# Dibaryon resonances

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Experimental data indicating the existence of dibaryon resonances are considered. The results of experiments on nucleon–nucleon scattering $NN \to NN$, $NN \to NN\pi$, deuteron photodisintegration $\gamma d \to np$, $\gamma d \to \pi^0 d$, $\gamma d \to \pi NN$, and pion–deuteron interaction $\pi d \to \pi NN$, $\pi d \to \pi d$, $\pi d \to pp$ are discussed. Particular consideration is given to the nonresonance interpretation of the experimental data.

## INTRODUCTION

During the last seven years in physics at intermediate energies there has been no flagging of interest in the problems of dibaryon resonances (at the Rochester conference in Tokyo in 1978 the designation $B^2$ was adopted for such resonances). The interest exists not only because of the discovery of a new phenomenon in what had appeared to be the so well studied nucleon–nucleon system. The point is that the problem of dibaryon resonances is intimately related to the quark structure of hadrons. One of the most probable solutions to this problem is in the quark–gluon bag model; indeed, it was in the bag model that predictions were made[1,2] of dibaryon resonances with masses greater than 2.1 GeV. More recently[3] there was proposed a dynamical model of bound hadron and quark channels that demonstrated the great importance of bag states for $NN$ interaction dynamics. Bearing in mind that the quark nature of hadron and nuclear structure is now almost beyond doubt, the increasing interest in dibaryon resonances is obvious and justified.

In this review we consider experimental studies that have given indications of the existence of dibaryon resonances. The experimental data are considered in three sections according to the experiments in which they were obtained—in nucleon–nucleon scattering, in deuteron photodisintegration, and in pion–deuteron interactions. In the fourth section, we consider interpretations of the experimental data. At the end, we briefly discuss experimental criteria for distinguishing resonances from pseudoresonances.

Work published mainly up to June 1982 is included in the review. More recent results published during the setting of the paper at the printers are given at the end of the corresponding sections.

## 1. NUCLEON–NUCLEON SCATTERING

### Total cross sections

Before we discuss the manifestation of dibaryon resonances in the total cross sections of nucleon–nucleon scattering, we consider how to express the total cross sections $\sigma$ and the differences $\Delta\sigma_L$ and $\Delta\sigma_T$ between the total cross sections for antiparallel and parallel spin states in terms of helicity and partial-wave amplitudes. In helicity amplitudes

$$\sigma = \frac{1}{2}[\sigma(\rightleftarrows) + \sigma(\rightrightarrows)] = \frac{2\pi}{k}\,\mathrm{Im}\,[\Phi_1(0) + \Phi_3(0)], \quad (1)$$

$$\Delta\sigma_L = \sigma(\rightleftarrows) - \sigma(\rightrightarrows) = \frac{4\pi}{k}\,\mathrm{Im}\,[\Phi_1(0) - \Phi_3(0)], \quad (2)$$

$$\Delta\sigma_T = \sigma(\uparrow\downarrow) - \sigma(\uparrow\uparrow) = \frac{4\pi}{k}\,\mathrm{Im}\,\Phi_2(0), \quad (3)$$

where $k$ are the c.m.s. momenta and $\Phi$ are the helicity amplitudes:

$$\Phi_1 = \langle ++ \mid \Phi \mid ++ \rangle, \quad (4)$$

$$\Phi_2 = \langle ++ \mid \Phi \mid -- \rangle, \quad (5)$$

$$\Phi_3 = \langle +- \mid \Phi \mid +- \rangle. \quad (6)$$

In terms of the partial-wave amplitudes, the expressions for the cross sections are

$$\sigma(\rightleftarrows) = \frac{4\pi}{k^2}\sum_J \mathrm{Im}\,\{(2J+1)R_J + (J+1)R_{J+1,J} + JR_{J-1,J} + 2[J(J+1)]^{1/2}R^J\}, \quad (7)$$

$$\sigma(\rightrightarrows) = \frac{4\pi}{k^2}\sum_J \mathrm{Im}\,\{(2J+1)R_{JJ} + (J+1)R_{J-1,J} + JR_{J+1,J} + 2[J(J+1)]^{1/2}R^J\}, \quad (8)$$

$$\Delta\sigma_L = \frac{4\pi}{k^2}\sum_J \mathrm{Im}\,\{(2J+1)(R_J - R_{JJ}) + R_{J+1,J} - R_{J-1,J} + 4[J(J+1)]^{1/2}R^J\}, \quad (9)$$

$$\Delta\sigma_T = -\frac{4\pi}{k^2}\sum_J \mathrm{Im}\,\{-(2J+1)R_J + (J+1)R_{J+1,J} + JR_{J-1,J} + 2[J(J+1)]^{1/2}R^J\}, \quad (10)$$

where $R_{JJ}$ and $R_{J\pm 1,J}$ are the spin triplet partial-wave amplitudes with $J = L$, odd, and with $J = L \pm 1$, even, respectively; $R^J$ is a mixed term of $L = J \pm 1$ states; $R_J$ is a spin singlet with $J = L$ even.

The clearest indication of effects in the two-proton system was obtained from measurements of the cross-section differences in pure spin states: $\Delta\sigma_L$ (Refs. 4–8) and $\Delta\sigma_T$ (Refs. 6, 9, and 10). Figure 1 shows the results of these measurements. There is a deep minimum at 1.5 GeV/$c$ and a maximum at 1.2 Gev/$c$ in the energy dependence of $\Delta\sigma_L$ and two maxima at 1.2 and 2.0 GeV/$c$ in the energy dependence of $\Delta\sigma_T$. Characteristically, there are no structures in the energy dependence of the spin-averaged total cross sections (Fig. 2). But if one considers, for example, the longitudinal cross sections with parallel and antiparallel spins, one finds structure at 1.5 GeV/$c$ in the energy dependence of the cross section $\sigma(\rightrightarrows)$ but not $\sigma(\rightleftarrows)$. It can be seen from the expressions (7) and (8) that the partial wave which characterizes the parallel cross section and is absent in the antiparallel cross

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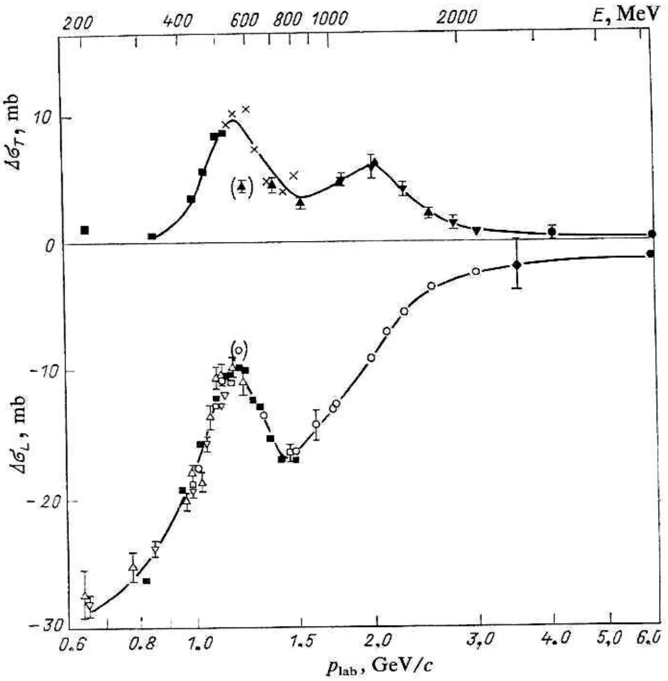


FIG. 1. Differences between the total cross sections in pure spin states.

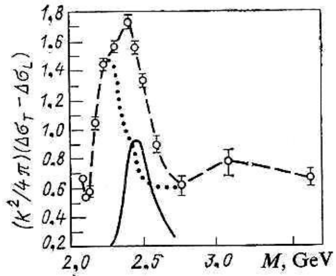


FIG. 3. Triplet structure at mass 2.45 GeV (the broken curve is based on the $\Delta\sigma_L$ data).

section is $R_{JJ}$. Thus, the resonance, if it is responsible for the structure at 1.5 GeV/$c$, can be in the state $^3P_1$, $^3F_3$, etc. Its mass, corresponding to the energy at which the effect in $\Delta\sigma_L$ is observed, is approximately 2.26 Gev, and the width is about 200 MeV. It can be seen from the expression (2) that $\Delta\sigma_L$ has a small background because of the cancellation of the backgrounds Im $\Phi_1(0)$ and Im $\Phi_3(0)$ in contrast to $\sigma$, and therefore the structure is clearly seen in $\Delta\sigma_L(p)$ but not in $\sigma(p)$.

It follows from (9) and (10) that the maximum at 1.2 GeV/$c$ observed in the energy dependence of both $\Delta\sigma_L$ and $\Delta\sigma_T$ is due to a spin singlet. The maximum in $\Delta\sigma_T$ at 2.0 GeV/$c$ could also be due to a spin singlet. Thus, at 1.2 GeV/$c$ (mass 2.15 GeV) and at 2.0 GeV/$c$ (mass 2.45 GeV) the resonance may be in the states $^1S_0$, $^1D_2$, $^1G_4$, etc.

Triplet structures can be expected in the energy dependence of the difference $\Delta\sigma_T - \Delta\sigma_L$. It follows from Fig. 3 that at 2.0 GeV/$c$ (mass 2.45 GeV) there is one further triplet structure in addition to the structure already known at 1.5 GeV/$c$; it is shown by the broken curve in the same figure. For the difference, we have

$$\Delta\sigma_T - \Delta\sigma_L \sim (2J+1)\,\mathrm{Im}\,R_{JJ} - (J+2)\,\mathrm{Im}\,R_{J+1,J} - (J-1)\,\mathrm{Im}\,R_{J-1,J} \quad (11)$$

and, therefore, the resonance can be only in the state $R_{JJ}$, since only the term with $R_{JJ}$ has a positive sign in $\Delta\sigma_T - \Delta\sigma_L$. This resonance may explain the asymmetry of the peak in $\sigma(\rightleftarrows)$ at 1.5 GeV/$c$, as can be seen from Fig. 4.

The value of $\Delta\sigma_L$ was measured with particular care at energies 200–800 MeV in experiments made at the meson factories at Los Alamos,[4] at SIN,[5] and at TRIUMF.[6] The aim of these experiments was to confirm the results[7] of experiments at the Argonne National Laboratory (ANL), which for the first time revealed structures in $\Delta\sigma_L$, and to look for new narrow structures whose existence had been mooted in a number of studies[11,12] (the step of the energy scale in the experiments was 20–40 MeV). The previously discovered structures at 600 MeV (mass 2.15 GeV) and 800 MeV (mass around 2.24 GeV) were confirmed and interpreted as indicating the existence of $^1D_2$ and $^3F_3$ dibaryon resonances. That the observed structures are associated with these partial waves can be seen from Fig. 5, in which the results of measurement of $\Delta\sigma_L$ are compared with the data of a phase-shift analysis,[13] from which the amplitudes $^1D_2$ and $^3F_3$ were eliminated. Another result of these experiments was the absence of narrow structures, though from this it cannot be concluded that between the $^1D_2$ and $^3F_3$ regions there are no resonances, since two or more partial waves can give contributions that cancel each other in $\Delta\sigma_L$.

The value of $\Delta\sigma_L$ was also measured[14] in $pd$ scattering. This made it possible to obtain the difference $\Delta\sigma_L(T=0) = 2\Delta\sigma_L(pd) - 3\Delta\sigma_L(pp)$ between the isoscalar nucleon–nucleon cross sections, though it is here necessary to take into account the Glauber correction and some other effects.[14] The result for $\Delta\sigma_L(T=0)$ is shown in Fig. 6. There is a clear peak around 1.5 GeV/$c$, an indication of an isoscalar dibaryon resonance. It should be noted that in the same region of momenta the nature of the energy dependence of the total cross sections of $np$ scattering is observed to

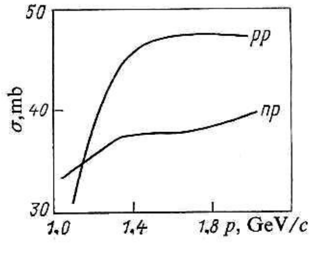


FIG. 2. Total cross sections of the $pp$ and $np$ interactions.

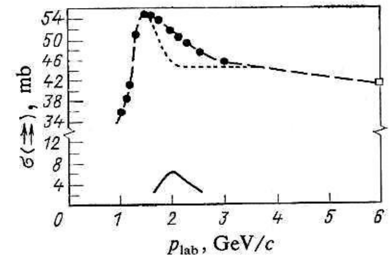


FIG. 4. Decomposition of $\sigma(\rightrightarrows)$ (with peaks at 1.5 and 2 GeV/$c$).

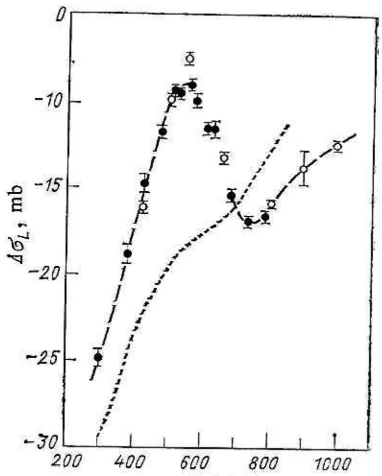


FIG. 5. Results of measurement of $\Delta\sigma_L$ in $pp$ scattering. The dotted curve is based on the data of the phase-shift analysis of Ref. 13 without allowance for the $^1D_2$ and $^3F_3$ states.

