LBL-3889
FERMILAB-Pub-75/54-THY

RADIATIVE DECAYS AS TESTS OF THE SYMMETRIES OF THE ψ PARTICLES*

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June 25, 1975

ABSTRACT

The success of the Okubo-Iizuka-Zweig rule for decays of ψ and ψ' suggests that the radiative decays $\psi \to \gamma$ + hadrons should be dominated by intermediates like $\psi \to \psi'$ + hadrons. This mechanism is consistent with experimental data which show $\Gamma(\psi \to \rho^0\pi^0)$ and $\Gamma(\psi \to \eta\gamma)$ to be comparable. If all ψ-like particles are isoscalar, $\Gamma(\psi \to \pi^0\gamma)$ should be very small. If all ψ-like particles are SU(3) singlets, $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma)$ should be large. Substantial violation of our predictions would be circumstantial evidence for the existence of non-singlet new quarks.

I. THE SUCCESS OF THE O-I-Z RULE

The O-I-Z rule[1] which describes the large enhancement of $\phi \to K\bar{K}$ over $\phi \to \pi\pi\pi$ seems to work in an even more striking fashion for the new particles. Assuming the ψ is composed of new quarks, the rule implies that the strong decays of ψ into hadrons composed of old quarks should be suppressed. If we guess that a 3 GeV hadron would typically have a width of order 500 MeV, then the suppression in the ψ system is a factor of about 10^{-4} which is to be compared with 10^{-2} for the ϕ. In addition to suppressed and allowed decays the new particles provide an intermediate category which we refer to as semi-suppressed, the prototype being $\psi' \to \psi\pi\pi$.[2] Correcting for phase space we find that this decay is enhanced by $\approx 10^2$ relative to the fully suppressed decays.[3]

The central purpose of this paper is to outline the consequences of the O-I-Z rule for radiative decays $\psi \to \gamma$ + hadrons, which follow from the general features of vector dominance. As we shall see, there are already data which support this application of the rule. Decays which may proceed through the semi-suppressed decays should be enhanced by between 10^1 and 10^3 relative to those which must proceed through suppressed decays. This conclusion follows if the extrapolation from $q^2 = 0$ to $q^2 = m_V^2$ is not so serious as to destroy the dominance of semi-suppressed over suppressed decays. Because of this extrapolation and because there may be several interfering intermediate vector mesons, we cannot say with more certainty what the precise rates should be.

II. VECTOR MESON DOMINANCE AND THE O-I-Z RULE

A good deal of caution is called for in dominating a real photon by one of the new vector mesons because of the large extrapolation required. This same extrapolation is required to compare photoproduction data for the ψ to the ψN total cross section, a computation which yields $\sigma_{TOT}(\psi N) \cong 1.5$ mb. If the extrapolation were to decrease the coupling of the ψ to the photon to the point where the 10^2 enhancement of semi- over fully-suppressed decays were obviated, then the implied ψN total cross section would be $\cong 15$ mb.

While this large cross section cannot be ruled out, there is direct evidence that the extrapolation is not nearly so serious a problem. The hadronic decay $\psi \to \rho^o \pi^o$ is observed with a partial width[4] of ~ 0.3 keV. The radiative decay $\psi \to \eta\gamma$ has been observed with a partial width 0.1 to 2.0 keV at DESY,[5] and we shall work with a nominal value of 0.5 keV. It is quite remarkable that these two-body decays, one radiative and one not, should have approximately the same rates. This can be phrased in a more quantitative fashion by assuming that ψ is an SU(3) singlet and that the photon is part of an octet. Then SU(3) predicts that $\Gamma(\psi \to \eta\gamma) = \frac{1}{3}\Gamma(\psi \to \pi^o\gamma)$. On the other hand, vector dominance gives the relation

$$\frac{1}{3}\Gamma(\psi \to \pi^o\gamma) \cong \frac{1}{3}\frac{e^2}{f_\rho^{\,2}}\Gamma(\psi \to \pi^o\rho^o) \sim 10^{-3}\,\Gamma(\psi \to \pi^o\rho^o).$$

The two relations combine to give a prediction in total disagreement with the data; this changes by $\lesssim O(10)$ if ψ is not an SU(3) singlet. The conclusion is that the decay $\psi \to \eta\gamma$ cannot be dominated by the same octet of vector mesons which contains ρ. The near equality of the decay rates into $\eta\gamma$ and $\rho^o\pi^o$ is in qualitative agreement with our hypotheses. The $\psi \to \eta\gamma$ decay is only semi-suppressed, gaining thereby a factor of 10^2, which compensates for the α introduced by the electromagnetic coupling.

