EXISTENCE OF TWO $T = 0$ VECTOR MESONS*

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We wish to interpret the various recently discovered vector meson states within the framework of the vector theory of strong interactions[1,2] (VTSI) proposed nearly two years ago. In particular, we concentrate our attention on the *two distinct* $T = 0$ vector mesons unambiguously predicted by VTSI. The following are some of the major points we would like to make:

(1) The 550-Mev peak in the $\pi^+\pi^-\pi^0$ mass plot for the reaction

$$\pi^+ + d \to \pi^+ + \pi^- + \pi^0 + 2p$$

studied by the Johns Hopkins–Northwestern group[3] may well be due to a *second* $T = 0$ vector meson state (tentatively called η^0) with exactly the same quantum numbers as the experimentally well established ω^0 at 785 Mev.

(2) In the language of VTSI, the ω^0 is to be identified with the vector meson coupled to the baryonic current whereas the η^0 with a lower mass is to be identified with the vector meson coupled to the hypercharge current.

(3) Most of the hard-core effect between two nucleons should come from the exchange of an ω^0 rather than from the exchange of an η^0.

(4) The conjectured η with a mass lower than the ρ ($T = 1$, $J = 1-$ two-pion resonance) mass is extremely helpful in understanding the nucleon structure.

(5) Generalized Clementel-Villi-Fubini type analyses applied to the observed nucleon form factors suggest that 120% of the isoscalar charge is due to η, and that 120% of the isovector charge is due to ρ; hence, using the argument of Gell-Mann and Zachariasen,[4] we infer that the universality relations implied by the couplings of the vector mesons to the appropriate conserved currents may hold approximately even at $s = m_\rho^2, m_\eta^2$.

Some time ago a theory of strong interactions was proposed which unambiguously predicts the existence of one $T = 1$ vector meson (p-wave two-pion resonance) and two $T = 0$ vector mesons ($T = 0$, $J = 1-$ three-pion resonances). Recent πN and $p\bar{p}$ experiments[5,6] have conclusively established that there indeed exist a $T = 1$ vector meson ρ with a mass of 750 Mev and a width of ~ 80 Mev and a $T = 0$ vector meson ω^0 with a mass of 785 Mev and a width <30 Mev. Moreover, Pevsner and collaborators[3] report that, in the reaction

$$\pi^+ + d \to \pi^+ + \pi^- + \pi^0 + 2p, \tag{1}$$

in addition to the clearly identified ω^0 peak (whose mass agrees well with that of Maglić *et al.*[6]), there is an indication for another peak in the Q-value plot for $\pi^+\pi^-\pi^0$ which might be associated with a three-pion resonance with a mass of ~ 550 Mev and a width <30 Mev. The statistics are still meager, and the effect may disappear later.[7] Neither the isospin nor the spin-parity assignment has been made. Yet in the present note we take this state seriously, and call it η^0. Moreover, we assume that η^0 is a $T = 0$ vector meson that decays strongly into three pions with $T = 0$, $J = 1-$, just like ω^0. (As the η mass is not far above the three-pion threshold, the two-body electromagnetic decay mode $\pi^0 + \gamma$ might also be detectable; if we use the method of Gell-Mann and Zachariasen[4] to compute the decay rate for $\eta^0 \to \pi^0 + \gamma$ from the π^0 lifetime, we obtain about 0.03 Mev for the *partial* width provided that $f_\eta^2/4\pi \sim 2$.)

Let us recall that the two $T = 0$ vector mesons of VTSI are coupled linearly to the two exactly conserved $T = 0$ currents of the strong interactions—the hypercharge current and the baryonic current. The following question naturally arises: Is $\omega^0(\eta^0)$ coupled to the baryonic current or to the hypercharge current? Note that here we have two particles or resonant states that have identical isospins and identical spin parities; moreover, their widths seem narrow in both cases. The only difference is that the ω mass is 230 Mev higher than the η mass. Yet according to VTSI, their roles in strong-interaction physics are quite distinct. For instance, if the pseudoscalar mesons, π and K, are to emerge as tightly bound states of $N\bar{N}$ and $N\bar{\Lambda}$ systems, glued by a heavy neutral vector meson as suggested by Teller and others,[1,8] the coupling of the baryonic vector meson ($B^{(B)}$ of reference 1) must be much stronger than the coupling of the hypercharge vector meson ($B^{(Y)}$ of reference 1); otherwise there would be a *very tightly* bound state of a $\bar{K}$ and an N.

