Polarization Phenomena in Nucleon-Nucleon Scattering at Intermediate
And High Energies Including the Present Status of Dibaryons

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We review experimental results concerning polarization phenomena in nucleon-nucleon scattering in which both the elastic scattering and hadron-production reaction are included. We also present summary of $S = 0$ dibaryon resonances and candidates by reviewing experimental data in the nucleon-nucleon system, $\pi d$ channel, $\pi d$ elastic scattering, $pp + \pi d$ channel, deuteron break-up reactions, and narrow structures in missing-mass spectra.

§1. Introduction

There are two energy regions based on the physics interests in the nucleon-nucleon system. Many structures were found at lower energies, up to roughly 4-GeV/c incident momentum. Related structures were also found in various channels beside the nucleon-nucleon system.

Above this energy region, remarkable spin effects were observed both in the elastic and hadron production in the nucleon-nucleon scattering. Further studies are pursued by using polarized beams and/or targets at Brookhaven, CERN, KEK, Serpukhov, and Fermilab.

§2. pp Scattering-Amplitude Measurements in the Multi-GeV Range

Recently results of measurements on a number of triple- and double-spin correlation parameters in proton-proton elastic scattering at 6 GeV/c over the $|t|$ range between 0.2 and 1.0 (GeV/c)$^2$ became available.$^1$ These new data permit the first nucleon-nucleon amplitude determination above the "dibaryon resonances" region. Polarized beams from the Argonne ZGS and polarized targets were utilized. The polarization of the recoil proton was measured

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with a carbon polarimeter. A total of 14 different spin observables were measured (five spin transfer, four depolarization, and five triple-spin correlation parameters). These have been combined with earlier results, resulting in 20 different spin observables for each of six $|t|$ values between 0.2 and 1.0 (GeV/c)$^2$. A solution for the amplitudes has been found at each $|t|$. The amplitudes are normalized so that $d\sigma/d\Omega = 1$.

Here we define scattering amplitudes in two different ways:

**i) s-channel helicity amplitudes**

\[
\begin{align*}
\langle ++ | -- &\rangle = \phi_1 \\
\langle -- | ++ &\rangle = \phi_2 \\
\langle -+ | ++ &\rangle = \phi_3 \\
\langle ++ | + &\rangle = \phi_4 \\
\langle ++ | - &\rangle = \phi_5 \\
\end{align*}
\]

**ii) t-channel exchange amplitudes ($N_0, N_1, N_2, U_0,$ and $U_2$ which have definite quantum numbers exchanged at asymptotic energy)**

Natural-parity exchange:

\[
N_0 = \frac{1}{2} (\phi_1 + \phi_3), \quad N_1 = \phi_5, \quad N_2 = \frac{1}{2} (\phi_4 - \phi_2)
\]

Unnatural-parity exchange:

\[
U_0 = \frac{1}{2} (\phi_1 - \phi_3), \quad U_2 = \frac{1}{2} (\phi_2 + \phi_4)
\]

Cross section:

\[
d\sigma/d\Omega = |N_0|^2 + 2|N_1|^2 + |N_2|^2 + |U_0|^2 + |U_2|^2
\]

(the subscripts correspond to the total s-channel helicity flip).

The results of the amplitude determination are shown in Fig. la for the exchange amplitudes and in Fig. lb for the s-channel helicity amplitudes. Note that the magnitudes of $N_0, \phi_1,$ and $\phi_3$ are scaled down a factor of 5 in Fig. 1.
Fig. 1a. pp scattering amplitudes at 6 GeV/c (exchange channel).
Fig. 1b. pp scattering amplitudes at 6 GeV/c (s-channel helicity channel).

In particular, the data show that the spin non-flip helicity amplitudes $\phi_1$ and $\phi_3$ are much larger than the spin-flip amplitudes. This indicates that helicity conserving exchange terms are dominant, as would be the case if exchanged gluons couple to current quarks in the nucleons. The amplitude picture seems easier to understand in terms of the s-channel helicity amplitudes, where little variation is observed in $\phi_1$, $\phi_3$, and $\phi_5$ over most of the t-range of this experiment. As noted above, the dominant amplitudes are $\phi_1 = \phi_3$. In addition, the $\phi_2$ amplitude remains almost real though there is a change in its magnitude. There is, however, a large variation in both the magnitude and direction of $\phi_4$. As has been noted by Kroll et al., surprisingly, the most interesting structure is in $\phi_2$ and $\phi_4$ themselves rather than in the combinations $N_2$ and $U_2$.

Various recent theoretical activities for the scattering amplitudes are summarized here. It is hoped that the new data will stimulate further work. The classical Regge description and predictions were in general agreement with the data. Wakaizumi et al. investigated the pp interaction at 6 and 12 GeV/c at all angles using the impact-parameter representation and the eikonal model. Fits to previous data allowed conclusions on the magnitude of the short-, medium-, and long-range components of the spin dependent eikonalas. Semiphenomenological phase-shift analyses were performed at 6 GeV/c.

