Dibaryon resonances

M. M. Makarov

B. P. Konstantinov Leningrad Institute of Nuclear Physics, Academy of Sciences of the USSR

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The present state of the problem of dibaryon resonances is surveyed. Experimental work on dibaryon resonances in nucleon-nucleon collisions, in the photodisintegration of the deuteron, and in pion-deuteron interactions is reviewed. Emphasis is placed on resonances with an isospin $T = 0$. The experimental data are compared with the predictions of partial-wave analyses of inelastic reactions. The results of phase-shift analyses of nucleon-nucleon scattering are stated. Some possible new experiments for observing dibaryon resonances are discussed.

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CONTENTS

INTRODUCTION

The past three years have seen qualitative progress in the physics of elementary particles at intermediate energies, thanks to the discovery of some new effects in two-nucleon systems which may be interpreted as evidence of dibaryon resonances. Such resonances are predicted by many theoretical models. The quark bag model,[1,2] for example, predicts a dibaryon resonance consisting of six quarks in a bag. The string model[3] describes a dibaryon resonance in which six quarks are connected to each other by strings. The nucleon–nucleon potential model[4] also predicts weakly bound systems and resonances. A search for dibaryon resonances is of fundamental importance to an understanding of nucleon–nucleon interactions and to a theory of hadron structure. Despite the importance of this problem, it was not until 1977 that experimental effects were reported which could be interpreted as evidence for the existence of dibaryon resonances. First came reports[5] of work carried out at the Argonne National Laboratory, in which a $^3F_3$ resonance might have been observed in nucleon–nucleon scattering, and a report[6] of experiments on the photodisintegration of the deuteron carried out at the University of Tokyo, from which it was concluded that an isoscalar 3^+ resonance exists. These studies were followed by many other experimental and theoretical studies of the problem of dibaryon resonances. Conferences were organized on the subject, and reviews[7,8] were published on some of the experimental approaches which were yielding indications of the existence of dibaryons. The purpose of the present review is to examine all the most important experimental approaches to the problem of dibaryon resonances.

1. DIBARYON RESONANCES IN PROTON-PROTON SCATTERING

a) $\Delta\sigma_L$

The first nucleon–nucleon scattering experiment which yielded an indication of dibaryon resonances involved measurement of the difference between the total longitudinal cross sections for antiparallel and parallel spin states, $\Delta\sigma_L$. Figure 1 shows the results of this experiment, which unexpectedly revealed a clearly defined structure: a deep minimum at a momentum of about 1.5 GeV/c. This structure is not found in the energy dependence of the total cross sections averaged over the spin, but it is found in the energy dependence of the total scattering cross sections for particles with parallel spins (Fig. 1). To see the origins of these effects, it is necessary to examine how the total cross sections σ and the differences between the cross sec-

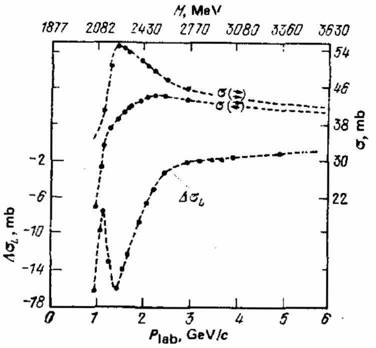

FIG. 1. Total cross sections and difference between the total cross sections in pure spin states.

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tions in the pure spin states ($\Delta\sigma_L$ and $\Delta\sigma_T$) are expressed in terms of the helicity amplitudes and the partial-wave amplitudes:

$$\sigma=\frac{1}{2}\sigma(\rightleftarrows)+\sigma(\leftleftarrows)]$$

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

$$\Delta\sigma_L=\sigma(\rightleftarrows)-\sigma(\rightrightarrows)$$

$$=\frac{4\pi}{k}\,\mathrm{Im}\,[\Phi_1(0)-\Phi_3(0)], \tag{2}$$

$$\Delta\sigma_T=\sigma(\uparrow\downarrow)-\sigma(\uparrow\uparrow)$$

$$=\frac{4\pi}{k}\,\mathrm{Im}\,\Phi_2(0), \tag{3}$$

where k is the momentum in the c.m. frame, and the Φ are the helicity amplitudes, given by

$$\Phi_1=\langle ++\,|\,\Phi\,|\,++\rangle, \tag{4}$$

$$\Phi_2=\langle ++\,|\,\Phi\,|\,--\rangle, \tag{5}$$

$$\Phi_3=\langle +-\,|\,\Phi\,|\,+-\rangle. \tag{6}$$

For the two-proton system there are only three independent cross sections, which unambiguously determine the imaginary part of the forward scattering amplitudes, $\Phi_1(0)$, $\Phi_2(0)$, and $\Phi_3(0)$.

In terms of the partial-wave amplitudes, the cross sections are given by

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

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

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

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

where R_{JJ} and $R_{J+1,J}$ are the spin triplet partial-wave amplitudes with odd $J=L$ and with even $J=L\mp1$, respectively; R^J is a mixed term of $L=J\pm1$ states; and R_J is a spin singlet with even $J=L$.

It can be seen from expressions (7) and (8) that the wave R_{JJ} appears in the parallel cross section (where the structure is observed experimentally) but not in the antiparallel cross section (where the structure is not observed). Thus the resonance, if it is responsible for the structure, may be in the $^3P_1$, $^3F_3$, $^3H_5$, etc., states. The mass of this resonance, which corresponds to the energy at which the effect is observed in $\Delta\sigma_L$, is about 2.26 GeV, and its width is about 200 MeV. In $\Delta\sigma_L$ there is a very low background, because the Im $\Phi_1(0)$ and Im $\Phi_3(0)$ backgrounds cancel out, as follows from (2), while there is a high background in the total cross section σ. It is for this reason that the structure can be seen clearly in $\Delta\sigma_L$ but not in σ.

Another structural feature observed in the $\Delta\sigma_L$ measurements is a peak at 1.2 GeV/c.

b) $\Delta\sigma_T$ and $\Delta\sigma_T-\Delta\sigma_L$

The difference $\Delta\sigma_T$ was also measured at the Argonne National Laboratory and at the TRIUMF meson factory in Vancouver. In the results (Fig. 2) we can clearly see peaks at 2.0 and 1.2 GeV/c. Since the 1.2-GeV/c peak is also found in $\Delta\sigma_L$, we conclude from expressions (9) and (10) that this structure could be caused only by a spin singlet. Furthermore, only a spin singlet could cause the peak at 2 GeV/c in $\Delta\sigma_T$. Accordingly, at 1.2 GeV/c (the corresponding mass is 2.15 GeV) and 2 GeV/c (2.45 GeV) the resonance may be in $^1S_0$, $^1D_2$, $^1G_4$, etc., states.

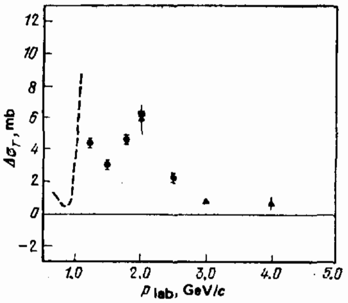

FIG. 2. Difference between total cross sections, $\Delta\sigma_T=\sigma(\uparrow\downarrow)-\sigma(\uparrow\uparrow)$.

If $\Delta\sigma_T$ contains only singlet structures, we can expect to find only triplet structures in the energy dependence of the difference $\Delta\sigma_T-\Delta\sigma_L$. As Fig. 3 shows, there is one more triplet structure, at 2 GeV/c, in addition to the structure at 1.5 GeV/c, with which we are already familiar and which is shown in the same figure. Let us examine the difference

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

It can be seen from this expression that the resonance must be in the R_{JJ} state, since only the term with R_{JJ} has a positive sign in the difference $\Delta\sigma_T-\Delta\sigma_L$. Incidentally, this resonance might possibly explain the asymmetry of the peak in $\sigma(\rightleftarrows)$ at 1.5 GeV/c.

c) Polarization

In order to determine the properties (the spin and parity) of the resonances correctly, we must study other characteristics of pp scattering. Figure 4 shows data[11] on the polarization at a fixed momentum transfer $|t|$. Here we see structure near 1.5 GeV/c but absolutely no evidence for a peak at 1.2 GeV/c. This result is to be expected, since the polarization does not include a singlet term. Polarization data can be used to determine which partial wave is described by the

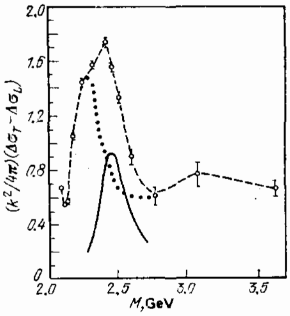

FIG. 3. Triplet structure at 2.0 GeV/c. Dotted curve—from $\Delta\sigma_L$ data.

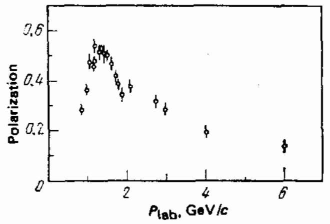

FIG. 4. Polarization at $0.1<|t|<0.2$.

Breit–Wigner formula.[12] The resonance effect can be studied by examining the energy dependence of the coefficients in the expansion of the differential cross sections and the polarization in Legendre polynomials[11,13]:

$$\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\sum_{n=0}^{\infty} a_n P_n(\cos\theta), \tag{12}$$

$$p\,\frac{d\sigma}{d\Omega}=\frac{1}{k^2}\sum_{n=2}^{\infty} b_n P_n^{(1)}(\cos\theta) \tag{13}$$

(the symmetry requires that n be even).

It turns out that all the coefficients a_n and b_n with $n \geqslant 8$ vanish completely in the momentum interval 1–2 GeV/c. We may thus ignore the waves with $J > 4$ and $L > 4$ in this interval. The possible R_{JJ} resonance at 1.5 GeV/c is accordingly a $^3P_1$ or $^3F_3$ state. Analysis of the values of b_n (Fig. 5) reveals that all the coefficients have some structure at about 1.5 GeV/c, but a $^3P_1$ resonance could not explain the increase in b_6 with the energy, since it does not include a $^3P_1$ wave. A detailed study of b_2, b_4, and b_6 has shown[12,14] that their strong energy dependence may be explained by a Breit–Wigner behavior of $^3F_3$. The data on $\Delta\sigma_L$ can be used to estimate the elasticity Γ_{el}/Γ for a $^3F_3$ resonance: 0.15–0.25.

The energy dependence of the polarization at the angle $\theta_{c.m.}=63°$ is interesting, since the $^3F_3$ wave does not contribute to the polarization at this angle ($P_3=0$). Figure 6 shows the p_{lab} dependence of the quantity $k^2p(d\sigma/d\Omega)/\sin 2\theta_{c.m.}$, which is proportional to

$$(2\,\mathrm{Im}\,{}^3P_0+3\,\mathrm{Im}\,{}^3P_1)\,\mathrm{Re}\,{}^3P_2-(2\,\mathrm{Re}\,{}^3P_0+3\,\mathrm{Re}\,{}^3P_1)\,\mathrm{Im}\,{}^3P_2, \tag{14}$$

if we ignore the higher-order partial waves. From phase-shift analysis we know that the $^3P_2$ partial wave has a weak energy dependence, so that the peak observed at 1.3 GeV/c might possibly be a consequence of a resonance in a $^3P_0$ or $^3P_1$ state.