In principle, it is possible to settle this question by studying the analytic structure of the KN

scattering amplitudes as functions of momentum transfer. For instance, if η^0 (but not ω^0) is the vector meson coupled to the hypercharge current, both the $T=1$ KN amplitude and the $T=0$ KN amplitude must have poles at $t=m_\eta^2$ with equal residues, but no poles should be present at $t=m_\omega^2$. In practice, however, this will not be feasible for a long time to come. A more practical way is to study the effects of η^0 and ω^0 on nuclear forces at short distances, keeping in mind that the coupling of the baryonic vector meson to the nucleon must be much stronger than the coupling of the hypercharge vector meson to the nucleon. Just as the baryonic vector meson is responsible for most of the attraction necessary to bind a baryon and an antibaryon to form a π or a K, the same particle must also be responsible for most of the observed short-ranged, very strong repulsion between two nucleons. In this connection we should recall an important observation made by Breit,[9] who also advocated the neutral-vector-meson approach to nuclear forces to account for the repulsive core and the spin-orbit force in a unified manner.[10] He demonstrates that with a vector coupling constant of the order of 10 and with a vector meson mass $\sim 4m_\pi$, the repulsive core radius would become too large in the sense that the central force in the intermediate region (distance $\sim 0.75/m_\pi$) would be completely dominated by the strong repulsion due to the vector meson. Although a rigorously quantitative discussion of Breit's argument must await a more reliable estimate of the two-pion exchange contribution to nuclear forces than is now available, there is no doubt that between ω with $m_\omega=5.9\,m_\pi$ and η with $m_\eta \doteq 4.0\,m_\pi$, the ω is the more likely candidate for the $T=0$ vector meson coupled strongly to the baryonic current. In the language of reference 1, this means that ω^0 is the vector meson associated with the $B_\mu^{(B)}$ field while η^0 is the one associated with the $B_\mu^{(Y)}$ field.[11]

It is encouraging that, in both $p\bar{p}$ collisions and π^+d collisions, ω mesons show up much more conspicuously than η mesons. In reaction (1) at $p_\pi^{(\mathrm{lab})}=1.23$ Bev/c, the cross section for ω^0 production seems to be about four times as large as that for η^0 production.[3] In $p+\bar{p}\rightarrow 5\pi,\ 7\pi$, there is hardly any evidence for η's.[6] Thus, contrary to Chew and Frautschi,[12] all strong interactions do not seem as strong as possible; rather some strong couplings such as the coupling of ω^0 to $N\bar{N}$ seem much stronger than other strong couplings such as the coupling of η^0 to $N\bar{N}$, as conjectured earlier.[1]

We now examine the nucleon structure problem in the light of the existence of ρ, η, and ω. Electron-proton scattering experiments carried out at Stanford and Cornell[13] have revealed that the neutron charge cloud has a fairly large positively charged "fringe." In a more sophisticated language, the average mass state responsible for the isoscalar form factor must be lower than that responsible for the isovector form factor. Applying Clementel-Villi[14] type fits to the nucleon form factors, it was concluded by Bergia <u>et al.</u>[15] (BSFV) that, if a simple resonance picture (which has its origin in the pioneer work of Nambu[16]) holds, the $T=1$, $J=1-$ two-pion resonance proposed by Frazer and Fulco[17] must have a higher mass than the $T=0$, $J=1-$ three-pion resonance proposed by Nambu[16] and Chew.[18] Thus the simple resonance picture of BSFV would run into trouble if the ω which has a higher mass than the ρ were the only $T=0$ vector meson (or the only $T=0$, $J=1-$ three-pion resonance).

