TABLE I. Upper limit on the cross sections for narrow resonances at three different masses.

h^+x^- \ m	2.25 GeV	3.1 GeV	3.7 GeV
π^+K^-	1×10^{-33}	4×10^{-35}	1×10^{-35}
$K^+\pi^-$	4×10^{-33}	8×10^{-35}	4×10^{-35}
$p\bar{p}$	...	4×10^{-34}	2×10^{-35}
K^+K^-	1×10^{-33}	5×10^{-35}	1×10^{-35}
$\pi^+\pi^-$	8×10^{-33}	5×10^{-34}	3×10^{-35}
pK^-	7×10^{-33}	4×10^{-34}	3×10^{-35}
$K^+\bar{p}$	2×10^{-33}	4×10^{-35}	8×10^{-36}
$p\pi^-$	4×10^{-32}	4×10^{-33}	5×10^{-34}
$\pi^+\bar{p}$	2×10^{-33}	4×10^{-35}	7×10^{-36}

The spectrum increases with mass because of the increase of the acceptance, and then decreases again at higher mass because of the production mechanism. The individual spectra exhibit the expected statistical fluctuations, *but there is no sharp peak in the mass region 1.25–5.0 GeV when all the overlapping spectra are compared.*

Using a production mechanism for a particle in the c.m. system of

$$d^3\sigma/dp_\perp{}^{*2}\,dp_\parallel{}^* = c\exp(-6p_\perp{}^*)/E^*,$$

independent of $p_\parallel{}^*$ and a persistent 5-standard-deviation peak above the background as a candidate for a new particle, we obtain typical upper limits of production times branching ratio for new resonances shown in Table I.

This result contradicts most of the present theoretical attempts to understand the existence of the J particle based on the charm model or the baryon-antibaryon model and so forth.[5] It should be noted, however, that the analysis at the present stage does not exclude an ordinary wide resonance of a width of a few hundred MeV. Finding such a resonance would depend on a detailed analysis of the acceptance and production mechanism, which we have not done.

We wish to thank the crew of the Brookhaven National Laboratory alternating-gradient synchrotron under Dr. H. Folsche and Dr. L. Smith for the superb operation of the accelerator. We thank also Ms. I. Schulz, Mr. J. Donahue, Mr. D. Osborne, Mr. C. Tourtellotte, and Mr. E. Weiner for technical assistance.

We wish to thank also Dr. S. L. Glashow, Dr. K. Johnson, Dr. F. Low, Dr. V. F. Weisskopf, and our colleagues at the Massachusetts Institute of Technology Center for Theoretical Physics for stimulating discussions. We also benefitted from discussions with T. D. Lee, B. W. Lee, M. Deutsch, R. R. Rau, S. Weinberg, T. T. Wu, and C. N. Yang.

*Permanent address: Institut de Physique Nucléaire, 91406 Orsay, France.

[1]J. J. Aubert *et al.*, Phys. Rev. Lett 33, 1404, 1624 (1974), and Nucl. Phys. B89, 1 (1975).

[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).

[3]C. Bacci *et al.*, Phys. Rev. Lett. 33, 1408, 1649(E) (1974).

[4]J. J. Aubert *et al.*, to be published.

[5]A. S. Goldhaber and M. Goldhaber, Phys. Rev. Lett. 34, 36 (1975); T. Applequist *et al.*, Phys. Rev. Lett. 34, 365 (1975); E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975); H. T. Nieh, T. T. Wu, and C. N. Yang, Phys. Rev. Lett. 34, 49 (1975); A. De Rújula and S. L. Glashow, Phys. Rev. Lett. 34, 46 (1975); M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

Duality Violation and the Production and Decay of New and Old Mesons*

John F. Bolzan,† Kevin A. Geer, William F. Palmer, and Stephen S. Pinsky
Department of Physics, The Ohio State University, Columbus, Ohio 43210
(Received 24 April 1975)

It is shown that the O meson, the $J^P=1^-$ daughter of the Pomeron, is quite successful in predicting a number of rates for duality-violating processes.