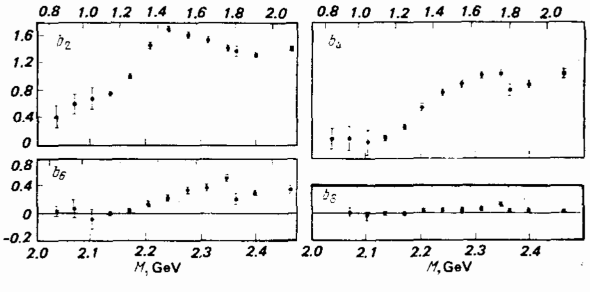

FIG. 5. Coefficients in the expansion of polarization data in Legendre polynomials.

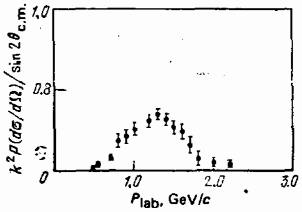

FIG. 6. Energy dependence of the polarization at $\theta_{c.m.}=63°$.

d) C_{LL}

The spin–spin correlation parameter $C_{LL}(\theta_{c.m.})$ has been measured in pp scattering for angles $70° \leqslant \theta_{c.m.} \leqslant 110°$ and for momenta from 1.0 to 3.0 GeV/c at the Argonne National Laboratory.[15] Figure 7 shows the values of C_{LL} at $\theta_{c.m.}=90°$; there is a sharp minimum at 1.2 GeV/c, a rapid falling off near 1.5 GeV/c, and some structure near 2 GeV/c. Let us first examine this rapid falling off at 1.5 GeV/c. For assistance in determining the partial-wave composition, Fig. 8 shows the dimensionless quantities $k^2C_{LL}(d\sigma/d\Omega)$ at $\theta_{c.m.}=90°$:

$$\left[k^2C_{LL}\left(\frac{d\sigma}{d\Omega}\right)\right]_{90°} = 0{,}77\,|{}^3F_3|^2+\mathrm{Im}\,A\cdot\mathrm{Im}\,{}^3F_3+\mathrm{Re}\,A\cdot\mathrm{Re}\,{}^3F_3+\ldots\text{terms without }{}^3F_3); \tag{15}$$

here A is the sum of other partial waves, which can be determined from the phase-shift analysis. Substituting these quantities and the parameters of the $^3F_3$ resonance, we can reproduce the rapid falling off, as shown in Fig. 8.

We turn now to the structure at 2.0 GeV/c. It follows from the earlier discussion that the resonance-like structure at 2 GeV/c is caused by a singlet state. The contribution of the singlet states to C_{LL} is

$$k^2C_{LL}\left(\frac{d\sigma}{d\Omega}\right)=-\,|{}^1S_0+5\,{}^1P_2P_2(\cos\theta)+9\,{}^1G_4P_4(\cos\theta)+\ldots|^2+\ldots\,. \tag{16}$$

The $^1G_4$ contribution should vanish at the angle $\theta_{c.m.}=74°$, where $P_4=0$; in fact, there is no structure at 2 GeV/c at 74°, as can be seen from Fig. 8(b). It follows that the possible resonance at 2 GeV/c is a $^1G_4$ resonance.

Finally, the sharp minimum at 1.2 GeV/c may possibly result from the $^1D_2$ singlet state. The identification as a singlet state follows from the maxima in $\Delta\sigma_L$ and $\Delta\sigma_T$. The structure in C_{LL} with a minimum at 1.2 GeV/c in Fig. 8 may also follow from a resonance-like behavior of $^1D_2$ (Ref. 16).

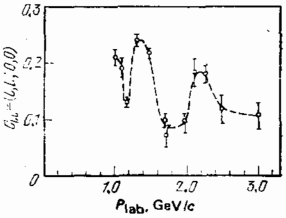

FIG. 7. The spin–spin correlation parameter C_{LL} at $\theta_{c.m.}=90°$.

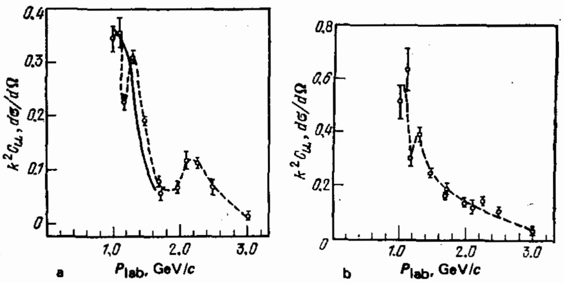

FIG. 8. a—$k^2 C_{LL}(d\sigma/d\Omega)$ at $\theta_{c.m.} = 90°$; b—at 74°. Dashed curve—curve drawn by hand to fit the experimental points; solid curve—contribution of the $^3F_3$ resonance.

e) C_{NN} and $C_{NN} - C_{LL}$

The spin-spin correlation parameter C_{NN} is pp scattering has been measured in many laboratories.[17-22] Data from the Argonne National Laboratory,[17] where C_{NN} was measured for $|t| \geq 0.2$ (GeV/c)^2 and for eight values of the proton momentum from 1.1 to 2.75 GeV/c, revealed an abrupt change in the nature of the angular dependence of C_{NN} at 1.1–2 GeV/c. The most interesting measurements were those at $\theta_{c.m.} = 90°$ (Fig. 9), since at this angle the parameter C_{NN} is related in a simple way to the cross sections in the triplet (σ_t) and singlet (σ_s) states:

$$\frac{1+C_{NN}}{1-C_{NN}} = \frac{\sigma_t}{\sigma_s}. \tag{17}$$

If these data are correct,[17] then the $C_{NN}(90°)$ maximum reached at 1.34 GeV/c leads to the value $\sigma_t/\sigma_s = 15$, which in turn indicates that a triplet state is highly dominant. Other measurements[18] yield a slightly lower value of σ_t/σ_s, but the important point is that the observed structure lies near the proposed $^1D_2$ and $^3F_3$ resonances and may be caused by them.

In a study carried out jointly by groups from the Leningrad Institute of Nuclear Physics and the Joint Institute for Nuclear Research,[18] in which C_{NN} was measured at five energies over the range 690–950 MeV, an analysis of the difference $C_{NN} - C_{LL}$ at the angle of 90° was proposed. Neither $^3F_3$ nor $^1D_2$ contributes to this difference. Yokosawa reported the experimental data available (Fig. 10) to a conference at Lausanne.[23] The sharp structure observed at 1.3 GeV/c, i.e., at the same momentum at which an effect is observed in the polarization ($\theta_{c.m.} = 63°$), indicates that the triplet state most likely to be responsible for this structure is the $^3P_0$ state.

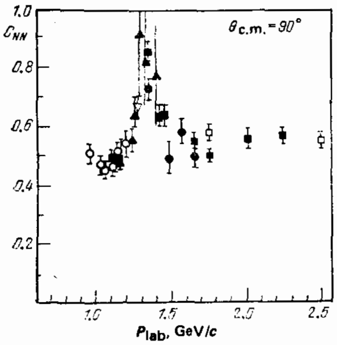

FIG. 9. The spin–spin correlation parameter C_{NN} at $\theta_{c.m.} = 90°$.

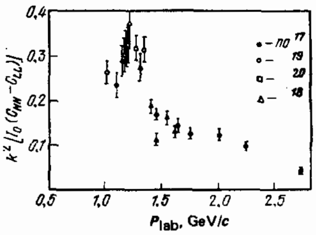

FIG. 10. $k^2[I_0(C_{NN} - C_{LL})]$ at 90° for various proton momenta.

f) Elastic scattering

The total elastic pp cross section also has structure[8] at 1.5 GeV/c (Fig. 11). The elastic cross section is expressed in terms of the partial-wave amplitudes by

$$\sigma_{el} = \frac{2\pi}{k^2}\sum_J (2J+1)(|R_{JJ}|^2 + |R_{J+1,J}|^2 + |R_{J-1,J}|^2 + |R^J|^2). \tag{18}$$

The size of the peak at 1.5 GeV/c is consistent with the suggestion of a $^3F_3$ resonance with the elasticity of 0.15–0.25 inferred from the $\Delta\sigma_L$ data.

The amplitude for forward elastic pp scattering, averaged over the spin, has been measured quite well.[24] The ratio of the real part to the imaginary part (Fig. 12) changes sign near 1.4 GeV/c, and nothing approaching a convincing explanation for this change has been proposed. In general, a situation of this type, involving a rapid decrease and a change in sign, is typical of the real amplitude near a resonance, unless the changes are weakened by background effects. The data in Fig. 12 can be explained well[16] by postulating $^1D_2$ and $^3F_3$ resonances.

The experimental momentum dependence of $d\sigma/dt$ at angles below 40° shows indications of a peak at 1.5 GeV/c, which fades with increasing angle and vanishes above 50°. This behavior can also be explained well on the basis of a $^3F_3$ resonance.

g) Dispersion analysis

Grein and Kroll[25] calculated the real part of $[\Phi_1(0) - \Phi_3(0)]$ through the use of dispersion relations and data on $\Delta\sigma_L$. They showed that the Argand diagram for the amplitude

$$A_3 = -\frac{p_{lab}}{k_{c.m.}}[\Phi_1(0) - \Phi_3(0)]$$

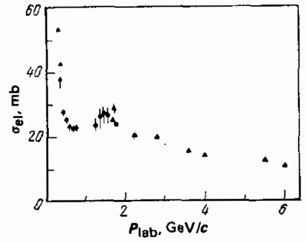

FIG. 11. Total cross section for elastic pp scattering.

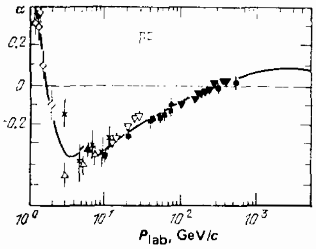

FIG. 12. The ratio (α) of the real part of the pp scattering amplitude to the imaginary part at $|t| = 0$.

has a clearly defined resonance-like behavior (Fig. 13) near 1.5 and 1.2 GeV/c.

h) Phase-shift analysis

Several groups have reported phase-shift analyses in the vicinity of the proposed dibaryon resonances.[16,26-29]

Hoshizaki[16] carried out a phase-shift analysis over the momentum interval 1.1–3 GeV/c, working from all the information available up to 1978 and from the real parts of the forward scattering amplitude found from the dispersion analysis by Grein and Kroll.[25] Figure 14 shows Argand diagrams which Hoshizaki constructed for the $^1D_2$ and $^3F_3$ states. The background was subtracted under the assumption that it had a smooth behavior and through an extrapolation from low energies into the resonance region. Figure 14 clearly indicates $^1D_2$ and $^3F_3$ resonances.

Arndt[26] recently carried out a phase-shift analysis of pp scattering: an energy-independent analysis up to 800 MeV and an energy-dependent analysis up to 900 MeV. His results again confirm the existence of $^1D_2$ and $^3F_3$ resonances.

A phase-shift analysis up to 750 MeV has been carried out at Saclay.[27] Two solutions were found above 550 MeV; although one of these solutions agrees well with Hoshizaki's results, it should be noted that this phase-shift analysis was carried out at energies below the resonance energy for the $^3F_3$ state.

