is due to the second-order effect of the light-nucleus excitation.

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Dynamics of the Zweig-Iizuka Rule and a New Vector Meson below 2 GeV/c^2*

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The breaking of the Zweig-Iizuka rule in vector-meson decays is explained by mixing the ω, φ, and ψ mesons with a new SU(4)-singlet meson O (a Pomeron daughter), expected to lie between 1.4 and 1.8 GeV/c^2. We predict rates for many ψ-decay modes. The O meson itself is predicted to decay copiously into $\rho\pi$, but its branching ratios into the $K\bar{K}$, e^-e^+, and $\mu^-\mu^+$ modes are severely suppressed.

The low rate of the decay $\varphi\to\rho\pi$ is explained by the Zweig-Iizuka (ZI) rule[1]: Processes described (in the zero-loop approximation) by disconnected quark diagrams are suppressed. If, as is currently widely believed,[2] the $\psi(3105)$ particle is a $c\bar{c}$ vector meson (c = charmed quark), this rule must also account for the small ψ width. Little is known about the dynamical origin of the ZI rule. It has been suggested[3] that an asymptotically free gauge theory could justify it. Such arguments, while giving an estimate of the overall violation of the rule, are ill suited for the study of specific decay modes. We analyze the breaking of the ZI rule in the context of dual dynamics and show that it results from the mixing of the ω, φ, and ψ mesons with an SU(4)-singlet [and therefore SU(3)-singlet] vector meson O. We then make detailed predictions for partial ψ decay rates and study the O meson itself. We find that the O meson (A) should lie in the 1.4–1.8-GeV/c^2 mass range, (B) should decay copiously ($\Gamma \gtrsim 35$ MeV) into $\rho\pi$, $\bar{K}K^*$, and possibly $\omega\pi\pi$, (C) exhibits severe suppression of decays into the $K\bar{K}$, $e\bar{e}$, and $\mu\bar{\mu}$ modes, and (D) should be photoproduced at the nanobarn level.

Dual dynamics and the O meson.—Consider the decay $\varphi\to\rho\pi$. The simplest diagram for it is that of Fig. 1(a). It is disconnected, thus the ZI rule applies. The disconnected diagram is forbidden in dual dynamics which describes the decay $\varphi\to\rho\pi$ by the one-loop diagram, Fig. 1(b). The φ pole in, say, the process $K\bar{K}\to\rho\pi$ is then induced by the diagram of Fig. 1(c), which is an odd-charge-conjugation replica of the even-charge-

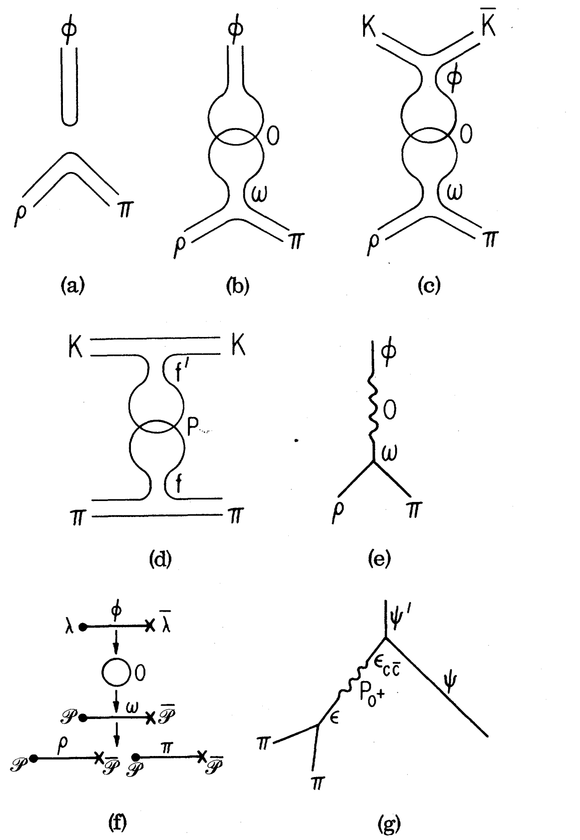

FIG. 1. An illustration of the ZI rule.

conjugation diagram Fig. 1(d) corresponding to the Pomeron term[4] in $K\pi$ scattering. In dual dynamics this Pomeron itself[5] is an even-signature Regge pole of slope $\alpha_P{}^1 \simeq \frac{1}{2}\alpha' \simeq 0.4$ GeV^{-2}. As such, it can support particles of spin and parity 2^+, 4^+, ... In the string picture[6] these correspond to closed strings without quarks on them. The Pomeron has daughters which are odd signatured and can support particles of spin and parity 1^-, 3^-, ... These also correspond to closed strings. Precisely these $J^P = 1^-$ closed strings appear as the intermediate states in the diagram for $\varphi \to \rho\pi$ decay [Fig. 1(b)]. We thus find that the ZI-rule-violating process $\varphi \to \rho\pi$ proceeds in a sequential-pole-dominated way: φ virtually transits to the 1^- state on any of the Pomeron daughters, which then virtually transits to an ω meson, which then decays into a $\rho\pi$ pair [Fig. 1(e)].