Moravcsik, Goldstein, and coworkers have commented on pp elastic scattering at
6 GeV/c in many articles. Several papers deal with the problem of how best to determine the amplitudes. An extensive amplitude analysis from \(|t| = 0.05\) to 1.0 (GeV/c)\(^2\) was also performed. Polarization tests of one-particle-exchange mechanisms were applied to the 6-GeV/c amplitudes and were shown to be satisfied, whereas they failed at lower energies. Finally, these authors also try to interpret the results for the 6-GeV/c amplitudes in the framework of QCD.

§3. pp Elastic Scattering at \(p_\perp > 2\) GeV/c

The spin-correlation parameters at \(p_\perp > 2\) GeV/c are given in measurements of \(C_{NN} (A_{NN}) = (N,N;0,0)\) and \(C_{LL} = (L,L;0,0)\) at 11.75 GeV/c covering large c.m. scattering angles. The results are shown in Fig. 2. At \(\theta_{c.m.} = 90^\circ\), one can obtain the value of \(C_{SS}\) from the relationship, \(C_{NN} - C_{SS} - C_{LL} = 1\). The parameters \(C_{NN}\) and \(C_{SS}\) at \(\theta_{c.m.} = 90^\circ\) are expressed in terms of s-channel helicity amplitudes as

\[
C_{NN} = \text{Re}(\phi_1^* \phi_2 - \phi_3^* \phi_4)/\sigma
\]

and

\[
C_{SS} = \text{Re}(\phi_1^* \phi_2 + \phi_3^* \phi_4)/\sigma.
\]

Fig. 2.

\(C_{NN} (A_{NN})\) and \(C_{LL}\) at 11.75 GeV/c at large angles.
For the data with $p_\perp > 2$ GeV/c we attempt to test the helicity conservation among the quarks based upon the assumption that the proton spins made from quarks and quark mass $\neq 0$ is the most important one. The helicity conservation requires that the helicity flip amplitudes must vanish as

$$\phi_2 = \langle--|++\rangle = 0,$$

then $C_{NN} = -C_{SS}$. The experimental data at $\theta_{c.m.} = 90^\circ$ show that $C_{NN} = 0.57 \pm 0.08$ and $C_{SS} = -0.30 \pm 0.16$. The results imply that we observe approximately helicity conservation among the quarks.

The energy dependence of $C_{NN}$, $C_{LL}$, and $C_{SS}$ at $\theta_{c.m.} = 90^\circ$ is predicted up to $p_{lab} = 12$ GeV/c by viewing the reaction amplitudes in the planar-transverse frame.

An asymmetry measurement in $pp^+ + pp$ elastic scattering at Brookhaven yielded high values (up to $\sim +25\%$) of the polarization parameter at $p_\perp > 2$ GeV/c. J. Soffer et al. describe the results in terms of soft- and hard-collision processes.

§4. Polarization in Hyperon Production

Most of the high-energy hyperon polarization data come from inclusive reactions, $pN + Hx$, where $N$ is the target (most commonly proton and Be) and $H$ is the produced hyperon. The $\Lambda$ polarization has been extensively measured at 400-GeV/c incident protons and is shown in Fig. 3 as a function $p_\perp$, the transverse momentum of the hyperon, and $x = p^*/p_{max}$. The disappearance of the polarization as $p_\perp$ vanishes results from parity invariance. One notices remarkable facts which are i) the magnitude of the polarization is independent of $p_\perp$ above $p_\perp$ of 2 GeV/c, ii) polarization increases for large $x$. The $\Lambda$ polarization has also been measured at 12 GeV/c at KEK, 26/26 and 31/31 GeV at the ISR. These results are similar to those measurements at 400 GeV/c.

The polarization of $\Xi^0$ and $\Xi^- $ produced by 400-GeV/c protons show a remarkable similarity compared to $\Lambda^0$. The $\Sigma^+$ polarization multiplied by -1 also shows a remarkable similarity. The $\bar{\Lambda}$ polarization is consistent with zero out to a $p_\perp$ of 2 GeV/c.
Fig. 3. Inclusive λ polarization as a function of $p_t$ for given $\bar{x}$s.

- Dark triangles: pp + λX at 400 GeV/c;
- White triangles: pBe + λX at 400 GeV;
- Dark circles: also Pb + λX at 400 GeV.

These interesting phenomena may be explained by various models where the strange quarks produced in the interaction become polarized by certain mechanisms. Additional data should help clarify the situation.

§5. Parity Violations in Nucleon-Nucleon Scattering

Parity violations in nucleon-nucleon scattering are expected from the standard model of weak interactions as an interference effect between a strong amplitude and a weak one.

The last in a series of experiments to search for parity violation in polarized proton scattering at 6 GeV/c became available. Two independent detector systems (ionization chambers and scintillation counters) were used to perform a transmission experiment. The hadronic parity violating asymmetry $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where $\sigma_+(\sigma_-)$ is the total cross section for positive (negative) helicity protons on a water target, was measured. The result for the longitudinal asymmetry is $A_L = (2.65 \pm 0.60 \pm 0.36) \times 10^{-6}$. The first error is statistical and the second is an estimate of systematic uncertain-
ties. This result is much larger than predictions based on meson-exchange calculations, but is consistent with a calculation that considers the effects of parity nonconservation at the quark level.