It is evident that the introduction of a second neutral vector meson with a mass lower than the ρ mass will help remedy this situation. Yet one may still argue that if η^0 is coupled less strongly than ω^0 to $N\bar{N}$, then the η meson effect might not help too much. This, however, is not necessarily the case. It can be shown, using an argument originally given by Gell-Mann and Zachariasen,[4] that if the "universal" coupling constant of η^0 to the hypercharge current defined at $s=0$ does not differ appreciably from the $\eta N\bar{N}$ coupling constant defined at $s=m_\eta^2$, then there must be a substantial contribution to the isoscalar charge form factor from the one η state, the crux of the matter here being that both η^0 and the "isoscalar photon" are coupled to the same conserved hypercharge current. Moreover, in a theory which is sufficiently symmetric between N and Ξ, it is easy to show that the transition "isoscalar photon" $\rightarrow \omega^0$ must be forbidden to the extent that the $N\Xi$ mass difference could be ignored. (Recall that the baryonic current is even under $N \rightleftarrows \Xi$, while the hypercharge current is odd.)

But let us work backwards, so to speak, and look at the experimental data first. If there are two $T=0$ vector meson states, it is natural to modify the BSFV formula in the following way:

$$F_1^{\,s}(q^2)=\frac{\alpha_\eta m_\eta^{\,2}}{q^2+m_\eta^{\,2}}+\frac{\alpha_\omega m_\omega^{\,2}}{q^2+m_\omega^{\,2}}+(1-\alpha_\eta-\alpha_\omega). \qquad (2)$$

Crudely speaking, α_η, α_ω, and $(1-\alpha_\eta-\alpha_\omega)$ represent the fractions of the isoscalar charge contributed by the one η state, the one ω state, and all other (hopefully very massive) states, respectively. If we regard $m_\eta^2 = 16 m_\pi^2$ and $m_\omega^2 = 32 m_\pi^2$ as experimentally determined quantities, the formula contains only two independent adjustable parameters, one of which is more or less determined by the requirement $\langle r_1^2\rangle_p^{1/2} = 0.8\times 10^{-13}$ cm, $\langle r_1^2\rangle_n^{1/2} = 0$. Crude numerical estimates show that the observed data can be adequately reproduced by[19]

$$\alpha_\eta = 1.2, \quad \alpha_\omega = -0.7.$$

On the other hand, for $F_1^V(q^2)$ the original BSFV form suffices so that we have

$$F_1^V(q^2) = \frac{\alpha_\rho m_\rho^2}{q^2 + m_\rho^2} + (1 - \alpha_\rho), \tag{3}$$

just as before; the data require

$$\alpha_\rho = 1.1 - 1.2, \quad m_\rho^2 = 19 m_\pi^2 - 22 m_\pi^2.$$

(The slight "discrepancy" between this value for m_ρ^2 and the "observed" value $m_\rho^2 = 29 m_\pi^2$ is somewhat puzzling.)

Gell-Mann and Zachariasen[4] have noted that if ρ and η are coupled to the conserved isospin and the hypercharge current, respectively, and if the bare masses of ρ and η are infinite (or very large), then the constants α_ρ and α_η are directly related to the form factors of the vector type couplings of the vector mesons to the nucleon at zero momentum transfer, or, equivalently, to the ratios of the "universal" coupling constant $f_\rho^2/4\pi$ or $f_\eta^2/4\pi$ at zero momentum transfer to the "polology" coupling constant measurable at $s = m_\rho^2$, m_η^2 denoted by $f_{\rho N\bar{N}}^2/4\pi$, $f_{\eta N\bar{N}}^2/4\pi$:

$$\begin{aligned} \alpha_\rho &= [1/F_{\rho N\bar{N}}(s)]_{s=0} = f_{\rho N\bar{N}}/f_\rho, \\ \alpha_\eta &= [1/F_{\eta N\bar{N}}(s)]_{s=0} = f_{\eta N\bar{N}}/f_\eta. \end{aligned} \tag{4}$$