Recently Freund and Nambu[1] have succeeded in constructing a model for the duality-violating $\varphi \to \rho\pi$ and $\psi(3105)\to\rho\pi$ amplitudes which meets with quantitative success. Basically, the decays proceed via pole dominance through an intermediary, the $O(J^P=1^-)$ meson, an SU(4) singlet and the daughter of the Pomeron. We extend the Freund-Nambu model to production and to other decays, making analogous use of several other mesons in the Pomeron family. Specifically, we consider $a+b\to\psi+X$, $\varphi+X$, $\psi'+X$, $O(1^-)+X$, and η_c+X, where $a+b$ designates any hadronic initial state (e.g., πp, pp, pd, ...) which does not contain λ or c quarks and in which a duality suppression mechanism is required for strong production. We also calculate $e^+e^-\to O(1^-)\to\mu^+\mu^-$.

The decay processes we consider are $\psi'\to p\pi$, $f'\to\pi\pi$, $O(2^+)\to\pi\pi$, $\psi\to p\bar{p}$, and $\psi\to\Lambda\bar{\Lambda}$.

The most familiar pole-dominance model is that of the photon–vector-meson coupling with

$$f_{\gamma v}^2/m_v^{\,p}=9:1:2:8 \text{ for } \rho:\omega:\varphi:\psi, \tag{1}$$

where p depends on one's theory of SU(4) symmetry breaking. In the literature $p=0$, 2, 3, and 4 appear. With $p=3$ a best fit is found to $V\to e^+e^-$.[2] The pole couplings of ρ, ω, φ, and ψ to $O(1^-)$ and of η, η', and η_c to $O(0^-)$ are taken to be SU(4) symmetric, with the nonet mixing scheme for the vector mesons and the Dashen *et al.*[3] mixing scheme for the O^- mesons. Thus

$$\mathcal{L}_{OV}=f_{OV}(\sqrt{2}\omega^\mu+\varphi^\mu+\psi^\mu)O^\mu(1^-), \tag{2}$$

$$\mathcal{L}_{OP}=f_{OP}(0.53\eta+1.65\eta'+\eta_c)O(0^-), \tag{3}$$

with SU(6) suggesting $f_{OV}\approx f_{OP}$. The tensor (T) couplings of f, f', and f_c, with nonet mixing, are analogous to Eq. (2).

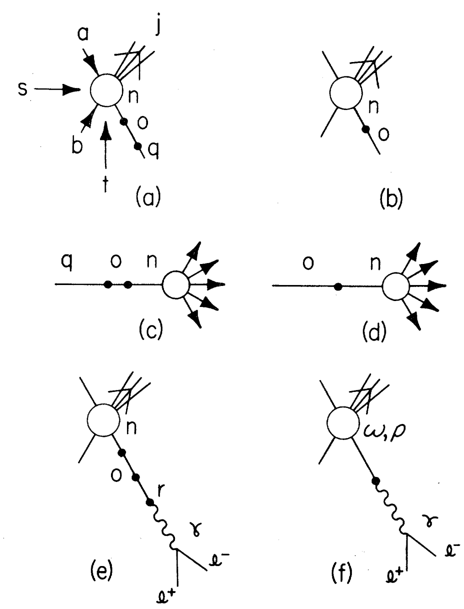

FIG. 1. Pole diagrams for duality-violating processes.

With these definitions, a general inclusive strong spin-averaged production cross section for a duality-forbidden state q referring to Fig. 1(a) is

$$\frac{S}{\pi}\frac{d^2\sigma^q}{dt\,dM_x^2}=\frac{1}{2S}\frac{f_{Oq}^2}{(m_q^2-m_O^2)^2+m_O^2\Gamma_O^2}\frac{f_{O1}^2}{(m_q^2-m_1^2)^2+m_1^2\Gamma_1^2}\times\sum_j|A_{1j}(m_q^2)|^2\left|1+\sum_{n=2}\frac{f_{On}}{f_{O1}}\frac{A_{nj}(m_q^2)}{A_{1j}(m_q^2)}\frac{m_q^2-m_1^2+im_1\Gamma_1}{m_q^2-m_n^2+im_n\Gamma_n}\right|^2, \tag{4}$$

where A_{nj} is the exclusive amplitude for producing one of a set of off-mass-shell mesons $\{n\}$ plus a set of particles labeled by j. The set of mesons n are the neutral members of an SU(4) multiplet with the same J^P as the O meson being considered, and which can be produced in duality-allowed processes. SU(4) symmetry for the off-mass amplitude $A_{nj}(m_q^2)$ implies $A_{nj}(m_q^2)/A_{ij}(m_q^2)\cong 1$. Then

$$\frac{d^2\sigma^q}{dt\,dM_x^2}=\frac{d^2\sigma^1(m_q^2)}{dt\,dM_x^2}\frac{f_{Oq}^2}{(m_q^2-m_O^2)^2+m_O^2\Gamma_O^2}\frac{f_{O1}^2}{m_q^2-m_1^2)^2+m_1^2\Gamma_1^2}F(m_q^2), \tag{5}$$

