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

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Abstract

It is shown that the O -meson, the $J^P = 1^-$ daughter of the Pomeron considered by Freund and Nambu,¹ is quite successful in predicting a number of rates for duality violating processes via pole dominance. In particular, the production of $\psi(3105)$ at BNL,² and the production of the ϕ at ANL³ are in good agreement with the model. The branching ratio of $\psi(3105)$ to $\bar{p}p$ observed at DESY⁴ is estimated, and a number of other interesting processes are calculated using other mesons on the tower of the $O(1^-)$.

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Recently Freund and Nambu¹ have succeeded in constructing a model for the duality violating $\phi \rightarrow \rho\pi$ and $\psi(3105) \rightarrow \rho\pi$ 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. If $SU(4)$ classification, with duality suppression, is sustained as the correct picture for the ψ , then there is experimental interest in cross sections and decay rates for other $\bar{c}c$ states as well as for the O meson states. In this note we extend the Freund-Nambu model to inclusive production processes and to other decays, making analogous use of several other mesons in the Pomeron family, e.g., $O(0^\pm)$ and $O(2^\pm)$ which lie below and above $O(1^-)$ in the $J-t$ plane with $2(\text{GeV}^2) < m_0^2 < 3(\text{GeV}^2)$. Specifically, we consider $a+b \rightarrow \psi+X$, $\phi+X$, $\psi'+X$, $O(1^-)+X$, 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 $e^+e^- \rightarrow O(1^-) \rightarrow \mu^+\mu^-$.

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

The most familiar pole dominance model is that of the photon-vector meson coupling which is given by

$$f_{\gamma V} \epsilon_\mu = \langle v | J_\mu^{\text{em}} | 0 \rangle \quad (1)$$

with

$$\frac{f_{\gamma V}^2}{m_V^p} = 9:1:2:8 \quad \text{for } \rho:\omega:\phi:\psi \quad (2)$$

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 $V \rightarrow e^+e^-$.⁵ The

pole couplings of ρ , ω , ϕ , ψ to $O(1^-)$ and η , η' , η_c to $O(0^-)$ are taken SU(4) symmetric, with the nonet mixing scheme for the vector mesons, and the Dashen, et al.⁶ mixing scheme for the O^- mesons. Thus

$$\mathcal{L}_{OV} = f_{OV} (\sqrt{2} \omega^\mu + \phi^\mu + \psi^\mu) O^\mu(1^-) \quad (3)$$

$$\mathcal{L}_{OP} = f_{OP} (0.53 \eta + 1.65 \eta' + \eta_c) O(0^-) \quad (4)$$

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

$$\mathcal{L}_{OT} = f_{OT} (\sqrt{2} f^{\mu\nu} + f'^{\mu\nu} + f_c^{\mu\nu}) O^{\mu\nu}(2^+) \quad (5)$$

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

$$\frac{s}{\pi} \frac{d^2 \sigma^q}{dt dM_x^2} = \frac{1}{2s} \frac{f_{0q}^2}{(m_q^2 - m_o^2)^2 + m_o^2 \Gamma_o^2} \frac{f_{01}^2}{(m_q^2 - m_1^2)^2 + m_1^2 \Gamma_1^2} \sum_j |A_{1j}(m_q^2)|^2$$

$$\left| 1 + \sum_{n=2} \frac{f_{0n}}{f_{01}} \frac{A_{nj}(m_q^2)}{A_{1j}(m_q^2)} \frac{m_q^2 - m_1^2 + i m_1 \Gamma_1}{m_q^2 - m_n^2 + i m_n \Gamma_n} \right|^2 \quad (6)$$

