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STRUCTURE IN NUCLEON-NUCLEON SYSTEM AND DINUCLEON RESONANCES[†]

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Abstract

An extensive amount of data were obtained from measurements of proton-proton elastic scattering up to 5 GeV/c. We summarize physics learned from these data as well as other related experimental results.

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I. I = 1 System

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

$$\Delta\sigma_L = (4\pi/k)\ \mathrm{Im}\{\phi_1(0) - \phi_3(0)\} = \sigma^{Tot}(\rightleftarrows) - \sigma^{Tot}(\rightrightarrows) ,$$

where arrows refer to initial proton spins along the beam direction and, for instance, $\sigma(\rightleftarrows)$ corresponds to σ_{++} referring to initial proton helicities.

Figures 1 and 2 show $\Delta\sigma_L$ data.[1,2] The large energy dependence are seen not only in $\Delta\sigma_L$, but in $\Delta\sigma_T$, polarization, C_{NN} = (N,N;0,0), and C_{LL} = (L,L;0,0). A remarkable energy dependence has also been observed in the results of $\Delta\sigma_T$ measurements up to 6.0 GeV/c.[3] To study the behavior in terms of the partial scattering amplitudes, the data on $(k^2/4\pi)\ \Delta\sigma_T$ are plotted as shown in Fig. 3 as a function of p_{lab}.

A summary of structure in nucleon-nucleon system is given in Reference 4, and here we update the current understanding.

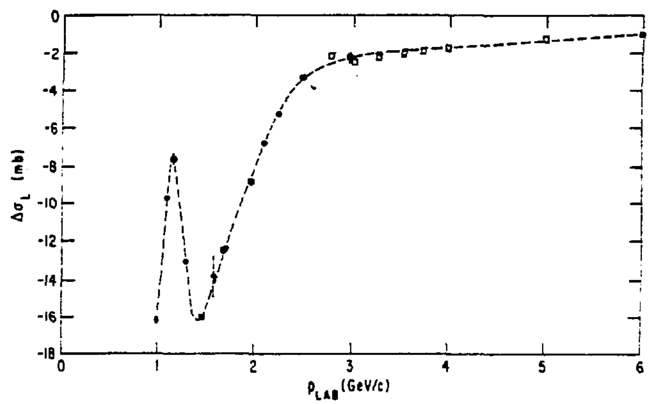


Fig. 1 Total Cross-Section Difference $\Delta\sigma_L = \sigma^{Tot}(\rightleftarrows) - \sigma^{Tot}(\rightrightarrows)$. The white squares are preliminary data.

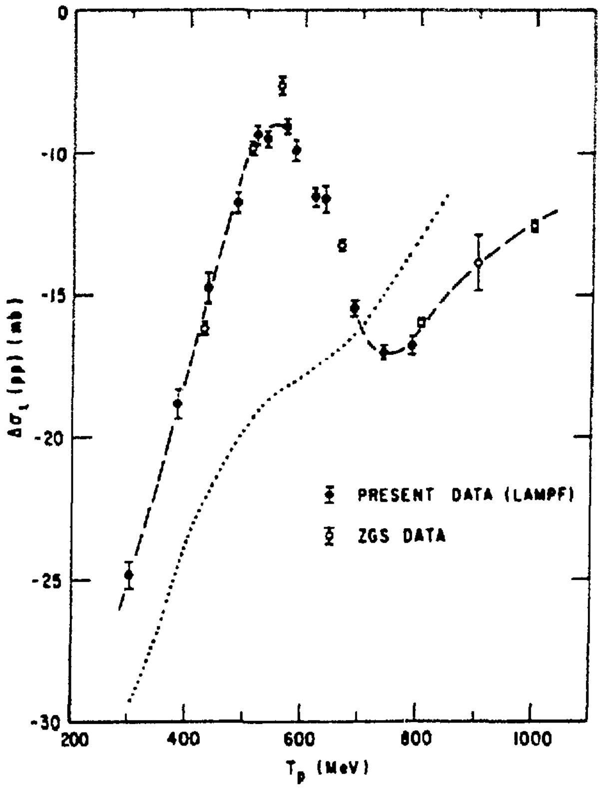


Fig. 2 Energy dependence of $\Delta\sigma_L$(pp). The dashed line is only to guide the eye. The dotted line is obtained when resonant amplitudes $^1D_2$ and $^3F_3$ are subtracted from the original $\Delta\sigma_L$ data.

