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Meson Towers and the Absence of Backward Peaks*

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The absence of backward peaks in $\pi^+\pi^-$, π^+K^-, K^+K^-, and $\bar{N}N$ elastic scattering is speculatively associated with the existence of direct-channel exchange-degenerate towers of meson resonances. Experimental evidence for meson towers associated with a (ω,ρ,f^0,A_2) master trajectory is presented. Consequences of a pure resonance picture of the low-energy $\bar{N}N$ elastic amplitude are explored.

THE absence of backward peaking in reactions that have no known u-channel particle exchanges is one of the most striking empirical facts of high-energy-scattering data. In many such reactions, the backward peak is absent even at fairly low energy, where direct-channel resonances are known to play a significant role. In any realistic dynamic model a strong correlation must therefore exist among the direct-channel resonances in order to maintain this antiperipheral feature of the backward scattering. Experimental studies indicate that for energy regions where a number of direct channel resonances exist, the cancellation of the backward peak is in many instances a very local phenomena. As an illustration, $\pi^+\pi^-$ elastic scattering is strongly peaked forward in the vicinity of 750 MeV, in qualitative agreement with the absence of u-channel exchanges (no $\pi^-\pi^-$ resonances).[1] The direct-channel explanation of this absence of backward peaking involves a 0^+ particle (the ϵ meson) with appropriate strength to cancel the the ρ-meson resonance contribution at 180°.[2]

Such observations indicate that there must exist an intimate connection between direct-channel forces and exchange forces. An attractive point of view is that direct-channel resonances "build up" the exchange amplitudes in some average sense. In order that the direct-channel resonances locally build up the fixed momentum transfer behavior of exchanges, it is necessary that the resonances occur in highly correlated sequences of angular momentum states with alternating parities called "towers." The $\rho(1^-)$, $\epsilon(0^+)$ sequence form the first tower in $\pi^+\pi^-\to\pi^+\pi^-$.[3]

Furthermore, in the absence of u-channel exchange forces, the s- (or t)-channel Regge residues and trajectories must be exchange degenerate.[4] Recently, explicit representations have been constructed that give towers and exchange degeneracy for reactions with no particle exchanges for the u channel.[5] These Veneziano representations build up the amplitudes from particle poles in the s and t channels and exhibit asymptotic Regge behavior for moving poles. However, these models are based on a zero-width approximation, and hence can only be regarded as prototypes of some future models. The purpose of this paper is to examine these qualitative ideas in light of present experimental data and to propose future tests of the tower nature of the meson spectrum.

To begin with, we consider the reactions (1)–(3) listed below. In each case, the u channel has no known meson particle poles, thereby forcing pairwise exchange degeneracy for the residues and trajectories in the other two channels as listed. Consistency within S-matrix theory then requires that the four trajectories (ω,ρ,f^0,A_2) coalesce into one master trajectory, for which experimental evidence already exists, as shown in Fig. 1.

		u channel	Exchange degeneracy
(1)	$\pi^+\pi^-\to\pi^+\pi^-$	$(\pi^+\pi^+)$	(ρ,f^0)
(2)	$\bar{K}^0K^+\to\bar{K}^0K^+$	$(\bar{K}^0K^-)$	(ρ,A_2)
(3)	$K^+K^-\to K^+K^-$	(K^+K^+)	(ω,f^0); (ρ,A_2); (ϕ,f')

The trajectory degeneracy holds for all reactions, whereas the residue degeneracy is required only for reactions with a missing channel.[6]

The lowest tower on the (ω,ρ,f^0,A_2) master trajectory consists of the following states:

$$\rho\ (J^PI^G=1^-1^+),\quad \omega\ (1^-0^-),$$
$$\epsilon\ (0^+0^+),\qquad \alpha\ (0^+1^-).$$

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[1] See, e.g., E. West *et al.*, Phys. Rev. **149**, 1089 (1966); N. Armenise *et al.*, Nuovo Cimento **44**, 999 (1968).

