# POSSIBLE EXISTENCE OF A $T = 0$ VECTOR MESON AT 1020 MeV†

J. J. Sakurai*
The Enrico Fermi Institute and the Department of Physics, The University of Chicago, Chicago, Illinois
(Received September 7, 1962)

The existence of two $T=0$, negative-$G$ vector mesons—one coupled to the baryon current ($B_B$ meson), the other coupled to the hypercharge current ($B_Y$ meson)—was first discussed within the framework of the vector theory of strong interactions[1] (VTSI). Subsequently Gell-Mann[2] and Ne'eman[3] have constructed a symmetry model based on the group SU(3) (unitary unimodular group in three dimensions) which can accommodate (but does not necessarily require) the two $T=0$ vector mesons of VTSI—the $B_Y$ meson as a member of a unitary octet and the $B_B$ meson as a unitary singlet. Although we have failed in our earlier attempt[4] to identify the 550-MeV meson of Pevsner et al.[5] as the conjectured second $T=0, J=1^{--}$ ($\text{spin}^{\text{parity}, \ G\text{-parity}}$) meson, there now appears new (rather weak) evidence for a $K\bar{K}$ resonance[6] which, as we shall show below, might be interpreted as the decay of a $T=0, J=1^{--}$ meson. We wish to discuss experimental and theoretical consequences of having a $T=0, J=1^{--}$ meson with mass $>2m_K$ in addition to the well established $T=0, J=1^{--}$ $\omega$ meson.

In a recent issue of this journal a Brookhaven-Syracuse group[6] reports the possible presence of a narrow resonance ($\Gamma \approx 20$ MeV) in the $K\bar{K}$ system with mass $\approx$1020 MeV in the reactions

$$K^- + p \to K^+ + K^- + \Lambda, \quad K^0 + \bar{K}^0 + \Lambda.$$

In discussing the quantum numbers of the resonating $K\bar{K}$ pair, which we tentatively refer to as the $\varphi$ meson, let us first observe that the $G$-conjugation parity of a $K\bar{K}$ system is given by

$$G = (-1)^{l+T}.$$

If the $G$-parity of the $\varphi$ meson is even, the $G$-allowed two-pion mode is likely to give a very large width. For instance, if the $\varphi$ meson were a $T=0, J=2^{++}$ particle, the two-pion mode would be expected to be more frequent than the $K\bar{K}$ mode by a factor of several hundred. So it is natural to assign a negative $G$-parity to the $\varphi$ meson, which leaves the following possibilities open:

$$T=0;\ 1^{--}, 3^{--}, 5^{--}, \cdots,$$

$$T=1;\ 0^{+-}, 2^{+-}, 4^{+-}, \cdots,$$

Fortunately the two sets of possibilities can readily be distinguished in bubble-chamber experiments. Let us recall[7]

$$|T=0, T_3=0, G \text{ odd}\rangle$$

$$= \tfrac{1}{2}[-|K^+K^-\rangle + |K^-K^+\rangle + i|K_1{}^0K_2{}^0\rangle + i|K_2{}^0K_1{}^0\rangle],$$

$$|T=1, T_3=0, G \text{ odd}\rangle$$

$$= \tfrac{1}{2}[-|K^+K^-\rangle - |K^-K^+\rangle + |K_1{}^0K_1{}^0\rangle + |K_2{}^0K_2{}^0\rangle].$$

We note that a $T=0$, negative-$G$ meson is forbidden to decay into $K_1{}^0 + K_1{}^0$, which means that the $\varphi$ peak should not show up for "double-$V^0$" $K$-pair events. (This is evident from Bose statistics alone.) On the other hand, a $T=1$, negative-$G$ meson is allowed to decay into "double $V^0$'s." We understand that the preliminary data[8] of the Brookhaven-Syracuse group[6] are, within limited statistics, consistent with the absence of the decay mode $\varphi \to K_1{}^0 + K_1{}^0$. Of course, the isospin of the $\varphi$ meson can be directly established by studying

$$K^- + d \to K^- + K^0 + \Lambda + p$$

at the same incident $K^-$-beam momentum as that of reference 6.

It appears that if future experiments conclusively confirm the existence of peaks in the $K^+K^-$ and $K_1{}^0K_2{}^0$ mass distributions but not in the $K_1{}^0K_1{}^0$, nor in the $K^+\bar{K}^0$ nor $K^-K^0$ distribution, then the only reasonable quantum number assignment for the $\varphi$ meson is $T=0, J=1^{--}$. For $T=0$, $J \geq 3$, and $G=-1$, the $K\bar{K}$ mode would be very much suppressed in comparison to the $\rho + \pi$ ($3\pi, \cdots$) mode because of the $f$- ($h$-, $\cdots$) wave centrifugal barrier. We have assumed throughout that $\varphi \to K + \bar{K}$ is a $G$-allowed transition; otherwise multipion modes would certainly predominate.