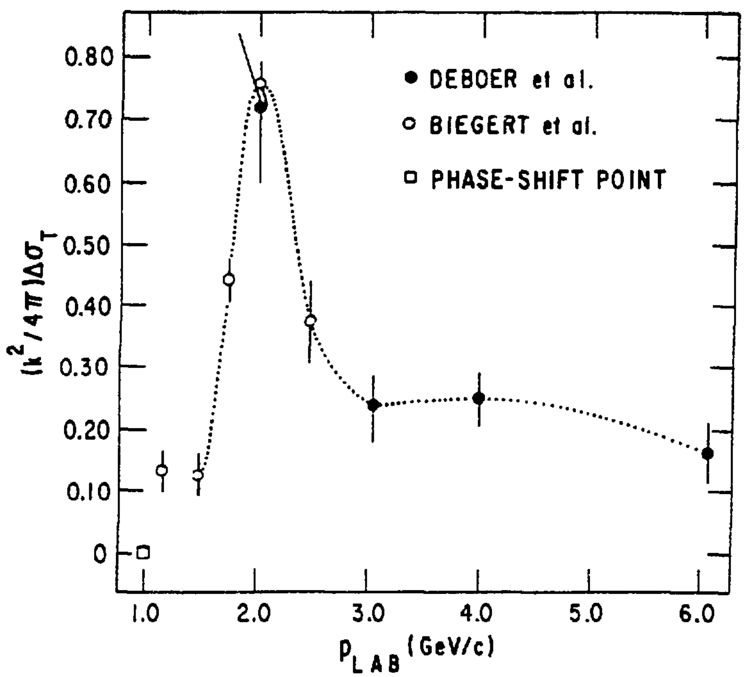


Fig. 3
A plot of $(k^2/4\pi)\ \Delta\sigma_T$.

Various analyses have been carried out using presently available data, and most analyses are consistent with the existence of dinucleon resonances. Particularly strong indication of resonances in the $^1D_2$ and $^3F_3$ states are established[5,6] as shown in Figs. 4 and 5.

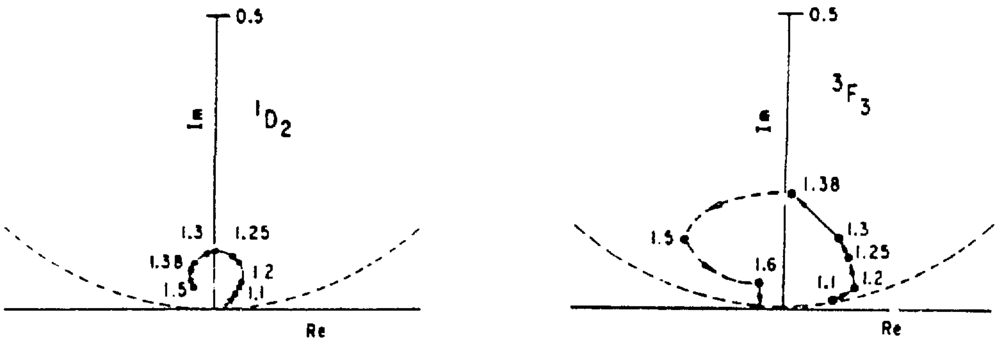


Fig. 4 Argand diagrams of the $^1D_2$ (a) and $^3F_3$ (b) partial waves (points are in GeV/c); the background contributions have been subtracted.

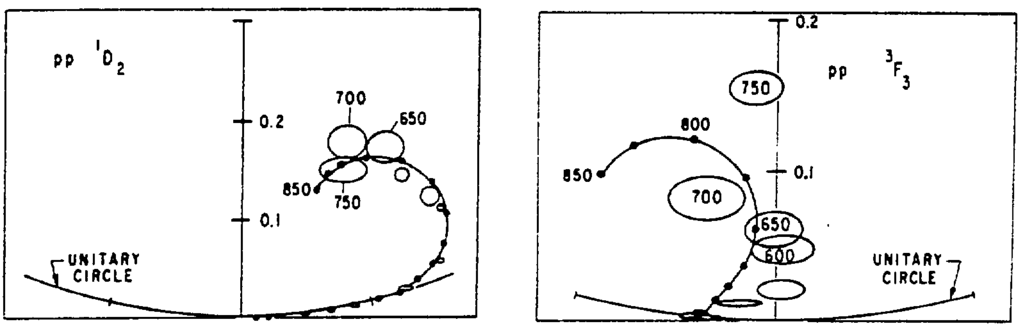
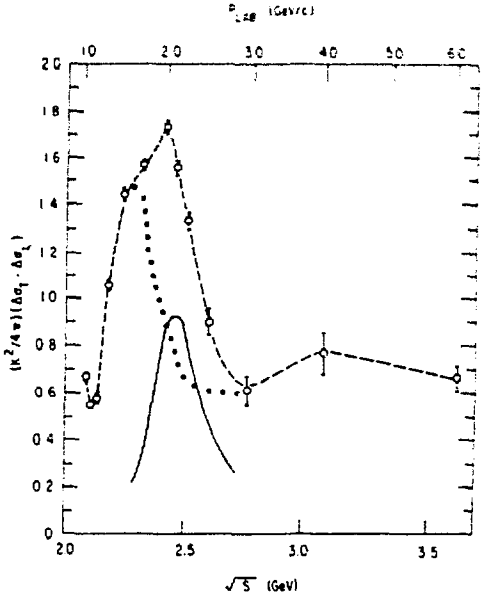


Fig. 5 Argand diagrams of the $^1D_2$ (a) and $^3F_3$ (b) partial waves based on Arndt's phase shifts (points are in kinetic energy, MeV). The ellipses represent the errors in the real and imaginary parts of the amplitudes for energy-independent solutions. The continuous curves represent the energy-dependent solutions.