[2] E. Malamud and P. Schlein, Phys. Rev. Letters **19**, 1056 (1967); W. D. Walker *et al.*, *ibid.* **18**, 630 (1967); A. B. Clegg, Phys. Rev. **163**, 1664 (1967); K. J. Braun, D. Cline, and V. Scherer, Phys. Rev. Letters **21**, 1275 (1968); G. A. Smith and R. J. Manning, University of California Radiation Laboratory Report No. 1917, 1968 (unpublished).

[3] In $\pi^+\pi^-$ elastic scattering near 1250 MeV the backward peak is not locally absent. Thus for a $[f^0(2^+),\rho'(1^-),\epsilon'(0^+)]$ tower in this mass region, the ρ' must be relatively inelastic.

[4] Exchange degeneracy was first suggested by R. Arnold, Phys. Rev. Letters **14**, 657 (1965), in analogy with potential theory. See also C. Schmid, *ibid.* **20**, 689 (1968).

[5] G. Veneziano, Nuovo Cimento **57**, 190 (1968). For an application to the $\pi\pi$ system, see J. Shapiro and J. Yellin, University of California Radiation Laboratory Report No. 18500 (unpublished); and C. Lovelace, CERN Report No. TH950, 1968 (unpublished).

[6] C. B. Chiu and J. Finkelstein, Phys. Letters **27B**, 510 (1968).

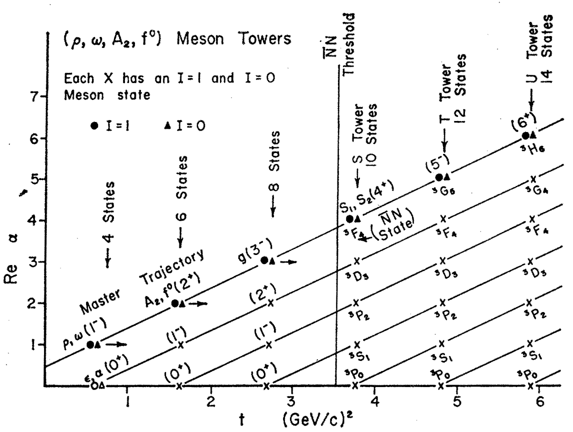

FIG. 1. Linearly rising (ω,ρ,f^0,A_2) master trajectory and the associated towers of meson states. The R_0 state is taken as the $I^G=0^-$ $\rho\pi$ state observed at a mass of 1636 MeV (Ref. 12). The S_1 and S_2 states are identified with the bumps observed in backward $\bar{p}p$ elastic scattering (Ref. 23). Since the isotopic spin of these states has not been obtained, we assume that one has $I=1$ and the other $I=0$. The spin and parities of the R_0, S_1, and S_2 have not been determined. For the towers above $\bar{N}N$ threshold, the states of lowest orbital angular momentum of the $\bar{N}N$ system have been listed.

Recent $\pi\pi$ phase shifts are very suggestive of a broad $I=0$ resonance state in the vicinity of 750 MeV, which could be identified as the ϵ above.[2] The discovery of an α particle, which could decay into $\pi\eta$ if its mass is greater than ~690 MeV or $\pi\pi\gamma$ if below $\pi\eta$ threshold, is crucial to this idea. In analogy to the ϵ particle, the α particle may be quite broad and could have escaped detection up to now. However, the present confusion concerning resonances in the 800–1000-MeV region decaying into $\pi\eta$ leaves the possibility that one of these states is to be identified with the α.[7] The production of the α may well be suppressed by the relative weakness of η exchange amplitudes. However, the α would presumably be made in inelastic baryon exchange reactions.