With the proposed $T=0, 1^{--}$ assignment, the $\varphi$ meson, which is forbidden to decay into $K_1{}^0 + K_1{}^0$, cannot be studied easily in the reaction $\pi^- + p \to K^0 + \bar{K}^0 + n$. Note also that $G$-conjugation invariance forbids $2\pi \rightleftarrows \varphi$ so that the $\varphi$ meson cannot be produced via the well known one-pion-exchange mechanism in the reaction $\pi + N \to K + \bar{K} + N$. For these reasons, the low-energy $K\bar{K}$ interactions recently discussed by Erwin et al.[9] have no relations whatsoever to the conjectured $T=0, 1^{--}$ $\varphi$ meson.

Work of the CERN-Paris group[10] on $p+\bar{p}\to K+\bar{K}+\omega$ is not too relevant either, because in $p+\bar{p}\to\varphi+\omega$ the $\varphi\omega$ system must be in a relative $p$ state for $s$-state capture.[11]

Because the $K\bar{K}$ threshold is near the mass of the $\varphi$ meson ($Q$ value of 32 MeV for $K^+ + K^-$, 24 MeV for $K^0+\bar{K}^0$), we expect a large apparent violation of charge independence in the decay $\varphi\to K+\bar{K}$. We obtain on the basis of the $T=0, 1^{--}$ hypothesis

$$N(K^0+\bar{K}^0)/N(K^+ +K^-) = N(K_1{}^0+K_2{}^0)/N(K^+ +K^-) = 0.65$$

(instead of unity), at 1020 MeV. It is also worth noting that because of the rapidly varying $p^3$ dependence that multiplies the usual Breit-Wigner form, the shapes of the $K^+K^-$ and $K_1{}^0K_2{}^0$ bumps are expected to be very asymmetric.

The decay rate for $\varphi\to K+\bar{K}$ can be calculated if the $\varphi$ meson is the $B_Y$ meson of VTSI coupled to the hypercharge current with strength $f_\varphi$ (where $f_\varphi$ is equal to $f_Y$ of reference 1). We obtain

$$\Gamma(\varphi\to K+\bar{K};\text{ both charge modes}) = \tfrac{4}{3}(f_\varphi{}^2/4\pi)p_K{}^3/m_\varphi{}^2,$$

where $p_K$ stands for the momentum of either $K$ meson in the rest system of the decaying $\varphi$ meson. Meanwhile, if the $\varphi$ meson is the $T=0$ partner of the vector meson octet (together with $\rho$ and $K^*$) in the unitary symmetry model,[2,3] we must have

$$(1/\sqrt{3})f_\varphi = \tfrac{1}{2}f_\rho = \gamma, .$$

where $f_\rho$ ($=f_T$ in reference 1) is the coupling constant of the $\rho$ meson to the isospin current, and $\gamma$ is the vector-meson coupling constant in Gell-Mann's notation.[2] Since $f_\rho$ can be determined from the observed width of the $\rho$ meson (taken to be 100 MeV), we obtain

$$\Gamma(\varphi\to K+\bar{K}) = \tfrac{3}{2}[(p_K{}^3/m_\varphi{}^2)/(p_\pi{}^3/m_\rho{}^2)]\Gamma(\rho\to\pi+\pi)$$
$$\approx 3.4\text{ MeV}.$$

(A similar calculation leads to a $K^*$ width of $\approx$30 MeV.[2]) On the other hand, if the $\varphi$ meson were a unitary-singlet vector meson, its decay into $K+\bar{K}$ would be forbidden to the extent that unitary symmetry is exact. It would then be impossible to estimate the decay rate for the $K+\bar{K}$ mode on the basis of unitary symmetry.

Because the $\varphi$ mass is above the $\rho\pi$ threshold, the proposed $1^{--}$ assignment fully allows the decay modes

$$\varphi\to\rho^{\pm,0}+\pi^{\mp,0}.$$

If the matrix element for this process is given (apart from the usual kinematical factors) by

$$(f_{\rho\pi\varphi}/m)\epsilon_{\mu\nu\lambda\sigma}\epsilon_\mu{}^{(\varphi)}k_\nu{}^{(\varphi)}\epsilon_\lambda{}^{(\rho)}k_\sigma{}^{(\rho)}$$

for each charge mode, we obtain[12]

$$\Gamma(\varphi\to\rho+\pi;\text{ three charge modes}) = (f_{\rho\pi\varphi}{}^2/4\pi)p^3/m^2.$$