It is extremely gratifying that the observed values of α_ρ and α_η are so close to unity. We do not yet understand the deep reason for this, but in view of (4), relations such as $\alpha_\rho \sim 1$ and $\alpha_\eta \sim 1$ seem much more plausible in a theory in which the vector meson states coupled to the conserved currents are introduced in the very beginning, rather than in a theory in which these rather narrow resonant states emerge dynamically, if they do at all, in a mysterious "self-generating" manner â la Chew.[20] Should the α's for other charged particles also turn out to be approximately equal to unity, then, even within the framework of dispersion theory in which all energy momenta are on the mass shell, it would become meaningful to talk about the universal coupling of $\rho(\eta)$ to the particles bearing isospins (hypercharges). Initial steps along this line have already been made in comparing the effect of ρ on πN scattering (proportional to $f_{\rho N\bar{N}} f_{\rho\pi\pi}$) with the width of ρ (proportional to $f_{\rho\pi\pi}^2$).[4,21,22] It appears likely that the notions of universality and conserved vector currents are important elements in our quantitative, as well as qualitative,[1] understanding of the dynamics of strong interactions.

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[2] J. J. Sakurai, Nuovo cimento 16, 388 (1960).

[3] Private communication from P. Schlein based on work of the Johns Hopkins–Northwestern group. Preliminary data of the group have been reported by A. Pevsner [Proceedings of the International Conference on High-Energy Physics held at Aix-en-Provence, September, 1961 (to be published)].

[4] M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[5] A. R. Erwin, R. March, W. D. Walker, and E. West, Phys. Rev. Letters 6, 628 (1961); E. Pickup, D. K. Robinson, and E. W. Salant, Phys. Rev. Letters 7, 192 (1961). These papers contain more complete references to the earlier papers on this subject.

[6] B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson, Phys. Rev. Letters 7, 178 (1961); N. H. Xuong and G. R. Lynch, Phys. Rev. Letters 7, 327 (1961); M. L. Stevenson, G. R. Kalbfleisch, B. C. Maglić, and A. H. Rosenfeld, Phys. Rev. (to be published).

[7] It is amusing that the threshold energy for $\eta + N$ coincides with the energy of an anomalously sharp peak in $\gamma + p \to \pi^+ + n$ observed by L. Hand and C. Schaerf [Phys. Rev. Letters 6, 229 (1961)]. Thus the Hand-Schaerf anomaly could be a cusp effect. Incidentally, contrary to J. S. Ball and W. R. Frazer [Phys. Rev. Letters 7, 204 (1961)], the usual 600-Mev πN resonance cannot possibly be attributed to a threshold effect due to $\pi + N \to \rho + N$ since the ρN threshold is 170 Mev above the 600-Mev resonance. It is possible that the 600-Mev resonance is a bound state of a ρ and an N (bound by the exchange of a ρ), which, however, decays strongly into $\pi + N$, etc. [J. J. Sakurai (to be published)].

[8] E. Teller, in Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics (Interscience Publishers, Inc., New York, 1956), Chap. VII, p. 18. See also Y. Fujii, Progr. Theoret. Phys. (Kyoto) 21, 232 (1959).

[9] G. Breit, Phys. Rev. 120, 287 (1960). See also R. S. McKean, Jr. (to be published).

[10] G. Breit, Proc. Natl. Acad. Sci. U. S. 46, 746 (1960).