A second qualitative test of the use of vector dominance in combination with the O-I-Z rule is to compare $\psi \to \eta\gamma$ and $\psi' \to \eta\psi$. Taking $\psi \to \psi'\eta \to \gamma\eta$ as a typical new vector meson mechanism for the radiative decay, we can correlate the orders of magnitude of $\Gamma(\psi \to \eta\gamma)$ and $\Gamma(\psi' \to \psi\eta)$. We expect, at the level of orders of magnitude, that

$$\Gamma(\psi \to \eta\gamma) \sim \left(\frac{e}{f_{\psi'}}\right)^2 \left(\frac{p_\gamma}{p_\psi}\right)^3 \left(\frac{m_{\psi'}}{m_\psi}\right)^2 \Gamma(\psi' \to \psi\eta) \ . \tag{1}$$

Using[4] $f_{\psi'}{}^2/4\pi = 30$ and $\Gamma(\psi' \to \psi\eta) = 9 \pm 4.5$ keV, we obtain 1.4 ± 0.7 keV for the right-hand side, which is consistent with the order of magnitude of the experimentally indicated range for $\Gamma(\psi \to \eta\gamma)$. This is clearly a very rough approximation since the decay may proceed through other intermediate states such as $\psi \to \psi\eta$ and, perhaps, $\psi \to \psi''\eta$. In addition the extrapolation of $f_{\psi'}$ (the coupling of ψ' to the photon) from $q^2 = 0$ to $q^2 = m_{\psi'}{}^2$ could well introduce important quantitative effects; we have only argued that these effects are not so large as to cancel the factor of $\sim 10^2$ enhancement due to the O-I-Z rule.[6]

Finally we wish to observe that the radiative decays $\phi \to \eta\gamma$ and $\phi \to \pi^0\gamma$ may also be understood by combining the O-I-Z rule with vector dominance. $\phi \to \pi^0\gamma$ is a fully-suppressed decay (assuming ϕ to be a pure $\bar{\lambda}\lambda$ state) and its observed rate[7] is indeed consistent with the mechanism $\phi \to \pi^0\rho \to \pi^0\gamma$. On the other hand, $\phi \to \eta\gamma$ is an allowed decay, via the mechanism $\phi \to \eta\phi \to \eta\gamma$. The experimental ratio $\Gamma(\phi \to \eta\gamma)/\Gamma(\phi \to \pi^0\gamma)$ is consistent with the factor of 10^2 which characterizes full O-I-Z suppression for ϕ decays. To compare with the experimental ratio,[7] $\Gamma(\phi \to \eta\gamma)/\Gamma(\phi \to \pi^0\gamma) = 8 \pm 4$, the O-I-Z factor $\sim 10^2$ must be multiplied by a phase space factor ~ 0.4, by a factor $\sim 2/3$ for the $\bar{\lambda}\lambda$ content of the η wave function, and by a factor f_ρ^2/f_ϕ^2 ~~$\sim 2/9$~~. — — —

III. IF ALL THE NEW VECTOR MESONS ARE ISOSCALAR

We now suppose on the basis of the previous discussion that in radiative decays of ψ the photon is dominated whenever selection rules allow by new vector mesons ψ, ψ', etc. composed of quarks which are also found in ψ. The selection rules are determined by the symmetries of the new particles and thus the relative rates allow us to infer something about the new spectroscopy.

As an especially interesting example, suppose that the new quarks are all isoscalars, as for instance in the charm model. In this case $\psi \to \pi^0\gamma$ must be fully suppressed since there are no new isovector vector-mesons with which to dominate the photon. Since the process could not proceed through a new vector meson it would be expected to have a partial width of about $(e/f_\rho)^2\Gamma(\psi \to \rho^0\pi^0) \simeq 3$ eV. If the partial width $\Gamma(\psi \to \pi^0\gamma)$ is vastly greater than this it would indicate that there are in fact new isovector vector-mesons which have quarks in common with the ψ. This in turn would mean that the new particles involve more than one species of new quark, at least two of which are not isoscalar.

IV. IF ALL NEW VECTOR MESONS ARE SU(3) SINGLETS

Next suppose that all the new quarks are SU(3) singlets, again as in the charm model. Then in addition to the suppression of $\psi \to \pi^0\gamma$

discussed above, we would expect $\psi \to \eta'\gamma$ to occur at a rate significantly larger than $\psi \to \eta\gamma$. For instance, if both the O-I-Z rule and SU(3) were exact we would expect

$$\frac{\Gamma(\psi \to \eta'\gamma)}{\Gamma(\psi \to \eta\gamma)} = \left(\frac{p_{\eta'}}{p_\eta}\right)^3 \cot^2\theta = 0.83 \cot^2\theta \qquad (2)$$