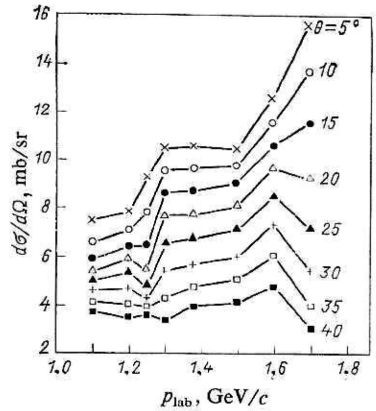


FIG. 7. Energy dependence of the differential cross sections of $np$ forward scattering at different angles $\theta$.

change—there is a shoulder around 1.4 GeV/$c$ (Ref. 15; see Fig. 2) and structure in the energy dependence of the diffraction peak for forward $np$ scattering[16] (Fig. 7).

In 1982, the results were published[17] of an experiment looking for resonance structures in the $np$ total cross section. In the meson factory at Los Alamos the total $np$ scattering cross section was measured in the interval from 40 to 770 Mev (corresponding to masses from 1.90 to 2.23 GeV). The experiment was made using the time-of-flight method. The high energy resolution ($\Delta M = 0.0014$ GeV at $M = 2.11$ GeV) also made it possible to look for narrow resonances. The result of this work was that no narrow structures in the $np$ total scattering cross section were found. The shoulder in the energy dependence of the cross section at momenta 1.4–1.6 GeV/$c$ (see Fig. 2), which has long been known, can be interpreted[18] as a manifestation of a $^3F_3$ dibaryon resonance. No anomalies were noted in the total cross section of the $NN$ interaction in the state with $T = 0$ obtained from this and other experiments. This indicates an absence of resonances in the system of two nucleons with $T = 0$.

### Elastic cross section and charge exchange

The elastic cross section can be expressed in terms of partial-wave amplitudes as follows:

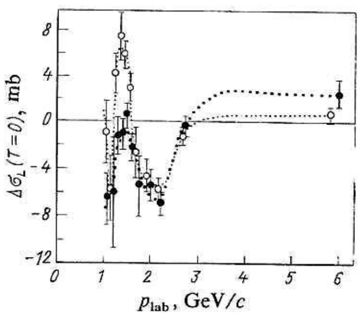


FIG. 6. Results of measurement of $\Delta\sigma_L(T=0)$. The black circles represent the final result, the open circles the preliminary result.

$$\sigma_{\text{упр}} = \frac{2\pi}{k^2} \sum_J (2J+1)\{|R_{JJ}|^2 + |R_{J+1,J}|^2 + |R_{J-1,J}|^2 + |R^J|^2 + |R_J|^2\}. \quad (12)$$

In the energy dependence of the total cross section of elastic $pp$ scattering there is a maximum at 1.5 GeV/$c$ (Ref. 19; Fig. 8). This maximum agrees with the assumption of $^3F_3$ resonance for the elasticity parameter $x = \Gamma_{el}/\Gamma = 0.15$–$0.25$ estimated from the data on $\Delta\sigma_L$.

It is known that the ratio of the real and imaginary parts of the amplitude of forward elastic $pp$ scattering changes sign near 1.4 GeV/$c$ (Ref. 20; Fig. 9). The rapid decrease of this ratio with the change of sign is typical of a real amplitude near resonance, provided there is no weakening by background effects. The data in Fig. 9 can be well explained by the existence of $^1D_2$ and $^3F_3$ resonances.

An experiment[21] made at the Leningrad Institute of Nuclear Physics determined the slope parameter of the diffraction peak of elastic $pp$ scattering at small angles at seven energies from 650 to 1000 Mev. It is known that in the energy dependence of the slope parameter in elastic $\pi^\pm p$ and $K^-p$ scattering a structure is observed—the slope parameter increases at the energies corresponding to the positions of the known resonances. It was suggested that if dibaryon resonances exist, there could be an analogous structure for elastic $pp$ scattering. The results of the experiment are shown in Fig. 10. In the energy dependence of the slope parameter of the diffraction peak there is no structure that could be associated with a manifestation of dibaryon resonances. Analysis of

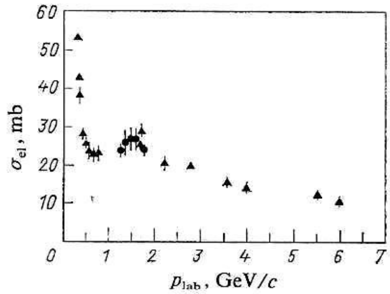


FIG. 8. Total cross section of elastic $pp$ scattering.

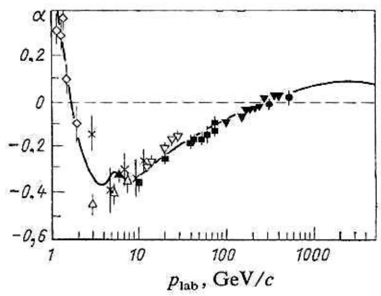


FIG. 9. Ratio of the real part of the *pp* scattering amplitude to the imaginary part at $|t| = 0$.

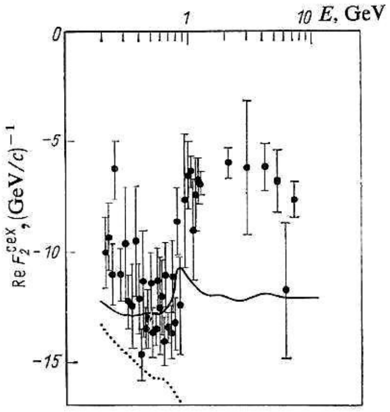


FIG. 11. Real part of the amplitude $F_2^{cex}(u=0)$ of the *np* charge-exchange process; the continuous curve was the point of departure for the dispersion calculations of Refs. 25 and 26; the dotted curve gives the predictions of the phase-shift analysis of Ref. 13.

the results of this experiment in the framework of the model of Ref. 22 in conjunction with data at higher energies[23] yielded a bound on the elasticity parameter of the $^3F_3$ resonance: $x \leqslant 0.1$.

Analysis[24] of the differential cross sections of *np* scattering for angles near 180° in the center-of-mass system (Fig. 11) at energies from 0.2 to 7.1 GeV led to the determination of Re $F_2^{cex}(u=0)$, where $F_2(0)$ is the amplitude corresponding to $\Phi(0)$ [see Eq. (5)] in the laboratory system. It can be seen that Re $F_2^{cex}(0)$ is large, in qualitative agreement with the presence of large spin effects, which are found in quasielastic *np* charge exchange on the deuteron. The most important thing is that at energies 0.7–1.0 GeV, where Re $F_2^{pp}(0)$ changes little, there is a positive jump of Re $F_2^{cex}(0)$ and, accordingly, a negative jump of the real part of the isoscalar amplitude Re $F_2(T=0) = \text{Re}\, F_2^{pp} - 2\text{Re}\, F_2^{cex}$. Such a behavior of Re $F_2(T=0)$ can be attributed to the existence of an isoscalar dibaryon resonance.

### Polarization

Figure 12 shows data on the measurement of the polarization in *pp* scattering.[27] There is a structure near 1.5 GeV/c but no indication of a peak at 1.2 GeV/c; this was to be expected, since the polarization does not include a singlet term. The resonance effect can be studied[28] on the basis of the energy dependence of the coefficients in the expansions of the differential cross sections and the polarization with respect to Legendre polynomials:

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \sum_{n=0}^{\infty} a_n P_n(\cos\theta), \qquad (13)$$

$$\frac{p\, d\sigma}{d\Omega} = \frac{1}{k^2} \sum_{n=2}^{\infty} b_n P_n(\cos\theta) \qquad (14)$$

(because of symmetry, $n$ must be even).

It was found that all coefficients $a_n$ and $b_n$ with $n \geqslant 8$ disappear completely in the region of momenta 1–2 GeV/c and therefore waves with $J > 4$ and $L < 4$ can be ignored. Therefore, the possible $R_{JJ}$ resonance at 1.5 GeV/c is $^3P_1$ or $^3F_3$. Analysis[28] of the values of $b_n$ (Fig. 13) showed that in the energy dependence of all the coefficients there is structure in the region 1.5–1.6 GeV/c. But a resonance in the state $^3P_1$ cannot explain the increase with the energy of the coefficient $b_6$, since this coefficient does not include a contribution of the $P_1$ wave:

$$b_6 = 1.8\,(\text{Im}\,{}^3F_3 \cdot \text{Re}\,{}^3F_4 - \text{Re}\,{}^3F_3 \cdot \text{Im}\,{}^3F_4) + \text{члены без }{}^3F_3 \text{ и } {}^3P_1. \qquad (15)$$

Detailed analysis[28] of the coefficients $b_2$, $b_4$, $b_6$ showed that their energy dependence can be explained by the behavior of $^3F_3$, which agrees with the Breit–Wigner formula.

New information is provided by analysis of the energy dependence of the polarization at the angle $\theta_{cms} = 63°$,[19] since at this angle the state $^3F_3$ does not contribute to the polarization. Figure 14 shows $k^2 p(d\sigma/d\Omega)/\sin 2\theta_{cms}$ as a function of $p_{lab}$. This quantity is proportional to

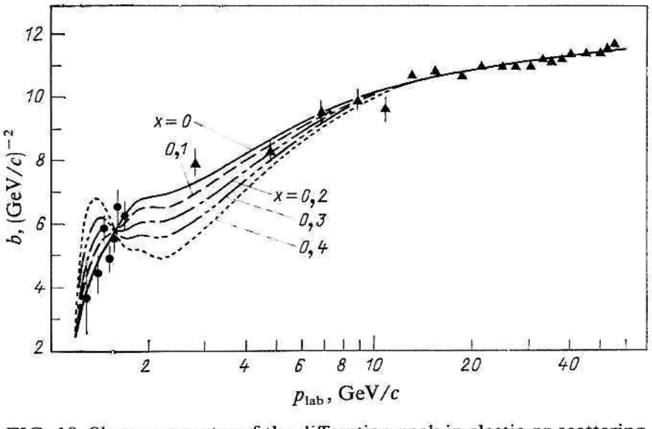


FIG. 10. Slope parameter of the diffraction peak in elastic *pp* scattering. The black circles and black triangles are the experimental points of Refs. 21 and 23, respectively; the curves correspond to the description of the data in accordance with the model of Ref. 22 for different values of the elasticity parameter for the $^3F_3$ resonance.

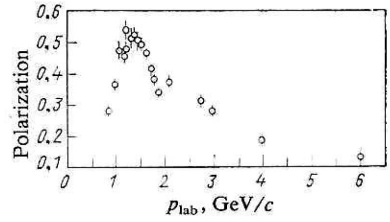


FIG. 12. Polarization for $0.1 < |t| \leqslant 0.2$.

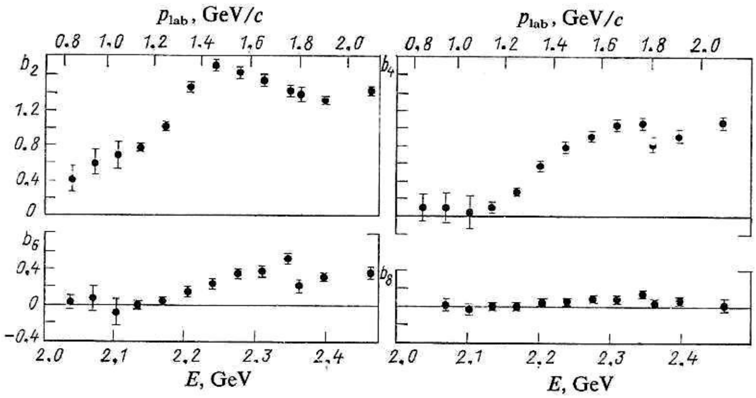


FIG. 13. Legendre coefficients in the expansion of the polarization data.

$$(2\ \mathrm{Im}\ {}^3P_0 + 3\ \mathrm{Im}\ {}^3P_1)\ \mathrm{Re}\ {}^3P_2 - (2\mathrm{Re}\ {}^3P_0 + 3\ \mathrm{Re}\ {}^3P_1)\ \mathrm{Im}\ {}^3P_2, \quad (16)$$

if the contribution of the higher partial waves is ignored. This means that the observed maximum at 1.3 GeV/$c$ could be a consequence of a resonance in the states ${}^3P_{0,1,2}$.

In 1981, the analyzing power for elastic $pp$ scattering at 17° in the laboratory system was measured at the meson factory at Los Alamos in the energy interval 318–800 MeV.[29] No structures at the level of accuracy 0.5% were found. This is not surprising, since the partial wave ${}^1D_2$ does not contribute to the analyzing power, and structure in the ${}^3F_3$ state should be observed at higher energies.

