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TENSOR MESON DOMINANCE AND REGGE COUPLINGS

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Meinem Vater Dr. Joseph Freund
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SUMMARY

The helicity structure of mesonic Regge couplings is discussed in the context of meson pole dominance for the matrix elements of vector currents and of the energy momentum tensor. Experimental tests of this helicity structure are proposed. The obtained couplings are incompatible with the $U(6)_W \times O(2)_{L_Z}$ symmetric quark model, and they therefore provide a guide toward $U(6)_W \times O(2)_{L_Z}$ symmetry breaking. Universal couplings for higher spin ($J > 2$) mesons are considered.

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1. INTRODUCTION

In this paper I want to discuss the helicity structure of the mesonic Regge-couplings that emerge from meson pole dominance (especially vector and tensor meson dominance) arguments and from experiment. These couplings turn out to be incompatible with the $U(6)_W \times O(2)_{L_Z}$ symmetric quark model. Modifications in multiplet assignment under the rest symmetry group $U(6) \times U(6) \times O(3)$ and the breaking of $U(6)_W \times O(2)_{L_Z}$ symmetry that might lift these difficulties will then be discussed.

Before going into details let me still make a few remarks on pole dominance models. Such models were in the "mainstream" of physics in the sixties. They were pursued with much enthusiasm towards the beginning and middle of that decade. The most popular of these models was (especially in Chicago!¹⁾) and still is, vector meson dominance (VMD) of the small q^2 matrix elements of the electromagnetic and weak vector currents. Towards the end of the sixties, with the advent of larger q^2 data, the limitations of any model that includes only a small number of poles became ever more apparent. On the theoretical side as well, new ideas about hadrodynamics, specifically duality, require the existence of infinitely many hadrons for every spin, parity, and internal quantum numbers assignment. Faced with the prospective of infinitely many, say vector mesons, one has to considerably increase one's humility when talking about VMD with one, or two, or three mesons or about field theoretic realizations of VMD. In the rest of the paper I will refer to such limited (to small q^2) models as

"first order" pole dominance models (in this special case as "first order" VMD).

The ideas of tensor meson dominance (TMD)²⁾ and scalar meson dominance (SMD)³⁾ of the matrix elements of the energy momentum tensor $\theta_{\mu\nu}$ and its trace θ , while also formulated in the early sixties, have come into the focus of theoretical activity⁴⁾⁻⁷⁾ only more recently.* One should hope therefore that many of the oversimplifications that one finds in VMD papers will not be repeated in the development of TMD and SMD.

I now want to go directly to the specific topics mentioned above.

*The reason for this is to a large extent that photons are "somewhat" more accessible in experiment than gravitons.

2. TMD and Helicity Conservation

It has been known for some time, that the Pomeranchuk contribution conserves s-channel helicity in πN -scattering⁸⁾ and in ρ^0 -photoproduction.⁹⁾ In addition, the important observation was made⁸⁾ that the f (or P' as it is sometimes called) Regge pole contribution to πN scattering also conserves s-channel helicity. We want to first review the recently established⁶⁾ connection of these facts with TMD and then to follow up their further, rather startling, consequences. Consider first the exchange degenerate ω -f-trajectory. A particle of spin J and parity $(-1)^J$ on this trajectory couples to the nucleons in the form

$$\bar{u}(p')(a(J)P_{\mu_1} + b(J)\gamma_{\mu_1}) P_{\mu_2} \dots P_{\mu_J} \epsilon^{\mu_1 \dots \mu_J} u(p) \quad (2.1)$$

where $P = p+p'$, u and $\bar{u}$ are the nucleon spinors, ϵ is the polarization tensor of the meson and $a(J)$, $b(J)$ are coupling constants. In order to have s-channel helicity conservation in πN scattering one must have

$$a(J) \equiv 0 \text{ for all } J \quad (2.2)$$

At $J=1$, the "first order" VMD of the isoscalar Pauli (anomalous magnetic) form factor (F_{2s}) of the nucleon at $t=0$, together with the interdiction of the ϕNN coupling by the quark model requires (because of the very small isoscalar anomalous magnetic moment of the nucleon)