Other possible resonances in the pp system include a singlet resonance in $\Delta\sigma_T$ at 2 GeV/c, and a triplet resonance appearing in $(k^2/4\pi)$ $(\Delta\sigma_T - \Delta\sigma_L)$ plot against $\sqrt{s}$ as shown in Fig. 6. We expect that the triplet peak at 2.0 GeV/c is due to a resonating partial wave R_{JJ}, since only R_{JJ} term has positive sign in $\Delta\sigma_T - \Delta\sigma_L = (2J+1)I_mR_{JJ} - (J+2)I_mR_{J+1,J} - (J-1)I_mR_{J-1,J}$. This possible resonance may explain the skewed bump in $\sigma^{Tot}(\ddagger)$ curve shown in Fig. 7.

Fig 6 New triplet structure at 2.0 GeV/c; the dotted curve is deduced from $\Delta\sigma_L$ data.



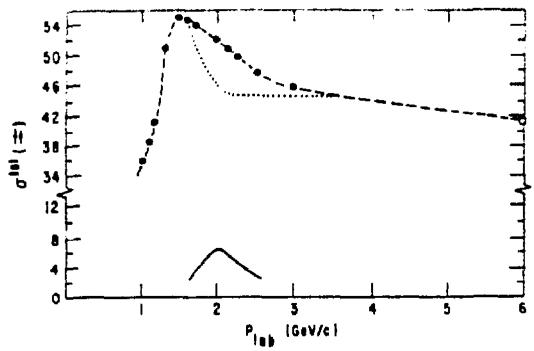


Fig. 7 Decomposition of $\sigma^{Tot}(\ddagger)$: assume 1.5-GeV/c peak as shown on the dotted curve and subtract that from $\sigma^{Tot}(\ddagger)$yielding a 2.0-GeV/c peak.

It has been pointed out that ambiguities exist in the pp phase-shift analyses above 500 MeV particularly in p partial waves, although other partial waves were relatively well settled.[7] We note that there is no $^3F_3$ partial-wave contribution to the polarization data at $\theta_{c.m.} = 63°$. We see an interesting structure in a plot of $k^2P(d\sigma/d\Omega)/\sin 2\theta_{c.m.}$ vs. p_{lab} as shown in Fig. 8. This quantity is proportional to

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

if higher waves are neglected.

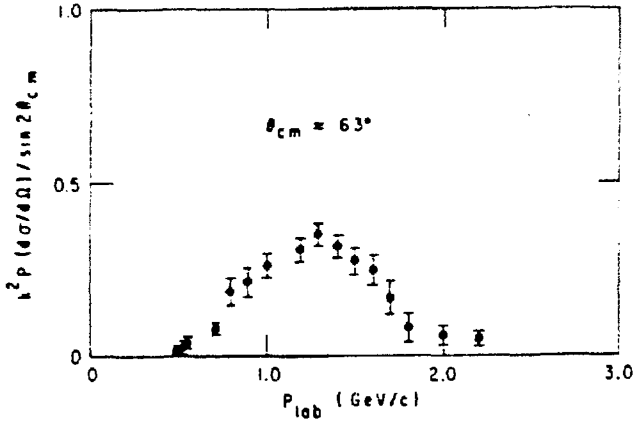
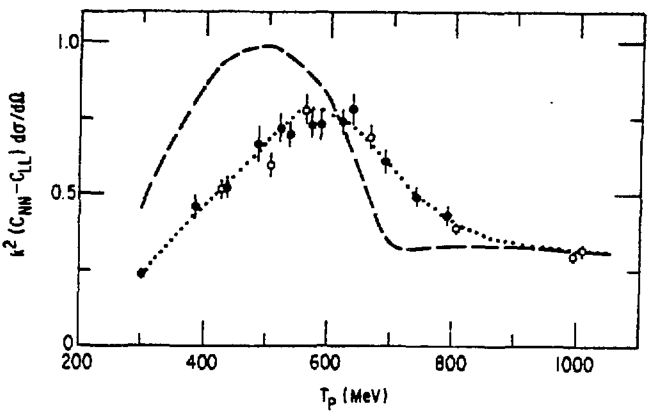


Fig. 8 Energy dependence of $P(d\sigma/d\Omega)$ at $\theta_{c.m.} = 63°$.