where

$$F(m_q^2)=\left|1+\sum_{n=2}\frac{f_{On}}{f_{O1}}\frac{m_q^2-m_1^2+im_1\Gamma_1}{m_q^2-m_n^2+im_n\Gamma_n}\right|^2$$

and $d^2\sigma^1(m_q^2)/dt\,dM_x^2$ is the off-shell inclusive production cross section for the particle 1. Similarly, for producing the O meson itself, referring to Fig. 1(b), the expression for O production is obtained from Eq. (5) by striking the first propagator term and replacing m_q^2 by m_O^2.

As our first example let us calculate the production of the $\psi(3105)$ in a proton-proton collision and its subsequent decay into e^+e^- [Fig. 1(e)], where n is the ω and r is the ψ, as compared to a vector-dominated background [Fig. 1(f)].

$$\left[\frac{d^2\sigma^\psi}{d^3p^+\,d^3p^-}\left(\frac{d^2\sigma_{\text{bg}}}{d^3p^+\,d^3p^-}\right)^{-1}\right]_{(p^++p^-)^2=m_\psi^2}=\frac{f_{\gamma\psi}^2}{f_{\gamma\omega}^2}\frac{2f_{OV}^4}{m_\psi^2\Gamma_\psi^2(m_\psi^2-m_O^2)^2}\mathcal{R}, \tag{6}$$

where $\mathcal{R}=(1+f_{\gamma\rho}/f_{\gamma\omega})^{-2}$, $m_\omega \cong m_\rho$, and[1] $f_{OV}=0.137$ GeV^2 for $m_O=\sqrt{2}$ GeV and 0.194 GeV^2 for $m_O=\sqrt{3}$ GeV. Integrating this expression over the 20-MeV resolution of Aubert *et al.*,[4] using the $p=3$ parametrization of the γV coupling,[2] we find that Eq. (6) yields a signal-to-background ratio of 19 (105) for $m_O^2=2$ (3) GeV^2.

These values are in rather good agreement with the Aubert *et al.*[4] data which seem to show a background of 2 or 3 events and a peak height of from 40 to 80 events. We should also keep in mind that our naive vector-dominated background is a lower-limit estimate.

With use of Eq. (5), the absolute cross section for ψ production in terms of off-mass-shell ω production amplitude is

$$\frac{d^2\sigma^\psi}{dt\,dM_x^2} \approx \frac{d^2\sigma^\omega(m_\psi^2)}{dt\,dM_x^2} \times \begin{cases} 1.5\times10^{-7} \text{ for } m_O=\sqrt{2}, \\ 8.0\times10^{-7} \text{ for } m_O=\sqrt{3}. \end{cases} \tag{7}$$

A check on the reliability of this estimate consists in using the same model to calculate the duality-forbidden φ production amplitude

$$\frac{d^2\sigma^\varphi}{dt\,dM_x^2} = \frac{d^2\sigma^\omega(m_\varphi^2)}{dt\,M_x^2} \times \begin{cases} 0.0042 \text{ for } m_O=\sqrt{2}, \\ 0.0040 \text{ for } m_O=\sqrt{3}. \end{cases} \tag{8}$$

In a recent experiment of Ayres *et al.*[5] the total and differential cross sections for $\pi^- p \to \varphi n$ have been measured, the density matrix similarity with $\pi p \to \omega n$ at higher energies noted, and an experimental ratio reported at 5 and 6 GeV/c,

$$\frac{\sigma(\pi^- p \to \varphi n)}{\sigma(\pi^- p \to \omega n)} = 0.0035 \pm 0.0010, \tag{9}$$

in good agreement with Eq. (8).