$$a(1) \approx 0 \quad (2.3)$$

in agreement with (2.2). Alternatively, in the context of VMD, the vanishing of the anomalous isoscalar nucleon magnetic moment is a consequence of Eq. (2.2). For $J=2$ the "first order" version of TMD requires the f and f' mesons to dominate the matrix elements of the energy momentum tensor $\theta_{\mu\nu}$ (except for the trace thereof) between nucleon states. At $t=0$ the matrix element of $\int d^3x \theta_{00}$ is normalized to the energy, while the matrix element of $\int d^3x (x_1 \theta_{02} - x_2 \theta_{01})$ is normalized to the spin projection of the proton onto the z axis. These two conditions together with the quark model, which forbids the $f'\bar{N}N$ coupling, lead to ⁶⁾

$$a(2) = 0 \quad (2.4)$$

again in accord with (2.2). How does one understand this result beyond the "first order" TMD approximation? In addition to the f and f' there are heavier 2^+ mesons, presumably an infinity of them, again in ideal nonets with f -like (built of nonstrange quarks) and f' -like (built of strange quarks) members. Including these higher mesons, one would be led only to a sum rule between the a -type coupling constants (Eq. (2.1)) of these mesons. This sum rule would also involve the graviton-meson transition moments for all these mesons. Why is then Eq. (2.4) obeyed in nature? As an analogy, let us consider the Sachs-electric form factor of the neutron (G_{En}). Here again the vanishing of the neutron charge is not accomplished by a cancellation between infinitely many vector meson contributions, but by the vanishing of each of these contributions individually. This same argument would not work in the case of the neutron's Dirac form-factor for which $F_{1n}(0) = 0$ but $F_{1n}(t) \neq 0$. The tensor form-factor

in question however, is the counterpart of the isoscalar Pauli form factor $F_{2s}(t)$ and indeed experimentally $F_{2s}(t) \equiv 0$. So, in the presence of infinitely many tensor mesons one expects a relation of the type (2.4) for each of them.

It was remarked by Salam and Jones⁷⁾, that if the Pomeranchuk singularity were a Regge pole then a 2^+ meson F would lie on it and (barring a cancellation between this meson and the f) a condition of the type (2.4) would then hold for F as well. This would be in line with the observed s -channel helicity conservation for the Pomeranchuk term in πN -scattering.⁸⁾ It is by no means obvious, that the Pomeranchuk singularity is a Regge-pole.* Whatever its nature, the Pomeranchuk singularity can contribute to the gravitational form factors of the nucleon. In fig. 1 we show a diagram (and its possible quark model realization) by which such a contribution can be obtained. Such a term has been shown to be needed also for SMD.¹⁰⁾ In either case it would correspond to a continuum, rather than a pole contribution. The helicity structure of such a contribution would again be all right because the Pomeranchuk is known to conserve s -channel helicity in πN -scattering. This Pomeranchuk contribution means that in gravitational (scalar or tensor) form factors TMD is not the whole thing but a continuum is present. No appreciable continuum is observed in electromagnetic (vector) form factors. But then, the electromagnetic current belongs to an $SU(3)$ octet and has odd charge conjugation properties.

* Even if it were a Regge-pole, it would not be of the usual type as this would mean a very strong violation of exchange degeneracy.

These are not the quantum numbers of the vacuum. The energy-momentum tensor has large parts with vacuum quantum numbers and these can lead to appreciable continuum contributions to gravitational form-factors.*

* After the completion of this work we learned that Dr. K. Raman (to be published) has independently arrived at a similar conclusion.

3. Helicity Structure of Regge Couplings. Experimental Consequences

We have seen above, that the helicity flip couplings to nucleons, of the Pomeranchuk (P) and of the ω -f and ϕ -f' Regge-poles vanishes. Thus, only the ρ - A_2 Regge pole can contribute to the s-channel helicity flip amplitudes (A) in $\pi^\pm N$ and $K^\pm N$ elastic scattering. In the s-channel helicity conserving (B) amplitude there are P and Regge (ρ, ω, f, A_2) contributions. In all these cases the leading term in the polarization will thus come from the interference of the ρ - A_2 term in the A amplitude with the P term in the B-amplitude.