Recently we have investigated this energy region by measuring C_{LL} = (L,L;0,0) around $\theta_{c.m.} = 90°$.[8] Figure 9 shows a plot of $k^2(C_{NN} - C_{LL})\ d\sigma/d\Omega$, which contains only coupled spin triplet partial waves with J = L±1 (such as $^1P_0$, $^1P_3$, $^3F_2$, $^3F_4$...) at $\theta_{c.m.} = 90°$, against the incident momenta. The dashed curve shows a rapid energy dependence in $(1 - C_{NN})$, and the peak position roughly coincides with the $^1D_2$ resonance. This leads us to note that the structure in the $(C_{NN} - C_{LL})$ curve is therefore also resonant-like. Probably $^3P_0$ or $^3P_2$ partial waves is responsible for the structure.

Fig. 9 Experimental value of $k^2\ (C_{NN} - C_{LL})\ d\sigma/d\Omega$ against the incident kinetic energy; the dotted curve is drawn to guide the eye. The dashed curve represents a fit by eye to the experimental values of $k^2(1 - C_{NN})d\sigma/d\Omega$.



It is our hope that ambiguities in the phase-shift analyses will be soon resolved when the results of C_{LL} and C_{SL} measurements covering forward angles at 1.18, 1.32, 1.47, 1.71, 2.00, 2.22, and 2.47 GeV/c performed at the ZGS, and C_{SS} measurements at LAMPF are analyzed.

Do we observe any structure above a mass of 2500 MeV? Measurements of $\Delta\sigma_L$ and $\Delta\sigma_T$ are yet to be made at small-momentum intervals. However, we have measured the parameter $C_{LL} = (L,L;0,0)$ in the region $p_{lab} = 2.5$ to 5.0 GeV/c as shown in

Fig. 10. We observe a remarkable energy dependence in $C_{NN} = (N,N;0,0)$ data at all angles[9] and also at $\theta_{c.m.} = 90°$.[10] Our recent data on $C_{LL} = (L,L;0,0)$ reveals an interesting structure.[11] Figure 11 shows the energy dependence of C_{LL} at $\theta_{c.m.} = 90°$. We attempt to interpret these structures assuming them as resonances in the term of the quantum number. We note that $k^2 C_{LL}(d\sigma/d\Omega) \approx -|\text{spin-singlet terms}|^2 - |\text{coupled triplet}|^2 + |\text{uncoupled and couplet triplet}|^2$. We observe no structure in the behavior of $k^2(C_{NN} - C_{LL})\, d\sigma/d\Omega$,[12] which contains only couplet triplet terms, against the incident momentum in the region of 3.0 to 4.0 GeV/c as shown in Fig. 12. Therefore the second dip seems due to a spin-singlet term: in a similar way, the first dip is considered as a spin-singlet, namely $^1G_4$.[13] . The contribution of spin-singlet partial waves to $k^2 C_{LL}\, d\sigma/d\Omega$ is written as follows:

$$k^2\ C_{LL}(d\sigma/d\Omega)_{\text{spin-singlet}} = -|{}^1S_0 + 5P_2(\cos\,\theta)\,{}^1D_2 + 9P_4(\cos\,\theta)\,{}^1G_4 + 13P_6(\cos\theta)\,{}^1I_6 + \ldots|^2,$$

where $P_n(\cos\theta)$ is the Legendre polynomial of degree n.

It is possible to consider the second dip (mass ≈ 2900 ± 100 MeV) as $^1I_6$ state because the dip around $\theta_{c.m.} = 90°$ disappears at $\theta_{c.m.} \approx 75^0$ where $P_6(\cos\theta) = 0$.

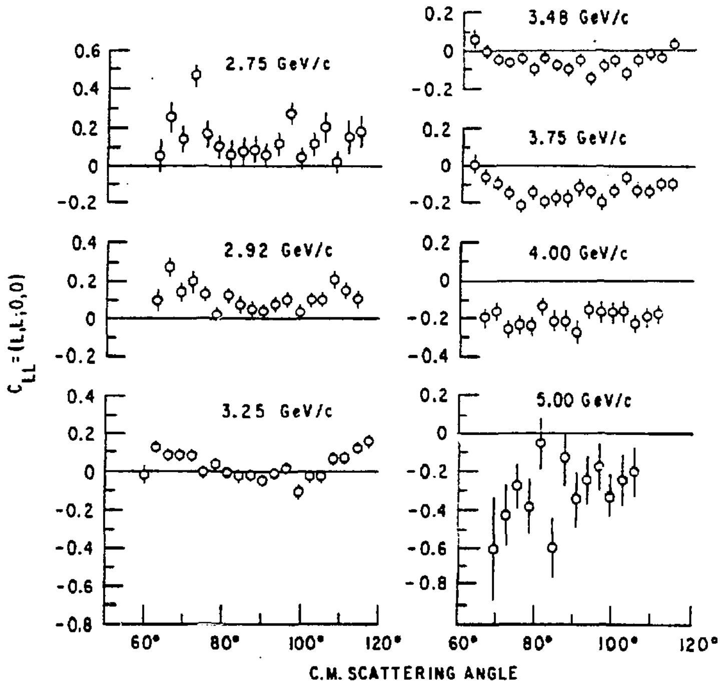


Fig. 10 C_{LL} = (L,L;0,0) data up to 5.00 GeV/c.