A search for parity nonconservation in the scattering of 1.5-GeV/c (800-MeV) polarized protons from an unpolarized water target has been made. The result for the longitudinal asymmetry is \( A_L = (1.7 \pm 3.3 \pm 1.4) \times 10^{-7} \), where the second uncertainty is an estimate of systematic effects. This result is much smaller than the 6-GeV/c result. A rapid decrease in the magnitude of \( A_L \) between 6 and 1.5 GeV/c is consistent with the trend of the quark-level calculation, although its validity is quoted above 5 GeV/c. This result is consistent with the expectation from meson-exchange calculations.

§6. Future Experiments on Spin Physics at High Energies

Protons from a polarized ion source have been accelerated to 16.5 GeV in the AGS and extracted. The intensity is \( 10^{10} \) protons/pulse and the polarization is 40%. The AGS is expected to produce polarized protons up to 22 GeV at an intensity of \( 2 \times 10^{10} \) protons/pulse and a polarization of 50%.

The CERN experiment UA-6 proposes to use the stored, unpolarized proton and antiproton beams in collision with an unpolarized and a polarized hydrogen gas jet target. A prototype of the polarized hydrogen gas jet target has successfully given \( \sim 95\% \) polarized hydrogen atoms with a density of \( \rho = 10^{12} \text{ cm}^{-3} \) over a 1-cm length in the beam direction, with future expectation of \( \rho = 10^{13} \text{ cm}^{-3} \). The apparatus of UA-6 has been designed to study the various inclusive reactions.

External polarized-proton and -antiproton beams from \( \Lambda^0 \) and \( \bar{\Lambda}^0 \) decay respectively are being built at Fermilab. The beam line will have a momentum of up to 200 GeV/c and provide \( 2 \times 10^7 \) proton/pulse at a polarization of 50%. The first-round experimental program includes measurements of difference between total cross section for antiparallel and parallel spin states for \( pp \) and \( \bar{p}p \) scattering, \( p^+p + \Lambda^0X \) and \( p^+p + \pi^0X \) at large \( p_L \), and \( p^+p + \pi^\pm X \) at large \( x \).
§5. Nucleon-Nucleon Scattering at Intermediate Energies and Present Status of Dibaryon Resonances

7.1. Introduction

Most of the experimental results in nucleon-nucleon scattering at intermediate energies are related to "resonant-like" structures. Here we will discuss the nucleon-nucleon scattering which impacts on the structures.

For nearly one decade, an extensive search for dibaryon resonances in the various reactions in the \( \text{NN}, \pi d, \gamma d \), and other channels has been made. A summary on this subject has been described earlier\(^{30}\) and here we attempt to update the status of dibaryon resonances. Many structures were found in the \( \text{NN} \) system and they were investigated by means of phase-shift analyses. The results confirmed Breit-Wigner behavior for some of them. Structures observed in the \( \text{NN}, \pi d, \gamma d \) channels are not explained by the standard theories, with the exception of some phenomenological models, and are well explained by adding the dibaryon admixture to theoretical models.

As evidence for the existence of dibaryons grows, it becomes crucial to understand the nature of these resonances. Earlier references to theoretical work (MIT bag model, string model, spring model, \( \pi N N \) and \( \pi N \pi N \) dynamics, Deck model, OPE three-body theory, OBE inelastic-threshold model, coupled-channels method etc.) were discussed in Ref. 2. Recent references are discussed in this paper. One nice way to clarify the nature of resonances is to thoroughly study the isospin-zero channels in the region where there is no \( \Delta \) excitation. Structures were seen in the existing \( \Delta \sigma_\pi(I = 0) \) data, although these are yet to be confirmed. We are expecting various experimental data in this channel in a few years.

We start with discussing structures in the \( \text{NN} \) channel and compare these with structures in other channels (\( \pi d, \gamma d \), etc.).

7.2. Nucleon-Nucleon System

A detailed description on the notation and definition of the spin observables is given in Ref. 2.
7.2.1. I = 1 System

A striking energy dependence has been observed in the difference between the proton-proton total cross sections for pure spin states:

\[ \Delta \sigma_L = (4\pi/k) \text{Im}[\phi_L(0) - \phi_3(0)] = \sigma_{\text{Tot}(+)} - \sigma_{\text{Tot}(\mp)} \]

and

\[ \Delta \sigma_T = -(4\pi/k) \text{Im} \phi_T(0) = \sigma_{\text{Tot}(++)} - \sigma_{\text{Tot}(++)} . \]

In the \( \Delta \sigma_L \) energy dependence, structures responsible to \( R_J \) (singlet) and \( R_{JJ} \) (uncoupled triplet) appear as peaks and dips respectively. On the other hand, in the \( \Delta \sigma_T \) energy dependence, \( R_J \) and \( R_{JJ} \) (coupled triplet) emerge as peaks and dips respectively.