Assuming this leading term to provide a good approximation for the entire polarization, we find the following relations (we assume SU(3) symmetry and exchange degeneracy to relate the $\rho\pi\pi$ to the $\bar{K}K$ and $A_2\bar{K}K$ Regge couplings)

$$P_{\pi^- p} / P_{\pi^+ p} = -1 \quad (3.1a)$$

$$P_{K^- n} / P_{K^- p} = -1 \quad (3.1b)$$

$$P_{K^+ n} / P_{K^+ p} = -1 \quad (3.1c)$$

$$\left(\frac{(\frac{d\sigma}{dt} p)_{\pi^+ p}}{(\frac{d\sigma}{dt} p)_{K^+ p}} \right) \cdot \left(\frac{\sigma_{K^+ p}^{(\infty)}}{\sigma_{\pi^+ p}^{(\infty)}} \right) + \frac{(\frac{d\sigma}{dt} p)_{K^- p}}{(\frac{d\sigma}{dt} p)_{K^+ p}} = 1 \quad (3.1d)$$

$$\frac{(\frac{d\sigma}{dt} p)_{K^- p}}{(\frac{d\sigma}{dt} p)_{K^+ p}} = \cos \pi \alpha_p(t) - \sin \pi \alpha_p(t) \cot \frac{\pi}{2} \alpha_p(t) \quad (3.1e)$$

Here $\alpha_\rho(t)$ is the exchange degenerate ρ - A_2 Regge trajectory
 $\alpha_\rho(t) \approx 1/2 + t/2m_\rho^2$, $\alpha_P(t)$ is the Pomeron trajectory,
 $\sigma_{\pi^+p}(\infty)$ and $\sigma_{K^+p}(\infty)$ are the asymptotic π^+p and K^+p total cross-
sections and P stands for polarization. One can obtain further relations
if one includes pp scattering.

The relations (3.1) hold essentially in any model in which of
the two interfering amplitudes one is sensitive only to ρ and A_2
(A in our case) and the other (B -in our case) also to P . Such models,
different though from the one considered here (namely the ρ - A_2 trajectory
is assumed to contribute only to the spin-flip rather than the helicity-
flip amplitude), have been discussed previously.¹¹⁾ We have here a
specific model for the amplitudes A and B , based on the theoretical
considerations of section 2 and backed by independent experiments.
We do not have to make a separate " ρ - A_2 only" assumption for the A
amplitudes to fit polarizations. The polarizations are here used to
test an otherwise established helicity structure for meson-baryon
scattering amplitudes. We also believe that it is worth spelling out
the new relations (3.1) as being tests of the model, independent of any
detailed fits to the data. With improved accuracy Eq. (3.1c) could be
used to measure $\alpha_\rho(t)$. The relations (3.1) are in agreement with
existing experiments. The "mirror symmetry" of $\pi^\pm p$ polarizations
(Eq. (3.1a)) is well known. Relations that involve K^+p polarizations
face somewhat less accurate experimental data. So, for all practical
purposes, for small t we can assume $\alpha_\rho(t) \approx 1$ (as a small departure
from this value would not be noticeable with present accuracies).

At 6 GeV/c, at small t ($t \sim 0.2 \text{ GeV}^2$) the first term in Eq. (3.1d) is very close to 1 while the second term is practically zero so that Eq. (3.1d) is obeyed.¹²⁾ The right hand side of Eq. (3.1d) is sensitive to the precise value of $\alpha_p(0)$ but at small t it is small, again in agreement with the experimental result for the left hand side of (3.1d). The relations (3.1) thus seem to agree with experiment. We shall not give here a more detailed comparison with the data.

4. Helicity Structure of Regge Couplings. Theoretical Consequences.

All particles situated on the ϕ -f' trajectory - containing strange quarks only - completely decouple from the nucleon. In Section 2 (Equation (2.2)), we have seen, that the helicity flip (HF) coupling to nucleons of all particles on the ω -f trajectory also vanishes. From these facts it follows, that the HF couplings to baryons of the exchange degenerate nonet of Regge poles to which ω -f and ϕ -f' belong, must be such that the SU(3)-singlet combination decouples and the octet has a D/F ratio of ¹³⁾

$$(D/F)_{HF} = 3 \quad (4.1)$$

all along the Regge trajectory (i.e. for all t).