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 amplitude is a function of s , t , and M_j^2 , in addition to the off-mass shell mass m_q^2 . 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 $A_{nj}(m_q^2)/A_{ij}(m_q^2) \cong 1$. This approximation is expected to be better than normal SU(4) results since there is no mass breaking. Then

$$\frac{d^2 \sigma_q}{dt dM_x^2} = \frac{d^2 \sigma^1(m_q^2)}{dt dM_x^2} \frac{f_{0q}^2}{[(m_q^2 - m_o^2)^2 + m_o^2 \Gamma_o^2]} \frac{f_{01}^2}{[(m_q^2 - m_1^2)^2 + m_1^2 \Gamma_1^2]} F(m_q^2) \quad (7)$$

where

$$F(m_q^2) = \left| 1 + \sum_{n=2} \frac{f_{0n}}{f_{01}} \frac{m_q^2 - m_1^2 + i m_1 \Gamma_1}{m_q^2 - m_n^2 + i m_n \Gamma_n} \right|^2$$

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 0 meson itself, referring to Fig. 1b, we have

$$\frac{d^2 \sigma^0}{dt dM_x^2} = \frac{d^2 \sigma^1(m_o^2)}{dt dM_x^2} \frac{f_{01}^2}{(m_o^2 - m_1^2)^2 + m_1^2 \Gamma_1^2} F(m_o^2) \quad (8)$$

If a specific final decay state is involved, (6), (7), or (8) must be multiplied by the branching ratio to the final state. Partial widths of the duality violating decays and of the 0 meson are given by (referring to Figs. 1c and d)

$$\Gamma_q = \frac{f_{0q}^2}{(m_q^2 - m_o^2)^2 + m_o^2 \Gamma_o^2} \frac{f_{01}^2}{(m_q^2 - m_1^2)^2 + m_1^2 \Gamma_1^2} \int d \text{ lips } |G_1(m_q^2)|^2 F(m_q^2) \quad (9)$$

$$\Gamma_o = \frac{f_{01}^2}{(m_o^2 - m_1^2)^2 + m_1^2 \Gamma_1^2} \int d \text{ lips } |G_1(m_o^2)|^2 F(m_o^2) \quad (10)$$

where $G_n(m_q^2)$ is the coupling of meson n with off-shell mass m_q^2 to the particular final state being considered; we have taken $G_n(m_q^2)/G_1(m_q^2) \cong 1$ by SU(4) symmetry.

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.1e) where n is the ω and r is the ψ , as compared to a vector dominated background (Fig.1f).

$$\left[\frac{d\sigma^\psi}{d^3p^+ d^3p^-} / \frac{d\sigma(\text{B.G.})}{d^3p^+ d^3p^-} \right] (p^+ + p^-)^2 = m_\psi^2 = \frac{f_{\gamma\psi}^2}{f_{\gamma\omega}^2} \frac{2f_{OV}^4}{m_\psi^2 \Gamma_\psi^2 (m_\psi^2 - m_o^2)^2} \mathcal{R} \quad (11)$$

where

$$\mathcal{R} = \frac{1}{\left(1 + \frac{f_{\gamma\rho}}{f_{\gamma\omega}}\right)}, \quad m_\omega \cong m_\rho, \quad \text{and}^1 \quad f_{OV} = \begin{cases} .137 \text{ GeV}^2 & \text{for } m_o = \sqrt{2} \text{ GeV} \\ .194 \text{ GeV}^2 & \text{for } m_o = \sqrt{3} \text{ GeV}. \end{cases}$$

Integrating this expression over the resolution of BNL,² Eq.(11) becomes

$$\frac{f_{\gamma\psi}^2}{f_{\gamma\omega}^2} \frac{2f_{OV}^2}{m_\psi^2 \Gamma_\psi W (m_\psi^2 - m_o^2)^2} \mathcal{R} \quad (12)$$

where W is the resolution. Using the $p=3$ parameterization of the γV coupling⁵ in Eq.(2) we find, with $W = 2 \text{ MeV}$, that Eq.(11) becomes

$$\begin{aligned} 19 & \text{ for } m_o = \sqrt{2} \text{ GeV} \\ 105 & \text{ for } m_o = \sqrt{3} \text{ GeV}. \end{aligned} \quad (13)$$

The values seem in rather good agreement with the BNL data which seem to show a background of two or three 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.