The first remarkable structures observed in the pp system were from \( \Delta \sigma_L \) measurements performed at the Argonne ZGS as shown in Fig. 4. All the presently available data\(^{31}\) are shown in Fig. 5, where one observes systematic differences between the BASQUE data and the rest of the data taken at LAMPF, Argonne ZGS, SIN, and SATURNE II. Figures 6 and 7 show \( \Delta \sigma_T \) data.\(^{33,34}\) In Fig. 7 selected data from Ref. 34 are shown. We observe a narrow peak with 20- to 40-MeV width at \( p_{\text{lab}} = 1.15 \text{ GeV/c} \) (mass, 2.14 GeV). Large energy dependence is also seen in the polarization parameters, \( C_{NK} = (N,N;0,0) \), and \( C_{LL} = (L,L;0,0) \), as reported in Ref. 2.

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Fig. 4. pp total cross sections for pure longitudinal initial spin states.
Various analyses have been carried out using presently available data to clarify the nature of the structure in the proton-proton system. Particularly strong indication of resonances in the $^1D_2$ ($B_1^2(2.14)$) and $^3F_3$ ($B_1^2(2.22)$) states are established in the phase-shift analyses. An attempt was made to test some of the pre-existing phase-shift solutions by comparing the
experimental values of $C_{LL} = (L,L;0,0)$ and $C_{SL} = (S,L;0,0)$ at 1.18 to 2.47 GeV/c$^{39}$ and of $C_{SS} = (S,S;0,0)$ at 487 to 791 MeV$^{40}$ with their predictions. By using the $C_{LL}$ data and the dispersion relations, values of $\Delta \sigma_L$ (inelastic) were calculated.$^{39}$ The results are shown in Fig. 8 and compared with theoretical predictions$^{41}$ which do not include diproton resonances. The $\Delta \sigma_L$ (inel) data were predicted as the contribution from the $^1D_2$ and $^3F_3$ amplitudes.$^{35}$ They were also explained in the Deck model with the dibaryon admixtures.$^{42}$ Existing theoretical models such as $\pi$-exchange or OBE models (not phenomenological models) developed in describing medium- and long-range forces, but not short-range force, break down rapidly with increasing energy. We note that amplitude tests for the dibaryon resonances were proposed.$^{43}$

The $^1D_2$ and $^3F_3$ partial waves in the Argand diagram are shown in Figs. 9 and 10. The polarization transfer parameters $K_{SS}$, $K_{LS}$, $K_{SL}$, and $K_{LL}$ at 597 to 800 MeV were measured.$^{44}$ The data are in satisfactory agreement with pre-existing phase-shift analyses. Recent measurements of the spin correlation parameter $(L,L;0,0)$ in the Coulomb-nuclear interference region$^{45}$ are useful for checking the predictions of phase-shift analyses. Resonance poles with $J^P = 2^+$, $2^-$, and $3^-$ found by $K$-matrix analysis were discussed by several
In an analysis of the three-channel approach by taking the \( \pi d \) channel along with the pp and NA, resonance poles were found in the mass region of \( B_1^2(2.17) \) for \( 2^+ \) and \( B_1^2(2.25) \) for \( 3^- \). It is conceivable that the short-range force is represented by dibaryon resonances. This may imply that the existence of baryon-baryon resonances is in exotic quark configurations.

Fig. 9. Argand diagrams of the \( ^1D_2 \) and \( ^3F_3 \) partial waves based on Hoshizaki's phase shifts (points are in lab momenta, GeV/c).

Fig. 10. Argand diagrams of the \( ^1D_2 \) (a) and \( ^3F_3 \) (b) partial waves based on Arndt's phase shifts (points are in kinetic energy, MeV). The ellipses represent the errors in the real and imaginary parts of the amplitudes for energy-independent solutions. The continuous curves represent the energy-dependent solutions.

We review other structure in the pp system besides the \( ^1D_2 \) and \( ^3F_3 \) states. Other possible resonances include a singlet resonance in \( \Delta \sigma_T \) (see Fig. 6) at 2 GeV/c, \( ^1G_4 \) \( (B_1^2(2.43)) \), and a triplet resonance appearing in \( (k^2/4\pi) \) \( (\Delta\sigma_T - \Delta\sigma_L) \) plot as shown in Fig. 11. We expect that the triplet peak
at 2.0 GeV/c is due to a resonating partial wave $R_{J J} (B_{1}^{2}(2.43))$, since only the $R_{J J}$ term has a positive sign in

$$\Delta \sigma_{T} - \Delta \sigma_{L} = (2J + 1) \text{Im} R_{JJ} - (J + 2) \text{Im} R_{J+1,J} - (J - 1) \text{Im} R_{J-1,J}.$$ 

We note that there is no $^{3}P_{3}$ partial-wave contribution to the polarization data at $\theta_{\text{c.m.}} = 63^\circ$. We see an interesting structure in the plot of $\kappa^{2}P(d\sigma/d\Omega)/\sin \theta_{\text{c.m.}}$ with respect to $p_{\text{lab}}$ as shown in Fig. 12. The quantity is proportional to

$$(2\text{Im}^{3}P_{0} + 3\text{Im}^{3}P_{1})(\text{Re}^{3}P_{2}) - (2\text{Re}^{3}P_{0} + 3\text{Re}^{3}P_{1}) (\text{Im}^{3}P_{2})$$

if higher partial waves are neglected.