The particle states for the second tower are the following:

$$\begin{array}{ll} f^0\ (J^PI^G=2^+0^+), & A_2\ (2^+1^-), \\ \rho'\ (1^-1^+), & \omega'\ (1^-0^-), \\ \epsilon'\ (0^+0^+), & \alpha'\ (0^+1^-). \end{array}$$

At present only the f^0 and A_2 are well established, but again the lower-spin states may be quite broad and difficult to disentangle. However, one possibility is that the splitting of the A_2 is due to the (A_2,α') states, in which case the α' would be a narrow resonance decaying into $\pi\eta$.[8] Furthermore, some evidence now exists for a $J^P=1^-$ inelastic $\pi\pi$ resonance near the mass of the f^0.[9]

The ϕ,f' also constitute an exchange-degenerate trajectory with the same universal slope as the (ω,ρ,f^0,A_2) master trajectory.[6] For the ϕ tower at 1020 MeV, a $I^G=0^+$ state is experimentally observed at 1070 MeV in the $\bar{K}K$ system.[10] Extending these arguments to π^+K^- elastic scattering, a broad 0^+ state is expected near the $K^*(890)$ for which some preliminary experimental evidence now exists. The recent experimental report of a possible 1^- $K\pi$ resonant state under the $K^*(1400, 2^+)$ is also suggestive of a tower in this mass region.[11]

If meson trajectories continue to rise linearly, as seems to be the case in the baryon system, then the tower hypothesis suggests the existence of a large number of meson states in the R(~1700 MeV), S(~1930 MeV), T(~2100 MeV), and U(~2300 MeV) mass regions (see Fig. 1). There is already evidence for several states in the R region with the ρ and ω quantum numbers of the leading states seemingly experimentally established.[10,12] We tentatively identify the "ω" with the recently observed $I^G=0^-$ state[12] (hereafter called R_0). However, the tower hypothesis predicts eight states in this region from the (ρ,ω,f^0,A_2) master trajectory alone, some of which may be very broad. The complete disintangling of these particles appears hopeless in the near future. A different approach is probably necessary to establish the meson towers in this and higher-mass regions.

Studies of $\bar{N}N$ scattering in the S- and T-mass regions may well provide an alternative method to test the tower hypothesis. The logical extension of the Veneziano-type models to the $\bar{N}N$ elastic amplitude would require that direct-channel resonances build up all the elastic-channel $\bar{N}N$ meson Regge-exchange amplitudes except the Pomeranchuk.[13] Using the optical theorem, we are then led to expect ~100–200 mb of resonance contribution to the $\bar{N}N$ total cross sections in the S region and ~50–100 mb in the T region.[14] The strength of the meson couplings to account for this large amount of cross section represents a qualitive departure from the usual picture[15] of the low-energy $\bar{N}N$ scattering process and may lead to the most direct experimental test of the tower hypothesis.

The absence of any appreciable backward peaking[16,17] even at momenta as low as 200 MeV/c reflects the absence of u-channel dibaryon exchange. At the same time,

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[7] A review of recent results concerning $\eta\pi$ resonances in the 900–1000 MeV mass region is given in R. Ammar *et al.*, Phys. Rev. Letters **21**, 1832 (1968).

[8] H. Benz *et al.*, Phys. Letters **28B**, 233 (1968); B. Levrat *et al.*, *ibid.* **22**, 714 (1966); Y. T. Trippe *et al.*, *ibid.* **28B**, 203 (1968).

[9] W. D. Walker (private communication).

[10] N. Barash-Schmidt *et al.*, Rev. Mod. Phys. **41**, 109 (1969).

[11] P. Antich *et al.*, Phys. Rev. Letters **21**, 1842 (1968).

[12] A $\rho\pi$ resonance with $I^G=0^-$, a mass of 1636 MeV, and width of 122 MeV has been observed by N. Armenise *et al.*, Phys. Letters **26B**, 336 (1968). The mass degeneracy between this state and the $g(1650)$ suggests that this is the leading $I=0$, 3^- vector meson on the R tower.