Using Eq. (7), the absolute cross section for ψ production, in terms of off-mass shell ω production amplitude is

$$\frac{d^2 \sigma_{\psi}}{dt dM_x^2} = \frac{d^2 \sigma^{\omega}(m_{\psi}^2)}{dt dM_x^2} \frac{f_{OV}^4}{(m_{\psi}^2 - m_o^2)(m_{\psi}^2 - m_{\omega}^2)}$$

$$\approx \frac{d^2 \sigma^{\omega}(m_{\psi}^2)}{dt dM_x^2} \begin{cases} 2.3 \times 10^{-7} & \text{for } m_o = \sqrt{2} \\ 1.5 \times 10^{-6} & \text{for } m_o = \sqrt{3}. \end{cases} \quad (14)$$

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

$$\frac{d^2 \sigma^{\phi}}{dt dM_x^2} = \frac{d^2 \sigma^{\omega}(m_{\phi}^2)}{dt dM_x^2} \frac{2f_{OV}^4}{(m_{\phi}^2 - m_{\omega}^2)(m_{\phi}^2 - m_o^2)^2} \times \begin{cases} .003 & \text{for } m_o = \sqrt{2} \\ .01 & \text{for } m_o = \sqrt{3} \end{cases} \quad (15)$$

In a recent Argonne experiment³ the total and differential cross section for $\pi^- p \rightarrow \phi n$ have been measured, the density matrix similarity with $\pi p \rightarrow \omega n$ at higher energies noted, and an experimental ratio reported, at 5 and 6 GeV/c

$$\frac{\sigma(\pi^- p \rightarrow \phi n)}{\sigma(\pi^- p \rightarrow \omega n)} = .0035 \pm .0010 \quad (16)$$

in good agreement with Eq.(15) and favoring the lower limit for the m_o mass.

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

$$\frac{d^2\sigma_{\psi}}{dt dM_x^2} \bigg/ \frac{d^2\sigma_{\psi}}{dt dM_x^2} = \frac{f_{o\psi'}^2}{f_{o\psi}^2} \frac{(m_{\psi'}^2 - m_o^2)^2 (m_{\psi'}^2 - m_w^2)^2}{(m_{\psi'}^2 - m_o^2)^2 (m_{\psi'}^2 - m_w^2)^2} \frac{d^2\sigma^w(m_{\psi'}^2)}{dt dM_x^2} \bigg/ \frac{d^2\sigma^w(m_{\psi}^2)}{dt dM_x^2}$$

$$\approx \left(\frac{f_{o\psi'}}{f_{o\psi}} \right)^2 \frac{d^2\sigma^w(m_{\psi'}^2)}{dt dM_x^2} \bigg/ \frac{d^2\sigma^w(m_{\psi}^2)}{dt dM_x^2} \times \begin{cases} .2 & \text{for } m_o = 1.4 \\ .18 & \text{for } m_o = 1.71 \end{cases} \quad (17)$$

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

$$\frac{d^2\sigma_{\psi' \rightarrow e^+e^-}}{dt dM_x^2} \bigg/ \frac{d^2\sigma_{\psi \rightarrow e^+e^-}}{dt dM_x^2} \approx .2 \left(\frac{f_{o\psi'}}{f_{o\psi}} \right)^2 \frac{\Gamma_{e^+e^-}^{\psi'}}{\Gamma_{e^+e^-}^{\psi}} \frac{\Gamma_{\psi}}{\Gamma_{\psi'}} \quad (18)$$

Using the lower limit for the width of the ψ' ,⁷ we find that (18) is $\leq .05 (f_{o\psi'}/f_{o\psi})^2$ where $f_{\psi'}/f_{\psi}$ may be estimated if a common strong decay mode can be observed, e.g., the $\rho\pi$ mode

$$\frac{\Gamma_{\psi' \rightarrow \rho\pi}}{\Gamma_{\psi \rightarrow \rho\pi}} = \left(\frac{m_{\psi'}^2 - m_o^2}{m_{\psi}^2 - m_o^2} \right)^2 \frac{m_{\psi'}^2 - m_{\rho}^2}{m_{\psi}^2 - m_{\rho}^2} \frac{m_{\psi}^3}{m_{\psi'}^3} \left(\frac{f_{\psi'}}{f_{\psi}} \right)^2 \quad (19)$$