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**Fig. 11.** Triplet structure at 2.0 GeV/c; the dotted curve is deduced from $\Delta \sigma_{L}$ data.

**Fig. 12.** Energy dependence of $P(d\sigma/d\Omega)$ at $\theta_{\text{c.m.}} = 63^\circ$.

This energy region has been investigated by measuring $C_{LL}$ around $\theta_{\text{c.m.}} = 90^\circ$. Figure 13 shows a plot of $\kappa^{2}(C_{NN} - C_{LL}) d\sigma/d\Omega$ at $\theta_{\text{c.m.}} = 90^\circ$. This quantity contains only coupled spin-triplet partial waves with $J = L \pm 1$ (such as $^{3}P_{0}, ^{3}P_{2}, ^{3}F_{2}, ^{3}F_{4}, \ldots$). The dashed curve shows a rapid energy dependence.
in the quantity \((1 - C_{\text{NN}})\) which consists of singlet partial waves only, and 
the peak position roughly coincides with the \(^1\text{D}_2\) resonance. This leads us to 
note that the structure in the \((C_{\text{NN}} - C_{\text{LL}})\) curve, which is very similar to 
Fig. 12, is therefore also resonant-like. The \(^3\text{P}_0\) or \(^3\text{P}_2\) state, \(B_1^2\) (2.18), 
is probably responsible for the structure. We note that a model of coupled 
nucleon and isobar channels predicts a resonant structure in the \(^3\text{P}_0\) channel 
as well as in the \(^1\text{D}_2\) and \(^3\text{F}_3\) channels.\(^{49}\)

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**Fig. 13.** Experimental values 
of \(f_t = k^2(C_{\text{NN}} - C_{\text{LL}}) \frac{d\sigma}{d\Omega}\) 
at \(90^\circ\) as a function of 
kinetic energy. The dotted 
curve is drawn to guide the 
eye. The dashed curve repres- 
ts a fit by eye to the 
experimental values of \(f_s = k^2(1 - C_{\text{NN}}) \frac{d\sigma}{d\Omega}\) at \(90^\circ\). 
(The statistical errors are 
comparable to those in \(f_t\).)

Do we observe any structure above a mass of \(2500\) MeV? A possible structure 
beyond this mass has been searched for by measuring the parameter \(C_{\text{LL}}\) around 
\(\theta_{\text{c.m.}} = 90^\circ.\)\(^{50}\) Figure 14 shows the energy dependence of \(k^2 C_{\text{LL}} \frac{d\sigma}{d\Omega}\). We now 
attempt to interpret these structures by assuming them to be resonances in 
terms of the quantum numbers. We note that

\[
k^2 C_{\text{LL}} \frac{d\sigma}{d\Omega} = - |\text{spin-singlet terms}|^2 - |\text{coupled triplet}|^2 
+ |\text{uncoupled and coupled triplet}|^2 .
\]

We observe no structure in the behavior of \(k^2 (C_{\text{NN}} - C_{\text{LL}}) \frac{d\sigma}{d\Omega},\) which con- 
tains only coupled triplet terms. Therefore, the second dip seems to be due 
to a spin-singlet term; in a similar way, the first dip is attributed to a 
spin-singlet term, namely, \(^1\text{G}_4\). It is possible to attribute the second dip 
(mass \(= 2900 \pm 100\) MeV) to a \(^1\text{I}_6\) state because the dip around \(\theta_{\text{c.m.}} = 90^\circ\).
disappears at \( \theta_{\text{c.m.}} = 75^\circ \), where \( P_6 (\cos \theta) = 0.50 \). The bump may be due to a \( R_{JJ} (B_1^2 (2.70)) \) state.

7.2.2. \( I = 0 \) System

Measurements of the difference between isoscalar nucleon-nucleon total cross sections for pure longitudinal initial spin states, \( \Delta \sigma_L (p\bar{d}) \), were performed using a polarized proton beam and a polarized deuteron target.\(^{51}\) One can extract \( \Delta \sigma_L (I = 0) \) data using both \( \Delta \sigma_L (p\bar{d}) \) and \( \Delta \sigma_L (p\bar{p}) \) as shown in Fig. 15. A significant structure is observed around 1.5 GeV/c. From the dispersion analysis of a forward \( I = 0 \) scattering amplitude using the data on \( \Delta \sigma_L (I = 0) \), Grein and Kroll\(^{52}\) showed that the Argand plot of the amplitude has a resonance-like behavior around 1.5 GeV/c.