### Spin–spin correlations

The spin–spin correlation parameter $C_{LL}(\theta_{cms})$ in $pp$ scattering was measured at the Argonne National Laboratory.[30] The results of measurement at 90° and 74° in the center-of-mass system are shown in Fig. 15. At 90° there is a pronounced minimum at 1.2 GeV/$c$, a rapid decrease around 1.5 GeV/$c$, and a structure near 2.0 GeV/$c$ not present at 74°.

If in the expression

$$k^2 C_{LL}\left(\frac{d\sigma}{d\Omega}\right)\Big|_{90^\circ} = 0.77\,|{}^3F_3|^2 + \mathrm{Im}\ A \cdot \mathrm{Im}\ {}^3F_3 + \mathrm{Re}\ A \cdot \mathrm{Re}\ {}^3F_3 + \text{члены без } {}^3F_3. \quad (17)$$

(where $A$ is the sum of the other partial waves) we substitute the parameters of the ${}^3F_3$ resonance and the estimate of these other partial waves from the results of phase-shift analysis, it is possible to obtain a rapid decrease of the measured quantity, as indicated in Fig. 15 by the continuous curve.

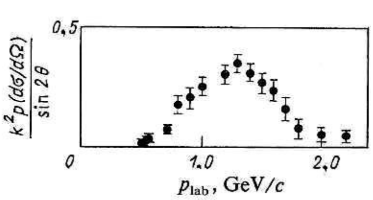


FIG. 14. Energy dependence of the polarization at $\theta_{cms} = 63°$.

Analysis of the energy dependence of $\Delta\sigma_T$ revealed that the resonancelike structure at 2.0 GeV/$c$ could be due to a singlet state. The contribution of the singlet state to $C_{LL}$ is

$$k^2 C_{LL}\left(\frac{d\sigma}{d\Omega}\right) = -\,|{}^1S_0 + 5\,{}^1P_2 P_2(\cos\theta) + 9\,{}^1G_4 P_4(\cos\theta) + 13 P_6(\cos\theta)\,{}^1I_6 + \dots|^2 + \dots \quad (18)$$

For $\theta_{cms} = 74°$, $P_4 = 0$ and the ${}^1G_4$ contribution must vanish. In fact, it follows from Fig. 15 that the structure at 2.0 GeV/$c$ observed for $\theta_{cms} = 90°$ disappears at $\theta_{cms} = 74°$, and this indicates that the possible resonance state at 2.0 GeV/$c$ is ${}^1G_4$.

With regard to the sharp minimum at 1.2 GeV/$c$, this does not contradict resonancelike behavior of the state ${}^1D_2$.

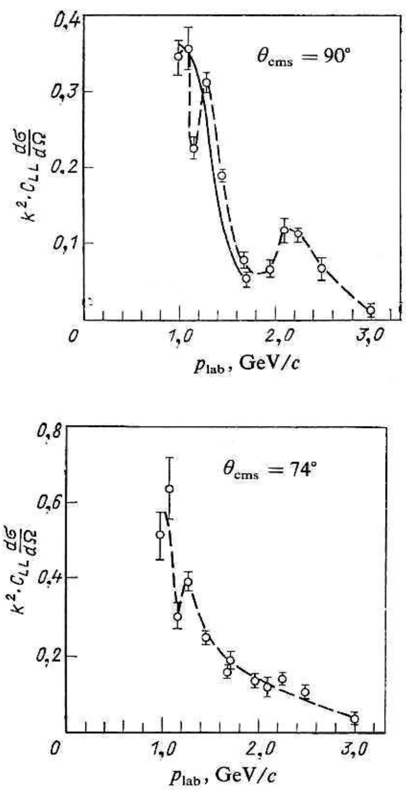


FIG. 15. The values of $k^2 C_{LL}(d\sigma/d\Omega)$ for different angles.

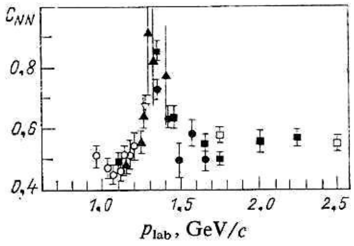


FIG. 16. Spin–spin correlation parameter $C_{NN}$ at $\theta_{cms} = 90°$.

Measurements of the spin–spin correlation parameter $C_{NN}$ were made at Gatchina,[31] at Argonne,[32] at SIN,[33] and at Los Alamos.[34] The results at $\theta_{cms} = 90°$ are of the greatest interest, since at this angle the parameter $C_{NN}$ bears a simple relation to the cross sections in the triplet and singlet states.

Figure 16 gives the results of these and earlier measurements.[16] There is a peak at 1.3 GeV/$c$, from which it follows that the triplet interaction dominates strongly over the single interaction in the two-proton system.

In connection with the measurements of the parameter $C_{NN}$, we must consider Refs. 31 and 35, which analyzed the spin-correlation measurements at $\theta = 90°$ in the center-of-mass system. At this angle, the analysis of $pp$ scattering is simplified, since the number of independent amplitudes is reduced to three by symmetry and the identity of the particles.

The moduli of these amplitudes are uniquely related to the observed quantities $d\sigma/dt$, $C_{LL}(90°)$, $C_{NN}(90°)$ and this makes possible the analysis. Indeed, the squares of the matrix elements can be expressed at 90° in the center-of-mass system as follows ($M^{S}_{m_f m_i}$):

$$\frac{1}{2}|M^0|^2 = \frac{d\sigma}{dt}(1 - C_{NN}), \quad (19)$$

$$|M^1_{10}|^2 = \frac{d\sigma}{dt}(C_{NN} - C_{LL}), \quad (20)$$

$$|M^1_{01}|^2 = \frac{d\sigma}{dt}(1 + C_{LL}). \quad (21)$$

Thus, the singlet part of the cross section is proportional to $(1 - C_{NN})$, while the triplet part is proportional to $(1 + C_{NN})$. This means that a maximum in $C_{NN}$ may appear because of either a minimum in the singlet part or a maximum in triplet part. The large value of $C_{NN}(90°)$, i.e., the large triplet-to-singlet ratio, reflects the important part played by spin in nucleon–nucleon dynamics.

On the basis of the expressions (19)–(21) and the results of measurements at 90° of $d\sigma/dt$, $C_{NN}$, and $C_{LL}$ the moduli of the singlet and triplet amplitudes were obtained in Ref. 31 (Fig. 17) and Ref. 35. It is correctly pointed out in Ref. 35 that the minimum in the singlet amplitude and the maximum in the triplet amplitude at 1.2–1.3 GeV/$c$ depend strongly on $d\sigma/dt$ (90°). Therefore, it is necessary to make a careful measurement of the differential cross section around 90° in order to establish whether the observed structures are a reflection of a dibaryon resonance (maximum in the triplet part) or an interference effect (minimum in the singlet part). The observed energy dependence of $C_{NN}$ agrees well with the existence of $^1D_2$ and $^3F_3$ resonances, as follows from phase-

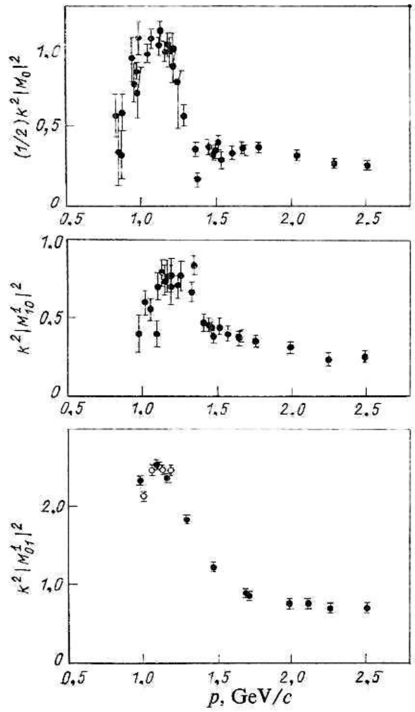


FIG. 17. Matrix elements of elastic $pp$ scattering through 90° in the center-of-mass system.

shift analyses, though it must be recognized that even a small change in the parameters of the $^1D_2$ resonance (of the phase from 1.7 to 0.8° and of the elasticity parameter from 0.707 to 0.67 at 1.34 GeV/$c$) leads, for example, to disappearance of the minimum in $|M^0|^2$. (A nonresonance interpretation of $C_{NN}$ data was discussed in Ref. 36.)

It was pointed out in Ref. 31 that the matrix element $|M^1_{01}|$ contains contributions of all triplet states apart from $^3P_0$, while $|M^1_{10}|$ contains contributions of states with $J = L \pm 1$, i.e., does not depend on the states $^3P_1$ and $^3F_3$. Therefore, the existing maxima in $|M^1_{01}|$ and $|M^1_{10}|$ do not permit the conclusion that there is a large resonance contribution of the $^3P_0$ and $^3P_1$ states, which enter the matrix elements differently.

Results were published in 1982 of an experiment[37] in which the parameter $C_{LL}$ in elastic $pp$ scattering was measured at $\theta_{cms} = 90°$ in the interval of momenta 2.5–5.0 GeV/$c$. These results reveal a definite structure in the energy dependence of $k^2 C_{LL}(d\sigma/d\Omega)$, namely, minima around 2 and 3.5 GeV/$c$ and a maximum at 2.5 GeV/$c$, and also a rapid decrease in the region of 2.75 GeV/$c$. The minimum at 3.5 GeV/$c$ is due to the spin singlet, like the structure discussed earlier at 2.0 GeV/$c$, which can be ascribed to a $^1G_4$ resonance. It follows from Eq. (18) that this minimum at 3.5 GeV/$c$ [$M = (2.9 \pm 0.1)$ GeV] can be regarded as an indication of a $^1I_6$ state, since the minimum disappears at $\theta_{cms} = 75°$, where $P_6(\cos\theta) = 0$. The rapid change in the energy dependence around 2.75 GeV/$c$ is similar to the behavior of $C_{NN}$ observed earlier and also agrees with the indication of a maximum at 2.75 GeV/$c$ in the preliminary data of Ref. 19 on $\Delta\sigma_L$. Structure is also observed in the energy dependence of $k^2(1 + C_{LL})d\varepsilon/d\Omega$, which contains only triplet states, but is absent in the experimental dependence of $k^2(C_{NN} - C_{LL})d\sigma/d\Omega$, which contains only a bound triplet. Therefore, if this is a resonance with mass $M = 2.7 \pm 0.1$ GeV, it is due to the triplet $R_{JJ}$.

### Inelastic reactions

It follows from the small value of the elasticity parameter of the dibaryon resonances that their decay must proceed mainly through other (inelastic) channels: $NN \to NN\pi$, $\pi d$, etc. Therefore, dibaryons can be expected to make an appreciable contribution to the production of mesons in nucleon–nucleon collisions. Such a model was considered in Ref. 38, where, in particular, it was shown that because of the large inelasticity the dibaryon resonances could be manifested in the energy dependence of the total cross sections of the inelastic channels.

The energy dependence of the $pn \to pp\pi^-$ reaction cross section in the energy interval 500–1000 MeV was measured at the Leningrad Institute of Nuclear Physics.[39] The values obtained for the cross sections are shown in Fig. 18 together with the results of other experiments that measured the cross sections of this reaction and the charge-symmetric reaction $np \to nn\pi^+$. It can be seen from the figure that the experimental data do not agree with the results of the calculation of Ref. 38. It follows from this that if resonances do exist, their parameters differ from the ones given in Ref. 38. Therefore, an estimate was made, within the framework of the model proposed in Ref. 38, of the extent to which the parameters of the resonances must be changed in order to describe the new experimental data. The possibility of describing the experimental data by any combination of the following resonances was considered: one at $M = 2.14$–$2.16$ GeV with width $\Gamma = 50$–$100$ MeV ($2^+$ resonance in the $T = 1$ channel) and two at mass $M = 2.22$–$2.26$ GeV with $\Gamma = 100$–$200$ MeV ($3^-$ resonance in the $T = 1$ channel and $3^+$ resonance in the $T = 0$ channel). It was found that a good description (continuous curve in Fig. 18) is obtained when there are either two resonances $2^+$ and $3^-$ (or $3^+$) with elasticity parameters close to the value obtained from the phase-shift analyses or all three resonances but with much smaller ($x < 0.1$) elasticity parameters.

The measured cross sections make it possible to determine directly the energy dependence of the isoscalar inelastic cross section $\sigma(T=0) = 3(2\sigma_{pn \to pp\pi^-} - \sigma_{pp \to pp\pi^0})$. For the $pp \to pp\pi^0$ reaction, the results of Refs. 40-42 were used. In the energy intervals 665–735 and 735–970 MeV, where direct measurements of this cross section have not been made, and the cross section changes little, interpolated values of the cross sections were used. Figure 19 shows $\sigma(T=0)$ for the proton energies at which the $pn \to pp\pi^-$ reaction was measured in the experiment at the Leningrad Institute of Nuclear Physics. It can be seen from the figure that the isoscalar cross section is equal to zero up to the energy 750 MeV.