In 1980, the results of a new phase-shift analysis by Hoshizaki at 1.1, 1.275, 1.45, and 1.7 GeV/c were reported. This analysis made use of data obtained recently at the synchrocyclotron of the Leningrad Institute of Nuclear Physics and at meson factories in the USA and Switzerland. These results confirm the existence of $^1D_2$ and $^3F_3$ resonances, and they also indicate a structure in the energy dependence of the absorption parameter in the $^3P_2$ wave at a momentum of about 1.7 GeV/c. The future will tell whether these results are at all pertinent to the structure in the difference $\Delta\sigma_T - \Delta\sigma_L$ at 2.0 GeV/c. Yet another implication of this new analysis is a possible resonance in the $^3P_0$ or $^3P_1$ wave at 1.3 GeV/c. Such a resonance would be consistent with earlier suggestions based on measurements of $C_{NN} - C_{LL}$ at 90° and measurements of the polarization at 63°.

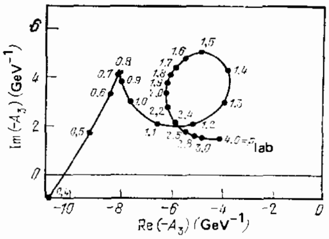

FIG. 13. Argand diagram for $[\Phi_1(0) - \Phi_3(0)]$.

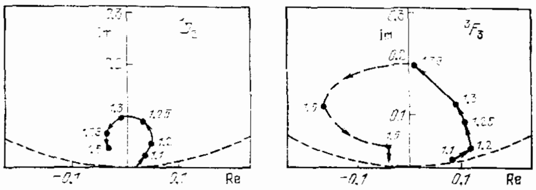

FIG. 14. Argand diagrams for the $^1D_2$ and $^3F_3$ partial waves from the phase-shift analysis by Hoshizaki.[16] The background has been subtracted.

Also published in 1980 were the preliminary results of a phase-shift analysis[29] carried out over the momentum interval 1.0–1.5 GeV/c by another Japanese group. The primary distinction between this phase-shift analysis of Hoshizaki's is that it does not use as initial data the forward scattering amplitudes found from the dispersion analysis by Grein and Kroll.[25] The results confirm the basic conclusions of Hoshizaki's phase-shift analysis.

i) Inelastic reactions

Since the resonances which have been proposed have a small elasticity, they should decay primarily through different (inelastic) channels: $NN \to NN\pi, \pi d$. We should thus expect a significant contribution from resonances in, for example, the production of single mesons, $pp \to pn\,\pi^+$, $pp\pi^0$. A model of this type which has been studied by König and Kroll[30] will be discussed later on in this review. It turns out that the introduction of $^1D_2$ and $^3F_3$ resonances substantially improves the description of the energy dependence of the cross sections for the inelastic channels in the state with $T = 1$ for the momentum interval 1–2 GeV/c.

j) Nonresonance interpretations of the experimental data

The publication of the first Argonne data and their explanation as resonances was followed immediately by papers suggesting nonresonance interpretations. The possibility of a nonresonance interpretation is based primarily on the fact that the observed energies lie near the threshold for the production of the (3.3) isobar and in an energy interval in which the cross sections for inelastic processes increase sharply.

Several papers have suggested that higher-order partial waves should be examined, that background effects should be evaluated in a different way,[31] that the experimental results might be explained by an inelastic-threshold model with one-boson exchange,[32] etc. These possibilities were discussed by Hidaka and Yokosawa,[14] who reported, in particular, that the results of the one-boson-exchange model were incompatible with the experimental data and that there was some arbitrariness in the results calculated by Minami.[31]

In a series of three papers over the past year, Silbar and Kloet[33] have examined the nucleon–nucleon dynamics of intermediate energies. They neither introduced nor found dibaryon resonances, but their Argand diagrams show, for example, a circular motion which is similar to that which emerges from the phase-shift analyses, but slower. This behavior was attributed to a large contribution of inelastic processes. We have two comments regarding these papers. First, although large spin-dependent effects and Argand diagrams similar to those of the phase-shift analyses are derived, the model used does not give a satisfactory description of many experimental results: the cross sections averaged over the spin, $\Delta\sigma_T$, etc. Second, it was pointed out at the Tokyo conference[34] that if the number of channels is assumed to be different from that in the model of Ref. 33 it becomes possible to obtain a resonance solution.

In a very recent paper, Hollas[35] attributes the structure in $\Delta\sigma_L$ and $\Delta\sigma_T$ to increases in the singlet and triplet cross sections which occur at different energies (the increases are shifted along the energy scale). The energy dependence of $\Delta\sigma_L$ and $\Delta\sigma_T$ is described well by Hollas's approach, but it is not clear how other experimental results are to be explained. Furthermore Hollas's study leans on data on the inelastic cross sections in the momentum interval 1–2 GeV/c, which are very uncertain.

The strongest criticism of the resonance interpretation has been advanced by Bugg in papers delivered to conferences at Argonne[36] (1978), Vancouver[37] (1979), and Lausanne[10] (1980; see also Ref. 38). Many of Bugg's points have subsequently been negated by measurements of $\Delta\sigma_L$ and $\Delta\sigma_T$ over the energy range 200–500 MeV at the TRIUMF meson factory.[10] The new data are slightly different from the Argonne data, so that they can be reconciled with the results of the phase-shift analysis, and the conflict with the inelastic data and with the ReF_3 calculations from the dispersion relations can be resolved.[10] These new data, however, confirm that there is structure in both $\Delta\sigma_L$ and $\Delta\sigma_T$. As a result of these new developments, Bugg's paper at the Lausanne conference accepts the resonance interpretation of the experimental data as possible, but not yet proved. Bugg's suggestion for a nonresonance interpretation is based on an analysis of the threshold effects associated with the opening of the $pp \to N\Delta$ channel and with inelastic reactions, which may in principle be responsible for the oscillations in $\Delta\sigma_L$ and $\Delta\sigma_T$.

Whether the structure observed near the isobar threshold is a resonance or a consequence of the opening of inelastic channels was discussed in detail by Edwards and Thomas.[39] For simplicity, they assumed only two channels: pp scattering in the $^1D_2$ state (an elastic channel) and quasi-two-particle $n\Delta^{++}$ scattering in a $^5S_2$ state (an inelastic channel). Their analysis shows that the appearance of resonances is not a consequence of the $n\Delta^{++}$ channel. The parameters for the $^1D_2$ resonance are approximately the same as those found in other studies.

TABLE I. Dibaryon resonances with $T=1$.

	B_1^2 (2.14)	B_1^2 (2.18)	B_1^2 (2.22)	B_1^2 (2.43)	B_1^2 (2.43)
State	$^1D_2$	$^3P_0$	$^3F_3$	$^1G_4$	Triplet
Mass, GeV	2.14–2.17	2.18–2.20	2.20–2.25	2.43–2.50	2.43–2.50
Width, MeV	50–100	100–200	100–200	~ 150	~ 150
J^P	2^+	0^-	3^-	4^+	
Energy (lab frame), GeV	0.585	0.665	0.831	1.271	1.271
Momentum (lab frame), GeV/c	1.2	1.3	1.5	2	2
Evidence	$\Delta\sigma_L$, $\Delta\sigma_T$, C_{LL} Phase-shift analysis	P, $C_{NN}-C_{LL}$	$\Delta\sigma_L$, P, C_{LL}, σ_{el} Dispersion analysis, phase-shift analysis	$\Delta\sigma_T$, C_{LL}	$\Delta\sigma_T-\Delta\sigma_L$

We see that the situation with regard to dibaryon resonances and the attitude of both theoreticians and experimentalists toward them are changing rapidly. It is thus quite possible that the table of proposed dibaryon resonances given here will also be changed in the near future. Table I shows the parameters of resonances with $T=1$ and cites the data obtained in proton–proton scattering in which the properties of the resonances can be seen. The designation B^2 was adopted for these resonances at the "Rochester" conference in Tokyo in 1978.

2. DIBARYON RESONANCES IN THE PHOTODISINTEGRATION OF THE DEUTERON

Historically the first experimental hint of the possible existence of dibaryon resonances emerged from experiments on the photodisintegration of the deuteron.[6,40] A Japanese group measuring the polarization of recoil protons at 90° in the c.m. frame observed a resonance structure in the energy dependence the polarization and a high value of the polarization itself at photon energies of 400–600 MeV (Fig. 15). The effects were attributed to a dibaryon resonance.

Several other experiments on the photodisintegration of the deuteron have been reported in recent years. Data are now available on the differential cross sections, the polarization of the recoil protons, the asymmetry of a polarized beam, and the asymmetry of a polarized target. Attempts have been made in several papers[41,42] to explain the data on the photo-

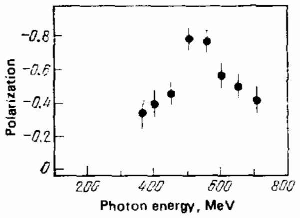

FIG. 15. Proton polarization ($\theta^*=90°$) resulting from photodisintegration of the deuteron.

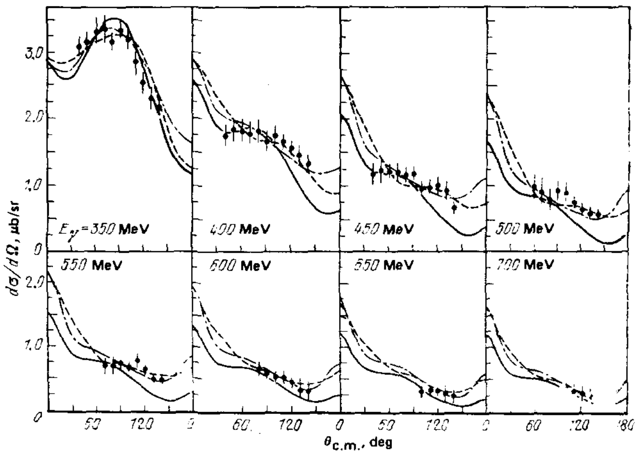

FIG. 16. Photodisintegration of the deuteron; differential cross sections. Solid curves—without resonances; dot-dashed curves—with $1(3^-)$ and $0(3^+)$ resonances; dashed curves—with $1(3^-)$ and $0(3^+)$ resonances.

disintegration of the deuteron on the basis of one of several models without hypothesizing the existence of dibaryon resonances, but these attempts have been unsuccessful. A model-independent analysis is necessary for determining whether these resonances exist. A partial-wave analysis meeting this requirement was carried out in 1978-79 (Refs. 43 and 44) over the photon energy range 350–700 MeV, which corresponds to $\sqrt{s} = 2.20–2.48$ GeV. Data on the differential cross sections (67 points) and on the polarization (37 points) were used. The nonresonance part of the $\gamma d \to pn$ amplitude was calculated from the Ogawa model.[41] Since the actual number of dibaryon resonances and their quantum numbers were not known at the outset, the approach taken in this analysis was to introduce the minimum number of resonances for which quantum numbers could be found which would satisfy the experimental data. All possible combinations $T(J^P)$ up to $J = 4$ were considered.

The results of this analysis showed that at least two dibaryon resonances are required in order to describe the experimental data (unless resonances were invoked, no solution could be found to fit the experimental data). The best solutions with acceptable values of χ^2 turned

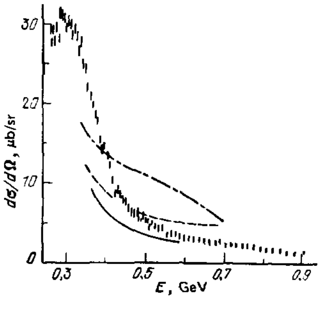

FIG. 17. Photodisintegration of the deuteron; $d\sigma/d\Omega(\theta^* = 180°)$. Solid curve—without resonances; dot-dashed curve—with $1(3^-)$ and $0(1^+)$ resonances; dashed curve—with $1(3^-)$ and $0(3^+)$ resonances.