![Graph](image1)

Fig. 15. \( \Delta \sigma_L (I = 0) \) together with \( \Delta \sigma_L (I = 1) \).

The polarization parameters of the pn elastic scattering were measured at KEK covering beam momenta from 1.30 to 1.82 GeV/c.\(^{53}\) The data are consistent with earlier predictions of the resonant-like behavior in singlet state \( {}^1F_3 \) (2190).\(^{54}\) Measurements of many other parameters are obviously needed for the \( I = 0 \) phase-shift analyses.
An extensive study on the $I = 0$ system is being undertaken at LAMPF (Los Alamos) using polarized neutron beams. A longitudinally polarized neutron beam is produced at forward angles when a longitudinally polarized proton beam strikes a deuteron target. In the energy interval of 500 to 800 MeV polarization value is $\sim 50\%$. The measurements include n-p elastic-scattering observables $C_{SS}$, $C_{LS}$, $C_{LL}$ etc. of a wide angular range at energies of 500, 650, and 800 MeV. Preliminary data show that predictions from presently available np phase-shift solutions are rather good. The total cross section measurements with spin will also be performed. We expect the experimental results will clarify the structure in $I = 0$ system.

We note that the np total cross-section data show no evidence for narrow resonances in a mass range below 2.23 GeV.

7.2.3. NN + N$\pi$

For lab momenta between 1 and 2 GeV/c, several sets of NN + N$\pi$ data are available. The reaction cross sections for $pp + p\pi^+$, $p\pi^-\pi^0$ (Ref. 58), and np + p$\pi^-$ (Ref. 59) are shown in Fig. 16 where the Deck model predictions with and without dibaryon admixture $^3F_3 (\beta_1^2 (2, 22))$ are also shown.

The inelastic cross sections in longitudinal spin states, $\Delta\sigma_{L\text{inel}}$, are discussed in Section 7.2.1.

Several depolarization parameters for the reaction $p^+p + p^+\pi n$ became recently available. It will be interesting to interpret the results together with the $\Delta\sigma_{L\text{inel}}$ data and to see if the effect of the $^3F_3$ dibaryon resonances can be detected.

Fig. 16. Cross sections for $pp + N\pi\pi$ vs. $p_L$. The solid lines represent the Deck model predictions and the dashed ones the Deck model with dibaryon admixture.
7.2.4. Conclusions on $I = 0$ and $I = 1$ Resonances in the Nucleon-Nucleon System

Candidates for dibaryon resonances that can couple to nucleon-nucleon systems are summarized in Table I.

<table>
<thead>
<tr>
<th>Candidates of the Dibaryon Resonances</th>
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<tbody>
<tr>
<td>(1) $I = 0$ Isospin State</td>
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<tr>
<td>$E_1^2(1.24)$</td>
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<tr>
<td>Mass, GeV</td>
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<td>Width, MeV</td>
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<tr>
<td>Quantum State</td>
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<tr>
<td>Note</td>
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7.3. Dibaryon Resonances in γd Scattering Experiment

The measured $γd + pnp^-$ cross section shows a rapid variation around a photon energy $k = 390$ MeV as shown in Fig. 17. The peak has been interpreted by the existence of a dibaryon resonance at a mass of 2.23 GeV/c² with a width of 40 MeV/c². This observation is consistent with the existence of $^3F_3$ ($B_1^2(2.22)$) resonant state discussed above.

Fig. 17. Cross section for $γd + pnp^-$ vs. $Eγ$. The dotted curve is the prediction of the model (Ref. 61). The solid curves includes second-order scattering terms.
Earlier a dibaryon resonance (mass of 2380) has been suggested by interpreting the result of $\gamma d + p^+ n$. However, the prediction by a model used to interpret the data has recently been experimentally tested, as shown in Fig. 18, and it seems necessary to repeat the analysis using the new information.

Fig. 18.
\[ \gamma d^+ + pn \text{ at } E_Y = 550 \text{ MeV} \]
\[ (\sqrt{s} = 280 \text{ MeV}). \]

7.4. Dibaryon Resonances in $\pi d$ Elastic Scattering

7.4.1. Cross-Section Measurements

It has been shown by several authors that there are effects of dinucleon resonances in $d$ elastic scattering. The effects are clearly seen in the angular region of $\theta_{c.m.} > 100^\circ$. We note that the forward region is well described by a Faddeev-type multichannel scattering theory, and the short-range behavior seems to appear at larger angles. Measurements in backward $\pi d$ elastic scattering were carried out at KEK. The data show two bumps at around 670 and 1100 MeV/c, two dips near 630 and 980 MeV/c, and a break at 550 MeV/c (see Fig. 19). The results of a phenomenological fit is consistent with the existence of three dibaryon resonances with masses of 2.362, 2.429, and 2.722 GeV in this energy region.