The constant $f_{\rho\pi\varphi}/m$ (where $m$ has been inserted to make the coupling constant dimensionless) cannot be determined without detailed dynamical considerations. This constant, however, can be deduced if we assume that $\pi^0$ decay is completely dominated by $\pi^0\to\rho+\varphi\to 2\gamma$. (This model is not expected to represent reality since we completely ignore the $\omega$ meson, but if both $\omega$ and $\varphi$ contributed, we could not arrive at a definite value for $f_{\rho\pi\varphi}/m$; hence we proceed.) Straightforward calculations based on the pole-dominance approximation outlined in Gell-Mann and Zachariasen[13] and in Gell-Mann, Sharp, and Wagner[14] lead to the results

$$f_{\rho\pi\varphi}{}^2/(4\pi m^2) \approx 0.02/m_\pi{}^2,$$

$$\Gamma(\varphi\to\rho+\pi;\text{ three charge modes}) \approx 9\text{ MeV},$$

for a $\pi^0$ lifetime of $2.2\times10^{-16}$ sec.

We emphasize again that our calculation on the $\rho\pi$ mode is useful only as an order-of-magnitude estimate. All we wish to claim is that we should not be too much surprised if, despite its small $Q$ value, the $K\bar{K}$ mode turns out to be almost as frequent as the $\rho\pi$ mode. Note also that if there are no cancellations between the $\rho+\varphi$ contribution and the $\rho+\omega$ contribution in $\pi^0$ decay,[15] the actual decay rate for the $\rho+\pi$ mode may well be smaller than the value estimated above. In any case, an experimental attempt should be made to detect $\varphi\to\rho+\pi$ by studying the $\pi^+\pi^-\pi^0$ mass distribution in various reactions. (It may be difficult to look for the $\rho+\pi$ mode in high-energy $K^-p$ collisions if $K^-+p\to Y_1{}^*+2\pi$ turns out to be frequent.) The Dalitz plot for $\varphi\to\pi^++\pi^-+\pi^0$ should reveal three very striking bands (similar to the kind observed in $p+\bar{p}\to\pi^++\pi^-+\pi^0$ by the Oxford-Padua group[16]) corresponding to the three charge states of the $\rho$ meson.

Let us now return to unitary symmetry. It has been suggested that a mass formula of the form

$$m = m_0\{1+aY+b[T(T+1)-\tfrac{1}{4}Y^2]\}$$

(where $Y$ and $T$ stand for hypercharge and isospin) be applicable to the members of a given unitary symmetry multiplet.[2,17] This formula holds remarkably well for the baryon octet[2] $(N, \Lambda, \Sigma, \Xi)$ and for the pseudoscalar meson octet[2] $(\pi, K, \eta)$ and possibly for the $J = \frac{3}{2}^+$ isobars[18] $(N_{3/2}^*, Y_1^*, \Xi_{1/2}^*$, and a "stable" $Y = -2, T = 0$ hyperon[19] at 1680 MeV). Whatever the deep reason for these numerologies may be, it is somewhat disturbing that the formula does not work for the vector mesons. With the observed $\rho$ and the $K^*$ mass of 750 MeV and 885 MeV, respectively, the $T = 0$ partner of the vector meson octet is predicted to be at 930 MeV, which is 150 MeV above the $\omega$ mass and 90 MeV below the $\varphi$ mass.

We would like to suggest that this discrepancy is due to mixing between $\omega$ and $\varphi$ arising from the fact that the $\omega$ and the $\varphi$ have the same quantum numbers as far as spin-parity, isospin, and $G$-parity are concerned. Specifically, we conjecture that without $\omega$-$\varphi$ mixing, the $\varphi$ meson would be the $T = 0$ member of a "pure" unitary octet with mass $\approx 930$ MeV, and the $\omega$ meson, which we assume to be a unitary singlet, would lie somewhat lower. The $\varphi$ mass and the $\omega$ mass are supposed to be rather close to start with, but the two states tend to repel each other as the mixing effect becomes operative.[20] Assuming that the two states repel symmetrically (in analogy with perturbation theory in nonrelativistic quantum mechanics), we can "predict" the mass of the physical $\omega$ meson to be lower than 840 MeV, but not very much lower than that (if there is to be mixing to start with). This is in agreement with observation.

Mixing between $\omega$ and $\varphi$ would imply violation of $R$ invariance[2,21] as well as violation of unitary symmetry. In fact, if the vector meson coupled to the baryon current turns itself into the kind coupled to the hypercharge current, the $N$-$\Xi$ level would split even in lowest order.[22] Thus the observed $N$-$\Xi$ mass difference (which corresponds to the term linear in $Y$ in the mass formula for the baryon octet) may emerge as a result of $\omega$-$\varphi$ mixing. Conversely, if there is a small mass difference between $N$ and $\Xi$, the $\omega$ and the $\varphi$ are expected to mix with each other; we can forbid the transition $\omega \rightleftarrows \varphi$ only in a model in which the $N$-$\Xi$ degeneracy is exact.