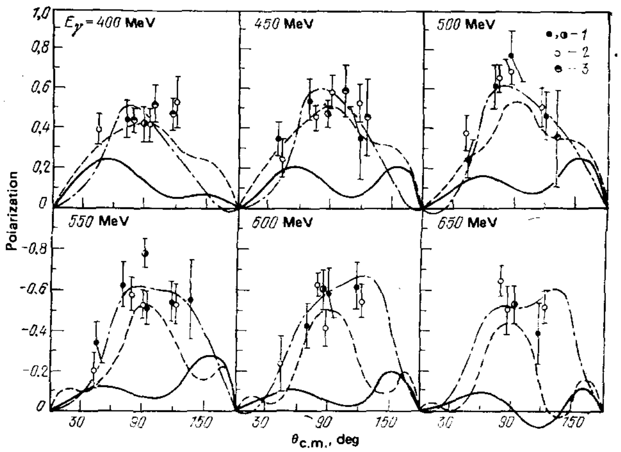

FIG. 18. Angular dependence of the proton polarization in the reaction $\gamma d \to np$. Experimental points: 1—from Refs. 6 and 43; 2—Refs. 47 and 48; 3—Ref. 49. The curves are the same as in Fig. 16.

out to be

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

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

The first point to be noted is that in all the solutions the parameters of the $1(3^-)$ resonance turn out to be approximately the same as those found in the phase-shift analysis by Hoshizaki.

Let us see how the partial-wave analysis of Refs. 43 and 44 describes the experimental data. We are of course particularly interested in the description of the results which were not included in this analysis.

Figure 16 shows some differential cross sections from Ref. 45. These data are incorporated in the analysis and they accordingly agree well with its results. Although the differential cross sections are not very sensitive to the parameters of the resonances, these experimental results cannot be explained without appealing to resonances. Differential cross sections for scattering through 180° in the c.m. frame were recently

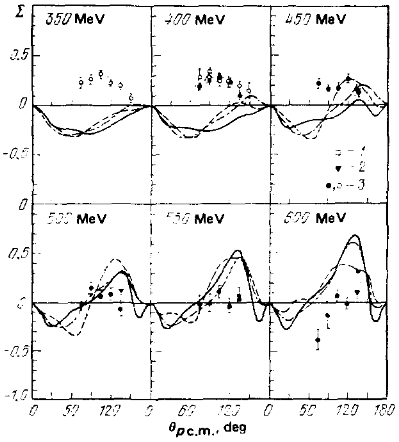

FIG. 19. Asymmetry in the scattering of a polarized beam. Points: 1—from Ref. 53; 2—Ref. 52; 3—Refs. 50 and 51. The curves are the same as in Fig. 16.

obtained at Bonn[46] for the energy interval 260–880 MeV. Figure 17 shows some preliminary data from these measurements; they do not agree with the results of the phase-shift analysis.

Figure 18 shows the angular dependence of the polarization of the recoil protons. The new data obtained by a Khar'kov group[47,48] for broad ranges of energies and angles correspond well to the resonance solutions of the partial-wave analysis.

The asymmetry parameters in the scattering of a polarized beam,

$$\sum(\theta, E_\gamma)=\frac{d\sigma_\perp-d\sigma_\parallel}{d\sigma_\perp+d\sigma_\parallel},$$

were recently measured at Khar'kov[50,51] and Bonn.[46,52] These results are shown along with some older results[53] in Fig. 19. Also shown here are the results of the partial-wave analysis, which do not agree with the experimental results.

The target asymmetry parameter $T=3/2(\sigma\uparrow-\sigma\downarrow)/(\sigma\uparrow+\sigma_0+\sigma\downarrow)$ has been measured in two experiments on the photodisintegration of polarized deuterons.[46,54] Figure 20 shows some preliminary results of these measurements, carried out of Bonn and Tokyo. These results are not described satisfactorily by the results of the partial-wave analysis.

What are we to conclude from this comparison of the available data on the photodisintegration of the deuteron with the results of the partial-wave analysis? Since the partial-wave analysis used data on only the differential cross sections and the polarization, and then only in a limited kinematic region, the resulting solutions are by no means guaranteed to give a correct description of experimental results in a different kinematic region or, especially, experimental results on other properties. The situation here is a quite common one for partial-wave analyses, where an effort is made to describe the experimental data available by means of the smallest number of parameters. The analysis of Ref. 43 incorporated only two dibaryon resonances, while there are evidently more, according to the nucleon–nucleon data; higher-order partial waves were not included; etc. Much more experimental information is now available on the photodisintegration of the deuteron over the energy range 200–900 MeV, and this information could be used for a new partial-wave analysis. The experimental results are shown in Table II, which was part of a report delivered by Kajikawa[55] to the Baryon 1980 conference in Toronto. Some changes have been made in the numbers of experimental points in this table to reflect new results obtained by the Khar'kov group. Increases in the amount of experimental evidence incorporated in the analysis should improve the quality of the analysis and should also substantially refine the parameters of the resonance amplitudes.

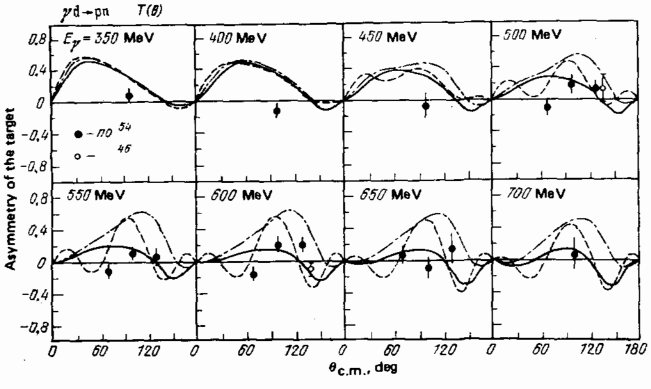

FIG. 20. Asymmetry of the target.

TABLE II. Summary of experimental data on the photodisintegration of the deuteron.

Quantity	E_γ, MeV	θ^*	Number of points	Accelerator	Reference
$d\sigma/d\Omega$	300–800	35°–140°	9×14	Lund	45
$d\sigma/d\Omega$	250–900	180°	80	Bonn	46
P	350–700	90°	8	Tokyo	6
P	350–700	40°–130°	19	Tokyo	13
P	350–450	50°–110°	8	Stanford	16
P	350, 400	70°–80°	3	Bonn	56
P	400–700	45°, 78°, 90°, 120°	40	Khar'kov	47, 48
Σ	200–600	75°–150°	90	Khar'kov	50, 51
Σ	450–700	135°	55	Bonn	46, 52
Σ	400	90°	1	Frascati	53
T	500, 600	130°	2	Bonn	46
T	300–450	70°–130°	23	Tokyo	54

It should be noted that the conclusion that dibaryon resonances exist from data on the photodisintegration of the deuteron was reached to a large extent because it is difficult or impossible to describe the experimental data, primarily on the polarization, in any other way, i.e., without appealing to resonances. A genuinely rigorous analysis would naturally be required for drawing definite conclusions. A more obvious approach is to carry out direct experiments, e.g., to measure the invariant mass distributions for many-particle decays. There is yet another study, carried out at Saclay,[57] which the authors believe yielded evidence for the existence of dibaryons in a study of many-particle final states. Argan *et al.*[57] reported the results of two experiments on the reactions $\gamma d\to pp\pi^-$ and $\gamma d\to pX$ at γ energies in the interval 300–500 MeV. The results of the first experiment are shown in Fig. 21, along with the results of an analysis carried out under the assumption of a quasifree production of mesons with rescattering of a pion by a recoil nucleon.[58] The peak at 410

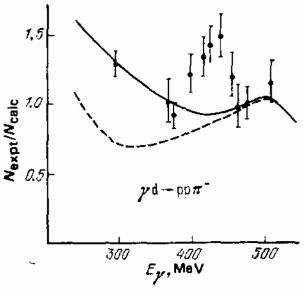

FIG. 21. Ratio of the experimental yield to that calculated in the model of quasifree pion production. Dashed curve—predictions of the model of Ref. 58, which includes quasifree production and first-order rescattering of the pion and the nucleon; solid curve—predictions incorporating second-order rescattering terms.

MeV suggests a resonance. The second experiment yielded an effect at approximately the same energy. Some new experiments are required here.

3. DIBARYON RESONANCES IN PION-DEUTERON INTERACTIONS

All the candidate dibaryon resonances have one property in common: a small elasticity. They must accordingly have decay channels other than the elastic channel, and this conclusion has raised the hope of finding dibaryon resonances in pion–deuteron interactions—in elastic πd scattering, in the reaction $\pi^+ d \to pp$. and in the deuteron disintegration $\pi d \to \pi pn$.

a) The first possible discovery of a dibaryon signal in elastic πd scattering was reported by Kanai *et al.*,[59,60] who analyzed experimental data obtained at the Leningrad Institute of Nuclear Physics[61] and at the Los Alamos meson factory.[62] An expanded version of this report appeared[63] in 1980 with an analysis of essentially all the data on elastic πd scattering at intermediate energies.

The idea underlying this analysis is simple. It has been established that elastic scattering can be described by using the Glauber theory or the Faddeev equation. The Glauber theory was accordingly used to derive the background part of the amplitude, which is of a nonresonance nature and which is essentially the basic part of the amplitude (at any rate, at angles below 90°); a resonance term is added to this background amplitude. The resonance term improves the agreement with experiment at large angles. Kanai and Mihaka[63] introduced three dibaryon resonances, (2^+, 3^-, and 0^+) or (2^+, 3^-, and 4^+), and varied their parameters. The introduction of these resonances substantially improved the agreement of the model with experiment (without the resonances, the value of χ^2 was about 1200, while with the resonances it was about 500, for 240 experimental points). The improvement was particularly marked in the momentum interval 350–500 MeV/c (Fig. 22). The calculations show that the minimum observed at angles of about 100° can be explained in a natural way on the basis of an interference between the background and dibaryon ($^3F_3$) terms. The increase in the cross section at angles near 180° is caused by pions from the decay of a resonance. At small angles, the resonance effect disappears because of the deuteron form factor and because of the high-order partial waves in the pion–nucleon amplitude. The parameters found for the $^3F_3$ resonance through this analysis agree with those found in other studies.

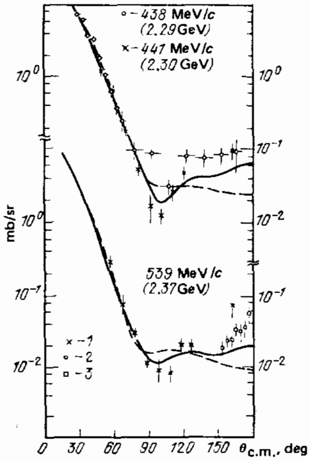

FIG. 22. Differential cross section for elastic πd scattering. Points: 1—From Ref. 62; 2—Ref. 61; 3—Ref. 64. Curves: solid—with resonances; dashed—without resonances.