The rapid energy dependence around 2.75 GeV/c as shown in Fig. 11 coincides with a similar behavior observed earlier in C_{NN} data,[10,14] and also coincides with a hint of a bump around 2.75 GeV/c in $\Delta\sigma_L$ preliminary data.[15] The structure also occurs in $k^2(1 + C_{LL})\ d\sigma/d\Omega$ vs. the incident momenta, which contains only the triplet waves, but is absent on the curve of $k^2(C_{NN} - C_{LL})\ d\sigma/d\Omega$ vs. the incident momenta, which contains only the coupled triplet. If the above structure is due to a resonance, the mass would be ~ 2700 ± 100 MeV and due to an $R_{J,J}$ state.

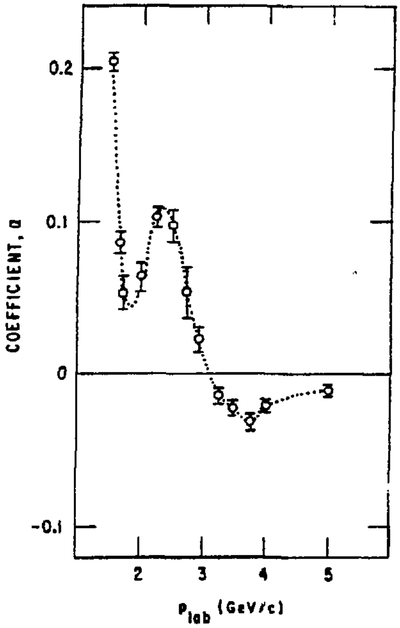


Fig. 11 $k^2 C_{LL}$ $(d\sigma/d\Omega)$ at $\theta_{c.m.} = 90°$ against p_{lab}.

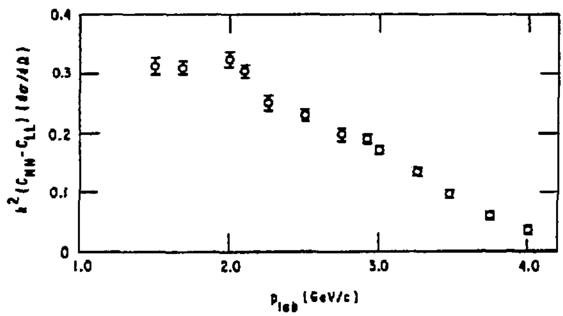


Fig. 12 Energy dependence of $k^2 (C_{NN} - C_{LL})\, d\sigma/d\Omega$ up to 4 GeV/c.

II. <u>I = 0 State</u>

Measurements were performed at the Argonne ZGS of the difference between isoscalar nucleon-nucleon total cross sections for pure longitudinal initial spin states, $\Delta\sigma_L$(pd), using a polarized proton beam and a polarized deuteron target.[16] One can extract $\Delta\sigma_L$ (I = 0) data using both $\Delta\sigma_L$(pd) and $\Delta\sigma_L$(pp) as shown in Fig. 13. A significant structure is observed around 1.5 GeV/c.

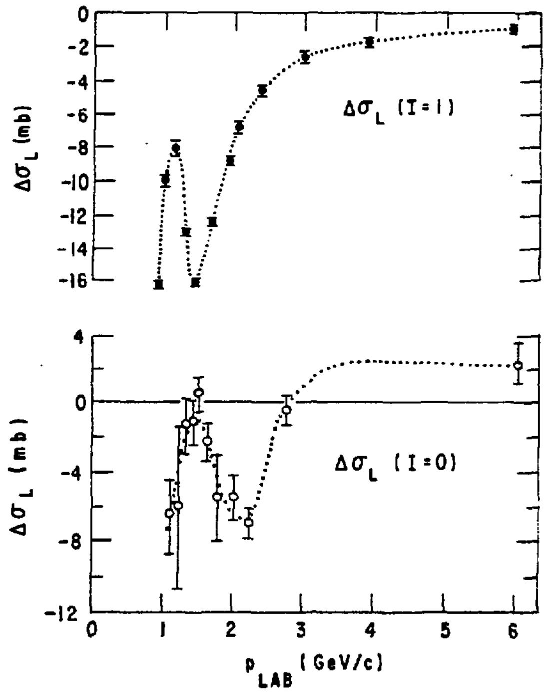


Fig. 13 $\Delta\sigma_L(I = 0)$ together with $\Delta\sigma_L(I = 1)$.