[13] H. Harari, Phys. Rev. Letters **20**, 1395 (1968); P. G. O. Freund, *ibid.* **20**, 238 (1968).

[14] U. Amaldi *et al.*, Nuovo Cimento **46**, 171 (1966).

[15] R. Bryan and R. J. N. Phillips, Nucl. Phys. **B5**, 201 (1968).

[16] B. Conforto *et al.*, Nuovo Cimento **54A**, 441 (1968).

[17] R. Goldberg (private communication); and J. English (private communication).

to build up full elastic amplitude from direct-channel meson resonances without a backward peak requires a strong *local* parity degeneracy of the meson states of the kind that towers could provide. In this picture of strong $\bar{N}N$ couplings to the meson towers, the $\bar{N}N$ system would necessarily play a dominant role in the dynamics of meson states, as originally suggested from a different viewpoint by Fermi and Yang.[18] This idea is consistent with the large Regge residues of the (ρ,ω,f^0,A_2) master trajectory determined from Regge-exchange analyses of elastic scattering.[19] In addition, the baryon-exchange production of meson states indicates that at least the low-lying states on the (ρ,ω,f^0,A_2) trajectory are strongly coupled to $\bar{N}N$.[20] The strong coupling of these states in both t-channel exchange and in the production by baryon exchange is qualitative evidence for the importance of these states in the direct-channel $\bar{N}N$ elastic amplitude. Viewing the direct-channel resonances as being built from exchange forces, the absence of a backward peak then requires the *local* parity degeneracy in the towers and the *exchange degeneracy* of the direct-channel trajectories.

Next we turn to the consequences of this resonance tower picture of the $\bar{N}N$ elastic and inelastic amplitudes. Since the $\bar{N}N$ total cross sections are relatively smooth even at low energy, a number of the states in the towers must be broad compared to the decay widths of the particles observed with the missing-mass spectrometer technique.[8,11] The ultimate test of towers and this resonance dominance model is a phase-shift analysis of the $\bar{N}N$ elastic amplitude. In view of the complexity of this system, such an analysis seems remote at present. Therefore, we must be content with less restrictive tests in the near future.

A minimal test is that the angular momentum states needed to fit the elastic angular distribution in the S and T energy regions be consistent with the J values of the particles in the towers. In the S region, this correspondence has been verified.[16,21]

Secondly, since $\sigma_{\text{inelastic}}/\sigma_t > \frac{1}{2}$, the mesons in the towers must couple strongly to the $\bar{N}N$ annihilation inelastic channels.[14] Therefore, a second test is that the bulk of the annihilation channels have angular momentum states populated in accordance with the tower hypothesis.[14,22] In this connection, it is interesting to note that the mean multiplicity of the $\bar{N}N$ annihilation is similar to the multiplicities of the pions for the decay of high-mass mesons produced in inelastic collisions.[22]

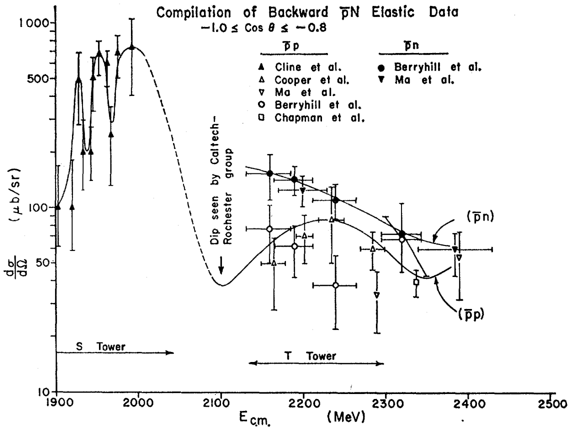

FIG. 2. Compilation of all available data on backward-hemisphere $\bar{p}p$ elastic scattering data as a function of the c.m. energy of the $\bar{N}N$ system. The data in the S region are from Ref. 23 and the data in the T region are from Ref. 25. The curve was drawn through the data by eye. A recent counter experiment (Ref. 26) covering the mass region of 2000–2400 MeV has revealed a sharp dip near 2100 MeV. This dip is schematically included in the curve drawn through the $\bar{N}N$ data to indicate the possible separation of the S- and T-tower regions.