For the other resonances, the situation is considerably more complicated. The $^1D_2$ resonance falls in a region corresponding to the production of the (3.3) isobar; i.e., the background itself has a resonance-like behavior. Accordingly, although the experimental data are described well in this region when a $^1D_2$ resonance is introduced, it is difficult to prove that the better agreement is in fact due to the resonance. In the region of B^2 (2.43 GeV) the general situation is such that it is not possible to find a satisfactory description of the experimental data, so that it is difficult to determine parameters for the resonance from the analysis. As evidence for the existence of a resonance, Kanai and Mihaka[63] cite the good description of the energy dependence of the differential cross section for scattering through 180°, particularly the maximum at 700 MeV/c; this dependence, however, can also be explained without a dibaryon.[65]

Some interesting results of this analysis are the values found for the partial widths for the resonances: 20 MeV for $^1D_2$ and 8 MeV for $^3F_3$. Other estimates of $\Gamma_{\pi D}/\Gamma_{\text{tot}}$ have been reported,[66] but all lead to small values ($\leqslant 0.1$). Grein *et al.*[67] calculated the ratio $x = \Gamma_{B^2 \to \pi d}/\Gamma_{B^2 \to \pi^+ np}$ from a model which they adopted for the wave function of the quark subsystems in a bag. The value of x turned out to be small for both $^1D_2$ and $^1F_3$ (1.5–3%) and relatively insensitive to the model. As follows from Ref. 67, the deuteron channel is suppressed because the dibaryon wave function is concentrated in a small spatial volume, comparable to that of the deuteron. The conclusion reached is that the small probability for the decay of the resonances into the πd channel makes it difficult to detect the presence of a resonance by analyzing the differential cross sections for elastic scattering. This circumstance may explain why a phase-shift analysis[68] carried out for elastic πd scattering for energies of 82–292 MeV failed to give a clear answer to the question of whether dibaryon resonances exist.

In Refs. 69 and 70, experimental data were analyzed with the help of the Faddeev equations to which a resonance term was added. At energies above 200 MeV, good agreement with the experimental data could not be found. This result forces us to be cautious about Kanai and Mihaka's conclusion[63] that data on the differential cross sections for elastic πd scattering can be used to detect resonances.

A dibaryon signal can, of course, be observed better in πd scattering through 180°, where there is the possibility in principle of detecting interference effects with a resonance dibaryon amplitude. Frascaria *et al.*[71]

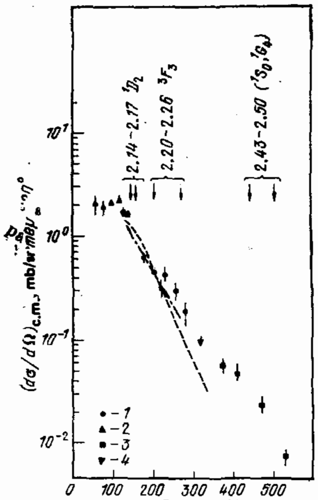

FIG. 23. Differential cross section for elastic πd scattering through 180°. Points: 1—from Ref. 71; 2—Ref. 72; 3—Ref. 64; 4—Ref. 62. The curves show the results of calculations based on various versions of the relativistic three-body theory. The arrows show the positions of resonances.

have studied the differential cross section for backscattering in a special experiment; the results are shown in Fig. 23. They believe that there is some structure near 250 MeV which can be explained on the basis of the production of a dibaryon resonance.

Since the probability for decay into the πd channel is small in general, we could expect to find a significant resonance signal only by observing quantities which are sensitive to an interference between the resonance and background amplitudes. Such a possibility exists in a study of the spin variables in elastic $\pi\vec{d}$ scattering. The first measurement of the tensor polarization t_{20} (180°) was carried out at 245 MeV/c. The measured value, $t_{20}=-0.23\pm0.15$, is difficult to reconcile with any of the various theoretical calculations. This circumstance was one of the leading arguments in favor of dibaryon resonances in the analysis by Kanai and Mihaka[63]: when they incorporated resonances, they found the value $t_{20}=-0.304$.

Kubodera *et al.*[70] have carried out calculations for polarization tensors and vectors in elastic $\pi\vec{d}$ scattering. They showed that the angular dependence in the case with a resonance is sharply different from that without a resonance. In the case with a resonance, the quantity iT_{11}, for example, oscillates. At the Lausanne conference, Bolger[73] reported new data from the SIN meson factory on pion scattering by polarized deuterons. Measurements of the parameter iT_{11} at 256 MeV showed (Fig. 24) that its magnitude does in fact oscillate, in good agreement with the predictions of Ref. 70, which were based on the assumption of a $^3F_3$ resonance.

b) There is reason to believe[67] that the dibaryon signal in the $\pi^+d\to pp$ reaction cannot be expected to be significantly larger than that in elastic πd scattering. It would thus be better to seek a dibaryon from measurements of the spin characteristics. The spin-dependent parameters A_{y0}, A_{0y}, A_{xx}, A_{zz}, and A_{zx} were recently measured at SIN for the inverse reaction[74] $pp\to\pi^+d$. These results, along with the results of earlier studies, made it possible to analyze the reaction $pp\to\pi^+d$ with the goal of finding evidence of dibaryon resonances. In a phenomenological analysis of the reaction $pp\to\pi^+d$ over the energy interval 400–800 MeV. Kamo and Watari[75] used a model in which the amplitude consisted of three parts: a Born amplitude with neutron exchange, a ΔN intermediate state, and a resonance amplitude. Their analysis showed that an amplitude with $^1D_2$ and $^3F_3$ dibaryon resonances must be included in order to find a successful description of the data on the differential cross sections and the polarization. This analysis yielded an unsatisfactory description of the spin characteristics. The basic shortcoming of this analysis, however, is that it was based on a specific model for the nonresonance part of the amplitude, and this model may be inaccurate. A model-independent partial-wave analysis is thus required.

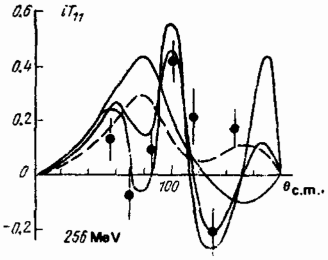

FIG. 24. Polarization vector in πd elastic scattering at 256 MeV. Experimental points: from Ref. 73. Curves[70]: various versions of calculations. Solid curves—with dibaryon resonances; dashed curve—without resonance.

Kamo *et al.*[76,77] have carried out a partial-wave analysis for energies ranging from the reaction threshold up to 578 MeV, i.e., over a range in which there are good measurements of the spin characteristics and

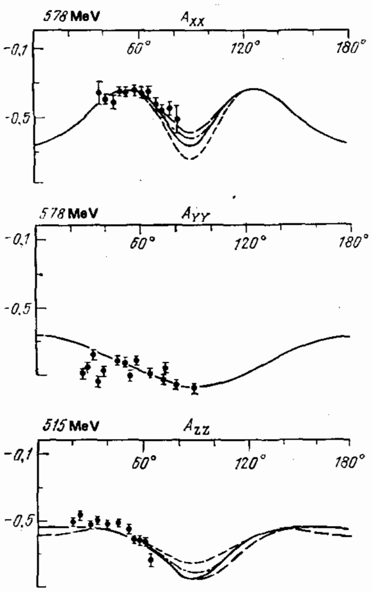

FIG. 25. Experimental data[74] and solutions of a partial-wave analysis[76] for the analyzing power A_{ij}.

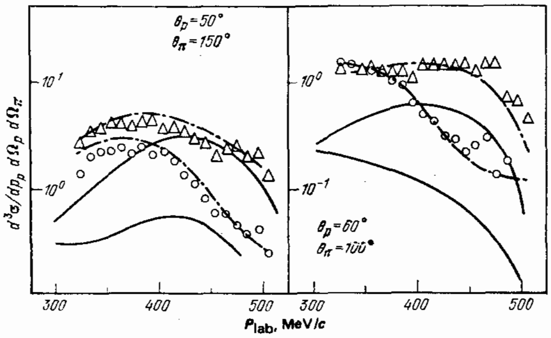

FIG. 26. Differential cross sections for various proton momenta. △—Data for π^+; ○—data for π^-. The curves show calculated results. Dot-dashed curves—with a resonance; solid curves—without a resonance.

which lies below the proposed 2^+ resonance (at 590 MeV) and the 3^- resonance (at 830 MeV), so that the energy dependence of the amplitudes is simplified. Figure 25 shows some of the descriptions of the various distributions. A total of four solutions were found. In all of them, there was a large ${}^1D_2 \to P_2$ amplitude, possibly because of either a ${}^1D_2$ resonance or an intermediate s-wave ΔN state. In two of the solutions, the amplitude for ${}^3F_3 \to D_3$ is large, and this amplitude can be attribued to a ${}^3F_3$ resonance. In both cases, however, we need a criterion for choosing among the solutions, and an analysis at higher energies will be required for confirming the resonances. It might be possible to choose the best solution by measuring the polarization vector T_{11}, for which the predictions of the various solutions are sharply different.

c) Experiments on the disintegration of the deuteron in the vicinity of the (3.3) isobar were recently carried out at the meson factor at Los Alamos.[78,79] The data for low neutron momenta can be described quite well in the impulse approximation. For a description of the data over the entire ranges of the variables, a diagram with a ${}^1D_2$ resonance was introduced; the parameters of this resonance were taken from Hoshizaki's phase-shift analysis.[16] The dibaryon-resonance effect should be visible in that part of the spectrum where the cross sections are small and where the contribution of a resonance amplitude can significantly alter the situation. Figure 26 shows results calculated from a diagram with a dibaryon resonance, along with results calculated without this diagram. The comparison shows that the introduction of the dibaryon resonance substantially changes the calculated results at large proton and neutron momenta and leads to quite good agreement with experiment.

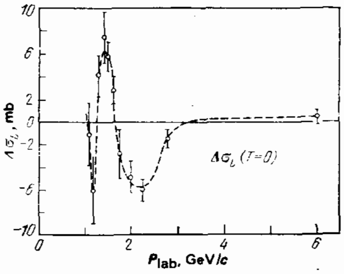

FIG. 27. Values of $\Delta\sigma_L(T=0)$.

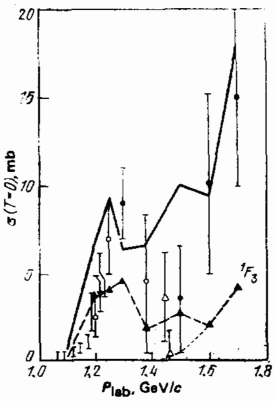

FIG. 28. Cross sections for inelastic interactions with $T=0$. Solid broken line—line connecting the results of the phase-shift analysis; heavy dashed broken line—${}^1F_3$ contribution; thin dashed broken line—background; points—experimental and interpolation values.

4. DIBARYON RESONANCES WITH $T=0$

As we mentioned earlier, the first indication of the existence of an isosinglet resonance arose in an analysis of data on the photodisintegration of the deuteron.[6] In neutron scattering by protons, there are four experimental facts which demonstrate a significant structure at the same values of the momentum.