Fig. 19. $\pi d$ elastic scattering at backward angles.
7.4.2. Tensor Polarization

The tensor polarization $t_{20}$ of $\pi^+d$ elastic scattering has been measured at $T_\pi = 120$ and 138 MeV at SIN as a function of scattering angle.\textsuperscript{67} While at the higher energy a strong oscillatory behavior prevails, a considerable flattening is observed at the lower energy as shown in Fig. 20. The results are interpreted by including three dibaryon resonances, $^1D_2$, $^3F_3$, and $^1G_4$. However, a similar experiment at LAMPF\textsuperscript{68,69} and at TRIUMF\textsuperscript{70} disagrees with the SIN data, although the measurements were at $T_\pi = 142$ MeV. Recently the SIN-ETH measurements were repeated utilizing a new type of polarimeter,\textsuperscript{71} and the results are consistent with the previous measurements.

Fig. 20. Angular distribution of $t_{20}^{\text{lab}}$. White triangles and black circles: data of Ref. 67 at $T_\pi = 138$ and 120 MeV; White circles and triangle: data of Ref. 68 at 142 MeV; Black square: data of Ref. 69 at 142 MeV; admixture of $^1D_2$ and $^1G_4$ dibaryon White square: data of Ref. 70 at 142 MeV. The dotted curve is a guide for the eyes.

7.4.3. Vector Polarization

Evidence for a dibaryon signal has been found in the measurement of the vector polarization $(iT_{11})$ in elastic $\pi d$ scattering covering the $T_\pi = 117$ to 325 MeV in 12 steps, (see Fig. 21).\textsuperscript{72} The striking oscillations observed in the vector polarization are not reproduced by conventional Faddeev amplitudes. The data were interpreted by including at least one of the three proposed $B =$
2 resonances \( \{^1D_2 (B_1^2(2140)), ^3F_3 (B_1^2(2220)), \) and \( ^1G_4 (B_1^2(2430)) \} \) with the result of Faddeev calculations. At the higher energies the general trend of the data favors the admixing of the \( ^1G_4 \) dibaryon resonance.

At KEK the vector polarization for the \( \pi^+d \) elastic scattering was measured at 0.74 and 1.50 GeV/c.\(^73\) The measurements cover a higher energy region than those investigated so far. The results are being interpreted.

Fig. 21. The vector polarization for \( \pi d + \pi d \) (Smith et al., Ref. 72). The dotted curve represents the standard theoretical predictions (Faddeev amplitudes). The solid curve is obtained by the admixture of \( ^1D_2 \) and \( ^1G_4 \) dibaryon resonances to the Faddeev amplitudes.

7.6. \( pp + d^* \) Reaction

Earlier H. Kamo and W. Watari found the effects of dinucleon resonances in the polarization data in \( pp + d^* \) reaction.\(^74\)

Many measurements of the cross section and polarization have been made in the energy range 400 to 1300 MeV.\(^75\) The \( d^* \) system has also been studied with polarized deuterons in the \( pp \) final state.\(^76\) The parameters of \( A_{NN} \) and \( A_{ll} \) for the \( pp + d^* \) reaction were measured at 1.28 and 1.46 GeV/c for the deuteron angles between 2.25° and 7.75° at LAMPF, and the data are being analyzed.\(^77\)

Earlier partial-wave analyses\(^78\) using the global data in this channel contribute significant information about the existence of highly inelastic dibaryon resonances. Measurements of spin-correlation parameter \( A_{NN} \) and polarization parameters\(^79\) at 90° between 500 and 800 MeV are useful to test predictions of the PWA analyses and improve the solutions. The results are included in recent energy-independent PWA analyses which find resonance poles with \( J^P = 2^+ \) and \( 3^- \).\(^47,80\) We note that a satisfactory description of available experimental data (1000 points) for the \( \pi^+d + pp \) process was
obtained using a model including $^3p_1$, $^1D_2$, and $^3F_3$ diproton resonances in the $I = 1$ channel. Our present understanding of the reaction $pp \to \Delta^n$ was discussed by comparing advanced calculations with experimental data.

Polarization measurements for $p^+p \to \Delta^+$ from $T_p = 1.0$ to $2.3$ GeV have been carried out at Saclay. Preliminary results have a peak at $140^\circ$ c.m. around $T_p = 1.9$ GeV (near 2700-MeV mass) as shown in Fig. 22. This is interpreted as a possible candidate for the $q^6$, structure near the energy predicted by the Cloudy Bag Model. In Table I, $B_{12}(2.70)$ with quantum number triplet $R_{JJ}$ is shown.

![Energy dependence of polarization parameter in $pp \to \Delta^+$ at $\theta_{c.m.} = 140^\circ$.](image)

7.7. Structures Revealed in the Nucleon-Nucleon Mass Spectrum

The $dp + (pn)p$ break-up reaction at 3.3-GeV/c deuteron momentum was studied using films from 1-m hydrogen bubble chamber. The effective mass distribution of two nucleons exhibits enhancements at $M_{pn} = 2020$ MeV with $\Gamma = 45 \pm 20$ MeV and 2130 MeV with $\Gamma = 20 \pm 10$ MeV. The $dp + (pn^+)$ + missing mass reaction was also studied. Structures were observed in $nn$ and $nn^+$ invariant mass spectra. The $nn$ system shows mass enhancements at 2.03 and 2.14 GeV. The $nn^+$ mass spectra exhibits enhancement at 2.390 GeV ($\Gamma = 42 \pm 20$) as shown in Figs. 23-25.
Fig. 23. The excitation energy distribution for the "non-spectator" (\(p_s > 350\) MeV/c) sample. The dashed and dotted lines represent the background originating from single and double scattering, respectively. The solid lines refer to the dp + pnp three-body phase space alone, and together with the two Breit-Wigner distributions.