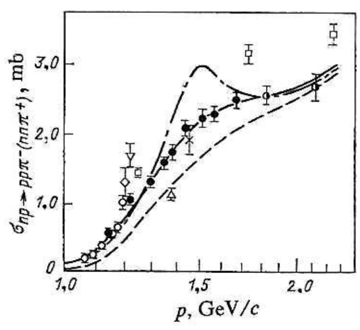


FIG. 18. Total cross sections of the $pn \to pp\pi^-$ and $pn \to nn\pi^+$ reactions. The black circles are the new experimental data of Ref. 39; the chain curve is with allowance for dibaryon resonances; the broken curve (without resonances) is from Ref. 38; the continuous curve represents the best variant of solution from Ref. 39.

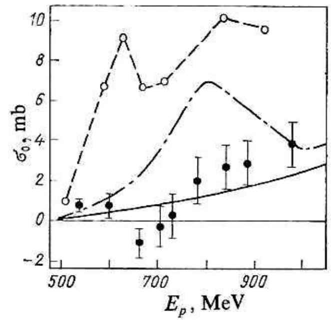


FIG. 19. Isoscalar inelastic cross section. The experimental points are the data of Ref. 39; the continuous curve represents the peripheral model of Ref. 38; the chain curve, the phase-shift analysis of $pn$ scattering[44,45]; the broken curve, the dispersion analysis of Ref. 46.

Resonances in the $T = 0$ channel may be particularly important for solving the problem of dibaryon resonances. The point is that in the $T = 0$ channel it is impossible to have isolated production of the (3,3) isobar, and this therefore eliminates the possibility of attributing dibaryon effects to isobar-production threshold phenomena. Indeed, these threshold effects are usually given[43] as arguments for a nonresonance (nondibaryon) interpretation of the experimental data. It follows from Fig. 19 that if in the $T = 0$ channel in the region of masses 2.12–2.30 GeV there are dibaryon resonances, then their elasticity parameters are small ($x < 0.05$). For comparison, the same figure shows the theoretical dependences of the isoscalar cross sections proposed earlier[44–46]; in them the elasticity parameter of the resonance in the $T = 0$ channel was equal to 0.1–0.2.

The differential cross sections of another inelastic channel, $\uparrow p + p \to p + \pi^+ + n$, were measured at Los Alamos in the meson factory in a kinematically complete experiment.[47] A large difference between the cross sections for different spin directions was found. The asymmetry $A = [\sigma(\uparrow) - \sigma(\uparrow)/\sigma(\uparrow) + \sigma(\uparrow)]$ varies from $-0.4$ to $+0.8$, clearly reflecting the spin dependence seen in the data on the total nucleon–nucleon cross sections.

In a paper presented to a conference at Santa Fe, Umland *et al.*[48] analyzed these data in terms of a peripheral model including exchange of $\pi$ and $\rho$ mesons. This model predicts an asymmetry appreciably less than is measured. The authors therefore included in the model production of $^1D_2$ and $^3F_3$ dibaryon resonances with parameters obtained in the phase-shift analysis of Ref. 49, namely, with the mass of the $2^+$ resonance equal to 2.17 GeV and the mass of the $3^-$

resonance equal to 2.2 GeV. The introduction of the resonances made it possible to describe the experimental data fairly well. An attempt to describe the same results without resonances was made in Ref. 50, in which it was assumed that the mesons are produced without the production of the intermediate isobars $P_{33}(\Delta)$ and $P_{11}(N^*)$. The isobar amplitudes were taken from the unitary model of Refs. 51 and 52. It proved possible to obtain a large value of the asymmetry and at some angles to describe the experimental data.

One would expect the dibaryon resonances to be manifested in the distributions with respect to the effective mass of the two nucleons. Much material has by now been accumulated on the two-nucleon mass distributions in investigations of hadron interactions with nucleons and nuclei at energies of several mega-electron-volts. The most complete discussion of these investigations is in Ref. 53, which contains detailed references to the appropriate studies. The distributions with respect to the effective mass of the two nucleons were obtained in experiments using different methods—bubble chambers,[54–56] spectrometers with spark chambers,[57] etc.; none of these experiments gave any indication of a dibaryon signal, despite a high statistical accuracy of the studies. It is not clear why dibaryon resonances, if they really exist, are not seen in the two-nucleon mass distributions. One can only suppose that in the many-particle splittings—the main ones that come into question—the dibaryon resonances conspire with ordinary baryon resonances, whose production cross sections are large. The large width of the presumed dibaryon resonances favors such a conspiracy, which can also be enhanced by interference of the baryon resonances with the background. The situation here differs little from that which is observed in investigations of baryon resonances in inclusive experiments, in which many resonances established by phase-shift analysis of pion–nucleon scattering do not appear in the effective-mass distributions for the reasons indicated earlier.

### Dispersion analysis

A dispersion analysis of all three amplitudes $F_1$, $F_2$, $F_3$ of $pp$ forward scattering was made by Grein and Kroll[25] in 1978. These amplitudes are related to the cross section as follows:

$$\sigma = \frac{4\pi}{p} \operatorname{Im} F_1, \tag{22}$$

$$\Delta\sigma_T = -\frac{4\pi}{p} \operatorname{Im} F_2, \tag{23}$$

$$\Delta\sigma_L = \frac{4\pi}{p} \operatorname{Im} F_3, \tag{24}$$

where $p$ is the momentum in the laboratory system.

The real parts of the amplitudes were obtained by using data on the cross sections in pure spin states, the results of phase-shift analysis at energies below the thresholds of the inelastic channels, and dispersion relations.

A new dispersion analysis of the $pp$ amplitudes was made by the same authors[26] in 1982 using the new experimental results obtained at SIN, TRIUMF, Los Alamos, and Saclay. They also used ANL data on $\Delta\sigma_L(pd)$ and the differential cross sections of $pn$ forward charge exchange, this making it possible to obtain a set of $pp$ and $pn$ amplitudes. It follows from the results of this analysis that there could be $T=1$ resonances, $3^-$ (2.31 GeV) and $4^+$ (2.39 GeV), and also a $T=0$ resonance with mass 2.25 GeV and anomalous parity ($1^+, 3^+, \ldots$). The energy dependence of the partial wave $^1D_2$ could be easily interpreted as a threshold effect. For completeness, it may be noted that an isoscalar resonance was first reported by the same authors in Ref. 46.

### Phase-shift analysis

Several groups have made phase-shift analyses of $pp$ scattering in the region of the masses of the presumed dibaryon resonances. It should be noted that in the inelastic region, i.e., at energies above 300 MeV, the phase-shift analysis is a difficult problem, since in the absence of a complete set of experiments it is ambiguous. However, with regard to the dibaryon resonances, the conclusions of the majority of the phase-shift analyses are in agreement.

Hoshizaki[49] made a phase-shift analysis in the interval of momenta 1.1–3.0 GeV/$c$, using all the expeirmental information available up to 1978 and the real parts of the forward scattering amplitudes from the dispersion analysis of Grein and Kroll. The Argand diagrams give a clear indication of the existence of $^1D_2$ and $^3F_3$ resonances. Two years later, Hoshizaki[58] published the results of a new phase-shift analysis at 1.1, 1.275, 1.45, and 1.7 GeV/$c$, including data obtained in the meson factories at SIN and Los Alamos and using the synchrocyclotron at the Leningrad Institute of Nuclear Physics. The resonancelike behavior in the states $^1D_2$ and $^3F_3$ was confirmed, and, in addition, an indication was found of a structure in the energy dependence of the absorption parameter in the $^3P_2$ wave at momentum around 1.7 GeV/$c$ and of the possibility of a resonance in the $^3P$ states at 1.3 GeV/$c$.

Arndt and VerWest[13] made a phase-shift analysis in the energy interval 0–850 MeV (energy independent) and 0–900 MeV (energy dependent). The results of this analysis (Fig. 20) also confirm the existence of the $^1D_2$ and $^3F_3$ resonances.

At Saclay, a phase-shift analysis was made[59] up to 750 MeV. In the region of high energies (above 550 MeV) two solutions were obtained, one of them in good agreement with

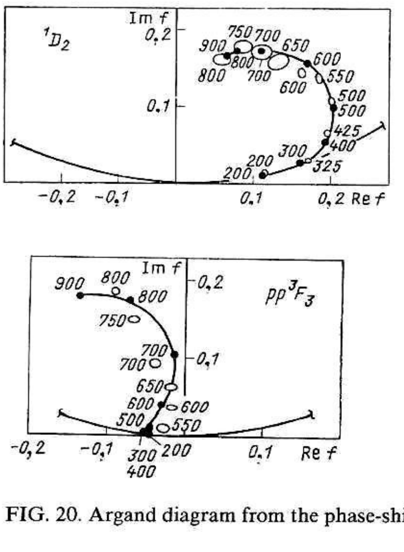


FIG. 20. Argand diagram from the phase-shift analysis of Ref. 13.

the results of Hoshizaki. It should be noted that this analysis was made at energies less than the resonance values for the $^3F_3$ state.

Two more Japanese groups[60,61] later published results of phase-shift analyses. These led to results close to those obtained by Hoshizaki and by Arndt and VerWet. It is important to emphasize that in one of these analyses[60] the forward scattering amplitudes from the dispersion analysis of Grein and Kroll were not used as input data. However, this did not significantly influence the final results.

In the phase-shift analysis made by Kazarinov's group[62] at Dubna there is a large inelasticity in the $^3P_0$ state this being evidence in support of a $^3P_0$ dibaryon resonance at 650 MeV.

A phase-shift analysis of *pp* scattering up to 831 Mev was made by Bugg's group.[63] The Argand diagrams for the $^3F_3$ and $^1D_2$ states and, less definitely, for the $^3P_2$ wave exhibit resonancelike behavior. It should be noted that in this analysis absorptions were established in some partial waves; in particular, because of this there is no absorption in the $^3P_0$ wave.

A phase-shift analysis in the energy interval 0.58–1.0 GeV was recently completed at the Leningrad Institute of Nuclear Physics.[64] The distinctive feature of this analysis is the use of a new method of selecting solutions, based on investigation of the pattern of the zeros of the amplitudes and the choice of the solutions whose zeros move (with increasing energy) along certain trajectories.[65] The results of the analysis confirm existence of resonance loops in the Argand diagrams for the $^1D_2$ and $^3F_3$ states. In addition, resonancelike behavior was detected in the $^3P_2$ state and, possibly, the $^3P_0$ state (Fig. 21). Similar conclusions about resonance behavior in the $^3P$ waves followed, as was shown, from analysis of the energy dependences of $C_{NN} - C_{LL}$ at 90° and the polarization at 63°.

A phase-shift analysis of *np* scattering at 1.1, 1.2, 1.25, 1.3, 1.38, 1.5, 1.6, and 1.7 GeV/*c* was made by a Japanese group.[45] In this analysis, the parameters of the $T = 1$ amplitudes were fixed using the results of phase-shift analysis of *pp* scattering. Another important restriction was that the newly obtained solutions must be smooth continuations of the solutions of the phase-shift analysis of *np* scattering at lower

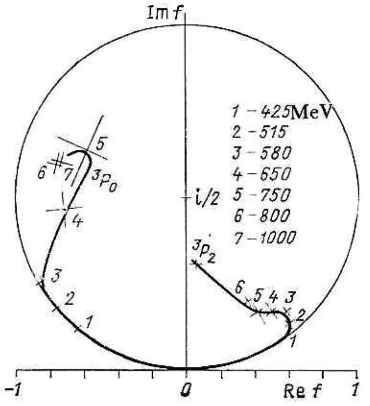


FIG. 21. Argand diagram for the Leningrad phase-shift analysis.[64]

energies. The analysis indicated the existence of a $^1F_3$ dibaryon resonance in the $T = 0$ channel (the parameters of the resonance are $M = 2.19$ GeV, $\Gamma = 50$ MeV, $x = 0.12$). However, the main experimental results providing the basis of the conclusion that there is an isoscalar resonance, namely, the inelastic cross section (see Fig. 19) in the $T = 0$ channel[38] and $\Delta\sigma_L(T = 0)$ (Ref. 14), underwent very appreciable changes. Obviously, a new phase-shift analysis of *np* scattering is needed.

### *K*-matrix analysis

In 1980–1981 there were published three papers[66–68] in which the *K*-matrix method was used to determine the poles in the scattering amplitude. In principle, this can establish whether the observed resonance phenomena are due to the opening of inelastic channels. In such work, one generally uses phase shifts obtained in phase-shift analyses of *pp* scattering.

The *K*-matrix method for the solution of the problems under discussion is presented in greatest detail in Ref. 68, in which a *K*-matrix analysis of the amplitudes of *pp* scattering was made for the states with the quantum numbers $3^-$ and $2^+$. For the $3^-$ state the *pp* and $N\Delta$ channels were taken into account; for the $2^+$ state, the *pp*, $N\Delta$, and $\pi d$ channels. It was found that the *K* matrix has poles in both channels, indicating the presence in them of dibaryon resonances. Since a dibaryon state was found in all the investigated systems (*pp*, $N\Delta$, and $\pi d$), it was concluded that the pole of the *K* matrix is not associated with the $n\Delta^{++}$ inelastic channel.

In Ref. 66, analytic continuation of the *T* matrix to the unphysical sheets also revealed poles near the $N\Delta$ bifurcation point. The parameters of the $^1D_2$ and $^3F_3$ resonances obtained in this work are close to the ones discussed earlier.