First, there is the difference between the isoscalar nucleon–nucleon total cross sections $\Delta\sigma_L(T=0)$. The difference $\Delta\sigma_L(\text{pd})$ was measured at the Argonne National Laboratory using a polarized proton beam and a polarized deuterium target.[80] The simplest calculations—which ignore the Glauber correction, the real part of the amplitude, and Coulomb-nuclear interference—yield $\Delta\sigma_L(\text{pd}) = \Delta\sigma_L(\text{pp}) + \Delta\sigma_L(\text{pn})$. The difference $\Delta\sigma_L(T=0) = 2\Delta\sigma_L(\text{pn}) - \Delta\sigma_L(\text{pp})$ can thus be found. As can be seen from Fig. 27, there is a clearly defined structure in the momentum dependence at about 1.5 GeV/c. This structure has led to the suggestion of a new isoscalar spin-singlet dibaryon resonance.[80]

The second of these four experimental facts is the sharp increase in the cross sections for meson production, σ_p, in a state with $T=0$ at momenta above

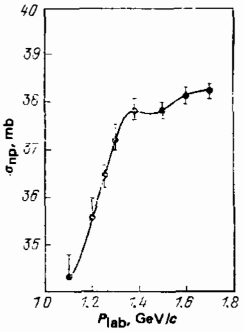

FIG. 29. Total cross sections for np scattering. Curve—results of a phase-shift analysis.

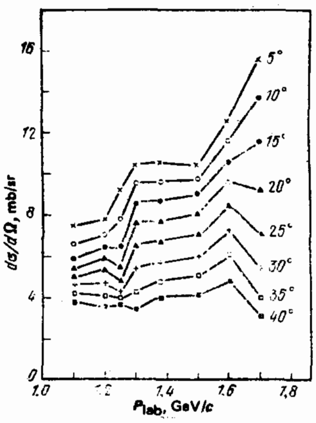

FIG. 30. Experimental dependence of the differential cross sections for forward np scattering. Curves—results of a phase-shift analysis.

1.1 GeV/c (Fig. 28; Ref. 81). Third, there is a change in the energy dependence of the total cross section σ(np): a knee at about 1.1 GeV/c (Fig. 29; Ref. 82). Fourth, there is the structure in the energy dependence of the diffraction peak for forward np scattering[21] at the same momenta (Fig. 30).

These results, particularly those on $\Delta\sigma_L(T=0)$, stimulated two series of studies. A Japanese group carried out 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, using all the information available on np interactions.[28,83,84] It should be noted that some of the data used for the phase-shift analysis were obtained through an interpolation of the results of different studies; the quality of this interpolation for the inelastic cross sections, for example, was not high. The energy dependence of $\sigma_p(T=0)$ is important, because it is one of the basic pieces of information used for the subsequent interpretation of the phase-shift analysis.

In this analysis of np interactions, the parameters of the amplitudes with $T=1$ were determined from a phase-shift analysis of proton–proton scattering. Another important limitation is that the solutions emerging from the np analysis should have been smooth continuations of the solutions of the phase-shift analysis for np scattering at lower energies.[85] Figure 31 shows the results of this new phase-shift analysis for the $^1F_3$ state.[86] A resonance-like structure can be seen for the $^1F_3$ wave. If we assume a smooth background, as indicated by the dashed curve in Fig. 31, and if we use the Breit–Wigner formula, we find the following parameters for the $^1F_3$ resonance: $M\sim 2.19$ GeV, $\Gamma \sim 50$ MeV, and $\Gamma_{el}/\Gamma \sim 0.12$.

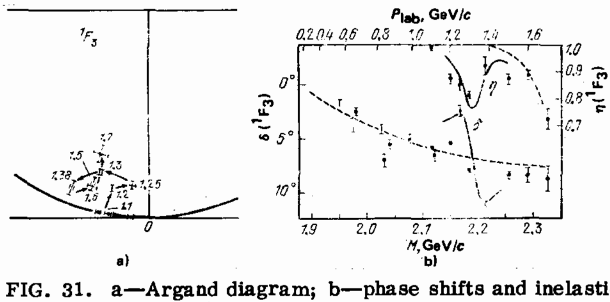

FIG. 31. a—Argand diagram; b—phase shifts and inelasticity parameters for the $^1F_3$ amplitude. Dashed curve—background; solid curve—Breit-Wigner resonance with the parameters given in the text proper.

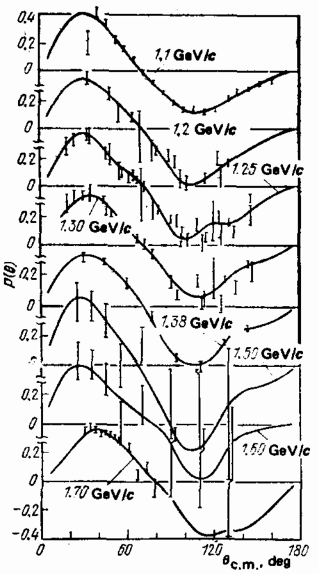

FIG. 32. Polarization in np scattering. Curves—results of a phase-shift analysis.

How well does this proposed resonance explain the observed behavior ?

Figure 28 shows the energy dependence of the cross sections of the inelastic reactions with $T=0$ according to the phase-shift analysis (the solid broken line) and according to experiment. The dashed lines show the contributions of the $^1F_3$ state and of the background. We can see a correspondence between the sharp increase in the cross sections above 1.1 GeV/c and the increase in the $^1F_3$ contribution.

The other observable quantites are also described well by the results of the phase-shift analysis, as is shown for σ(np) in Fig. 29 and for $[d\sigma(\mathrm{np})]/d\Omega$ in Fig. 30. Figure 32 shows data on the polarization; here there is no structure in the energy dependence. This absence of structure is indirect confirmation that the resonance in the singlet state—the quantity $p\,d\sigma/d\Omega$—is expressed exclusively in terms of a triplet amplitude. The polarization in np scattering was measured very recently at momenta of 1.06, 1.28, and 1.44 GeV/c at the Japanese KEK accelerator with a polarized deuterium target.[87] The preliminary results of this experiment correspond well to Hoshizaki's phase-shift analysis.[28,83]

Significantly, it is quite difficult to devise a nonresonance interpretation of the observed structures. There are no inelastic channels with $T=0$ which open up near 1.1 GeV/c. The ΔN channel, which opens up at 1.25 GeV/c, is not related to an np state with $T=0$. The cross section for pair production of mesons is small at these energies. There are accordingly no threshold effects which might produce resonance-like structures in the cross sections. Incidentally, this circumstance means that it would in principle be a simpler matter to choose among the various theoretical models for dibaryon resonances on the basis of their description of this particular resonance, if it exists.

Another approach was developed by Grein, Kroll and König.[88] Working from measurements of $\Delta\sigma_L$, they showed that the effect in $\Delta\sigma_L$ could not be explained by any reasonable model, e.g., the Deck model for the reaction $NN \to NN\pi$ (Ref. 30). Other information was obtained from the forward differential cross sections for np charge exchange. These results can be used, along with the forward NN amplitudes from the earlier analysis by Grein and Kroll[25] and the new pn amplitude obtained from measurements of $\Delta\sigma_L$, to calculate $\operatorname{Im} F_2(\mathrm{pn}) = -(P_{1ab}/4\pi)\Delta\sigma_T(T=0)$ from the dispersion relations. The values of $\Delta\sigma_T$ calculated from experimental data on forward charge exchange from the Los Alamos and SIN meson factories[89] exhibit a minimum of roughly the same magnitude as that of the maximum in $\Delta\sigma_L(T=0)$, and at the same energy. The two structures may be discussed together. It follows from the expressions for $\Delta\sigma_L(T=0)$ and $\Delta\sigma_T(T=0)$,

$$\Delta\sigma_L(T=0) = \frac{4\pi}{k^2}\operatorname{Im}\sum_{\mathrm{Odd}}[(2J+1)R_J - R_{J-1,J} + R_{J+1,J} + 4\sqrt{J(J+1)}R^2] - \frac{4\pi}{k^2}\operatorname{Im}\sum_{\mathrm{Even}}(2J+1)R_{JJ}, \tag{21}$$

$$\Delta\sigma_T(T=0) = -\frac{4\pi}{k^2}\operatorname{Im}\sum_{\mathrm{Odd}}[-(2J+1)R_J + JR_{J-1,J} + (J+1)R_{J+1,J} + 2\sqrt{(J+1)J}R^J], \tag{22}$$

that only a resonance in a bound triplet state could simultaneously produce a maximum in $\Delta\sigma_L$ and a minimum in $\Delta\sigma_T$ (we cannot, of course, rule out the possible existence of several resonances, which cancel out). An approximation by the Breit–Wigner formula (of $\Delta\sigma_L$ and $\Delta\sigma_T$ simultaneously) yielded the following parameters for the resonance: $J^P = 1^+ \Gamma_{el}/\Gamma \sim 0.3$, $\varepsilon = 4.4$ or 0.6 (ε is the mixing parameter) for $J^P = 1^+$; $\Gamma_{el}/\Gamma \sim 0.13$, $\varepsilon = 3.0$ or 0.5 for $J^P = 3^+$; $M \sim 2.25$ GeV; and $\Gamma \sim 100$ MeV.

Grein *et al*. themselves made two comments about this analysis. First, the values which they found for $\Delta\sigma_T(T=0)$ at energies above the inelastic thresholds disagree—seriously—with the predictions of the phase-shift analyses. Second, if the older data[90] are used for the charge-exchange cross sections, different values are found for $\Delta\sigma_T$; it would then follow from a joint analysis of $\Delta\sigma_L$ and $\Delta\sigma_T$ that there would have to be at least two resonances, which cancel out in $\Delta\sigma_T$. One would be a singlet and the other a bound doublet. Their masses and widths would be the same, because of the errors in the data and the analysis.

Since the resonance has a small elasticity, it may be possible to see evidence of it in the cross sections for inelastic reactions. In pursuit of this possibility, the cross sections calculated from the Deck model, which gives a good description of the experimental data at high energies,[30] were augmented with contributions from resonances: the $T=0$ resonance under discussion here and the $T=1$, $J^P = 3^-$ resonance, which is the one which has been established most solidly. Interference terms were ignored. By virtue of unitarity, the contribution of the resonance to the total $T=0$ inelastic cross section is given by

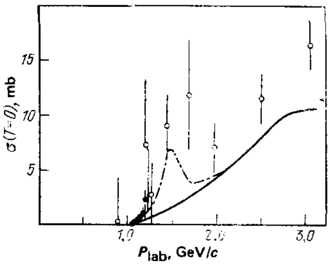

FIG. 33. Inelastic cross section in the state with $T=0$ (the experimental points are taken from Ref. 88).

$$\sigma^{\mathrm{res}}(T=0) = \frac{2\pi}{k^2}\frac{(2J+1)\Gamma_{el}(\Gamma-\Gamma_{el})m^2_{\mathrm{res}}}{(m^2-m^2_{\mathrm{res}})^2+m^2_{\mathrm{res}}\Gamma^2}V(m^2), \tag{23}$$

where the threshold factor $V(m^2) = [(m^2 - m^2_{\mathrm{thr}})/(m^2_{\mathrm{res}} - m^2_{\mathrm{thr}})]^{J/2}$ is introduced so that the cross section for the production of the resonance in the inelastic channel will vanish at the threshold for meson production. Figure 33 compares the calculations with experimental data; we see that the introduction of the resonances significantly improves agreement with experiment. Good data on the cross sections for the inelastic channels will be required, however, to test all these conclusions.