Fig. 24. The two neutrons excitation energy distribution for the sample enriched in "non-spectator" events. The solid and dotted lines refer to the background calculated by using data from the dp + ppp\(\bar{\pi}^+\) reaction and FOOWL program, respectively.

Fig. 25. The "nnp\(+\)" invariant mass distribution for the events with \(p_s > 0.3\) GeV/c and "nnp" system emitted backward in the dp cm. The solid and dotted lines have the same meaning.
These measurements were remeasured by a Tokyo group using the KEK 1-m liquid hydrogen bubble chamber. The chamber was exposed to a beam of deuterons at ten momenta in the range 2.0 - 3.7 GeV/c. The pn and pp effective mass distribution show no structure. A similar attempt was also made by a Kyoto group (counter experiment) at KEK.

7.8 Narrow States in Missing-Mass Spectra

The missing-mass spectra for the reaction $p + ^3\text{He} \rightarrow d + X$ and $^3\text{He} + p \rightarrow d + X$ have been measured at $T_3^\text{He} = 2.7$ GeV and $T_p = 0.925$ GeV respectively at the Saturne National Laboratory (see Fig. 26). There is an indication for a narrow structure at 2.12 GeV. Similar mass and width have been found in the deuteron break-up study. The data also show narrow structures at the following masses:

$$M = 2.240 \pm 0.005 \text{ GeV} \quad (\Gamma_{1/2} = 0.016 \pm 0.003 \text{ GeV}),$$
$$M = 2.192 \pm 0.003 \text{ GeV} \quad (\Gamma_{1/2} = 0.025 \pm 0.006 \text{ GeV}).$$

The results are compared with various theories. It is interesting to note that this mass coincides with $B_1(2.22)$ in the $^3F_3$ state. Further studies in this reaction are underway at Saclay.

Fig. 26. Missing-mass spectra in double differential cross sections measured in the reaction $^3\text{He}(p,d)X$ (laboratory system). Data have been binned into 5-MeV intervals.
Summary

During the past several years, an extensive search for structures, which could be related to the existence of dibaryons, has been made in various reactions. The results are summarized in Table II. The dinucleon resonance has opened a new era in the nucleon-nucleon system and is crucially important for the development of the quark models that require six quarks in a bag although many other interpretations without the quark concept exist.

Structures discovered in various reactions are in general not explained by standard theoretical models without the admixing of resonances. The results of existing proton-proton phase-shift analyses by various authors are in good agreement; resonant-like behavior is found in $^1D_2$ and $^3F_3$ states. The nature of these resonances are considered as:

1) Unconventional resonances (caused by short-range forces); existence of six-quark state dibaryon resonances. Measurements as shown in Fig. 8 clearly demonstrate the need of short-range forces which are represented by dibaryon resonances.

2) Conventional resonances (caused by ordinary medium to long range meson-exchange forces); channel-coupling effects (NN to NA, AA, πD) or other nuclear theoretical techniques.

Since the $I = 0$ channel cannot couple to NA or πD channels, discovery of $I = 0$ resonances below mass 2200 MeV would support the existence of exotic quark states. The study is underway, as described in Section 7.2.2.

In order to determine further whether dibaryon resonances are caused by exotic quark configurations, the following attempts should be made:

1) Spin measurements above the $^3F_3$ resonances to clarify high-mass candidates $B_1^2(2.42)$, $B_1^2(2.70)$, and $B_1^2(2.90)$.

2) Confirmation of the $B_0^2(2.22)$ resonance by utilizing polarized neutron beams.

3) Accurate measurements in those channels discussed above which produced narrow-width resonances, $^1D_2$ ($B_1^2(2.14)$) and $^3F_3$ ($B_1^2(2.22)$).
TABLE II
Summary of Dibaryon Structures Found in Various Reactions

<table>
<thead>
<tr>
<th>NUCLEON-NUCLEON</th>
<th>( I = 1 )</th>
<th>( I = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma d \to pp \pi^- )</td>
<td>( ^3P_0 ) or ( ^3P_2 )</td>
<td>( ^3F_3 )</td>
</tr>
<tr>
<td>( \pi^+d \to pp ) and ( pp \to d\pi^+ )</td>
<td>( ^1S_0 )</td>
<td>( ^3F_3 )</td>
</tr>
<tr>
<td>( dp \to (pn)p )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( dp \to ppp\pi )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^4\text{He} \to (dpp)n )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^3\text{He} \to dX )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MASS (MeV)

2000 2200 2400 2600 2800 3000
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