In what follows we shall restrict ourselves to the first Pomeron daughter and disregard all higher daughters (we shall discuss this important assumption later). Let us call the O meson the 1^- state on the first Pomeron daughter. Its existence is expected on more general dynamical grounds. We show here that through sequential pole dominance useful predictions are obtained for the partial ψ-decay rates.

Before going into details, let us still elucidate how a closed string can be odd under charge conjugation. In all field-theoretical models leading to stringlike bound states, the strings carry an orientation. In the Nielsen-Olesen model, for instance, at any point of the string there is a magnetic field tangent to the string, which when integrated over the cross section of the string leads to the quantized flux. The direction of the magnetic field orients the string. There are thus closed strings with two types of orientations. Under charge conjugation the magnetic field changes sign so that the two types of closed strings get interchanged. Their (properly normalized) sum and difference are thus even and odd eigenstates of charge conjugation, respectively. It is these odd-charge-conjugation states that we have in mind. Unfortunately, useful predictions for the O-meson couplings cannot be made from dual-resonance models as these have the wrong Pomeron intercept $[\alpha_P(0) = 2]$ and the wrong number of dimensions ($d = 26 \neq 4$).

O mass and O-ω, O-φ, and O-ψ transitions. —The O meson is the 1^- state on the first Pomeron daughter. The intercept of its Regge trajectory is $\alpha_O(0) = \alpha_P(0) - 1 = 1 - 1 = 0$. Its slope is the same as that of the Pomeron, $\alpha_O{}' = \alpha_P{}' \approx \frac{1}{3} - \frac{1}{2}$ GeV^{-2}. We thus expect $m_0{}^2 \simeq 1 - \alpha_O(0)/\alpha_O{}' \simeq 2$–$3$ GeV$^2/c^4$ so that $m_0 \approx 1.4$–1.8 GeV$/c^2$. Before mixing through the sequential pole diagrams [Fig. 1(e)], the O is a pure SU(4) [and therefore SU(3)] singlet. If we call the O-V ($V = \omega, \varphi, \psi$) transition amplitude f_{OV} then we have

$$f_{O\psi} = f_{O\varphi} = f_{O\omega}/\sqrt{2} = f \, . \qquad (1)$$

The mass of the O meson and the amplitude f are the only open parameters of our model.

Predictions independent of the parameter f. —In the sequential pole model f cancels out in the ratio $\Gamma_{\psi\to\rho\pi}/\Gamma_{\varphi\to\rho\pi}$ and we find (assuming $m_\rho \simeq m_\omega$)

$$\frac{\Gamma_{\psi\to\rho\pi}}{\Gamma_{\varphi\to\rho\pi}} = \left(\frac{m_\varphi{}^2 - m_O{}^2}{m_\psi{}^2 - m_O{}^2}\right)^2 \frac{m_\psi{}^2 - m_f{}^2}{m_\varphi{}^2 - m_\rho{}^2}\,\frac{m_\varphi{}^3}{m_\psi{}^3}\left[1 - \frac{m_\pi{}^2}{(m_\varphi - m_\rho)^2}\right]^{-3/2} . \qquad (2)$$

With $m_O = 1.41$ and 1.73 GeV we obtain, respectively, 0.0115 and 0.087 for the right-hand side of Eq. (2). Assuming $\Gamma_{\varphi\to\rho\pi} \simeq \Gamma_{\varphi\to 3\pi}$, we find from experiment that $\Gamma_{\varphi\to\rho\pi} \approx 615$ keV. So we predict that $\Gamma_{\psi\to\rho\pi} = 12.7$ keV (69 keV) for $m_O = 1.41$ GeV (1.73 GeV). Both these values are compatible with existing experiments.

It now becomes clear why assuming dominance by the first Pomeron daughter was of essence. For higher Pomeron daughters the corresponding O-like mesons would be more massive and if one of them were to dominate, one would find a much too large $\psi\to\rho\pi$ width. In reality, an infinity of radial recurrences of the O type participates, cancelations are possible, and were the prediction (2) not to be experimentally confirmed, these extra states and possible SU(4)-breaking effects on Eq. (1) would then have to be taken into account. The quantitative picture would then change considerably while the basic qualitative picture would stay the same. The radial excitations of the O may become important at any rate for the decays of radial excitations of the ψ (ψ', ψ'', ?).