## 2. $\gamma d$ REACTIONS

### Deuteron photodisintegration

In Ref. 69, published in 1977, the results were given of measurement of the polarization of the recoil protons from deuteron photodisintegration. At photon energy in the region of 500 MeV a resonance structure was found in the energy dependence of the polarization of the recoil protons at 90° in the center-of-mass system and also a large value of the polarization itself. These effects were explained[70] by assuming the existence of a dibaryon resonance.

To test this hypothesis and to determine the parameters of the resonance, a partial-wave analysis[71] was made during 1978–1979 of the deuteron photodisintegration reaction. The analysis used the data then available on the differential cross sections[72] and the polarization of the recoil protons.[69] The interval 350–700 MeV of photon energies, corresponding to masses 2.20–2.48 GeV, was considered. The aim of the analysis was to add dibaryon resonances to the nonresonance part of the amplitude and to determine their number and parameters. The nonresonance part of the $\gamma d \to pn$ amplitude was calculated in accordance with the model of Ogawa *et al.*[73] Since the number of dibaryon resonances was not known in advance, a minimal number of resonances was

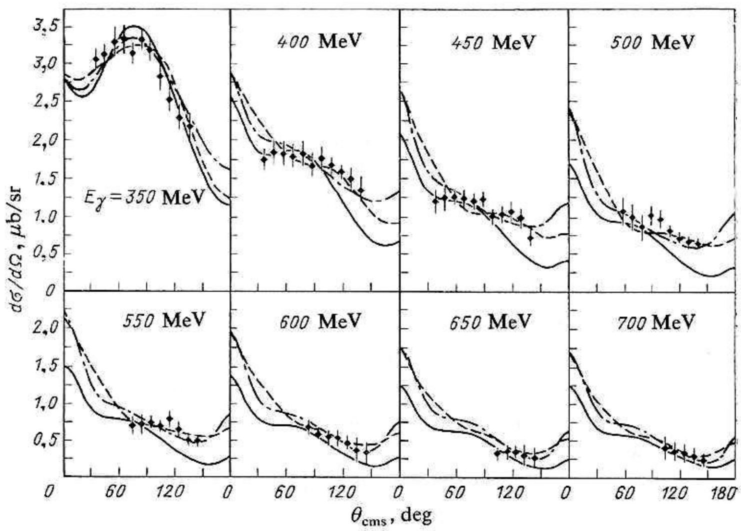


FIG. 22. Differential cross sections in deuteron photodisintegration. The continuous curve is without resonances; the chain curve, with allowance for $1(3^-)$ and $0(1^+)$ resonances; the broken curve, with allowance for $1(3^-)$ and $0(3^+)$ resonances. The points are the data of Ref. 72.

initially introduced, the quantum numbers of the resonances being determined in such a way as to satisy the experimental data. All possible $T(J^P)$ combinations up to $J = 4$ were considered.

The analysis showed that to describe the experimental data one requires at least two dibaryon resonances (the nonresonance amplitude alone led to solutions that did not satisfy the experimental data at all). The best solutions with acceptable $\chi^2$ values were

$$1\,(3^-)\ M = 2.26\,\text{GeV and } 0\,(1^+)\ \ M = 2.36\,\text{GeV},$$
$$1\,(3^-)\ M = 2.26\,\text{GeV and } 0\,(3^+)\ \ M = 2.36\,\text{GeV}.$$

Characteristically, in all the solutions the parameters of the $1(3^-)$ resonance were found to be close to the results obtained from the $NN$ scattering data.

As an example of the description of the experimental data included in the analysis one can take the differential cross sections for angles 50–150° in the center-of-mass system (Ref. 72; Fig. 22). Although the sensitivity of the differential cross sections to the parameters of the resonances is low, the experimental data are described much better when the resonances are taken into account.

The polarization of the recoil protons depends much more strongly on the contributions of the resonances. Figure 23 shows both the old data included in the partial-wave analysis and new data obtained for a wide range of angles and energies by the Khar'kov group.[74] These results correspond well to the resonance solutions of the partial-wave analysis.

However, the results of the partial-wave analysis do not agree with more recent data obtained mainly at Khar'kov,[75]

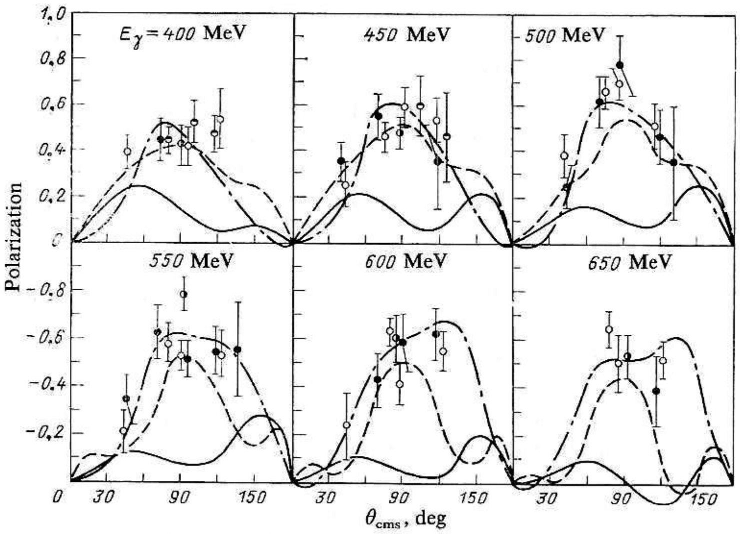


FIG. 23. Angular dependences of the proton polarization in deuteron photodisintegration. The open circles are the new experimental data of Ref. 74. The curves are the same as in Fig. 24.

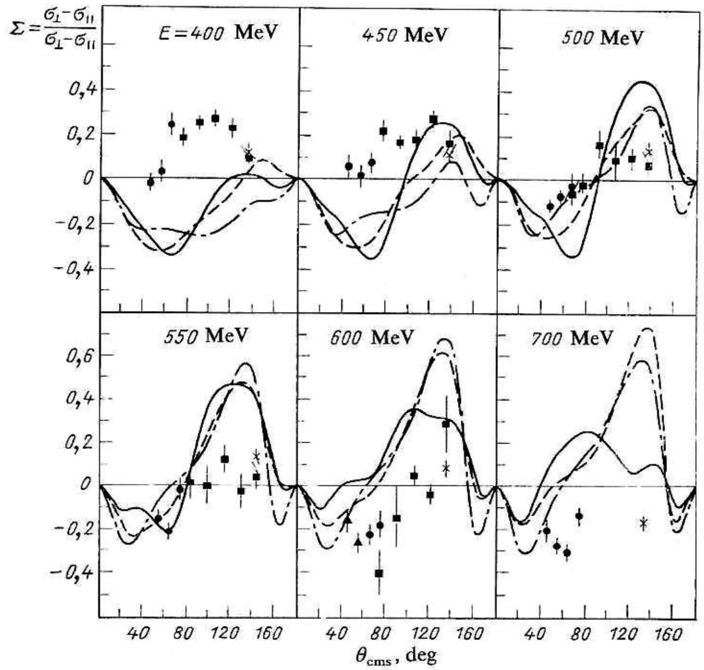


FIG. 24. Asymmetry of the scattering of a polarized beam. The black squares are from Ref. 75, the black circles from Ref. 76, and the crosses from Ref. 77; the chain curve is without resonances; the broken curve, with allowance for $1(3^-)$ and $0(1^+)$ resonances; the continuous curve, with allowance for $1(3^-)$ and $0(3^+)$ resonances.

Erevan,[76] and Bonn[77] in measurements of the asymmetry parameter Σ of the scattering of a polarized beam (Fig. 24), the results of measurement of the target asymmetry parameter $T$ (Refs. 78 and 79; Fig. 25), and also the even more recent data on the differential cross sections at small angles[80] and the polarization of the recoil protons at large angles.[81] This situation is rather typical of phase-shift analyses, in which one attempts to describe the existing experimental data by a minimal number of parameters. In fact, the partial wave analysis took into account only two dibaryon resonances, whereas the nucleon–nucleon data suggest that there are probably more; in addition, a limited number of partial waves was taken into account, and so forth.

In connection with this problem, we should mention Ref. 82, in which deuteron photodisintegration was considered once more in different models that do not take into account dibaryon resonances. It was shown in this paper that in the existing models it is impossible to describe the experimental data on the polarization of the recoil protons and this, in the view of the authors of Ref. 82, is an argument for the existence of the dibaryon resonances.

### The $\gamma d \to \pi^0 d$ reaction

Effects of the manifestation of dibaryon resonances in the $\gamma d \to \pi^0 d$ reaction were considered in Refs. 83 and 84. There are several advantages of looking for dibaryons in this reaction compared with the $\gamma d \to np$ reaction. In the $\gamma d \to \pi^0 d$ reaction only resonances with isospin 1 can be excited, whereas in the $\gamma d \to pn$ reaction resonances with isospins 0 and 1 both contribute; the nonresonance background in the $\gamma d \to \pi^0 d$ reaction can be calculated with good accuracy in the framework of the impulse approximation, and this background decreases rapidly with increasing square of the momentum transfer, so that at large production angles of the $\pi^0$ mesons the relative contribution of the resonances must increase. In Refs. 83 and 84 it was assumed that two mechanisms contribute to the $\gamma d \to \pi^0 d$ amplitude—the impulse approximation and the production of dibaryon resonances. The parameters that characterize the resonance channel were found by fitting to the available experimental data on the energy dependence of the differential cross section at angle 130°. Three resonances in the $T = 1$ channel were considered: $2^+$ with mass $M = 2.17$ GeV, $3^-$ with mass 2.22 GeV, and $0^+$ with mass 2.43 Gev.

Figure 26 shows the dependence on the photon energy of the asymmetry of the angular distribution of the $\pi^0$ mesons in the $\gamma d \to \pi^0 d$ reaction due to the linear polarization of the photons. It can be seen that above 400 MeV there is an appreciable sensitivity of the asymmetry to the contribution of the resonances. This sensitivity is manifested most clearly at large angles. The same conclusion can be drawn for the angular dependence of the differential cross section.

### Photoproduction on the deuteron

The most obvious way of looking for dibaryon resonances is in direct experiments investigating the invariant mass distributions. In exclusive experiments one can in some cases almost completely suppress the effects of background processes. An experiment of this type in photoproduction on

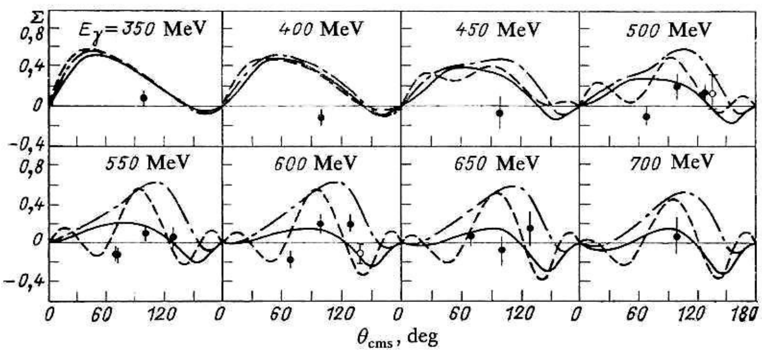


FIG. 25. Target asymmetry. The open circles are from Ref. 78, the black circles from Ref. 79. The curves are the same as in Fig. 24.

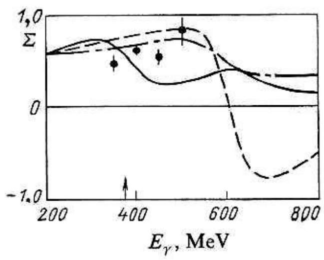


FIG. 26. Dependence of the asymmetry of the angular distribution of $\pi^0$ mesons in the $\gamma d \to \pi^0 d$ reaction on the photon energy (angle 135°). The continuous and chain curves are with allowance for dibaryon resonances; the broken curve, without resonances.

the deuteron was made at Saclay.[85] In the $\gamma \to d \to \pi^- + p + p$ reaction the momenta and angles were measured for the $\pi^-$ and for one of the protons; this completely determined the kinematics of the reaction. In the $\gamma d \to NN\pi$ process, the invariant mass $Q_{N\pi}$ and the momentum $P$ of the spectator nucleon are the parameters that describe the reaction. When $Q_{N\pi}$ and $P$ are constant, the contribution of quasifree scattering also remains constant. Considering the different intervals of $P$, one can suppress the contribution of the quasifree scattering. The result of the experiment was that for small $P$ ($P = 50$ MeV/$c$, $Q_{N\pi} = 1276$ MeV) the agreement with quasifree scattering is good (Fig. 27), but at large $P$ ($P = 150$ MeV/$c$, $Q_{N\pi} = 1246$ MeV) the data cannot be reproduced by any of the variants of the theory—neither by quasifree scattering, nor by the addition to it of pion and proton rescattering, nor with allowance for isobar rescattering. At large $P$, the energy dependence has a maximum at 400 MeV, which, in the opinion of the authors, may be an indication of a dibaryon resonance.

A further experiment by the same group investigated the inclusive reaction $d(\gamma, p)X$, which is less sensitive to interference effects. An effect found at approximately the same energy (390 MeV) was interpreted as an indication of a dibaryon resonance with mass 2.23 GeV and width of order 40 MeV.