A recent phase-shift analysis using these data by a Kyoto group[17] suggests that there exists a partial wave whose behavior is consistent with the Breit-Wigner resonance formula, namely, the spin singlet $^1F_3$ wave. From the dispersion analysis of a forward I = 0 scattering amplitude using the data on $\Delta\sigma_L$ (I = 0), Grein and Kroll[18] showed that the Argand plot of the amplitude has a resonance-like behavior around 1.5 GeV/c, and that suggests the existence of a spin-singlet dibaryon resonance.

The $\Delta\sigma_L$ (I = 0) data around 1.2 GeV/c have only a few points with large errors. There is a hint of structure around 1.2 GeV/c revealed in the I = 0 total cross section data[19,20] as shown in Fig. 14.[21]

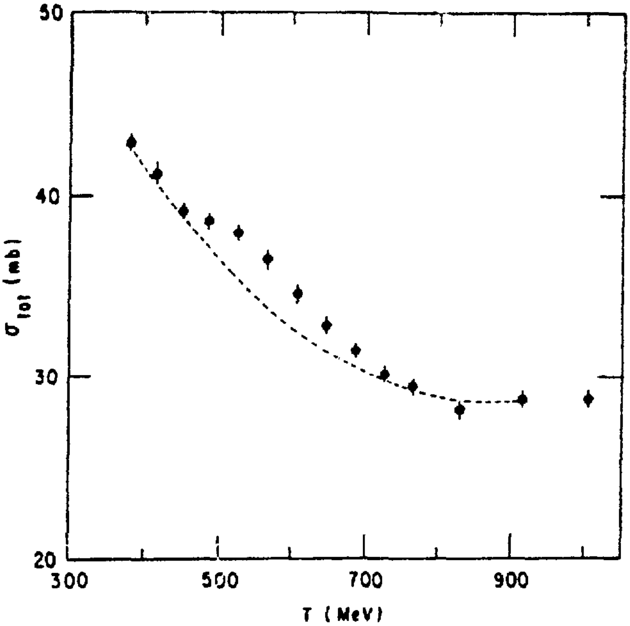


Fig. 14

I = 0 total cross section. The dotted line is to guide the eye for an assumed background.

III. Conclusion on I = 0 and I = 1 Resonances

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

IV. Structure Appearing in Other Channels

Many authors have attempted to interprete the results using not only elastic-scattering results, but other channels such as πD elastic scattering, $pp \to \pi D$, γD reactions etc.

i) Possible Nucleon Resonance in γd Scattering Experiment

Kamae et al.[22] suggested the possible existence of a dinucleon resonance by measuring the proton polarization in the reaction $\gamma d \to p^{\uparrow} n$. They observed

Table I

Candidates of the Dinucleon Resonances

(i) I = 1 Isospin State

	$B_1^2(2.14)$	$B_1^2(2.18)$	$B_1^2(2.22)$	$B_1^2(2.43)$	$B_1^2(2.43)$	$B_1^2(2.70)$	$B_1^2(2.90)$
Mass, GeV	2.14 - 2.17	2.18 - 2.20	2.20 - 2.25	2.43 - 2.50	2.43 - 2.50	2.70 ± 0.10	2.90 ± 0.10
Width, MeV	50-100	100-200	100-200	~ 150	~ 150		
Quantum State	$^1D_2$	Triplet P	$^3F_3$	Probably $^1G_4$	Triplet R_{JJ}	Triplet R_{JJ}	Probably $^1I_6$

(ii) I = 0 Isospin State

	$B_0^2(2.22)$	$B_0^2(2.43)$
Mass, GeV	2.20 - 2.26	2.40 - 2.50
Width, MeV	100-200	
Quantum State	$^1F_3$	Triplet

Note: Fewer candidates in I = 0 compared to I = 1 are merely due to the lack of experimental data; much experimental attempts will be made to explore I = 0 state.

an energy dependence in the polarization. They interpreted some of the data as an indication of the existence of the deeply bound Δ-Δ state. Their estimates of mass and width of the possible resonance was 2380 and 200 MeV respectively. From the angular dependence of their polarization data, they estimated spin parity and isospin as $(J^P,I) = (3^+,0)$. They obtained reasonable fits to the polarization data by introducing their dibaryon resonance with mass around 2380 MeV in addition to the $^3F_3$ dinucleon resonance with mass around 2260 MeV described in the body of this paper. Without the $^3F_3$ resonance, they could not obtain good fits by using only the resonance of 2380 MeV. This fact also supports the $^3F_3$ diproton-resonance picture.