Dakhno *et al*.[99] recently reported measurements of the cross sections for the reaction $\mathrm{pn} \to \mathrm{pp}\pi^-$ at nine energies in the interval 550–1000 MeV. It follows from their results that there is no maximum in the energy dependence of the cross section which would correspond to the resonance proposed by Grein *et al*.[88] The values found in Ref. 99 for the isoscalar cross section σ_0 do not agree with the predictions of Ref. 84 or 88. This disagreement means that, if dibaryon resonances do exist in the $T=0$ channel, their parameters are quite different from the existing theoretical predictions.[84,88]

A few comments can be made regarding other structures in a state with $T=0$. Hoshizaki's phase-shift did not yield a clearly defined resonance-like behavior in the Argand diagrams for other states. On the other hand, the data on pp scattering have already improved to the point that we can see possible resonances in ^{3}P waves in the $T=1$ channel. As a consequence, there may be a modification of certain $T=0$ states, e.g., the ^{1}P state, so that their Argand diagrams would exhibit a resonance behavior. In any case, the contribution of the ^{1}P wave to $\Delta\sigma_L(T=0)$ is large. Some of the triplet phase shifts might have some structure above 1.7 GeV/c. In one case, the structure may correspond to the dibaryon state ($T=0, J=3, M=2.35$ GeV) which was proposed for an explanation of data on the photodisintegration of the deuteron. The same resonance can explain the energy dependence of the cross sections for pair production of mesons. Figure 34 shows the results of a parametrization[91] of the cross sections for $NN \to d\pi\pi$ reactions. The large cross section for pair production of mesons in the $T=0$ state confirms the possible existence of a resonance with $T=0$,

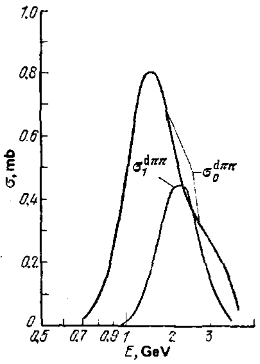

FIG. 34. Total cross sections for the reaction $NN \to d\pi\pi$ for states with isospins $T=0$ and $T=1$.

$J=3$. Further measurements are obviously necessary. Table III is a table of dibaryon resonances with $T=0$ which Yokosawa reported to the Lausanne conference.

What are the arguments against the existence of dibaryon resonances with $T=0$? We should emphasize at the outset that the data which were used as initial data for Hoshizaki's phase-shift analysis[83] or with which Grein *et al.*[88] compared their results are exceptionally contradictory, as can be seen by comparing the experimental points for $\sigma(T=0)$ in Figs. 28 and 33. This discrepancy in the experimental data could of course have seriously affected both the results of the phase-shift analysis and the results of Grein *et al.*, since Grein *et al.* also used inelastic cross sections for choosing the parameters. It is thus not surprising that the resonances with $T=0$ in these studies differ.

Bugg[10] has offered some arguments which he believes show that it is premature to propose the existence of dibaryon resonances with $T=0$. First, he states that the tendency of the $^1F_3$ phase shift (i.e., that of the wave in which the resonance is observed) toward positive values at energies below 500 MeV which was found in Hoshizaki's phase-shift analysis does not agree with the results of an unambiguous phase-shift analysis[85] which was carried out on the basis of a large number of really solid experimental points obtained from the meson factories. In this connection we note that in selecting solutions Hoshizaki (as mentioned earlier) actually used the results of an unambiguous phase-shift analysis by Bugg[85] to obtain a smooth dependence of the phase shifts. There is, of course, some difference in the phase shifts, but the difference does not exceed 2–3° for the $^1F_3$ wave. Bugg's second argument runs as follows: Since the results of the phase-shift analysis show a large inelasticity ($T=0$) between 500 and 1000 MeV, this effect is probably a consequence of $NN \to \Delta\Delta$ and/or $NN \to NN^*(1420)$ reactions. Since there is a 50% probability that $N^*(1420)$ will decay into $N\pi\pi$, both these reactions should lead to a large cross section for pair production of mesons, in contradiction of experiment. With regard to this second argument, we note that a large inelasticity may be caused by factors other than these channels. In a recent paper, König and Kroll[30] convincingly explained a large inelasticity in the $T=0$ state on the basis of production of single mesons, working from the Deck model. Bugg's third argument is his strongest. It concerns the results of Grein *et al.*,[88] who in fact raised the point themselves: The results contradict the results of Bugg's phase-shift analysis below 500 MeV. Bugg's call for a careful reanalysis with attention to both the experimental data and the results of the phase-shift analysis thus seems completely reasonable.

TABLE III. Dibaryon resonances with $T=0$.

	B_0^2 (2.14)	B_0^2 (2.22)	B_0^2 (2.43)
State	Triplet?	$^1F_3$	Triplet?
Mass, GeV	2.14–2.17	2.20–2.26	2.40–2.50
Width, MeV	50–100	100–200	

CONCLUSION

We have seen that the experimental data on dibaryon resonances are contradictory in many ways. Over the past two years, the number of candidate dibaryon resonances has at least tripled. There is the possibility that we are attending the birth of a dibaryon spectroscopy. At any rate, we already have predictions of a rich spectrum of resonances in the nucleon–nucleon channel. The individual theoretical studies have not been discussed in this review, but it has been pointed out that dibaryon resonances are predicted by many models. Unfortunately, one of the major questions involved here remains unanswered: Just what is a dibaryon—an ordinary nuclear system of a quasideuteron nature or a six-quark bound state? The $^3F_3$ resonance, the one most clearly expressed, corresponds to an impact parameter of 0.9 F for the two protons. This distance is much smaller than the size of the deuteron (~1.7 F) and corresponds better to the dimensions of an ordinary baryon resonance. At a purely qualitative level, this circumstance indicates that the $^3F_3$ resonance is probably a six-quark state rather than a nuclear system,[14] but all this requires quantitative confirmation. What is needed at the moment is much new experimental information, as soon as possible, to resolve the question of whether dibaryons actually exist and then, if they do exist, to determine their nature and to construct at least a phenomenological systematics.

One of the simplest systematics makes the interesting suggestion that we search for narrow dibaryon resonances. We will begin with this possibility to survey briefly some proposed experiments.

MacGregor[92] has suggested a rotational model according to which the masses of the dibaryon resonances are determined by the energies of the rotational states of a two-nucleon system, $E = E_0 + E_{\rm rot} \cdot l(l+1)$. According to this model, the resonances $^1D_2(2.14)$, $^3F_3(2.26)$, and $^1G_4(2.46)$ conform well to a straight line $\sim l(l+1)$ (Fig. 35), so that low-lying resonances $^1S_0(2.02)$ and $^3P_1(2.06)$ should exist. The basic suggestion[93] is to seek these resonances in the energy dependence $\sigma_{pp}(E)$. There are energy regions in which the total cross section for pp scattering has not been measured, and the masses of the proposed $^1S_0$ and $^3P_1$ resonances fall in

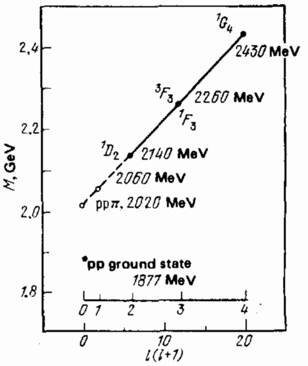

FIG. 35. Dibaryon rotational levels.

these regions (Fig. 36). Although MacGregor's model does not give the widths of these resonances, their total widths can be expected to be comparable in magnitude to the elastic widths of the "established" $^3F_3$ and $^1D_2$ resonances, i.e., 5–20 MeV. Furthermore, there is some basis for assuming[93] that the height of these peaks in the total cross section may be of the order of 10 mb.

Another estimate of the widths of the low-lying resonances is based on the approximation of coupled channels, and it draws on the results of a phase-shift analysis of elastic pp scattering in the pertinent energy range.[96] According to this estimate, the widths of the low-lying resonances should be less than 0.6 MeV. At any rate, measurements of the total pp cross sections near 300 and 390 MeV with a small energy step would be of considerable interest. The following two circumstances may be offered as further arguments for such an experiment: 1) The data on $\Delta\sigma_L$ indicate that there is yet another minimum below 1 GeV/c. 2) In the dispersion analysis by Grein and Kroll, there is a sharp change in the slope of the trajectory on the Argand diagram at a momentum of about 800 MeV/c (Fig. 13).

Fukawa *et al.*[97] have recently proposed several experiments as part of the search for dibaryon resonances. They suggest seeking dibaryon resonances during backward production in the quasi-two-particle reactions

$$\pi^+ d \to \pi^+ B^{2(+)}, \quad \hookrightarrow \Delta^0(p\pi^-)+p \qquad \pi^+ d \to \pi^0 B^{2(++)}, \quad \hookrightarrow p+p \qquad e^- d \to e^- B^{2(+)}, \quad \hookrightarrow pp\pi^-$$

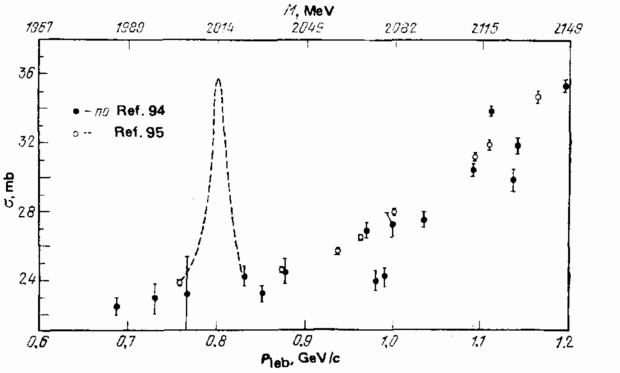

FIG. 36. Total pp cross sections at intermediate energies.

The t dependence of the cross sections would have to be measured in order to reduce background effects.

What other experiments could be proposed to search for dibaryon resonances? For proof of the $^3F_3$ resonance it would be worthwhile to measure $(\Delta\sigma_L)_{el}$ and $(\Delta\sigma_L)_{inel}$ separately, since their energy dependences are sharply different, according to Hoshizaki's phase-shift analysis.[16] For a study of the $^1D_2$ resonance it would be useful to measure the spin–spin correlation parameters for various beam and target polarizations. In general, measurements of correlation parameters yield much information. It has been pointed out elsewhere[7] that it would be important to measure the parameter C_{NN} in proton–proton scattering. If a $^1F_3$ dibaryon resonance does exist, the angular dependence of the parameter C_{NN} in pn scattering would change sharply in the momentum interval[84] 1.1–1.7 GeV/c. The angular dependence of the polarization tensor in the reaction $\pi\vec{d}\to pp$ would be an extremely rich source of information.

It should be emphasized that the resolution of this problem of dibaryon resonances is intimately related to research on inelastic reactions. In all the theoretical results on the resonance decay probabilities,[98] the $NN\to NN\pi$ channel has the highest probability. The observation of resonances in inelastic reactions might resolve one of the most important questions: Are the experimental effects a consequence of the existence of resonances, or are they caused by some other dynamic effects? To test the various models for pion production in nucleon–nucleon collisions, a study should be made of the two-nucleon state with $T=0$, because the background is much smaller than for the $T=1$ channel, in which the (3.3) isobar is intensely produced. Finally, it is necessary to begin polarization measurements in inelastic many-particle reactions.