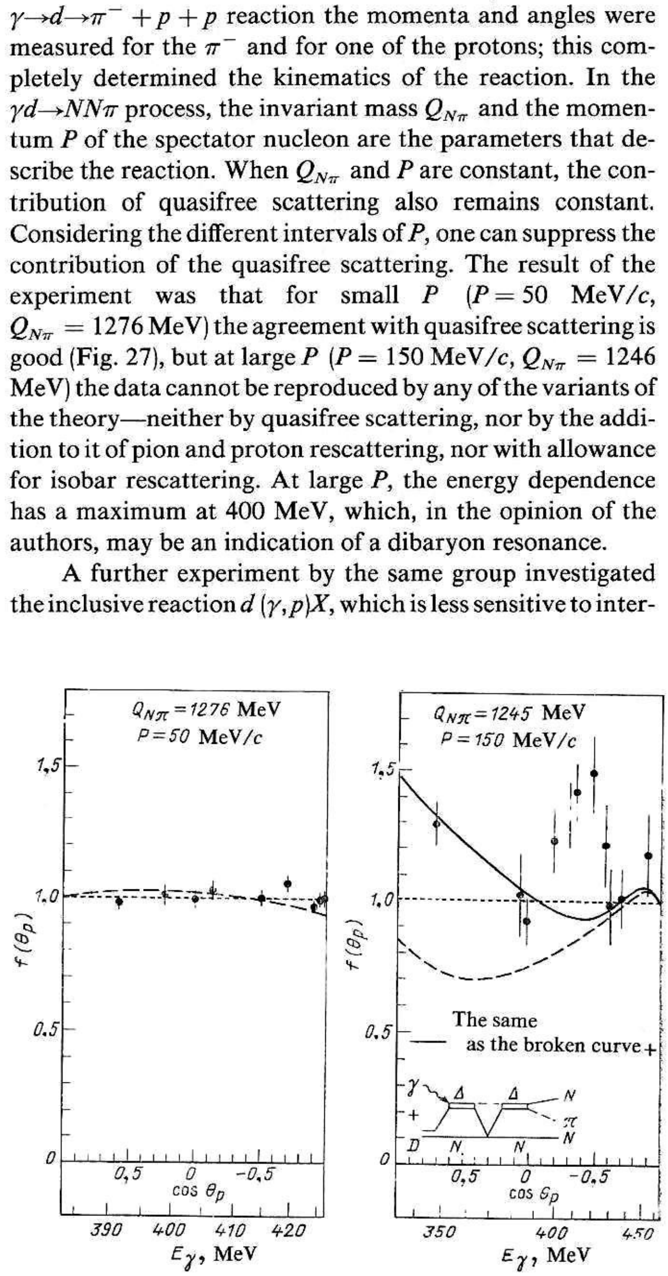


FIG. 27. Energy dependence of the $\gamma d \to pp\pi^-$ reaction cross section. The dotted curve corresponds to quasifree scattering, the dashed curve to quasifree scattering with $\pi^-$ and $p$ rescattering.

We should also mention the report[86] of two anomalies with dibaryon masses 2.16 and 2.24 Gev found in a $^4$He($\gamma$, $p\pi$) experiment.

## 3. PION–DEUTERON INTERACTIONS

### Partial widths of dibaryon decay

As we have already said, the small elasticity parameters of the dibaryon resonances indicate a high probability of their decay into other channels: $\pi d$ and $\pi NN$. Therefore, we must consider the question of the partial decay widths of the resonances, since it is they that determine the experiments in which there are the greatest possibilities for detecting a dibaryon resonance.

The existing studies[87] show, for example, that the ratio $\Gamma_{\pi d}/\Gamma$ (where $\Gamma$ is the total width) is small and is not more than 10%, some studies leading to an even smaller estimate, 1% and less.[88] In Ref. 89, the ratio $\Gamma_{B^2 \to \pi^+ d}/\Gamma_{B^2 \to \pi^+ pn}$ was calculated on the basis of a model proposed by the authors for the wave function of quark subsystems in a bag. The ratio was calculated as a function of the dibaryon mass, and for all the considered masses it was small (1.5–3%). The smallness is essentially due to concentration of the dibaryon wave function in a relatively small (compared with the deuteron) region of space, and, in the opinion of the authors, the suppression of the deuteron channel because of the dibaryon wave function is a qualitative phenomenon not dependent on detailed assumptions. In Ref. 90, the partial decay widths of dibaryon resonances were calculated by perturbation theory. The results of these calculations for $^1D_2$ and $^3F_3$ dibaryon resonances are given as functions of the parameter $\beta$ (the dibaryon form factor) in Table I.

The partial decay widths of dibaryon resonances were also calculated in other studies,[88] and in all estimates $\Gamma_{NN\pi} > \Gamma_{NN} > \Gamma_{\pi d}$. The strength with which a resonance is manifested naturally depends on the entrance and exit channels. Therefore, among all the dibaryon production reactions in $NN$ and $\pi d$ collisions (Fig. 28) the strongest dibaryon signal is to be expected in the $NN \to NN\pi$ process and the weakest in the $\pi d \to \pi d$ process. From the available estimates for the partial decay widths of the resonances it can be established, for example, that the probability of observing the $^1D_2$ resonance in the $\pi d \to \pi NN$ process is almost an order of magnitude higher than the probability of observing the resonance $^3F_3$, etc.

We should also mention the indication[36] that theoretically it is easier to look for a dibaryon in a three-particle final state ($\pi NN$) than in a two-particle state ($\pi d$). For if a dibaryon resonance is produced, the amplitude of the $NN \to N\Delta$ channel will have resonance dependences with respect to the total energy $S$ (because of the dibaryon) and with respect to the two-particle energy $W$ (because of the isobar). Therefore, in this channel it is in principle possible to separate these dependences experimentally, so that one can hope to distin-

TABLE I. Partial widths of dibaryon resonances.

| Dibaryon (mass, GeV) | Width, $m_\pi$ | $\beta$, MeV/$c$ | | | |
|---|---|---|---|---|---|
| | | 180 | 280 | 380 | 480 |
| $2^+$ (2,18) | $\Gamma$ | 0,54 | | | |
| | $\Gamma_{N\Delta}$ ($^5S_2$) | 0.35 | 0.35 | 0,34 | 0.34 |
| | $\Gamma_{NN}$ ($^1D_2$) | 0,13 | 0,14 | 0.15 | 0.15 |
| | $\Gamma_{\pi d}$ ($^3P_2$) | 0,06 | 0,05 | 0,05 | 0,05 |
| $3^-$ (2,22) | $\Gamma$ | 1 | | | |
| | $\Gamma_{N\Delta}$ ($^5P_3$) | 0,88 | 0,73 | 0.60 | 0.50 |
| | $\Gamma_{NN}$ ($^3F_3$) | 0.11 | 0,26 | 0.39 | 0.48 |
| | $\Gamma_{\pi d}$ ($^3D_3$) | 0,013 | 0,014 | 0,012 | 0.010 |

guish the dibaryon amplitude (for example, by considering kinematic regions with different contributions of the isobar).

In the case when two nucleons in the final state form a deuteron, there is a one-to-one relation betweeen $S$ and $W$. Therefore, despite the experimental attraction of the two-particle final state, it becomes impossible to separate the $S$ and $W$ dependences of the amplitude unless one has a very special model for the $W$ dependence.

### $\pi d \rightarrow \pi pn$ reactions

A kinematically complete investigation of deuteron disintegration by ions was made in two experiments.[91,92] In the region of the (3,3) isobar, the $\pi^\pm d \rightarrow \pi^\pm pn$ reactions were investigated in an experiment in the meson factory at Los Alamos.[91] The experimental data at small momentum transfers could be fairly well described by a calculation that took into account the contribution of the pole diagrams (Fig. 29). But clearly one must look for a manifestation of dibaryon resonances in the kinematic region outside the dominance of the main diagrams. Such a region, in which the contribution of the pole diagrams is small, is determined, for example, by large momenta of both nucleons. At large momenta of the nucleons, the experimental data could not be described by the theory, and therefore the authors of Ref. 91 added a diagram with a $^1D_2$ dibaryon resonance and parameters close to those obtained in the phase-shift analyses of $NN$ scattering. The partial width of the $B^2 \rightarrow \pi d$ channel was taken equal to 0.08. The phases of the $N\Delta$ and $\pi d$ channels relative to the background amplitude were chosen as free parameters. In this case, it was possible to describe the experimental data at large nucleon momenta (Fig. 29).

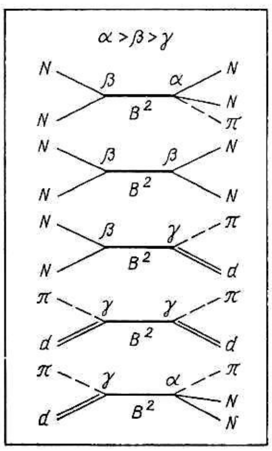


FIG. 28. Diagrams containing a dibaryon in the intermediate state.

At a higher energy, the reaction $\pi^- d \rightarrow \pi^- pn$ was investigated at the Leningrad Institute of Nuclear Physics.[92] The total energy $\sqrt{s} = 2.29$ GeV was close to the mass of the $^3F_3$ dibaryon resonance, and therefore one could expect a manifestation of it. Figure 30 shows the experimental momentum spectra of the protons (respectively, neutrons) for different restrictions on the momentum of the neutron (respectively, proton). At momenta greater than 200 MeV/$c$, a contribution from the dibaryon resonances could be expected. The same figure shows results of the calculation of Ref. 93, in which Obrant took into account coherently single and double scattering of the pion by the nucleons of the deuteron, the $pn$ interaction in the final state, and the Fermi motion of the nucleons. Diagrams with dibaryon resonances were not taken into account in the calculation. As can be seen from the comparison of the results of the calculation and the experimental data, the theory corresponds to the experiment both in the region of quasielastic scattering and far outside this region. In the spectra of the nucleons at momenta greater than 200 MeV/$c$ an appreciable contribution of pion rescattering by the nucleons of the deuteron is observed, and there are no grounds for adding to the theory any diagrams associated with dibaryon resonances.

How can the results of these two experiments be reconciled? It could be that the large discrepancy between the theory that does not take into account dibaryon resonances and the experiment of Ref. 91 is due to the insufficiently accurate allowance for double pion scattering. In fact, a calculation in accordance with the theory of multiple scattering without addition of dibaryon resonances explains qualitatively[92] the experimental data obtained at Los Alamos (Fig. 31). The same conclusion can be reached by comparing with experiment calculations made by means of the relativistic Faddeev equations.[94] The remaining small difference between theory and experiment (Fig. 31) could be explained either by rescattering of the pions by the nucleons with a multiplicity greater than two, which could be important in the region of the (3,3) isobar, or in fact by a contribution of a $^1D_2$ dibaryon resonance. And the fact that the resonance could be manifested in the Los Alamos experiment (the re-

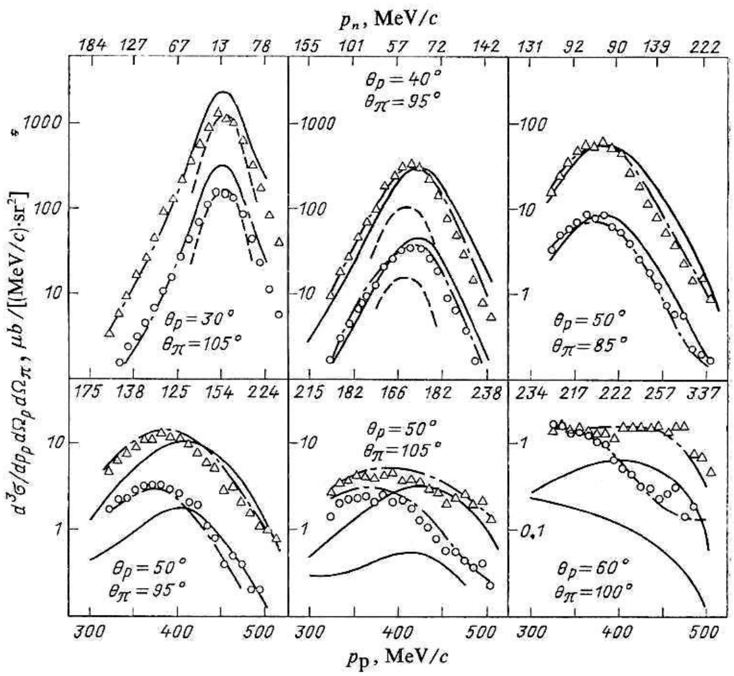


FIG. 29. Differential cross sections of the $\pi^\pm d \to \pi^\pm pn$ reaction.[91] The open triangles are for $\pi^+$, the open circles for $\pi^-$; the continuous and broken curves represent calculations without allowance for dibaryon resonances; the chain curve is with allowance for them.

gion of $^1D_2$) but was not seen in the Leningrad experiment (the region of $^3F_3$) can be explained by the large difference between the products of the partial decay widths in the entrance and exit channels for the $^1D_2$ and $^3F_3$ resonances (see Table I).