where θ is the singlet-octet pseudoscalar mixing angle. In contrast to the pseudoscalar mass mixing formula

$$\cot^2\theta = \frac{m_{\eta'}^2 - \frac{1}{3}(4\,m_K^2 - m_\pi^2)}{m_\eta^2 - \frac{1}{3}(4\,m_K^2 - m_\pi^2)}\,, \qquad (3)$$

this expression is extremely sensitive to the value of θ. For θ between 0.1 and 0.4 radians $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma)$ varies between 83 and 4.6. The observed total width for $\Gamma(\psi \to \text{hadrons})$ might exclude the upper end of this range at a point depending on the precise value of $\Gamma(\psi \to \eta\gamma)$ which is believed to lie between 0.1 and 2 keV.

Equation (2) would be correct if both the O-I-Z rule and SU(3) were exact. In fact, as mentioned above, the O-I-Z rule seems astonishingly good for the new particles. It is more likely that Eq. (2) could fail quantitatively as a consequence of SU(3) breaking. Breaking of SU(3) has been partially taken into account through wave function mixing and mass splitting in obtaining Eq. (1). In some models such as a quark model with SU(3) singlet, color-SU(3) octet gluons, this would be a complete description of SU(3) breaking. More generally we might anticipate an additional 10%-20% SU(3) breaking in the interaction itself. To estimate how this might influence our result we introduce an SU(3) breaking parameter

$$X = \frac{\langle \psi \mid \eta_8 \gamma_1 \rangle}{\langle \psi \mid \eta_1 \gamma_1 \rangle} \tag{3}$$

where γ_1 denotes the dominance of the photon by new SU(3) singlet vector mesons. Now the ratio of the amplitudes for $\psi \to \eta' \gamma_1$ and $\psi \to \eta\gamma_1$ is changed from cot θ to

$$\frac{\langle \psi \mid \eta' \gamma_1 \rangle}{\langle \psi \mid \eta \gamma_1 \rangle} = \frac{\cos\theta + X \sin\theta}{\sin\theta - X\cos\theta} . \tag{4}$$

Taking the relatively large values $|X| \approx 0.2$ and $|\theta| \approx 0.3$ we still find $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma) \gtrsim 3$. Thus the qualitative conclusion is unchanged: the decay $\psi \to \eta'\gamma$ should occur at a substantially greater level than $\psi \to \eta\psi$, even in the presence of SU(3) breaking.

It is not clear whether the hypothesis that all the new quarks are SU(3) singlets is consistent with the experimental fact that $\psi \to \eta\gamma$ and $\psi \to \pi^o \rho^o$ occur at comparable rates. With the hypothesis that all new vector mesons are SU(3) singlets, if the O-I-Z enhancement factor for $\psi \to \eta\gamma$ is $O(10^2)$, it could be canceled by the factor $\sin^2\theta$ if θ were about 0.1 radians; then $\psi \to \eta\gamma$ would be expected to occur at the rate of a fully suppressed radiative decay which is much less than the observed rate. Thus depending on the precise values of θ , the SU(3) breaking parameter X and the O-I-Z enhancement factor $\approx O(10^{2\pm1})$, the hypothesis that all new quarks are SU(3) singlets may or may not be consistent with the experimental evidence that $\psi \to \eta\gamma$ is a semi-suppressed decay. Notice that $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma)$ provides a cleaner test of this hypothesis since the O-I-Z enhancement factor cancels in the ratio.

V. ARE SOME OF THE NEW PARTICLES ISOVECTORS?

The occurrence of $\psi \to \pi^0\gamma$ at a level vastly greater than 3 eV would indicate that there are isovector mesons in the ψ family. While this is impossible in the charm scheme it can be accommodated by some models with ~~three new quarks~~.[8,9] In Harari's model it would require that the good SU(3) be the one whose generators are the sums of the generators of the two SU(3)'s associated with the two sets of quarks, since otherwise all the ~~new~~ $H = 0$ vector mesons would remain SU(3) singlets under the SU(3) associated with the light quarks which compose η and η'. Similarly, if $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma) \lesssim 3$, there would be a strong indication that not all the new vector mesons were SU(3) singlets. It is not possible to make precise predictions for $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma)$ for the situation in which some ψ-like mesons are singlets and others are octets. For example, if the ψ is a singlet and the ψ' and ψ'' are octets, the allowed SU(3) vertices include $\psi \to \psi'\eta_8$, $\psi \to \psi''\eta_8$, $\psi \to \psi\eta_1$. While the relation between $\psi \to \eta\gamma$ and $\psi \to \eta'\gamma$ would be uncertain in Harari's model with "diagonal" SU(3), the naive SU(3) relation $\Gamma(\psi \to \pi^0\gamma)/\Gamma(\psi \to \eta\gamma) = 3$ would be restored.