Interest in the problem of dibaryon resonances is at an extremely high level. The plans for essentially all the intermediate-energy accelerators include dibaryon studies. As a measure of the interest in this problem, we might note that just in the year from May 1979 to June 1980 ten proposed experiments were accepted for the Los Alamos meson factory which were related in one way or another to the search for dibaryon resonances. There is every reason to believe that this massive attack on dibaryons will be rewarded with a solution of this important problem.

[1] R. L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977).
[2] P. Mulders *et al.*, Phys. Rev. Lett. **40**, 1543 (1978); A. Aerts *et al.*, Phys. Rev. **D17**, 260 (1978).
[3] M. Imachi *et al.*, Prog. Theor. Phys. **55**, 551 (1976); **57**, 517 (1977).
[4] T. Ueda, Phys. Lett. **B74**, 123 (1978).
[5] I. P. Auer *et al.*, Phys. Lett. **B67**, 113 (1977); **B70**, 475 (1977).
[6] T. Kamae *et al.*, Phys. Rev. Lett. **38**, 468 (1977).
[7] L. I. Lapidus, Preprint R2-11762, Joint Institute for Nuclear Research, Dubna, 1978.
[8] A. Yokosawa, Phys. Rept. **64**, 47 (1980).
[9] W. de Boer *et al.*, Phys. Rev. Lett. **34**, 558 (1975); E. K. Biegert *et al.*, Phys. Lett. **B73**, 235 (1978).

[10] D. V. Bugg, Report on the 1980 Intern. Symposium on High Energy Physics with Polarized Beams and Polarized Targets, Lausanne, 1980.

[11] M. G. Albrow *et al.*, Nucl. Phys. **B23**, 445 (1970).

[12] K. Hidaka *et al.*, Phys. Lett. **B70**, 479 (1977).

[13] B. A. Ryan *et al.*, Phys. Rev. **3**, 1 (1971).

[14] K. Hidaka and A. Yokosawa, Surveys in High Energy Physics, London, 1979, p. 141.

[15] I. P. Auer *et al.*, Phys. Rev. Lett. **41**, 1436 (1978).

[16] N. Hoshizaki, Prog. Theor. Phys. **60**, 1796 (1978); **61**, 129 (1979).

[17] D. A. Bell *et al.*, Phys. Lett. **B94**, 310 (1980).

[18] Borisov *et al.*, Preprint LINP-581, Leningrad, 1980.

[19] D. Besset *et al.*, Nucl. Phys. **A345**, 435 (1980).

[20] H. B. Willard *et al.*, in: Proc. of Intern. Symposium on High Energy Physics with Polarized Beams and Polarized Targets, Argonne, 1978, AIP Conf. Proc., 1979, No. 51, p. 420.

[21] J. Bystricky and F. Lehar, Nucleon-Nucleon Scattering Data, Karlsruhe, 1978.

[22] A. Lin *et al.*, Phys. Lett. **B74**, 273 (1978).

[23] A. Yokosawa, Report on the 1980 Intern. Symp. on High Energy Phys. with Polarized Beams and Polarized Targets, Lausanne, 1980.

[24] U. Amaldi *et al.*, Ann. Rev. Nucl. Sci. **26**, 385 (1976).

[25] W. Grein and P. Kroll, Nucl. Phys. **B137**, 173 (1978).

[26] R. A. Arndt, LAMPF Nucleon-Nucleon Workshop, 1978; Private communication to prof. A. Yokosawa (1980).

[27] J. Bystricky *et al.*, Preprint D PH PE 79-01, Saclay, 1979.

[28] N. Hoshizaki, in: Proc. of the Second Meeting on Exotic Resonances, Hiroshima, Japan, 1980, p. 1.

[29] H. Kanada *et al.*, Proc. of the Second Meeting on Exotic Resonances, Hiroshima, Japan, 1980, p. 20.

[30] A. König and P. Kroll, Nucl. Phys. **A356**, 345 (1981).

[31] S. Minami, Phys. Lett. **B74**, 120 (1978); Phys. Rev. **D18**, 3273 (1978).

[32] M. Arik and P. G. Williams, Nucl. Phys. **B136**, 425 (1978).

[33] W. M. Kloet and R. R. Silbar, Nucl. Phys. **A338**, 281 (1980); R. R. Silbar and W. M. Kloet, Nucl. Phys. **A338**, 317 (1980); W. M. Kloet and R. R. Silbar, Preprint LA-UR-80-1997.

[34] T. Ueda *et al.*, in: Proc. of 1979 INS Symposium on Particle Physics in GeV Region, Tokyo, 1979, Contr. No. 23.

[35] C. L. Hollas, Phys. Rev. Lett. **44**, 1186 (1980).

[36] D. V. Bugg, in: High Energy Physics with Polarized Beams and Polarized Targets, Argonne, 1978, AIP Conf. Proc. **51**, 362 (1979).

[37] D. V. Bugg, Nucl. Phys. **A335**, 171 (1980).

[38] D. V. Bugg, J. Phys. G **5**, 1349 (1979).

[39] B. J. Edwards and G. H. Thomas, Phys. Rev. **D22**, 2772 (1980).

[40] T. Kamae *et al.*, in: Proc. of the INS Symposium on Electron and Photon Interactions at Resonance Region and on Related Topics, Tokyo, 1975, P. 495.

[41] K. Ogawa *et al.*, Nucl. Phys. **A340**, 451 (1980).

[42] J. M. Laget, Nucl. Phys. **A312**, 265 (1978).

[43] H. Ikeda *et al.*, in: Proc. of the Meeting on Exotic Resonances, Hiroshima, HUPD-7813, Oct. 1978, p. 17; Phys. Rev. Lett. **42**, 1321 (1979).

[44] K. Nakamura, cited in Ref. 34, p. 425.

[45] P. Dougan *et al.*, Z. Phys. **A276**, 55 (1976).

[46] W. J. Schwille, cited in Ref. 34, p. 143.

[47] A. S. Bratashevskiĭ *et al.*, Yad. Fiz. **31**, 860 (1980) [Sov. J. Nucl. Phys. **31**, 444 (1980)].

[48] A. S. Bratashevskiĭ *et al.*, Yad. Fiz. **32**, 418 (1980) [Sov. J. Nucl. Phys. **32**, 216 (1980)].

[49] F. F. Liu *et al.*, Phys. Rev. **165**, 1478 (1968).

[50] V. G. Gorbenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 130 (1979) [JETP Lett. **30**, 118 (1979)].

[51] V. G. Gorbenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 387 (1979) [JETP Lett. **30**, 359 (1979)].

[52] R. Broekmann *et al.*, Bonn IR-79-25, Bonn University, 1979.

[53] G. Barbiellini *et al.*, Phys. Rev. **154**, 988 (1967).

[54] N. Awaji *et al.*, paper submitted to Baryon 1980, Toronto.

[55] R. Kajikawa, talk given at Baryon 1980, Toronto, DNPU-31-80, Sept. 1980.

[56] R. Kose *et al.*, Z. Phys. **A220**, 305 (1969).

[57] P. E. Argan *et al.*, Phys. Rev. Lett. **46**, 96 (1981).

[58] J. M. Laget, Nucl. Phys. **A296**, 388 (1978).

[59] K. Kanai *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 133 (1979) [JETP Lett. **30**, 121 (1979)].

[60] K. Kanai *et al.*, Prog. Theor. Phys. **62**, 153 (1979).

[61] A. V. Kravtsov *et al.*, Nucl. Phys. **A322**, 439 (1979).

[62] R. H. Cole *et al.*, Phys. Rev. **C17**, 681 (1978).

[63] K. Kanai and A. Mihaka, Prog. Theor. Phys. **65**, 266 (1981).

[64] R. Keller *et al.*, Phys. Rev. **D11**, 2389 (1975).

[65] L. A. Kondratyuk and F. M. Lev, Yad. Fiz. **23**, 1056 (1976) [Sov. J. Nucl. Phys. **23**, 556 (1976)].

[66] Y. A. Simonov and M. van der Velde, J. Phys. G **5**, 493 (1979).

[67] W. Grein *et al.*, Preprint SIN, 1980.

[68] J. Arvieux and A. S. Rinat, Preprint WIS-80-26, 1980.

[69] E. Ferreira and G. Munguia, Preprint PUC NC 14/8, 1980.

[70] K. Kubodera *et al.*, J. Phys. G **6**, 171 (1980).

[71] R. Frascaria *et al.*, Phys. Lett. **B91**, 345 (1980).

[72] R. J. Holt *et al.*, Phys. Rev. Lett. **43**, 1229 (1979).

[73] J. Bolger *et al.*, Phys. Rev. Lett. **46**, 167 (1981).

[74] E. Aprile *et al.*, Nucl. Phys. **A335**, 245 (1980).

[75] H. Kamo and W. Watari, Prog. Theor. Phys. 62, 1035 (1979); **64**, 338 (1980).

[76] H. Kamo *et al.*, in: Proc. of the Second Meeting on Exotic Resonances, Hiroshima, 1980, p. 31.

[77] H. Kamo, W. Watari, and M. Yonezawa, Prog. Theor. Phys. **64**, 2144 (1980).

[78] J. H. Hoftiezer *et al.*, Preprint Rice University, Houston, Texas, 1980.

[79] J. H. Hoftiezer *et al.*, Phys. Rev. **C23**, 4071 (1981).

[80] H. Spinka, in: Proc. of Intern. Symposium on High Energy Physics with Polarized Beams and Polarized Targets, Argonne, 1978, AIP Conf. Proc. **51**, 382 (1979).

[81] M. Kleinschmidt *et al.*, in: Proc. of the Eighth Intern. Conference on Few Body Systems and Nuclear Forces, Graz, Austria, Vol. II, 1978, p. 164.

[82] T. J. Devlin *et al.*, Phys. Rev. **D8**, 136 (1973).

[83] N. Hoshizaki, cited in Ref. 34, p. 475.

[84] K. Hashimoto, Y. Higuchi, and N. Hoshizaki, Prog. Theor. Phys. **64**, 1678 (1980).

[85] D. V. Bugg *et al.*, Phys. Rev. **C21**, 1004 (1980).

[86] K. Hashimoto and N. Hoshizaki, Prog. Theor. Phys. **64**, 1693 (1980).

[87] K. Ogawa, cited in Ref. 34, p. 322.

[88] W. Grein, A. König, and P. Kroll, Preprint WU B 80-13; Phys. Lett. **B96**, 176 (1980).

[89] B. E. Bonner *et al.*, Phys. Rev. Lett. **41**, 1200 (1978); W. Hurster *et al.*, to be published in Phys. Lett.

[90] G. Bizard *et al.*, Nucl. Phys. **B85**, 14 (1975).

[91] F. Lehar *et al.*, Preprint DPh PE 79-28, Saclay, 1979.

[92] M. H. Mac Gregor, Phys. Rev. **D20**, 1616 (1979).

[93] T. H. Fields and A. Yokosawa, Phys. Rev. **D21**, 1432 (1980).

[94] G. Giacomelli, Prog. Nucl. Phys. **12**, 214 (1971).

[95] P. Schwaller *et al.*, Nucl. Phys. **A316**, 317 (1979).

[96] J. Wainer and E. Lomon, Preprint MIT-CTP 825, 1979.

[97] M. Fukawa *et al.*, Preprint NUP-A-79-13, 1979.

[98] M. Araki *et al.*, Prog. Theor. Phys. **63**, 2133 (1980).

[99] L. G. Dakhno *et al.*, Preprint LIYaF-692, Leningrad Institute of Nuclear Physics, Leningrad, 1981.

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