We may argue that if we start with a theory that is completely invariant under unitary symmetry transformations, it should stay invariant, hence no $\omega$-$\varphi$ mixing, etc. However, it may well be that unitary symmetry is dynamically unstable with respect to $\omega$-$\varphi$ mixing. Once a slight violation of unitary symmetry is triggered, $\omega$ and $\varphi$ get mixed; this leads to a small $N$-$\Xi$ mass difference, which in turn results in a larger amount of $\omega$-$\varphi$ mixing. This cycle goes on until the $\omega$ and the $\varphi$ get separated so well that there is no further mixing. Here we may have, so to speak, a "bootstrap mechanism" for unitary symmetry violation.

All this, of course, is extremely speculative. In any case, it appears that major progress in strong interaction physics will be made when we understand the detailed dynamical mechanism responsible for the observed breakdown of unitary symmetry.

Most of the ideas contained in this paper were developed while the author was on leave at the California Institute of Technology. He wishes to thank Professor M. Gell-Mann for many enlightening discussions[23] as well as for the hospitality extended to him at California Institute of Technology. He also wishes to acknowledge the value of an interesting communication from Professor S. L. Glashow who independently noted the importance of the $K^+K^0$ mass difference and the possible $\rho + \pi$ decay mode of the $\varphi$ meson. Thanks are also due to Dr. N. P. Samios for informative discussions on the experimental status of the $K\bar{K}$ interaction.

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†Work supported by the U. S. Atomic Energy Commission.

*Alfred P. Sloan Foundation Fellow.

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[12]We neglect possible interference effects among the three charge modes arising from the fact that the three $\rho$ bands in the Dalitz plot for $\varphi \rightarrow \pi^+ + \pi^- + \pi^0$ overlap each other. (This is essentially a zero-width approximation for $\rho$.)

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[20]A similar mixing mechanism has been discussed by Gell-Mann[2] in connection with the mass formula for the vector meson octet.

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[22]A symmetry-breaking mechanism of this kind was considered already in reference 1.

[23]This does not necessarily mean that Professor Gell-Mann agrees with the content of this paper.

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# EFFECTS OF REGGE POLES ON THE POLARIZATION IN HIGH-ENERGY NUCLEON-NUCLEON SCATTERING*

Ivan J. Muzinich
Department of Physics, University of Washington, Seattle, Washington
(Received October 8, 1962)

Several authors[1] have realized the importance of Regge poles in strong interaction physics. The Regge poles in one channel of a two-body scattering process control the asymptotic behavior of the scattering amplitude in the energy of the "crossed channel" in a simple way. Analysis of high-energy diffraction scattering in terms of Regge poles has already been considered in some detail.[2]

Under the Regge pole hypothesis, the polarization will also have some well-defined features at high energies. In $N$-$N$ scattering it will be shown that the polarization decreases with a power of the energy; the power is determined by the Pomeranchuk Regge trajectory and the Regge trajectory with the quantum numbers of the $N$-$\bar{N}$ channel that lies closest to the Pomeranchuk Regge trajectory.

The polarization in $N$-$N$ scattering is related to the five independent helicity amplitudes defined by Goldberger, Grisaru, MacDowell, and Wong[3] (GGMW) as

$$P d\sigma/d\Omega = \mathrm{Im}[(\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^*], \qquad (1)$$

where $P$ is the magnitude of the polarization and $d\sigma/d\Omega$ is the differential cross section per unit c.m. solid angle. By means of Eqs. (4-23) and Eq. (4-1) of GGMW, the polarization is related to the five independent scalar amplitudes defined in GGMW by

$$P d\sigma/dt = \tfrac{1}{2}\pi[m/(\tfrac{1}{4}s - m^2)](ut/s)^{1/2}\,\mathrm{Im}[(G_3 + G_5)(G_2 + G_4)^*], \qquad (2)$$

where $m$ is the nucleon mass, $s$, $t$, and $u$ are the usual Mandelstam variables, and $d\sigma/dt$ is the differential cross section per unit momentum transfer. The physical region for the $N$-$N$ channel is defined by

$$s > 4m^2, \quad t < 0, \quad \text{and } u < 0. \qquad (3)$$

By analytic continuation there are two other physical processes associated with the $N$-$N$ problem; they are the $N$-$\bar{N}$ $t$ channel and the $N$-$\bar{N}$ $u$ channel. The Regge poles of the $N$-$\bar{N}$ $t$ channel control the high-energy behavior of the $N$-$N$ amplitude near the forward direction, and the Regge poles of the $N$-$\bar{N}$ $u$ channel control the high-