At $t = m_\omega^2$ ($\alpha(t) = 1$) this is precisely the D/F ratio of baryon anomalous magnetic moments as was to be expected from VMD. If one combines this with the $SU(6)_W$ prediction for total magnetic moments

$$\mu_p / \mu_n = - 3/2 \quad (4.2)$$

then one obtains the stronger results

$$\mu_p = 3 \quad \mu_n = - 2 \quad (4.3)$$

which are in quite good agreement with experiment. So, at $t = m_\omega^2$ Eq. (3.1) together with $SU(6)_W$ -symmetry form a compatible and acceptable set of assumptions. As of $t = m_f^2$ ($\alpha(t) = 2$) and further up the exchange-

degenerate ω -f trajectory, Eq. (3.1) and $SU(6)_W \times O(2)_{L_z}$ symmetry become dramatically incompatible¹⁴⁾. Collinear $SU(6)_W \times O(2)_{L_z}$ symmetry requires the $(D/F)_{HF}$ ratio to change along the Regge-trajectory. At $t = m_J^2$ where $\alpha(m_J^2) = J$, $SU(6)_W \times O(2)_{L_z}$ predicts a $(D/F)_{HF}(J)$ of

$$(D/F)_{HF}(J) = 3 \left(2 - \frac{3m_J}{2m_B} \right)^{-1} \quad (4.4a)$$

where m_B is really some "central" baryon mass. For comparison, $SU(6)_W$ and VMD predict the total proton magnetic moment to be

$$\mu_p = \frac{2m_B}{m_1} \quad (4.5)$$

As this number is very close to 3 (see Eq. (4.3)) we can eliminate m_B from (4.4) and find

$$(D/F)_{HF}(J) = 3 \left(2 - \frac{m_J}{m_1} \right)^{-1} \quad (4.4b)$$

We see from here that

$$(D/F)_{HF}(1) = 3 \quad (4.6)$$

as stated above. For $J \geq 2$ however, the right-hand side of Eq. (4.4b) takes values, very different from 3. $J \geq 2$ means $L \geq 1$ for the rest-symmetry $U(6) \times U(6) \times O(3)$. So what goes wrong is the full $U(6)_W \times O(2)_{L_z}$

group. Only for $L = 0$ ($J=1$), where the $0(2)_{L_z}$ becomes trivial, are there no troubles. Full $U(6)_W \times 0(2)_{L_z}$ symmetry is in trouble on other accounts as well. Thus, for instance, the ratios of D to S-wave couplings in $B \rightarrow \omega\pi$ and $A_1 \rightarrow \rho\pi$ decays are incorrectly predicted. The reason for this is not hard to understand. The $f \rightarrow \pi\pi$ decay is pure D-wave. There is a unique $U(6) \times 0(2)$ invariant coupling of the $L=1$, $(6, \bar{6})$ (to which the f , A_1 , and B belong) to the $L=0$ $(6, \bar{6})$'s (to which π , ρ , ω belong). Therefore the ratios of all couplings to the $f \rightarrow \pi\pi$ coupling must be Clebsch-Gordan coefficients of $U(6)_W \times 0(2)_{L_z}$ and as such dimensionless numbers. All S-wave couplings must then be suppressed by a factor p_{cm}^2 so as to have dimensionless ratios to the D-wave $f \rightarrow \pi\pi$ coupling. So, S-wave decays of A_1 and B are suppressed. Thus any symmetry breaking mechanism that will lead to an S-wave coupling independent of p_{cm} , will radically alter all D/S wave coupling ratios. What is the way out of these difficulties? There are two possibilities:

A)¹⁴⁾ It could happen, that while at $L=0$ the mesons fall in the representation $(6, \bar{6}; L=0)$ of $U(6) \times U(6) \times 0(3)$, at $L \neq 0$; this is not anymore the case. For $L \neq 0$ the mesons could be in an L -dependent mixture of $(6, \bar{6})$ and $(\bar{6}, 6)$. The prediction (4.4) is then relaxed and for a suitably chosen mixture of $(6, \bar{6})$ and $(\bar{6}, 6)$ one can obtain (4.1) instead while maintaining exact $SU(6)_W \times 0(2)_{L_z}$. For reference, the required ratio of $(\bar{6}, 6)$ to $(6, \bar{6})$ as a function of J is

$$\eta(m_J^2) = 1 - 4 \left[3 \frac{m_1}{m_J} - \frac{m_J^2}{m_1^2} + 2 \right]^{-1} \quad (4.7)$$

where we have put $J = L+1$ as befits the $J = L+S$ spin triplet trajectory. This notation also coincides with that of Eqs. (4.4). Again Eq. (4.5) was used to eliminate m_B .