Determination of the parameter f.—In the sequential pole model we readily find (again assuming $m_\omega = m_\rho$)

$$\frac{\Gamma_{\varphi\to\rho\pi}}{\Gamma_{\varphi\to K\bar{K}}} = \frac{3}{2}\frac{g_{\omega\rho\pi}^2}{g_{\varphi\bar{K}K}^2}\frac{f^4(m_\varphi^2 - m_\rho^2)}{(m_O^2 - m_\varphi^2)^2(m_\varphi^2 - 4m_K^2)^{3/2} m_\varphi}\left[1 - \frac{m_\pi^2}{(m_\varphi - m_\rho)^2}\right]^{3/2} \tag{3}$$

[here the $g_{\omega\rho\pi}$ and $g_{\varphi\bar{K}K}$ coupling constants multiply the invariants and $\varphi^\mu(P_K - P_{\bar{K}})_\mu$, respectively]. Using the SU(3) relation $g_{\varphi K\bar{K}} = -g_{\rho\pi\pi}/\sqrt{2}$, the experimentally substantiated SU(6) relation $g_{\omega\rho\pi}^2 = 4g_{\rho\pi\pi}^2/m_\rho^2$, and again assuming that $\Gamma_{\varphi\to\rho\pi} \approx \Gamma_{\varphi\to 3\pi}$, we determine from the experimental value $\Gamma_{\varphi\to 3\pi}/\Gamma_{\varphi\to K\bar{K}} \simeq 0.2$ and Eq. (4) that $f = 0.16\ \mathrm{GeV}^2$ ($0.224\ \mathrm{GeV}^2$) for $m_O = 1.41$ GeV (1.73 GeV).

Further predictions for partial ψ and O decay rates.—The sequential pole model with the parameter f determined by Eqs. (6) makes detailed predictions for quite a few partial ψ and O decay rates. We record here (assuming throughout that $m_\rho = m_\omega$)

$$\frac{\Gamma_{\psi\to K\bar{K}}}{\Gamma_{\varphi\to K\bar{K}}} = \frac{f^4}{(m_O^2 - m_\psi^2)^2}\left(\frac{1}{m_\varphi^2 - m_\psi^2} - \frac{1}{m_\omega^2 - m_\psi^2}\right)^2\left(\frac{m_\psi^2 - 4m_K^2}{m_\varphi^2 - 4m_K^2}\right)^{3/2}\frac{m_\varphi^2}{m_\psi^2}, \tag{4a}$$

$$\frac{\Gamma_{O\to K\bar{K}}}{\Gamma_{\varphi\to K\bar{K}}} = f^2\left(\frac{1}{m_\varphi^2 - m_O^2} - \frac{1}{m_\omega^2 - m_O^2}\right)^2\frac{m_\varphi^2}{m_O^2}\left(\frac{m_O^2 - 4m_K^2}{m_\varphi^2 - 4m_K^2}\right)^{3/2}, \tag{4b}$$

$$\frac{\Gamma_{O\to\rho\pi}}{\Gamma_{\varphi\to\rho\pi}} = \frac{(m_O^2 - m_\varphi^2)^2(m_O^2 - m_\rho^2)m_\varphi^3}{f^2(m_\varphi - m_\rho^2)m_O^3}\left[1 - \frac{m_\pi^2}{(m_\varphi - m_\rho)^2}\right]^{-3/2}, \tag{4c}$$

$$\frac{\Gamma_{O\to e^+e^-}}{\Gamma_{\omega\to e^+e^-}} = 2f^2\left(\frac{m_\omega}{m_O}\right)^3\left(\frac{1}{m_O^2 - m_\omega^2} - \frac{1}{m_O^2 - m_\varphi^2} + \frac{2}{m_O^2 - m_\psi^2}\right)^2. \tag{4d}$$

