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Abstract: We calculate the mass spectra for vector and pseudoscalar mesons in broken SU(4) and study the dependence of the wave functions on the parameters which determine the mixing between singlet and fifteenplet. With these wave functions various two-body decays of $\Psi(3.1)$ are computed.

1. Introduction

In two previous papers [1)2)] we studied the mass formulas and the decay properties of meson multiplets in broken SU(4) with special emphasis on the decay of the narrow vector meson $\Psi(3.095)$. It was found, that if one places the usual vector mesons (ρ, K^*, ω, ϕ) together with the $\Psi(3.095)$ into a $1 \oplus 15$ representation of SU(4), the three I = 0 vector mesons ω, ϕ and Ψ came out as rather pure states ω_σ, ω_s and ω_c respectively ($\omega_\sigma = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$, $\omega_s = s\bar{s}$, $\omega_c = c\bar{c}$). The same SU(4) symmetry breaking was applied to the pseudoscalar mesons. Contrary to the vector mesons the three I = 0 members of the $1 \oplus 15$ representation η, η' and Ψ_P came out strongly mixed in the basis η_σ, η_s and η_c , being dominantly η_8, η_0 and η_{15} states, respectively. This has the consequence that radiative widths for the decays of the Ψ are rather large [2)] , inconsistent with the experimentally known total width of the Ψ .

In this paper we investigate the possibility to remedy this defect. In our previous work we did not employ the most general expression for the mass mixing matrix. By introducing an additional parameter in the off-diagonal matrix elements we are able to change the wave functions of the η, η' and Ψ_P mesons in such a way that the radiative decay widths for the Ψ are reduced.

2. Mixing Analysis

In ref. 1 we obtained the general expression for the squared mass matrix M based on the mixing of the fifteenplet with the singlet. In the 8, 15, 0 representation it has the following form [1)]

$$M = \begin{pmatrix} m + 11\, m_1 - 9m_2 & -2\sqrt{2}\, m_1 & A \\ -2\sqrt{2}\, m_1 & m + 4\, m_1 & B \\ A & B & m_0 \end{pmatrix} . \qquad (2.1)$$

The definition of the parameters in (2.1) and their relation to the masses of the I = 0 members of the fifteenplet can be obtained from our earlier work [1]. This determines two parameters $m_1 = \frac{1}{6}(K^* - \rho)$ and $m - 9m_2 = \frac{1}{2}(3\rho - K^*)$ leaving four free parameters: A, B, m_o and $\alpha = (3m_2 - m_1)/2\sqrt{2}m_1$. Having at our disposal only three input masses (m_ω, m_ϕ and m_ψ), we fixed the ratio $B/A = \alpha$. This assumption is suggested by the observation that pure ideal mixing is equivalent to the constraints [1]

$$B/A = \alpha \;, \qquad A = -2\sqrt{6}\,m_1 \;, \qquad m_o = m + 4m_1\,(1-\sqrt{2}\alpha) \;. \tag{2.2}$$

Therefore the constraints $B/A = \alpha$ is plausible for the vector mesons which are supposed to be rather ideally mixed. For the pseudoscalar mesons, which seem to be far from ideal mixing (already in SU(3)), this constraint is less justified. In the following we abandon this constraint and introduce a new parameter $\beta \equiv B/\alpha A$ with the expectation that β should be near one for the vector mesons ($\beta_V \approx 1$), and $\beta_P \neq 1$ for the pseudoscalar mesons. There is also no a priori justification for the constraint $\alpha_V = \alpha_P$, as has been used in ref. 2. To begin with we study first the vector mesons. In the expansion

$$|\psi\rangle = \alpha_\sigma^{(\psi)}|\omega_\sigma\rangle + \alpha_s^{(\psi)}|\omega_s\rangle + \alpha_c^{(\psi)}|\omega_c\rangle \;, \tag{2.3}$$

the coefficients $\alpha_i^{(\psi)}$ are now functions of β_V. The interesting quantities for the strong decays of the ψ into normal hadrons are $\alpha_\sigma^{(\psi)}$ and $\alpha_s^{(\psi)}$. In ref. 2 we saw that these coefficients must be extremely small (of the order of 10^{-4}), which could be achieved with $\beta_V = 1$ only if the ρ mass was decreased to $m_\rho = 0.760$. For m_ρ larger than this value one has to choose $\beta_V < 1$ to obtain small enough $\alpha_\sigma^{(\psi)}$ and $\alpha_s^{(\psi)}$.