A second possible mechanism[10] for $\psi \to \eta\gamma$ and $\psi \to \eta'\gamma$ proceeds by O-I-Z allowed intermediate states such as $\psi \to \eta_c\psi \to \eta\gamma$ and $\psi \to \eta_c\psi \to \eta'\gamma$, where η_c is a new pseudoscalar meson with quarks in common with ψ. The importance of this mechanism depends on the magnitude of $\eta_c - \eta$ and $\eta_c - \eta'$ mixing. If the mixing is as large as 1%, this mechanism would be of the same magnitude as the semi-suppressed mechanism discussed above. If $\eta_c \to$ hadrons is a fully suppressed decay, like $\psi \to$ hadrons, then the mixing is surely

$\lesssim 10^{-4}$ and the mechanism is unimportant compared to the one we have discussed. In either case, the discussion of $\psi \to \pi^{o}\gamma$ in Section III is not affected, and the discussion of $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma)$ in Section IV is also unaffected provided that $\eta_c - \eta$ and $\eta_c - \eta'$ mixing respects SU(3) to within 20% in the amplitudes.

If the data confirm our predictions which follow from assuming the new mesons are SU(3) singlets, it should be possible to use radiative decays to study the SU(3) composition of other mesons which have $C = +1$. It would be especially interesting to search for $\psi \to \gamma + E(1420)$, since the SU(3) assignment of the E and its role in $\eta - \eta'$ mixing is uncertain.

ACKNOWLEDGMENTS

We would like to acknowledge valuable discussions with L. S. Brown, M. B. Einhorn, F. J. Gilman, H. Harari, and J. S. Whitaker. We would also like to thank Professor B. W. Lee for the hospitality and support of the Fermi National Accelerator Laboratory.

FOOTNOTES AND REFERENCES

* This work was supported in part by the U. S. Energy Research and Development Agency (ERDA).

1. S. Okubo, Phys. Letters 5, 165 (1963); J. Iizuka, K. Okada, and O. Shito, Prog. Theo. Phys. 35, 1061 (1966); G. Zweig, 1964, unpublished.

2. G. S. Abrams, et al., Phys. Rev. Lett. 33, 1453 (1974); ibid. 34, 1181 (1975).

3. In making this estimate we compare $\Gamma(\psi' \to \psi\pi\pi)$ corrected for phase space to $\Gamma_{TOT}(\psi \to \text{hadrons})$. This choice of comparison reflects a prejudice that the underlying dynamics are controlled by quark amplitudes and that the transformation of the quarks into hadrons is not important in determining the relevant rates. If instead we thought that the hadrons were the fundamental dynamical entities, we would compare $\psi' \to \psi\pi\pi$ to a particular ψ decay such as $\psi \to \omega\pi\pi$ in which case we would find the former to be enhanced by 10^4, a factor similar to that for allowed decays.

4. V. Luth, SPEAR Magnetic Detector Group, presented to the European Physical Society, Palermo, June, 1975.

5. Cited by B. Wiik, Proceedings of the Tenth Recontre de Moriond, Meribel les-Allues, ed., J. Tran Thanh Van.

6. The application of vector dominance to $\psi \to \pi^+\pi^-\gamma$ requires caution as well. Some of the problems are discussed in R. N. Cahn, "On the Separation of $\psi \to \pi^+\pi^-\gamma$ from $\psi \to \pi^+\pi^-\pi^0$," Fermilab PUB 75/46 THY, unpublished, and W.-y. Tsai, L. L. DeRaad, Jr., and K. A. Milton, "Resonance Model Description of the Decay $\psi(3.1) \to \pi^+\pi^-\gamma$," UCLA/75/TEP/9. The latter authors find that the inclusion of gauge invariant couplings may reduce the predicted rate for $\psi \to \pi^+\pi^-\gamma$ by a factor 0.17. The coupling we use for $\psi \to \gamma +$ pseudoscalar $(\epsilon_{\mu\nu\alpha\beta}\, \epsilon^{\mu}(\psi)\, \epsilon^{\nu}(\gamma)\, k^{\alpha}(\psi)\, k^{\beta}(\gamma))$ is necessarily gauge invariant so there is no analogous additional suppression factor. Of course the vector dominance estimate of $\psi \to \pi^+\pi^-\gamma$ is also subject to the other uncertainties discussed in the text.

7. J. Le Francois, Proceedings of the 1971 International Symposium on Electron and Photon Interactions at High Energies, ed., N. B. Mistry, Cornell University, Ithaca, N. Y., 1971.

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10. We thank J. Bjorken and F. Wilczek for calling this mechanism to our attention.