Using the above value of f, the known values of the ω, φ, and ψ masses, $m_O = 1.41$–1.73 GeV, and the experimental values of the widths $\Gamma_{\varphi\to K\bar{K}}$, $\Gamma_{\varphi\to\rho\pi}$, and $\Gamma_{\omega\to e^+e^-}$, we find from Eqs. (4) that $\Gamma_{\psi\to K\bar{K}} = 0.2$–$1.0$ eV, $\Gamma_{O\to K\bar{K}} = 288$–$90$ keV, $\Gamma_{O\to\rho\pi} = 47$–$90$ MeV, and $\Gamma_{O\to e^+e^-} = 2.2$–$1.1$ eV, the first (second) value corresponding always to $m_O = 1.41$ ($m_O = 1.73$) GeV. We first note that O has a "normal" width $\gtrsim 40$ MeV. Yet its branching ratios into both the $K\bar{K}$ and e^+e^- modes are "unusually" small: $\lesssim 1\%$ and $\lesssim 10^{-5}\%$, respectively. This is so because O is to a very good approximation an SU(3) singlet. The suppression of the $\psi\to K\bar{K}$ mode is again due to the fact that ψ is an almost pure SU(3) singlet; indeed the value of 0.2–1.0 eV quoted above is so small that even electromagnetic effects are larger.

Finally, we can use the sequential pole model to predict [we treat $\epsilon(700)$ as a zero-width particle and assume that $m_O \simeq 1.75$ GeV] that $\Gamma_{\varphi\to\omega\epsilon}/\Gamma_{O\to\omega\epsilon} = 0.0016$–$0.4$, the lower (upper) limit corresponding to pure D wave (S-wave) decay. With $\Gamma_{\psi\to\omega\epsilon} \sim 20$ keV, this gives $\Gamma_{O\to\omega\epsilon} \simeq 12.5$–$0.050$ MeV. At either end of the spectrum we would still expect $\Gamma_{O\,\mathrm{tot}} \lesssim 100$ MeV.

The above results can be replicated by first diagonalizing the 4×4 isosinglet vector-meson mass matrix with nonvanishing off-diagonal entries (in the ω, φ, ψ, and O basis) given by Eq. (1). To obtain the correct ω-ρ mass difference one should then take into account the mixing of the ρ with the P-wave $\pi\pi$ continuum.

The upshot of all this is that the O is a massive ($m_O = 1.4$–1.8 GeV) vector meson that copiously decays into 3π ($\rho\pi$) and possibly also into 5π ($\omega\sigma$) and $K\bar{K}^*$, but very rarely into $K\bar{K}$ or lepton pairs. Its full width is expected in the 50–100 MeV range. We find it imperative that this meson be searched for.

O production.—In view of our analysis of O decays we see that one could search for the O meson in the $\pi^+\pi^-\pi^0$ spectra in various hadronic experiments (e.g., $pp\to\pi^+\pi^-\pi^0X$, $\bar{p}p\to\pi^+\pi^-\pi^0X$, etc.). We also note that O can be photoproduced and the cross section is

$$\sigma_{\gamma p\to Op}\approx 2\sigma_{\gamma p\to\omega p}f^2\left[\frac{1}{m_0^2-m_\omega^2}-\frac{\sigma_{\varphi p}}{\sigma_{\omega p}}\left(\frac{1}{m_0^2-m_\varphi^2}\right)+2\frac{\sigma_{\psi p}}{\sigma_{\omega p}}\left(\frac{1}{m_0^2-m_\psi^2}\right)\right]^2, \tag{5}$$

yielding $\sigma_{\gamma p\to Op}=3.3$ nb (4.8 nb) for $m_0=1.41$ GeV (1.73 GeV). The small value of this cross section is again due to the SU(3)-singlet nature of the O which suppresses its diffractive couplings to the photon. We believe this nanobarn-level cross section nevertheless to be of experimental interest.

At this point we might ask whether the O meson has been found yet in experiments or, if not, then why not? The $\omega(1675)$ is certainly a candidate for being the O, though it is also reasonably accounted for as a radial excitation of the ω meson. The latter interpretation provides no reason for the strong suppression of the e^+e^- mode predicted for the O. This can be used as a crucial test [for a radial excitation the $K\bar{K}$ mode need not be suppressed either, though the $\rho'(1600)$ also seems not to decay into 2π]. Also if $\omega(1675)$ is a radial excitation one would expect its photoproduction cross section to be much larger than the value given by Eq. (11). There have been searches for heavy vector mesons in the $\mu\bar{\mu}$ mode but these would obviously miss the O meson. We therefore believe the existence of the O meson to be an experimentally open problem.

Comparison with the asymptotic freedom arguments.—In the work on asymptotic freedom,[3] the ZI rule is accounted for by viewing the rule-violating decays to proceed via the chains φ or $\psi\to 3$ color gluons $\to$ pions. If the color gluons are sufficiently energetic, their coupling to the quarks in φ or ψ is sufficiently small (asymptotic freedom) and the pionic decays of φ and ψ are suppressed. Our picture replaces the 3-color-gluon continuum state by a single-particle state, the O meson (with the same quantum numbers), as dictated by dual dynamics. In field-theoretic approaches to dual dynamics the O-meson string is a "quarkless" concentration of gluonic energy, so that the analogy is quite close. The important difference is that the sequential pole model puts more predictivity in our hands.