A third test would be direct observation of mesons in the towers in elastic and inelastic $\bar{N}N$ scattering. Although difficult, some progress has been made in this regard. Since cancellations of the tower contributions to $\bar{N}N$ elastic scattering in the backward hemisphere would most likely not be completely exact, fluctuations in the angular distribution as a function of energy can probably be used to detect mesons in the tower. Fluctuations of this variety have recently been observed in S and T regions as shown in Fig. 2.[23–26]

The large dip in the cross section for elastic scattering in the backward hemisphere can be qualitatively interpreted as a valley between the S and T tower. The narrowness of the fine structure observed in the S tower may represent narrow-resonance states, but might also come from broader resonance states which are cut off on the lower side by centrifugal-barrier effects in the $\bar{N}N$ system. In the T and U regions the meson states may overlap sufficiently so that individual states are not resolvable, which would be in accordance with recent experimental evidence.[26]

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[18] E. Fermi and C. N. Yang, Phys. Rev. **80**, 1739 (1949). All experimentally established mesons have the quantum numbers of the $\bar{N}N$ system, which is suggestive of a dominant role of $\bar{N}N$ in the dynamics.

[19] V. Barger, M. Olsson, and D. D. Reeder, Nucl. Phys. **B5**, 411 (1968).

[20] D. Cline, report given at the SLAC Backward Processes Conference, 1969 (unpublished).

[21] J. English (private communication) has obtained results similar to that of Ref. 16, using the backward-hemisphere $\bar{p}p$ elastic scattering data of Ref. 23.

[22] In the S region it has been shown that the annihilation channels require angular momentum states at least $L=2$ and, in the T region, $L=3$ is required. See Ref. 14 and also D. Cline, in Argonne National Laboratory Report No. ANL/High Energy Physics 6812, 1968 (unpublished).

[23] D. Cline, J. English, D. D. Reeder, R. Terrell, and J. Twitty, Phys. Rev. Letters **21**, 1268 (1968).

[24] See D. Cline, in *Proceedings of the Informal Meeting on Meson Spectroscopy* (W. A. Benjamin, Inc., New York, 1968).

[25] J. Berryhill (private communication); W. A. Cooper *et al.*, Phys. Rev. Letters **20**, 1059 (1968); Z. A. Ma, D. L. Parker, G. A. Smith, R. J. Sprafka, M. A. Abolins, and A. Rittenberg, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN, Geneva, 1968); J. Lys *et al.*, Phys. Rev. Letters **21**, 1116 (1968).

[26] B. C. Barish, Bull. Am. Phys. Soc. **14**, JA3 (1969); A. Tollestrup and F. Lobkowizc (private communication).

In the S region the nearness of the $\bar{N}N$ threshold could result in centrifugal-barrier factors which would suppress some of the high-spin states in the tower in the low-mass region. In this case, appreciable structure in the $\bar{p}p$ and $\bar{p}n$ total cross sections in this region may be observable. The observation of this structure would be striking evidence for the existence of meson towers which dominate low-energy $\bar{N}N$ elastic scattering.[27] Furthermore $\bar{N}N$ annihilation at rest should proceed through the 1^- states in the S tower, which can be directly tested experimentally by the relative populations in the four annihilation quadrants (ω,ρ,η,π).