A similar attempt was made at Kharkov and the results were discussed by P. V. Sorokin in this symposium.

ii) Other References on Dibaryons or Nucleon-Nucleon Scattering

Other authors have suggested the possibility of the existence of diproton resonances. R. Kammerud et al. analyzed the data of large-angle proton-proton elastic scattering at intermediate momenta, and they speculated the existence of dibaryon masses at about 2.2, 2.6, 3.4 and 3.9 GeV by observing slope changes in $d\sigma/dt$.[23] A similar conclusion was also drawn earlier by L. M. Libby and E. Predazzi.[24]

K. Kanai et al.[25] and K. Kubodera et al.[26] show that there are effects of dinucleon resonances in πd elastic scattering. The effects are clearly seen in the angular region of $\theta_{c.m.} > 100°$. H. Kamo and W. Watari found effects of dinucleon resonances in the polarization data in $pp \to \pi d$ reaction.[27] R. Frascaria et al. observed dinucleon-resonance signals in the π^+d excitation function of 180°.[28]

T. Ueda et al. discussed the existence of dinucleon resonances in πNN and $\pi\pi NN$ dynamics.[29] S. Furuichi et al. investigated channel coupling effects in relation to the exotic resonances.[30]

Many attempts have been made to explain the nucleon-nucleon structure as threshold effects or something equivalent, using exchange models such as the Deck model,[31] the OPE three-body theory,[32] the OBE inelastic-threshold model,[33] and recently coupled channels method.[34] However, most of these attempts do not seem successful. We remark that there is a report[35] that the $^1D_2$ diproton amplitude satisfies all standard resonance criteria, and has no pole corresponding to a diproton resonance.

V. Quark Models and Dinucleons

The dinucleon resonance opens a new era in the nucleon-nucleon system and is crucially important for further development of the quark models that require six quarks in a bag[36-39], depicted in Fig. 15; e.g. Mulders et al[37] predicted rich resonance structure in NN channel above mass of 2180 MeV.

The string model and the spring model[40] suggest dibaryon resonances, which are made of six quarks combined together with strings or springs, such as shown in Fig. 16.

Apart from the bag model and the string model, a SO_4 symmetry has been proposed for the classification of dinucleons and baryoniums.[41]

Recently a way of implementing the dual-topological unitarization program hasbeen found in which baryons and other multiquark hadrons are put on the sphere and appear at the same topological-complexity level as ordinary $q\bar{q}$

mesons.[42,43] This permits one to have a lowest-order "spherical bootstrap", within which unitarity, duality and crossing can be consistently satisfied. With this framework, masses of the baryonium as well as the qqqqqq dibaryon are predicted.[42] In general, the predictions are not inconsistent with the dinucleon resonances listed above.

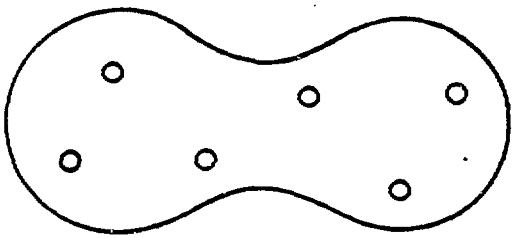


Fig. 15 Dinucleon resonance in bag model. Solid line and circles represent cavity and quarks respectively.

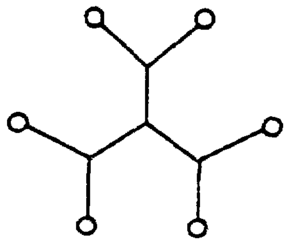


Fig. 16 Dinucleon resonance in string model.

References

1. I. P. Auer et al. Phys. Lett. 67B, 113 (1977); I. P. Auer et al., Phys. Lett. 70B, 475 (1977); I. P. Auer et al., Phys. Rev. Lett. 41, 354 (1978).

2. I. P. Auer et al., to be published in Phys. Rev. D24, (1981).

3. W. deBoer et al., Phys. Rev. Lett. 34, 558 (1978); E. K. Biegert et al., Phys. Lett. 73B, 235 (1978); data points at 1.2 and 1.5 GeV/c are being revised (J. B. Roberts, private communication).

4. A. Yokosawa, Physics Reports 64, (1980); and references therein.

5. N. Hoshizaki, Prog. Theor. Phys. 60, 1796 (1978); 61, 129 (1979).

6. R. A. Arndt, Talk given during LAMPF Nucleon-Nucleon Workshop, July, 1978; R. Bhandari, R. Arndt et al., Phys. Rev. Lett. 46, 1111 (1981); Resonance poles found by K-matrix analysis are also discussed by B. J. Edwards and G. H. Thomas, Phys. Rev. D22, 2772 (1980), and B. J. Edwards, Phys. Rev. D23, 1978 (1981).