Further particles on the Pomeron trajectory and its daughters.—Along with the O meson there are further particles on the Pomeron trajectory and on its daughters. They are all SU(4) singlets and of course, color singlets. In particular, close to the O in mass we expect a 2^+ and a 0^+ particle, then further recurrences every $1/\alpha_P'\simeq 2-3$ GeV^2. A completely analogous discussion of the ZI rule can be made for the case of $^3P_2$ and $^3P_0$ $\bar{\lambda}\lambda$ and $c\bar{c}$ states. The scalar counterpart of the O also matters in the $\psi'\to\psi\pi\pi$ decay as shown in Fig. 1(g).

Pomeron daughters show up also as exchanges in diffractive processes. Reggeized O exchange is suppressed in pseudoscalar meson baryon scattering (as the O couples very weakly only to $K\bar{K}$ as was explained above); however, it can occur in pp scattering. Here, however, it is hard to distinguish from Regge-Regge cuts in view of their similar energy dependence [$\alpha_O(0)\simeq\alpha_{RR}(0)\simeq 0$].

Conclusions.—We have shown that a simple quantitative understanding of the ZI rule and its violation emerges by mixing the ω, φ, and ψ mesons with the vector meson O on the Pomeron's first daughter. This meson is expected also from dual dynamics. The O meson is predicted to have a mass between 1.4 and 1.8 GeV/c^2,[7] a "normal" width Γ_O of approximately 50 to 100 MeV, and to decay copiously into 3π ($\rho\pi$) and possibly also 5π (i.e., $\omega\epsilon$). Its $K\bar{K}$ decay is strongly suppressed, but depending on its mass a $K\bar{K}\pi$ mode may be significant. Its $e\bar{e}$ and $\mu\bar{\mu}$ decay modes are severely suppressed, and its photoproduction occurs also only at the nanobarn level. In view of its strong theoretical *raison d'être*, and of its unmistakable decay and production features, we believe the search for the O meson to be both simple and important.

Note added.—Following the completion of this work we received a preprint by R. C. Brower and J. R. Primack in which vector mesons on Pomeron daughters are also considered. Unlike us, they suggest that the $\psi(3105)$ and $\psi'(3695)$ particles themselves lie on Pomeron daughters. They do not discuss the Zweig-Iizuka rule.

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[7]If the radial excitations of the O do participate significantly in the sequential pole model, then the O itself could be heavier, though its other peculiar characteristics such as anomalously small $e\bar{e}$ and $K\bar{K}$ decay rates would still clearly identify it.

COMMENTS

Comments on Ar L_{23}-Shell Fluorescence Yields and Argon-Charge-State Fractions*

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New theoretical numbers for fluorescence yields are used to calculate charge states of argon produced by bombardment with H^+ and He^+ ions. High-resolution x-ray-spectrometer data are used to determine charge-state fractions. Average fluorescence yields determined using this new data still show discrepancies with Auger-electron data.

The determination of the Ar L_{23}-shell fluorescence yield[1-4] for various projectiles and projectile energies has been a topic of much confusion. The average fluorescence yield $\bar{\omega}$ is determined in a number of different ways. The usual way is to measure the absolute x-ray-production cross section σ_x and the ionization cross section σ_I from which $\bar{\omega}$ is given as σ_x/σ_I. Stolterfoht, de Heer, and van Eck[1] get the various charge states for argon from a study of Auger electrons. The $\bar{\omega}$ is determined then from theoretical values of fluorescence yields, which in turn are calculated from average production rates for each charge state together with the experimental charge-state fractions. My previous experiment[4] determines the charge-state fractions from high-

TABLE I. Relative fraction of argon charge states produced by H^+ and He^+ ions. These charge states were calculated using theoretical fluorescence yields of Chen and Crasemann (Ref. 5).

Ion	Energy (MeV)	q_0	q_1	q_2	q_3	q_4	q_5	q_6
H^+	0.150	0.871	0.083	0.033	0.010	0.002	0.002	0.001
	0.200	0.876	0.081	0.031	0.009	0.001	0.001	0.0004
	0.500	0.901	0.072	0.017	0.006	0.001	0.001	0.0005
He^+	0.260	0.758	0.105	0.089	0.038	0.006	0.003	0.001
	0.500	0.735	0.103	0.098	0.074	0.009	0.007	0.001
	1.000	0.716	0.096	0.106	0.046	0.016	0.015	0.003