The same approach yields the cross section for $\psi'(3700)$ production in terms of the ψ cross section:

$$\frac{d^2\sigma^{\psi'}}{dt\,dM_x^2}\left(\frac{d^2\sigma^\psi}{dt\,dM_x^2}\right)^{-1} \approx \left(\frac{f_{O\psi'}}{f_{O\psi}}\right)^2 \frac{d^2\sigma^\omega(m_{\psi'}^2)}{dt\,dM_x^2}\left(\frac{d^2\sigma^\omega(m_\psi^2)}{dt\,dM_x^2}\right)^{-1} \times \begin{cases} 0.2 \text{ for } m_O=\sqrt{2}, \\ 0.18 \text{ for } m_O=\sqrt{3}. \end{cases} \tag{10}$$

Assuming that the off-shell ω production amplitudes do not change appreciably between m_ψ^2 and $m_{\psi'}^2$, we have, for the e^+e^- final state,

$$\frac{d^2\sigma^{\psi' \to e^+e^-}}{dt\,dM_x^2}\left(\frac{d^2\sigma^{\psi \to e^+e^-}}{dt\,dM_x^2}\right)^{-1} \approx 0.2\left(\frac{f_{O\psi'}}{f_{O\psi}}\right)^2 \frac{\Gamma_{e^+e^-}{}^{\psi'}}{\Gamma_{e^+e^-}{}^{\psi}} \frac{\Gamma_\psi}{\Gamma_{\psi'}}. \tag{11}$$

Using the lower limit for the width of the ψ',[6] we find that (11) is $\lesssim 0.05(f_{O\psi'}/f_{O\psi})^2$, where $f_{\psi'}/f_\psi$ may be estimated if a common strong decay mode can be observed, e.g., the $\rho\pi$ mode,

$$\frac{\Gamma_{\psi' \to \rho\pi}}{\Gamma_{\psi \to \rho\pi}} = \left(\frac{m_\psi^2 - m_O^2}{m_{\psi'}^2 - m_O^2}\right)^2 \frac{m_{\psi'}^2 - m_\rho^2}{m_\psi^2 - m_\rho^2} \frac{m_\psi^3}{m_{\psi'}^3}\left(\frac{f_{\psi'}}{f_\psi}\right)^2. \tag{12}$$

From Eq. (8) the cross section for $O(1^-)$ production is

$$\frac{d^2\sigma^{O(1^-)}}{dt\,dM_x^2} \approx \frac{d^2\sigma^\omega(m_O^2)}{dt\,dM_x^2} \times \begin{cases} 0.019 \text{ for } m_O=\sqrt{2}, \\ 0.013 \text{ for } m_O=\sqrt{3}. \end{cases} \tag{13}$$

One may also ask whether the $O(1^-)$ might be found in the e^+e^- final state in the Aubert *et al.*[4] experiment. Comparing the production process, Fig. 1(e), with n being the ω and r being the sum of the ω, φ, and ψ, to a vector-meson-dominated background, Fig. 1(f), we find

$$\left[\frac{d^2\sigma(O(1^-) \to e^+ + e^-)}{d^3p^+\,d^3p^-}\left(\frac{d^2\sigma_{\text{bg}}}{d^3p^+\,d^3p^-}\right)^{-1}\right]_{(p^+ + p^-)^2 = m_O^2} = \begin{cases} 6.68\times10^{-4} \text{ for } m_O=\sqrt{2} \text{ GeV}, \\ 2.3\times10^{-2} \text{ for } m_O=\sqrt{3} \text{ GeV}. \end{cases} \tag{14}$$

At the Stanford Linear Accelerator Center, the $O(1^-)$ effect in $e^+e^- \to O(1^-) \to e^+e^-$ or $\mu^+\mu^-$ is also small, with little help from the interference effect because the $O(1^-)$ is so broad. A simple calculation yields

$$\sigma(e^+e^- \to O(1^-) \to \mu^+\mu^-)/\sigma(e^+e^- \to \mu^+\mu^-:\text{QED}) \approx 10^{-6}. \tag{15}$$

Using Eq. (6) we can calculate the inclusive cross section for η_c, which will be mediated by the $O(0^-)$

and the η and η'; we have, with $f_{OV} \approx f_{OP}$ and $m_{\eta_c} \gtrsim 2$ GeV,

$$\frac{d^2\sigma^{\eta_c}}{dt\,dM_x^2} \lesssim \frac{d^2\sigma^{\eta}}{dt\,dM_x^2} \times 10^{-6}. \tag{16}$$

Production of f' and f_c may be analogously calculated, with the value of f_{OT} inferred from decay data. The experimental limit $\Gamma_{f' \to 2\pi} < 12$ MeV indicates that $f_{OT} < 0.185$ GeV (0.28 GeV) for $m_O^2 = 2$ GeV^2 (3 GeV^2) implies $\Gamma_{O(2^+) \to 2\pi} < 69$ MeV (30 MeV).