The question is what becomes of the mixture that is orthogonal to that given by (4.7). Does it also correspond to some mesons?¹⁵⁾

The alternative possibility is

B) Breaking $U(6)_W \times O(2)_{L_z}$ with a 3P_0 spurion (i.e. a small spin-orbit coupling). This has been repeatedly suggested in literature as a remedy for the undesired $U(6)_W \times O(2)_{L_z}$ predictions¹⁶⁾. To lowest order in this spurion (in couplings of one $L = 1/2$ multiplet to two $L=0$ multiplets) one is left with a residual "quasicoplanar" $U(3) \times U(3)$ symmetry.*)

This quasicoplanar $U(3) \times U(3)$ symmetry requires certain correlations in the decays of $L = 1$ mesons which are compatible with the existing data.**) The peculiarity of the 3P_0 spurion as required in order to achieve (4.1), is that its strength is fixed and cannot be a small parameter. This makes a perturbative treatment of the spurion

*) In the rest frame of the $L \neq 0$ particle, the plane is defined by the momentum $\vec{k}$ of one of the $L = 0$ particles and by the direction of the vector $\vec{V}$ whose components are $V_{a_1} = \epsilon_{a_1 a_2 \dots a_L} k_{a_2} \dots k_{a_L}$, where $\epsilon_{a_1 \dots a_L}$ is the orbital polarization tensor of the $L \neq 0$ particle.

**) The relations obtained by other means in ref. 16) are due to this quasicoplanar $U(3) \times U(3)$ symmetry.

somewhat questionable. We are presently investigating both possibilities.

A) and B) with the objective of identifying a unique quark model interpretation of the helicity-structure of Regge-couplings found in the previous sections.*)

*) The solution of this problem may be of importance also for the inclusion of quark spin in dual resonance models.

5. Conclusions

From the arguments presented above we learn that the observed helicity structure of Regge couplings in πN -scattering has further consequences that agree with existing experiments (Section 3). It also agrees with theoretical expectations from vector and tensor meson dominance ideas. But it disagrees with the $U(6)_W \times O(2)_{LZ}$ -symmetric quark model. As such it may be a useful guide for understanding the mechanism of $U(6) \times O(2)$ breaking.

We finally want to make one more observation. The universality of Regge-couplings induces a universality not only in the couplings of vector and tensor mesons but also in the couplings of higher spin ($3^-, 4^+, \dots$) particles lying on the exchange degenerate nonet of mesonic Regge-trajectories. The universality of vector and tensor meson couplings is dynamically understandable in terms of their coupling to the vector currents and energy momentum tensor respectively. What are the corresponding operators for the higher spin mesons? An answer to this question was provided a few years ago¹⁷⁾ when it was suggested that in a quark model the corresponding operators are

$$Z_{\mu_1 \dots \mu_J} = \bar{\psi} (\gamma_{\mu_1} \overleftrightarrow{\partial}_{\mu_2} \dots \overleftrightarrow{\partial}_{\mu_J} + \text{symm.}) \lambda_1 \psi \quad (5.1)$$

The importance of these operators has more recently also been observed in discussions of scale invariance.¹⁸⁾ It is interesting, that in a free quark model all operators (5.1) are conserved.¹⁹⁾ This corresponds to the invariance of the quark model under the infinite-parameter group of transformations

$$\delta \psi = i^J \alpha_k \overset{v_1}{\partial}_{\mu_1} \dots \overset{v_{J-1}}{\partial}_{\mu_{J-1}} \overset{v_J}{\partial}_{\mu_J} \lambda_k \psi \quad (5.2)$$

where the α 's are the infinitesimal parameters. In reality the Z-tensors of Eq. (5.1) are not conserved. It is an interesting question whether consistent field theories of systems of mesons up to a certain high spin, coupling to the (non-conserved) "currents" defined (via a Noether argument) by the transformations (5.2) can be constructed. These would be the higher links in a chain of field theories starting with the Yang-Mills theory for $J=1$, the theory of gravitation^{*)} for $J=2, \dots$

^{*)} Even this $J=2$ theory has been worked out so far only for an SU(3)-singlet boson (i.e. k limited to zero in Eq. (5.4)).

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Figure Captions

Fig. 1: a) "shortcircuited" Pomeranchuk (P) exchange contribution to gravitational ($h \equiv$ graviton) form factor of the hadron H. A summation over all hadrons H_i and H_j (such that the vertex $H_i H_j P$ does not vanish) is understood;

b) quark model realization of diagram 1a for $H, H_i, H_j =$ nonexotic mesons. To this one has to add diagrams where H_i, H_j and/or the exchanged hadrons are baryons or exotic hadrons in the sense of P.G.O. Freund, Lett. al Nuovo Cimento 4, 147 (1970).

(a)

(b)

Fig. 1