7. Private communication, R. Arndt, N. Hoshizaki, and H. Kanada.

8. G. R. Burleson et al., ANL-HEP-PR-81-43 (1981).

9. D. Miller et al., Phys. Rev. Lett. 36, 763 (2976); Phys. Rev. D16, 2016 (1977).

10. A. Lin et al., Phys. Lett. 74B, 273 (1978).

11. I. P. Auer et al., ANL-HEP-PR-81-42 (1981).

12. C_{NN} = (N,N;0,0) data: D. Miller et al., Phys. Rev. D 16, 2016 (1977): A. Lin et al., Phys. Lett. 74B, 273 (1978); D. A. Bell et al., Phys. Lett. 94B, 310 (1980); D. Besset et al., Nucl. Phys. A345, 435 (1980); M. McNaughton et al., Phys. Rev. C13, 838 (1981); M. McNaughton et al., to be published; V. A. Efimovyh et al., Phys. Lett. 99B, 28, (1981).

13. I. P. Auer et al., Phys. Rev. Lett. 41, 1436 (1978); Reference 4, p. 63.

14. Reference 4, p. 64.

15. Reference 4, p. 57.

16. I. P. Auer et al., Phys. Rev. Lett. 46, 1177 (1981).

17. K. Hashimoto et al., Prog. Theor. Phys. 64, 1678 (1980); K. Hashimoto et al., preprint (February 1981).

18. Private communication.

19. T. J. Devlin et al., Phys. Rev. D8, 136 (1973).

20. P. Schwaller et al. Nucl. Phys. A316, 317 (1979).

21. The structure was pointed out by K. Imai.

22. T. Kamae et al., Phys. Rev. Let. 38, 471 (1977); H. Ikeda et al., Phys.
Rev.
Lett. 42, 1321 (1979); K. Nakamura, Proc. 1979 INS Symp., Tokyo, Japan, p. 425 (November 1979).

23. R. C. Kammerud et al., Phys. Rev. D4, 1309 (1971).

24. L. M. Libby and E. Predazzi, Lettere Al Nuovo Cimento, Vol. II, N. 18, 881 (1969).

25. K. Kanai et al., Prog. Theor. Phys. 62, 153 (1979); K. Kanai and A. Minaka, Prog. Theor. Phys. 65, 266 (1981).

26. K. Kubodera et al., Phys. Lett. 87B, 169 (1979); K. Kubodera et al., J. Phys. G6, L1 (1980).

27. H. Kamo and W. Watari, Prog. Theor. Phys. 62, 843 (1979); H. Kamo and W. Watari, and M. Yonezawa, p. 31, Proceedings of the 2nd Meeting on Exotic Resonances, HUPD-8010, Hiroshima, Japan (1980).

28. R. Frascaria et al., to be published.

29. T. Ueda, Phys. Lett. 74B, 123 (1978); Phys. Lett. 79B, 487 (1978); M. Araki et al., Prog. Theor. Phys. 63, 335 (1980); M. Araki et al., OUAM 81-8-7 (1981).

30. S. Furuichi et al., Prog. Theor. Phys. 61, 1127 (1979); S. Furuichi et al., p. 60, Proceedings of the 2nd Meeting on Exotic Resonances, HUPD-8010, Hiroshima, Japan (1980).

31. E. L. Berger, P. Pirila and G. H. Thomas, ANL-HEP-PR-75-72 (unpublished).

32. W. M. Kloet et al., Phys. Rev. Lett. 39, 1643 (1977); W. M. Kloet and R. R. Silbar, 45, 970 (1980).

33. M. Arik and P. G. Williams, Nucl. Phys. B136, 425 (1978).

34. W. Metz et al., Workshop on Pion Production and Absorption in Nuclei, Bloomington, Indiana (October, 1981), TRI-PP-81-59) and references therein; R. J. Ver West, Texas A&M preprint (1981).

35. D. D. Brayshaw, Phys. Rev. Lett. 37, 1329 (1976).

36. R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977); and (errata) 38, 617 (1977).

37. P. J. G. Mulders, A. Th. M. Aerts and J. J. DeSwart, Phys. Rev. Lett. 40, 1543 (1978); A. Th. M. Aerts et al., Phys. Rev. D17, 260 (1978).

38. C. W. Wong and K. F. Liu, Phys. Rev. 41, 82 (1978); F. Myhrer, to be published.

39. D. B. Lichtenberg et al., Phys. Rev. D18, 2569 (1978).

40. M. Imachi et al., Prog. Theor. Phys. 55, 551 (1976); 57, 517 (1977); S. Ishida and M. Oda, Prog. Theor. Phys. 60, 828 (1978); 61, 1401 (1979).

41. M. Kocs and A. B. Balantekin, Nuovo Cimento 52A, 500 (1979).

42. G. F. Chew and C. Rosenzweig, Phys. Reports 41, 263 (1978).

43. L. A. P. Balazs and B. Nicolescu, Proc. Workshop on Baronium and Other Unusual Hadron States, Orsay, France, June 1979, eds. B. Nicolescu, J. M. Richard and R. Vanh Mau.