Finally, the partial width for $\psi(3105) \to \bar{p}p$ may be calculated via the sequential decay chain $\psi \to O(1^-) \to \omega \to \bar{p}p$, with the result

$$\Gamma_{\psi \to \bar{p}p} = \frac{2 f_{OV}^4}{(m_\psi^2 - m_O^2)^2 (m_\psi^2 - m_\omega^2)^2} \frac{m_\psi}{3} \left(1 - \frac{4m_p^2}{m_\psi^2}\right)^{1/2} \left(\frac{g_{\omega\bar{p}p}^2(m_\psi^2)}{4\pi}\right) \left(1 + \frac{2m_p^2}{m_\psi^2}\right), \tag{17}$$

where $g_{\omega\bar{p}p}^2$ is evaluated at the ψ mass. Assuming ideal mixing and universal isospin current coupling, we have

$$\frac{g_{\omega\bar{p}p}^2}{4\pi} \approx \frac{9 g_{\rho p p}^2}{4\pi} \sim \frac{9}{4} \frac{g_{\rho\pi\pi}^2}{4\pi} \approx 6.5$$

on shell. Thus we have

$$\Gamma_{\psi \to p\bar{p}} = \frac{g_{\omega\bar{p}p}^2(m_\psi^2)}{g_{\omega\bar{p}p}^2(m_\omega^2)} (1.035 \text{ keV}) \text{ for } m_O^2 = 2 \text{ GeV}^2. \tag{18}$$

Similarly we have, from the sequential-pole model,[1]

$$\frac{\Gamma_{\psi\rho\pi}}{\Gamma_{\varphi\rho\pi}} = 0.0115 \frac{g_{\omega\rho\pi}^2(m_\psi^2)}{g_{\omega\rho\pi}^2(m_\varphi^2)}. \tag{19}$$

Defining

$$\frac{g_{\omega\rho\pi}^2(m_\psi^2)}{g_{\omega\rho\pi}^2(m_\varphi^2)} = x \frac{g_{\omega\bar{p}p}^2(m_\psi^2)}{g_{\omega\bar{p}p}^2(m_\omega^2)}, \tag{20}$$

it is reasonable that $x \gtrsim 1$ since we expect these amplitudes to extrapolate off shell in a qualitatively similar way. Thus we have

$$\Gamma_{\psi \to \bar{p}p} = \frac{87}{x} \frac{\Gamma_{\psi \to \rho\pi}}{\Gamma_{\varphi \to \rho\pi}} \text{ keV}. \tag{21}$$

If we estimate further that

$$\frac{\Gamma_{\psi \to \rho\pi}}{\Gamma_{\varphi \to \rho\pi}} \approx \frac{\Gamma_{\psi \to 3\pi}}{\Gamma_{\varphi \to 3\pi}}, \quad \Gamma_{\varphi \to 3\pi} = 615 \text{ keV}, \tag{22}$$

we have

$$\Gamma_{\psi \to \bar{p}p} = \frac{0.14}{x} \Gamma_{\psi \to 3\pi}. \tag{23}$$

With $x = 1$ this is consistent with experimental results.[7]

A similar calculation for the $\bar{\Lambda}\Lambda$ final state indicates $\Gamma_{\psi \to \bar{\Lambda}\Lambda}/\Gamma_{\psi \to \bar{p}p} \sim 0.9$, reasonably close to the experimental result.[7]

*Work supported in part by the U. S. Atomic Energy Commission.

†Work performed in partial fulfillment of the requirements for the Ph.D. degree at The Ohio State University, Columbus, Ohio 43210.

[1]P. G. O. Freund and Y. Nambu, Phys. Rev. Lett. 34, 1645 (1975).

[2]K. Geer, G. B. Mainland, W. F. Palmer, and S. S. Pinsky, Phys. Rev. D 11, 2480 (1975); D. Yennie, Phys. Rev. Lett. 34, 239 (1975).

[3]R. F. Dashen, I. J. Muzinich, B. W. Lee, and C. Quigg, Fermilab Report No. FNAL 75/18-THY (unpublished).

[4]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[5]D. S. Ayres, R. Diebold, A. F. Greene, S. L. Kramer, J. S. Levine, A. J. Pawlicki, and A. B. Wicklund, Phys. Rev. Lett. 32, 1463 (1974).

[6]M. K. Gaillard, B. W. Lee, and J. L. Rosner, Fermilab Report No. FNAL 75/14-THY (unpublished).

[7]G. Hansen, in Proceedings of an International Conference on High Energy Physics, Palermo, Italy, 23–28 June 1975 (to be published).