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

$$\frac{d^2\sigma^{O(1^-)}}{dt dM_x^2} \approx \frac{d^2\sigma^w(m_o^2)}{dt dM_x^2} \times \begin{cases} .019 & \text{for } m_o = 1.41 \\ .013 & \text{for } m_o = 1.73 \end{cases} \quad (20)$$

One may also ask whether the $O(1^-)$ might be found in the e^+e^- final state in the BNL experiment. Comparing the production process Fig.1e with

n being the ω and r being the sum of the ω , φ and ψ , to a vector meson dominated background Fig.1f, we find

$$\frac{d^2\sigma(O(1^-) \rightarrow e^+ + e^-)}{d^3p^+ d^3p^-} \bigg/ \frac{d^2\sigma(B.G.)}{d^3p^+ d^3p^-} \bigg|_{(p^+ + p^-)^2 = m_0^2} = \frac{1}{(m_0^2 - m_\omega^2)^2} \left| 1 + \frac{f_{\rho\gamma}}{f_{\omega\gamma}} \right|^{-2} Z$$

$$= \begin{aligned} & 1.1 \times 10^{-4} \quad \text{for } m_0 = \sqrt{2} \\ & 1.3 \times 10^{-2} \quad \text{for } m_0 = \sqrt{3} \end{aligned} \quad (21)$$

where

$$Z = \frac{4f_{OV}^4}{m_0^2 \Gamma_0^2} \left| 1 + \frac{1}{\sqrt{2}} \frac{f_{\varphi\gamma}}{f_{\omega\gamma}} \frac{m_0^2 - m_\omega^2}{m_0^2 - m_\varphi^2} + \frac{1}{\sqrt{2}} \frac{f_{\psi\gamma}}{f_{\omega\gamma}} \frac{m_0^2 - m_\omega^2}{m_0^2 - m_\psi^2} \right|^2$$

At SLAC the $O(1^-)$ effect in $e^+e^- \rightarrow O(1^-) \rightarrow e^+e^-$ or $\mu^+\mu^-$ is also small, with little help from the interference effect because the $O(1^-)$ is so broad.

A simple calculation yields

$$\sigma(e^+e^- \rightarrow O(1^-) \rightarrow \mu^+\mu^-) / \sigma(e^+e^- \rightarrow \mu^+\mu^- : Q.E.D.) = \frac{Z}{m_0^4} \approx 10^{-6}$$

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

$$\frac{d^2\sigma_{\eta_c}}{dt dM_x^2} = \frac{d^2\sigma_\eta}{dt dM_x^2} (m_{\eta_c}^2) \frac{.28 f_{OP}^4}{(m_{\eta_c}^2 - m_0^2)^2 + m_0^2 \Gamma_0^2} \frac{1}{(m_{\eta_c}^2 - m_\eta^2)^2 + m_\eta^2 \Gamma_\eta^2}$$

$$\times \left| 1 + \frac{f_{O\eta'}}{f_{O\eta}} \frac{m_{\eta_c}^2 - m_\eta^2 + im_{\eta'}\Gamma_{\eta'}}{m_{\eta_c}^2 - m_{\eta'}^2 + im_{\eta'}\Gamma_{\eta'}} \right|^2 \quad (22)$$

For $f_{OV} \sim f_{OP}$ and $m_{\eta_c} \geq 2$ GeV, we have⁸

$$\frac{d^2 \sigma_{\eta_c}}{dt dM_x^2} \leq \frac{d^2 \sigma_{\eta}}{dt dM_x^2} \times 10^{-6} \quad (23)$$

Production of f' and f_c may be analogously calculated, with the value of f_{OT} inferred from decay data. The experimental limit $\Gamma_{f' \rightarrow 2\pi} < 12$ MeV indicates that $f_{OT} < .185$ GeV (.28 GeV) for $m_o^2 = 2$ GeV² (3 GeV²) implies $\Gamma_{O(2^+)} \rightarrow 2\pi < 69$ MeV (30 MeV).

