding energies are made explicit.

The ${}^3S_1 - {}^3D_1$ nucleon-nucleon system is particularly complex. Although isospin conservation forbids any $N\Delta$ channel, the $\Delta\Delta({}^3S_1)$, $\Delta\Delta({}^3D_1)$, $\Delta\Delta({}^1D_1)$ and $NN^*({}^3S_1)$ channels can all be expected to have significant roles. The $\Delta\Delta({}^1D_1)$ has a particularly strong one-pion exchange coupling and cannot, therefore, be ignored compared to the lower effective threshold $\Delta\Delta({}^3S_1)$ and $NN^*({}^3S_1)$. The $\Delta\Delta({}^3D_1)$ must also be included because of its important role in the deuteron elastic magnetic form factor.^{27–29} The large Δ magnetic moment and the opposing spin and orbital angular momentum alignments of the 1D_1 and 3D_1 $\Delta\Delta$ states have important consequences for that form factor. The consequences of various balances between the coupling to the four isobar channels mentioned, for both the deuteron^{27,28} and the six-quark resonances,¹⁰ will be discussed.^{24,29} In particular, total coupling strength to the $\Delta\Delta({}^1D_1)$ state is strongly restricted by deuteron data.^{27–29}

IV. CONCLUSIONS

We have constructed realistic models for nucleon-nucleon scattering partial waves at intermediate energies by using meson exchange potentials and short range, energy dependent boundary conditions with explicit coupling to the low orbital angular momentum $N\Delta$, $\Delta\Delta$, and $NN^*(1440)$ channels. They provide good descriptions of the physics of all the nucleon-nucleon channels that are non-trivial for $T_L \leq 1$ GeV. The spreading of the threshold effects by the Breit-Wigner mass distributions of the isobars is very important in fitting the data, as is the large scale dependence due to the one-pion range transition potentials. As before,⁵ the characteristic increase of attraction (or decrease of repulsion) below threshold, followed by a sharp decrease in the phase shift and a minimum in inelasticity above threshold³⁰ is important in fitting the physical data. This critical behavior is not obtained by including the coupling to in-

termediate states in the derivation of an adiabatic nucleon-nucleon potential.^{21,32} The best way to get an accurate representation of this energy dependence is to explicitly couple channels using potential (and boundary condition) matrices.

We have re-investigated the 3P_0 , ${}^3F_2 - {}^3F_3$, 1D_2 and 3F_3 two-nucleon systems with transition potentials and width simultaneously taken into account, and with extra isobar channels where indicated. These more realistic models provide improved fits to the analyzed phase parameters^{19–21} (some of which have changed significantly from those available during the preparation of Ref. [5]). The results confirm the coupled channel nature of the 1D_2 and 3F_3 structures. There is no need to attribute these structures to exotic six-quark states, nor does such a model describe the data well.^{2,3} Confirmation of the existence of the previously inferred structure in the 3P_0 channel^{6,21–23} is shown to require more experimental information on the inelasticity parameter. That parameter determines the short range coupling strength which, in turn, determines the structure. A previous prediction of coupled channel structure in the 3P_2 channel,⁵ near $T_L = 800$ MeV, is confirmed, and is close to that indicated by the recent phase shift analyses.^{19–21}

The present method allows us to develop improved models for the 1S_0 system and examine the consistency with the measured two-pion production cross section at $T_L = 800$ MeV.²⁶ The ${}^3S_1 - {}^3D_1$ model is being extended to be consistent with deuteron properties, including the sensitive magnetic form factor.^{27–29} Both of these, together with the improved 1D_2 system model, will provide a more reliable extrapolation of these phase parameters to the region² where six-quark f -matrix poles affect these states. The size of these effects will be more closely predicted.²⁴

The improved models for all of the nucleon-nucleon partial waves enable more reliable predictions of the magnitude of observable effects produced by the six-quark f -poles, as these depend on interference between the resonant and non-resonant states.^{9,10} The better extrapolation to higher energies will, in general, help identify the most sensitive experiments for accurate phase shift analyses.

An important advantage of the present calculation over that of Ref. [5] is that it predicts the S -matrix elements for the production of isobars as a function of the isobar mass. One can then predict, through the subsequent decay of the isobars, the observable distributions in the $NN\pi$ and $NN^*\pi$ final states.^{1,33} We plan to do this in collaboration with the authors of Ref. [1]. The comparison with production data will further restrict our coupled channel models. The relative strength of coupling to different isobar channels is often poorly determined by comparison with the elastic data, but is very sensitive to production data.

ACKNOWLEDGEMENTS

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ERRATUM

ISOBAR WIDTH EFFECTS IN THE COUPLING OF NUCLEON TO ISOBAR CHANNELS

P. Gonzales and E. L. Lomon

The following changes should be made to MIT preprint #1328 dated February 1986:

- Page 14, 7 lines after equation: End paragraph with "The fit for ϵ_2 is reasonable.", and delete the remainder of the paragraph, *i.e.*, "but the model produces an oscillation in the value around $T_L = 720$ MeV. This may be ascribable to the rapid onset of inelasticity at $T_L = 600$ MeV, followed by a drop in $\delta(^3P_2)$ starting near $T_L = 800$ MeV."
- Page 17: Replace Fig. 9. Caption remains the same.