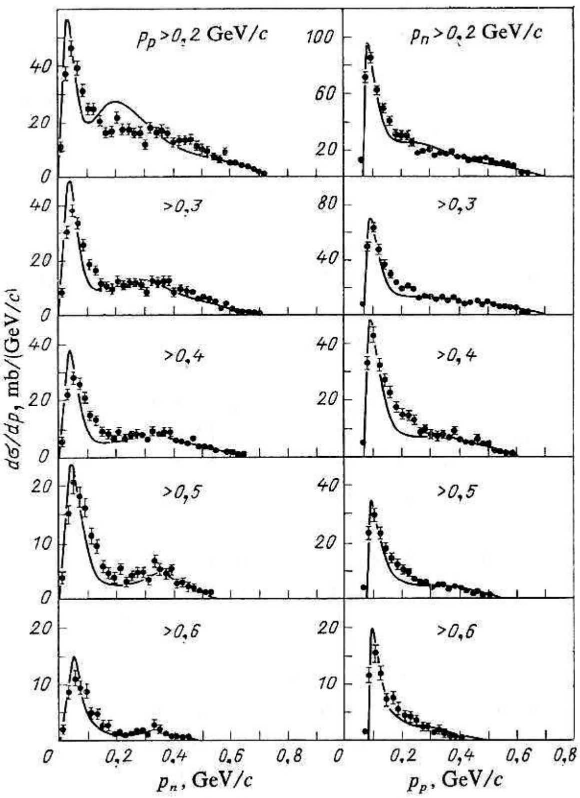


FIG. 30. Momentum spectra of neutrons and protons with different restrictions on the momentum of the other nucleon.[92] The curves represent the calculation in accordance with the theory of multiple scattering.[93]

Thus, to explain these experimental data there is no need to invoke the $^3F_3$ resonance. With regard to the $^1D_2$ resonance, if it exists, its partial decay width to the $\pi d$ channel is appreciably less than the value given in Ref. 91.

The inclusive spectra of protons produced in deuteron disintegration by $\pi^\pm$ mesons were measured at SIN.[95] The $d(\pi^\pm, p)X$ reactions were investigated under kinematic conditions close to those of the Saclay photoproduction experiments. It was to be expected that for fixed emission angle and momentum of the detected proton the energy dependence of the cross sections should have maxima corresponding to a dibaryon resonance. As in the photon experiment, the back-

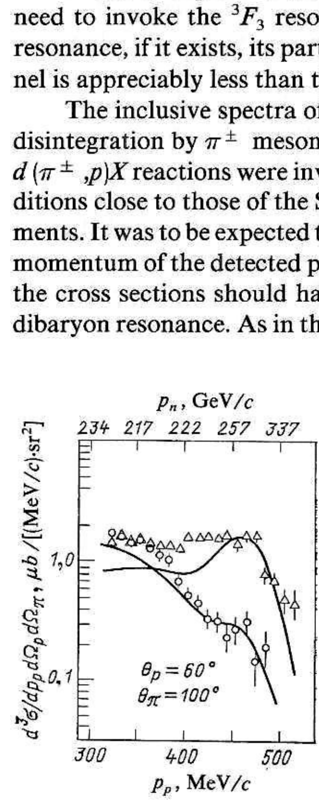


FIG. 31. Experimental data the same as in Fig. 29. The curves represent the calculation in accordance with the theory of multiple scattering.[93]

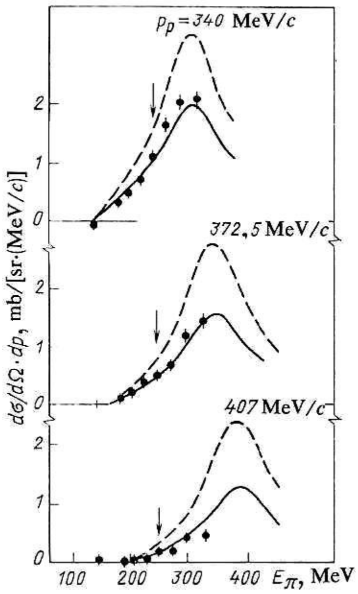


FIG. 32. Energy dependence of the $d(\pi^-, p)X$ reaction cross section. The arrows indicate the position of the resonance

ground of the quasielastic processes was suppressed by the fact that the protons were detected at large momenta and at a large angle. The results of measurements in a $\pi^-$ beam (the final state was $\pi^- pp$, as in the photoproduction experiment) are shown in Fig. 32. No effect in the neighborhood of the mass 2.23 GeV was found. The difference between the results of the pion and photon experiments could be due to the following reasons: 1) the structure in the photon experiment is due to a $T = 0$ dibaryon resonance, which cannot be produced in a pion experiment; 2) the dibaryon coupling constants in the $\gamma d$ and $\pi d$ channels differ strongly; 3) the effect observed in the photon experiment has nothing to do with the problem under discussion.

#### Elastic $\pi d$ scattering

The possibility of detecting dibaryon resonances in elastic $\pi d$ scattering was first pointed out in Ref. 96 in 1979. Two years later there appeared an extended variant of this paper,[97] which analyzed practically all the data on elastic $\pi d$ scattering in the region of intermediate energies.

As we have already pointed out, the greatest difficulty in the analysis of all the experimental data is that besides the resonance amplitude there is almost always a nonresonance part of the amplitude, i.e., a background part. Therefore, without accurate knowledge of the background amplitude it is impossible to estimate quantitatively the contribution of the dibaryon resonances. For elastic $\pi d$ scattering there is a possibility of calculating the background amplitude with less uncertainty than for other processes.

In Ref. 97, the background amplitude was determined using Glauber's theory and the Faddeev equations. It was found that the two approaches lead to approximately the same description of the $\pi d$ scattering data, even in the region of large angles, where one would expect Glauber's theory to fail. On the basis of this it was concluded that for the background amplitude one can use a calculation in accordance with Glauber's theory taking into account only single and double scattering. To this amplitude the resonance part was added. Four dibaryon resonances were introduced: $B^2_1(2.17, 2^+)$, $B^2_1(2.22, 3^-)$, $B^2_1(2.32, 2^-)$, and $B^2_1(2.43, 0^+$ or $4^+)$, the existence of which was assumed on the basis of Hoshizaki's phase-shift analysis.[49] The parameters of the resonances were chosen in order to obtain the best description of the experimental data—the differential cross sections of elastic scattering. It was found that introduction of the resonances appreciably improves the description of the experimental results (Fig. 33) at pion momenta 300–500 MeV/$c$, particularly at large angles. The minimum observed in the experiments around 100° can be explained naturally by interference between the background terms and the $3^-$ and $2^-$ dibaryon terms. The growth of the cross section at angles near 180° is due to pions from the decay of dibaryon resonances. At small angles, the effect of the dibaryon resonances disappears because of the deuteron form factor and the large partial waves in the pion–nucleon amplitude.

The good description of the energy dependence of the differential cross section of scattering through 180°, in particular the maximum at 700 MeV/$c$, was advanced in support of the existence of resonances in Ref. 97, but it is known[98] that this dependence may also be explained without dibaryon resonances.

It should be mentioned that the authors of Refs. 96 and 97 were criticized in Ref. 89 for using unrealistic background amplitudes to describe the elastic scattering in the region of large angles. Namely, in this region it is easier to

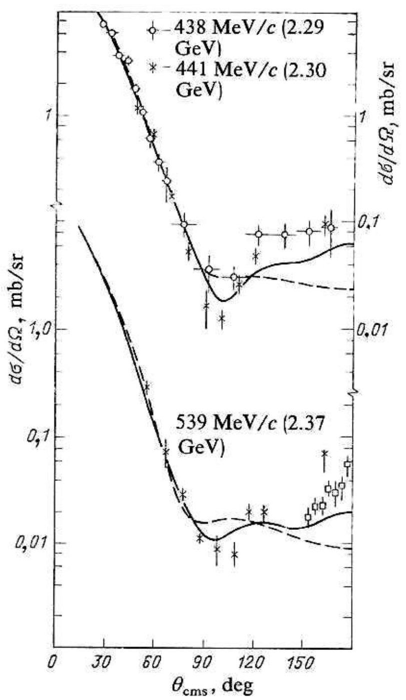


FIG. 33. Differential cross sections of elastic $\pi d$ scattering. The continuous curve is with allowance for resonances, the broken curve without resonances.

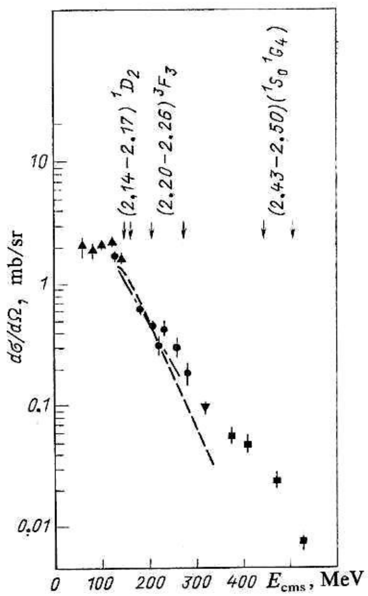


FIG. 34. Energy dependence of elastic $\pi d$ scattering through angle 180°. The curves represent calculations using different variants of the relativistic three-body theory. The arrows indicate the positions of the resonances.

detect the dibaryon signal by virtue of the interference of the background and resonance amplitudes.

A special experiment to look for dibaryon resonances in elastic $\pi d$ scattering at 180° was made at SIN.[99] In the opinion of the authors, the energy dependence of the differential scattering cross section through 180° exhibited a structure in the neighborhood of 250 MeV in the center-of-mass system (Fig. 34) that could be due to the production of a dibaryon resonance.

The results of experiments on elastic $\pi d$ backward scattering at higher energies 0.4 — 0.15 Gev were analyzed by Kondratyuk *et al.*[100] using the results of Ref. 101. The energy dependence of $d\sigma/d\Omega$ (180°), the angular distributions at different energies, and the polarization parameters were calculated. It was found that the values of $d\sigma/s\Omega$ (180°) calculated without allowance for the dibaryon resonances lie below the experimental data in the regions 0.4–0.6 and 1.2–1.5 GeV/$c$. In the first region, one can expect a contribution of $^3F_3(2.26)$ and $^1G_4(2.43)$ dibaryon resonances, and in the second a contribution of a resonance with mass 2.9–3.0 GeV. Assuming that the difference between the experimental and theoretical values does indeed arise because of an ignored contribution of dibaryon resonances, the $\pi d$ partial widths of the resonances were estimated and found to be 9.5% for $^3F_3$, 2.8% for $^1G_4$, and 2% for the resonance with mass 2.9 GeV. When the resonances were taken into account, a significantly better description of the experimental data was obtained.

The necessity of introducing dibaryon resonances can be most clearly seen in the angular dependence of the differential cross sections at pion momenta 500–700 MeV/$c$. Figure 35 shows the experimental results of Ref. 102 for pion scattering angles 150–180° and as calculated in two variants—without dibaryon resonances (broken curve) and with

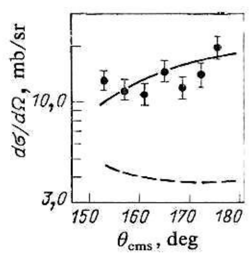


FIG. 35. Elastic $\pi d$ backward scattering at momentum 593 MeV/$c$.[102] The curves are taken from Ref. 100: the continuous curve is with allowance for dibaryon resonances, the broken curve is without resonances.

a contribution of $^3F_3$ and $^1G_4$ resonances (continuous curve) under the assumption that they decay into the $\pi d$ system in the $D$ and $F$ waves, respectively. Inclusion of the resonance contribution significantly improves the description of the experimental data.

Much information about dibaryon resonances can be obtained by measuring the polarization characteristics in elastic $\pi d$ scattering. This is due to the fact that, since the probability of decay into the $\pi d$ channel is small, an appreciable resonance signal can be expected only in the case of observation of quantities sensitive to the interference between the resonance and background amplitudes. In Ref. 103, the tensor and vector polarizations were calculated. The background amplitude was calculated using Faddeev's equations. To this amplitude were added terms corresponding to $^1D_2$, $^3F_3$, and $^1G_4$ dibaryon resonances. Figure 36 shows the results of calculation of the vector polarization $it_{11}$. The broken curve shows the results of the calculation without allowance for the dibaryon resonances. The continuous curves are the results of the calculation with allowance for them for different mixing parameters $\varepsilon$ (dibaryons with given $J$ are associated in the $\pi d$ channel with two pion states with angular momenta $l_\pi = J \pm 1$). It follows from Fig. 36 that at pion energy 256 MeV the vector polarization in certain variants of the calculation with allowance for dibaryon resonances oscillates and that the angular dependences for the cases with and without the resonances differ strongly.