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

$$\Gamma_{\psi \rightarrow \bar{p}p} = \frac{2f_{OV}^4}{(m_\psi^2 - m_o^2)^2 (m_\psi^2 - m_\omega^2)^2} \times \frac{m_\psi}{3} \left(1 - \frac{4m_p^2}{m_\psi^2}\right)^{\frac{1}{2}} \left(\frac{g_{\omega\bar{p}p}^2(m_\psi^2)}{4\pi}\right) \left(1 + \frac{2m_p^2}{m_\psi^2}\right) \quad (24)$$

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

$$\frac{g_{\omega\bar{p}p}^2}{4\pi} \approx \frac{9}{4\pi} \frac{g_{\rho pp}^2}{4\pi} \sim \frac{9}{4} \frac{g_{\rho\pi\pi}^2}{4\pi} \approx 6.5 \quad \text{on shell}$$

Thus we have

$$\Gamma_{\psi \rightarrow p\bar{p}} = \frac{g_{\omega\bar{p}p}^2(m_\psi^2)}{g_{\omega\bar{p}p}^2(m_\omega^2)} (1.035 \text{ keV}) \quad \text{for } m_o^2 = 2 \text{ GeV}^2 \quad (25)$$

Similarly we have, from the sequential pole model,¹

$$\frac{\Gamma_{\psi \rightarrow \rho\pi\pi}}{\Gamma_{\phi \rightarrow \rho\pi\pi}} = .0115 \frac{g_{\omega\rho\pi}^2(m_\psi^2)}{g_{\omega\rho\pi}^2(m_\phi^2)} \quad (26)$$

Defining

$$\frac{g_{\omega\rho\pi}^2(m_\psi^2)}{g_{\omega\rho\pi}^2(m_\phi^2)} = x \frac{g_{\omega\bar{p}p}^2(m_\psi^2)}{g_{\omega\bar{p}p}^2(m_\omega^2)} \quad (27)$$

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

$$\Gamma_{\psi \rightarrow \bar{p}p} = \frac{87}{x} \frac{\Gamma_{\psi \rightarrow \rho\pi}}{\Gamma_{\varphi \rightarrow \rho\pi}} \text{ keV} \quad (28)$$

If we estimate further that

$$\frac{\Gamma_{\psi \rightarrow \rho\pi}}{\Gamma_{\varphi \rightarrow \rho\pi}} \approx \frac{\Gamma_{\psi \rightarrow 3\pi}}{\Gamma_{\varphi \rightarrow 3\pi}} \quad \text{with } \Gamma_{\varphi \rightarrow 3\pi} = 615 \text{ keV} \quad (24)$$

we have⁷

$$\Gamma_{\psi \rightarrow \bar{p}p} = \frac{.14}{x} \Gamma_{\psi \rightarrow 3\pi} \cong \frac{1.0}{x} \text{ keV}. \quad (30)$$

Thus the branching ratio is $\leq .013$ which is consistent with experimental results.⁴ A similar calculation for the $\bar{\Lambda}\Lambda$ final state indicates $\Gamma_{\psi \rightarrow \bar{\Lambda}\Lambda} / \Gamma_{\psi \rightarrow \bar{p}p} \sim 0.9$, reasonably close to the experimental result.⁴

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References and Footnotes

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8. Taking account, in production, of the $\lambda\bar{\lambda}$ components of η and η' will only change this result slightly.

Figure Caption

Figure 1. Pole diagrams for duality violating processes.

(a)

(b)

(c)

(d)

(e)

(f)