In summary, the empirical evidence for the absence of backward peaks has significant consequences for bootstrap theories of strong interactions. The consistency condition for the bootstrap in these reactions apparently implies the existence of towers of meson states. Applying these ideas to the low-mass mesons, we are lead to predict a new state near the ω mass with $J^PI^G=0^+1^-$. The observation of this state will be a strong check on the tower hypothesis. Applying these ideas to the low-energy $\bar{N}N$ elastic amplitude suggests that the bulk of the cross section comes from correlated direct-channel resonances. The dominance of the vector-meson–tensor-meson trajectory suggests that the meson towers from this trajectory will be strongly coupled to the $\bar{N}N$ system and leads to the sets of states shown in Fig. 1. We have found no obvious inconsistencies of this somewhat radical model with the present $\bar{N}N$ data and, in fact, have given some evidence in support of the hypothesis. Further $\bar{N}N$ studies, particularly in the S region, will provide crucial tests for the existence of these towers.

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[27] The present total cross-section data in the 1900–2000 MeV $\bar{N}N$ mass region are not inconsistent with the existence of such structure. See Ref. 14.

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High-Energy Collision Processes in Quantum Electrodynamics. I

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We have made a systematic study of all two-body elastic scattering amplitudes in quantum electrodynamics at high energies. In particular, we have calculated the high-energy behavior of the following processes: (1) Delbrück scattering, (2) electron Compton scattering, (3) photon-photon scattering, (4) electron-electron scattering, (5) electron-positron scattering, and (6) electron-proton scattering. The processes (1) and (2) are calculated up to the sixth order in the coupling constant e, the process (3) up to the eighth order, and the processes (4), (5), and (6) up to the fourth order. Our calculations show that all of these amplitudes are proportional to s, the square of the center-of-mass energy, as s becomes large. In other words, we have found that, to these orders, $\lim_{s\to\infty} d\sigma/dt$ exists and is nonzero for all $t\neq0$, where $-t$ is the square of the momentum transfer. Furthermore, we found it meaningful to assign a factor (we call it the impact factor) to each particle. More precisely, for the high-energy scattering of $a+b\to a+b$, the imaginary coefficient of s for the scattering amplitude is proportional to $\int d\mathbf{q}_\perp[(\mathbf{q}_\perp+\mathbf{r}_1)^2]^{-1}[(\mathbf{q}_\perp-\mathbf{r}_1)^2]^{-1}\mathcal{J}^a(\mathbf{r}_1,\mathbf{q}_1)\mathcal{J}^b(\mathbf{r}_1,\mathbf{q}_\perp)$, where $2\mathbf{r}_1$ is the momentum transfer, and $\mathcal{J}^a(\mathbf{r}_1,\mathbf{q}_\perp)$ and $\mathcal{J}^b(\mathbf{r}_1,\mathbf{q}_\perp)$ are the impact factors of particles a and b, respectively. The integration is over the two-dimensional transverse momentum of the virtual photons. The important point is that $\mathcal{J}^a$ $(\mathcal{J}^b)$ does *not* depend on what particle b (a) is. We have explicitly found the impact factors for the photon (up to e^4) and for the electron, the positron, and the proton (up to e^2). In the case of Delbrück scattering, we have also taken care of all higher-order diagrams with an arbitrary number of photons exchanged between the virtual pair and the proton or nucleus. The coefficient of s in this case can be expressed as the integral of the above-mentioned product $\mathcal{J}^a\mathcal{J}^b$ times modified photon propagators. The impact factor therefore appears to express an intrinsic property of a particle. Our result is consistent with neither the most straightforward interpretation of the Regge-pole model nor that of the droplet model. These inconsistencies are closely related to the nonplanar nature of the diagrams under consideration. Our results on Delbrück scattering are also qualitatively different from those of Bethe and Rohrlich based on the impact-parameter approximation.

1. INTRODUCTION

HIGH-ENERGY collision processes have occupied one of the central places in both experimental and theoretical physics in the last decade. On the experimental side, this is evidenced by the planning of the 200-BeV accelerator at the National Accelerator Laboratory. Aside from the obvious problem of searching for intermediate bosons, quarks, and other possible heavy particles, many significant experiments to be carried out with an accelerator of this size must be con-

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