The vector polarization at these energies was measured

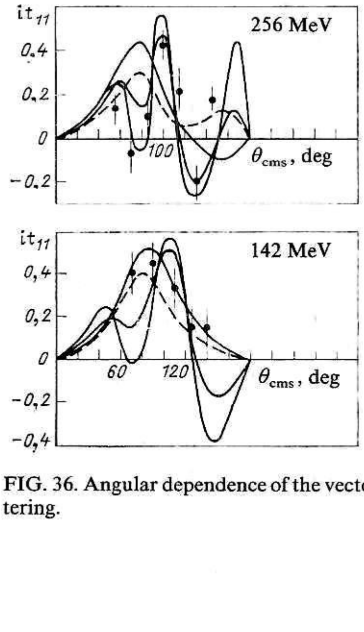


FIG. 36. Angular dependence of the vector polarization in elastic $\pi d$ scattering.

in the meson factory at SIN.[104] The results of the experiment are shown in Fig. 36.

At 142 MeV, the experimental data agree with both the calculation taking into account the dibaryon resonances and the one without them. At 256 MeV, the results of measurement of the vector polarization reveal an oscillatory behavior, which cannot be described by the calculation that did not take into account the dibaryon resonances. Thus, an indication was obtained of the existence of at least one dibaryon resonance.

It should be mentioned that the results of this experiment have frequently been discussed. In one of the papers[105] it was concluded on the basis of a phase-shift analysis of $\pi d$ scattering that there are no grounds for including a $^3F_3$ dibaryon resonance to describe the experimental data, it being sufficient to have a contribution of the $2^+$ and, possibly, $4^+$ amplitudes. In Ref. 106, Grein and Locher considered the complete set of $\pi d$ variables needed to detect dibaryon resonances. They pointed out that for identification of resonances and determination of their parameters it is necessary to study in detail the energy dependences of many characteristics.

The angular dependence of the tensor polarization $t_{20}$ in elastic $\pi^+ d$ scattering was measured in experiments made at the meson factories at Los Alamos[107,108] (at 142 MeV) and at SIN (at 138 MeV).[109] The results are shown in Fig. 37.

At one point (near 150°) they do not agree. It should be emphasized that the results of the two experiments cannot be described by theoretical curves that either include (broken curve) or do not include (dotted curve) meson absorption. The most important result is the discovery of a strong and rapid oscillation in the interval of angles 140–180°. At 150°, the value of $t_{20}$ reaches the maximally possible theoretical value $1/\sqrt{2}$. As was shown in nuclear reactions,[110] such a maximum is associated with resonances in the corresponding compound nuclei. In Fig. 37, the chain curve shows the results of a calculation that took into account $^1D_2$, $^3F_3$, and $^1G_4$ dibaryon resonances. The oscillation is not described by the calculated curve. But in the calculation the employed partial width of the dibaryon was taken to be small compared with the total width and also compared with the background. Therefore, the results obtained may indicate that this constant is in reality larger. In any case, the observed oscillation of $t_{20}$ indicates a strong interference of the high partial waves with the background. We note that the value measured for $t_{20}$ at 180° agrees with the value at $t_{20} = -0.304$ obtained in Ref. 97, in which dibaryon resonances were taken into account.

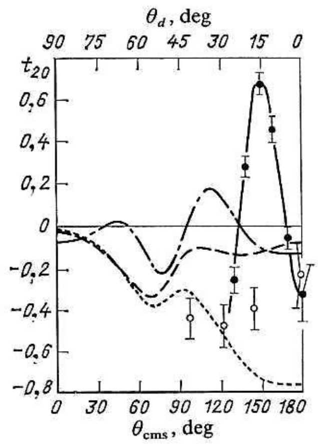


FIG. 37. Angular dependence of the tensor polarization in elastic $\pi d$ scattering. The experimental points are taken from Ref. 109; the continuous curve is drawn through the experimental points; the chain curve represents different variants of calculations with dibaryon resonances; the broken and dotted curves represent calculations without them.

### $\pi^+ d \to pp$ reactions

In the $\pi^+ d \to pp$ reaction, the dibaryon signal cannot be expected to be appreciably greater than in elastic $\pi d$ scattering on account of the small partial width for the entrance channel. It is therefore better to look for a dibaryon in a measurement of spin characteristics. The spin-dependent parameters $A_{y0}$, $A_{0y}$, $A_{xx}$, $A_{zx}$ were measured at SIN[111] for the inverse reaction $pp \to \pi^+ d$. These data together with results of earlier studies made it possible to analyze the $pp \to \pi^+ d$ process with the aim of finding proofs for dibaryon resonances. In a phenomenological analysis of the $pp \to \pi^+ d$ reaction in the region of energies 400–800 MeV,[112] a model was used in which the amplitude consisted of three parts: a Born amplitude with neutron exchange, the amplitude of a $\Delta N$ intermediate state, and a resonance amplitude. The analysis showed that to describe the data on the differential cross sections and the polarization a contribution of an amplitude with $^1D_2$ and $^3F_3$ dibaryon resonances is needed. However, in this analysis the spin characteristics were not described satisfactorily. The main shortcoming of this analysis was that it used a specific model for the nonresonance part of the amplitude, which could be inaccurate. Therefore, a model-independent partial-wave analysis is needed. In Ref. 113, such analyses were made. Their results do not contradict the existence of dibaryon resonances.

Among the new experimental results, we must mention the measurement at SIN of the vector polarization,[114] and also the differential cross sections measured at the Leningrad Institute of Nuclear Physics and at SIN.[115]

## 4. EFFECTS OF INELASTIC THRESHOLDS OR DIBARYON RESONANCES?

Almost immediately after the suggestion that the results of experiments on the $NN$ interaction in pure spin states should be explained by means of dibaryon resonances, nonresonance interpretations of the experimental data were proposed. In early papers on this subject,[116] the emphasis was placed on the need to consider the contribution of high partial waves, to estimate more accurately the background, and so forth. These suggestions were discussed in Ref. 117, in which an answer to these original objections was given.

The possibility of a nonresonance interpretation is associated above all with the fact that the experimentally observed effects are near the threshold of the (3,3) isobar and in the region of energies in which the cross section of the inelastic processes increases strongly. This led to the appearance of numerous papers in which the phenomena ascribed to dibaryon resonances were explained without dibaryons by a growth of the inelastic cross sections and threshold phenomena associated with the production of the isobar. The theoretical papers that interpret the experimental data without invoking dibaryon resonances are discussed most fully in Ref. 43.

As early as 1978 there was published Ref. 118, in which the data on $\Delta\sigma_L$ were interpreted without the introduction of dibaryon resonances. An isobar model for the inelastic channels was considered. It was assumed that meson-exchange interactions, which were introduced into the isobar model, could lead to the $\Delta\sigma_L$ behavior observed experimentally. However, it was already pointed out in Ref. 117 that the results of the one-boson exchange model are incompatible with the experimental data.

In Ref. 119, the structures in $\Delta\sigma_L$ and $\Delta\sigma_T$ were explained by a growth of the singlet and triplet cross sections taking place at different energies (shifted in the energy scale). The energy dependence of $\Delta\sigma_L$ and $\Delta\sigma_T$ was well described in Ref. 119, but it was not clear how other experimental results should be explained. In addition, the work of Ref. 119 was based to a large degree on data on the cross sections of the inelastic channels that were not sufficiently well known. There are also problems of a purely theoretical kind in this paper.[43]

A unitary dynamical model for particle interaction at intermediate energies was developed in Refs. 51 and 120. In this model, one can explain many (but not all!) experimental data; the circular motion in the Argand diagram for the $^1D_2$ and $^3F_3$ amplitudes is obtained without the introduction of dibaryon resonances (in this connection, see the conclusions of the present review). However, in the quoted papers there was no investigation of whether or not the model corresponds to the existence of a dibaryon resonance, although *a priori* it was not introduced into the model. In part, these questions were considered in Refs. 121 and 122.

The amplitudes of elastic scattering in the $^1D_2$ and $^3F_3$ waves were considered in Refs. 123 and 124, in which it was concluded that the amplitudes in these waves can be described without introducing dibaryon resonances. However, it was pointed out in Ref. 43 that the conclusions of Refs. 123 and 124 must be interpreted with care in view of the simplifications that were made, in particular the approximation of the left-hand cuts by poles near the $N\Delta$ threshold.

A unified theory of $NN\to\pi d$, $\pi d\to\pi d$, and $NN$ reactions was proposed in Ref. 125, in which a set of equations coupling the $NN$ and $\pi d$ channels was used to study in detail $pp\to\pi^+ d$, $\pi d\to\pi d$, and $NN\to NN$ scattering. It was found that the majority of the differential cross sections could be described without the introduction of dibaryon resonances. However, this theory does not describe the polarization characteristics in the elastic channel.

The same processes were investigated in Ref. 126, the main conclusion of which is that the majority of the characteristics can be described without the introduction of dibaryon resonances. However, the quantitative description of elastic scattering and the $\pi d\to pp$ channel is unsatisfactory.

In Ref. 127, a model was considered in which effective $N\Delta$ thresholds with different relative orbital angular momenta are determined. The values of these thresholds were found to be close to the values of all the conjectured dibaryon resonances except the triplet with mass 2.43 GeV. However, it should be noted that the model contains an appreciable number of uncertainties.

The main shortcoming of most of the quoted papers is that they did not analyze the possibility that the inelastic $NN\to N\Delta$ channel leads to the appearance of poles in the partial-wave amplitudes.

The interpretation of the experimental data by means of dibaryon resonances was criticized in Ref. 128 on the following basis. The values of Im $F_3$ obtained from the experimental data of Ref. 7 were small in the energy interval 400–600 MeV and required almost the entire inelastic cross section to be in the state $^1D_2$. This leads to inelastic amplitudes in the other channels which are too small to explain the large polarization in the $pp\to\pi^+ d$ process. New, more accurate measurements[4–6] of $\Delta\sigma_L$ make it possible to have inelasticity in other partial waves, and, thus, this problem disappeared. And although there is another problem—a certain discrepancy between the predictions of the phase-shift analysis for Re $F_3$ and the value of this quantity calculated by Grein and Kroll using dispersion relations, Bugg no longer ruled out an interpretation with dibaryon resonances in his later papers of Refs. 6 and 129.

In Ref. 130, Bohr's resonance criterion was used for the dibaryon amplitudes. The residues at the pole of the resonance amplitude are factorized, and then the widths of the $pp\to\pi d$, $pp\to pp$, $\pi d\to\pi d$ processes must satisfy the relation $\Gamma^2_{pp\to\pi d}=\Gamma_{pp\to pp}\Gamma_{\pi d\to\pi d}$. Applying this relation for the $^3F_3$ and $^1D_2$ dibaryon resonances, the authors of Ref. 130 assert that it is satisfied only for the $^1D_2$ resonance but not for $^3F_3$. With regard to this test, one must say the following. For the $NN\to NN$ and $\pi d\to\pi d$ channels the results of the corresponding phase-shift analyses were taken in Ref. 130; this is natural, but it may be suspect because of the uncertainty in the analyses themselves. For the $pp\to\pi d$ process, purely model calculations from Ref. 131 are used. It is clear that if other values, also obtained in model calculations, are taken for $\Gamma_{pp\to\pi d}$, Bohr's criterion will also be satisfied for the $^3F_3$ resonance.

Briefly, we have considered above the main directions of the investigations aimed at a nonresonance interpretation of the experimental data.

## 5. CONCLUSIONS

It can be seen from the foregoing discussion that the problem of dibaryon resonances is complicated. It is complicated both from the experimental point of view—it is necessary to distinguish the effects on a large background—and from the point of view of the subsequent theoretical interpretation—not every peak or anomaly has a resonance origin.

Generally speaking, a resonance is a pole in a partial-wave amplitude situated in the complex plane near the physical region. Pseudoresonances are defined as peaks of irregularities caused by the opening of inelastic channels and not poles of the $S$ matrix. From the experimental point of view, the criterion for the existence of a resonance is a loop on the Argand diagram for the partial-wave amplitude. However, this condition is only necessary and is not sufficient, and it therefore cannot be used for the unambiguous identification of resonances.

It was shown in Refs. 132 and 133 that Argand diagrams for partial-wave amplitudes that correspond to true resonances also correspond to pseudoresonances. Indeed, the box diagram containing a resonance and a particle in the intermediate state and giving, for example, a contribution to the $NN(N\Delta)NN$, $\pi d(N\Delta)\pi d$ reactions has square-root and logarithmic singularities in the partial-wave amplitude which generate closed loops in the Argand diagrams. An experimental difference between pseudoresonances and true resonances was found in Refs. 87 and 133 by constructing the Argand diagram for the total and not the partial amplitude and comparing the radii of the Argand loops for different scattering angles. In particular, for the backward and forward scattering angles the radii of the loops in the Argand diagram for true resonances are equal, while the radii of pseudoresonance loops are much larger for forward than for backward scattering.

Among the other methods of determining true resonances, we must mention the search for poles in the $P$ matrix, which stands in a one-to-one relation with the $S$ matrix. This was done for $S$ waves by Simonov in 1981.[3] In addition, there is also the method of direct determination of a pole of the $S$ matrix, as was one in Refs. 66–68 by means of the $K$-matrix method, though it is true that in this case there is the problem of left-hand cuts,[43] which still awaits its final solution.

At the same time, interest in dibaryon resonances does not flag but rather grows. During 1980–1981 alone, more than 60 papers relating in some way to the dibaryon problem were published in the journals. Moreover, the current programs for all intermediate-energy accelerators include investigations of dibaryon resonances. All this indicates the importance of the problem and the need for new efforts to resolve it.


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