[11] Because of an unfortunate historic accident, the nomenclature implied by this identification is contrary to that of Gell-Mann [M. Gell-Mann in his report at the La Jolla Conference on the Theory of Strong and Weak Interactions, June, 1961 (unpublished); also M. Gell-Mann, Phys. Rev. (to be published), and reference 4]. Despite $m_\rho \approx m_\omega$, ρ and ω do not seem to belong to the same octet of the unitary symmetry model. Rather the observed ω is Gell-Mann's B, and our conjectured η is Gell-Mann's ω. Independently of Gell-Mann, A. Salam and J. C. Ward [Nuovo cimento 20, 419 (1961)] and Y. Ne'eman [Nuclear Phys. 26, 222 (1961)] have constructed vector meson theories of strong interactions based on unitary symmetry. Such theories can also accommodate two $T=0$ vector mesons, one belonging to an octet, the other being a singlet all by itself even though Salam and Ward and Ne'eman considered only the one belonging to the octet. In all such models, the postulated symmetries must be badly broken. So far, the only practical advantage of such theories over the original VTSI of reference 1 seems to be the prediction of an $|S|=1$ vector meson, which might be identified with K^* of M. H. Alston, L. W. Alvarez, P. Eberhard, M. L. Good, W. Graziano, H. K. Ticho, and S. G. Wojcicki [Phys. Rev. Letters 6, 300 (1961)]. If the Y_1^* spin is $\frac{3}{2}$, and the $\Lambda\Sigma$ parity is even, then the observed very small Σ/Λ branching ratio for Y_1^* may fit nicely with Gell-Mann's "eightfold way" (but not the unitary symmetry model based on the Sakata triplet) which requires $f_{\pi\Sigma\Sigma}{}^2=0$ with "D-type" meson-baryon couplings. See, e.g., J. Franklin (to be published). Note also that Franklin's choice $f_{\pi\Lambda\Sigma}{}^2 \gg f_{\pi\Sigma\Sigma}{}^2 \approx 0$ can accommodate Y_0^*, Y_1^*, and Z^* ($T=2$) as $p_{3/2}$ pion-hyperon resonances belonging to a "representation 27" of the "eightfold way." (Recall that $8\times 8=1+8+8+10+10=27$.)

[12] G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 5, 580 (1960); Phys. Rev. 123, 1478 (1961).

[13] R. Hofstadter and R. Herman, Phys. Rev. Letters 6, 293 (1961); R. M. Littauer, H. F. Schopper, and R. R. Wilson, Phys. Rev. Letters 7, 144 (1961). According to R. Hofstadter (private communication), more reliable data will become available in the near future.

[14] E. Clementel and C. Villi, Nuovo cimento 4, 1207 (1958).

[15] S. Bergia, A. Stanghellini, S. Fubini, and C. Villi, Phys. Rev. Letters 6, 367 (1961).

[16] Y. Nambu, Phys. Rev. 106, 1366 (1957).

[17] W. R. Frazer and J. R. Fulco, Phys. Rev. 117, 1609 (1960). See also S. D. Drell, in Proceedings of the 1958 Annual International Conference on High-Energy Physics at CERN (CERN, Geneva, 1958), p. 27, and a remark made by M. Gell-Mann after Drell's talk (p. 33, loc. cit.).

[18] G. F. Chew, Phys. Rev. Letters 4, 142 (1960). However, Chew's "dynamical" approach to the three-pion resonance, in which each pair of pions resonate in $T=1$, $J=1$, faces several difficulties which will be discussed elsewhere.

[19] We would like to emphasize the preliminary nature of these numbers. A more detailed analysis using Eq. (2) is now in progress by R. Hofstadter and collaborators using their new data.

[20] It is true that even in the approach of Chew and others $\alpha_\rho=\alpha_\eta=1$ would follow if the ρ state and the η state completely dominated the unsubtracted dispersion representations for the charge form factors. The narrow widths of ρ and η, however, suggest that these states are relatively weakly coupled to pions; thus the dominance of ρ and η would be rather surprising in Chew's "dynamical" approach.

[21] J. J. Sakurai, Bull. Am. Phys. Soc. 5, 414(T) (1960); Enrico Fermi Institute of Nuclear Studies Report EFINS-60-63 (unpublished).

[22] In the La Jolla Conference, June, 1961, the author reported that the universality hypothesis requires the ρ width to be about 170 Mev (in agreement with the information on the ρ width available at that time[5]) provided that the parameter C_1 of Bowcock, Cottingham, and Lurié (which essentially measures the effect of the ρ contribution on πN scattering, and is proportional to $f_{\rho\pi\pi}f_{\rho N\bar{N}}$ of the vector meson approach) has been correctly evaluated in J. Bowcock, W. N. Cottingham, and D. Lurié [Phys. Rev. Letters 5, 386 (1960)]. At that time M. Cini remarked that more detailed calculations by G. Höhler and collaborators have shown that the BCL value for C_1 must be reduced by a factor of 2 or 3. Meanwhile, the more recent $p\bar{p}$ experiments of Maglić et al.[6] and Stevenson et al.[6] suggest that the ρ width is probably as small as 80 Mev. Thus the universality hypothesis seems to be valid again.