However it is not possible to increase m_ρ above 0.763 GeV by lowering β_V without blowing up the coefficients $\alpha_\sigma^{(\psi)}$ and $\alpha_s^{(\psi)}$. By looking for solutions consistent with the experimentally known branching ratios of the decays $\psi \to \rho\pi$, $\bar{K}K^*$, $\bar{K}K$, $\bar{p}p$, $\bar{\Lambda}\Lambda$ etc. [3] it is essential to obtain also the right value for the ratio $\alpha_s^{(\psi)}/\alpha_\sigma^{(\psi)}$ and not just small values for these coefficients. For example from the experimentally known ratio for $\Gamma(\psi \to K^{*+}K^-)/\Gamma(\psi \to \rho^+\pi^-) = 0.36 \pm 0.17$ [3] we have the two solutions for $r = \alpha_s^{(\psi)}/\alpha_\sigma^{(\psi)}$ namely $r_1 = -(1{,}6 \pm 0{,}2)$ and $r_2 = 0{,}2 \pm 0{,}2$. In the same way the ratio $\Gamma(\psi \to \Lambda\bar{\Lambda})/\Gamma(\psi \to p\bar{p}) = 0.76 \pm 0.53$ [3] leads to $r_1' = -(3.3 \pm 0.7)$ and $r_2' = 0.5 \pm 0.7$. Thus in order to fit the two ratios $\Gamma(\psi \to K^*K)/\Gamma(\psi \to \rho\pi)$ and $\Gamma(\psi \to \Lambda\bar{\Lambda})/\Gamma(\psi \to \bar{p}p)$ we have to choose $0 \leq r \leq 0.4$. For r within these limits the octet component of ψ : $\alpha_8^{(\psi)} = \frac{1}{\sqrt{3}}\left(\alpha_\sigma^{(\psi)} - \sqrt{2}\,\alpha_s^{(\psi)}\right)$ is reduced compared to $\alpha_\sigma^{(\psi)}$. We have $\alpha_8^{(\psi)}/\alpha_\sigma^{(\psi)} = 0.4 \pm 0.2$ whereas for the other solution $r_1 = -(1.6 \pm 0.2)$ this ratio is 1.9 ± 0.2. We see that even for the preferred solution of r the ψ does not behave as a pure SU(3) singlet concerning the decays into uncharmed mesons. [4] Nevertheless the octet component $\alpha_8^{(\psi)}$ is small enough to give for the decay $\psi \to K\bar{K}$ a branching ratio below the experimental upper limit (see table 3a).

It is gratifying that these constraints on $\alpha_\sigma^{(\psi)}$ and $\alpha_s^{(\psi)}$ can be built into the mass mixing problem. With $m_\rho = 0.7605$ GeV $\beta_V = 0.9961$ and $\alpha_V = 21.26$ we obtain the wave functions of the mixed vector mesons together with the masses of the charmed vector mesons as given in table 1. The corresponding r is equal to $r = 0.26$. Unfortunately all solutions with a higher ρ mass lead to unacceptable values for r. For example $m_\rho = 0.763$, $\beta_V = 0.971$ and $\alpha_V = 21.6$ give $r = -1.6$ and $|\alpha_\sigma^{(\psi)}| = 1.14 \cdot 10^{-4}$ which fits the decays $\psi \to p\bar{p}$, $\psi \to \rho\pi$ and $\psi \to K^*\bar{K}$ but not $\psi \to \Lambda\bar{\Lambda}$.

Regarding the pseudoscalar multiplet, our previous calculation with $\beta_P = 1$ resulted in too large coefficients $\alpha_c^{(\eta)}$, $\alpha_c^{(\eta')}$, $\alpha_\sigma^{(\psi_P)}$ and $\alpha_s^{(\psi_P)}$. A numerical study showed that these coefficients can be reduced appreciably by increasing β_P. An optimal solution has been obtained for $\beta_P = 2.50$. The mass of is now $m_{\psi_P} = 2.98$ GeV instead of $m_{\psi_P} = 2.73$ GeV with $\beta_P = 1$ [2], whereas the masses of D and F remain unchanged. But the ψ_P mass can be controlled by the parameter α_P without spoiling the wave functions. For example with $\alpha_P = 18.1$ instead of $\alpha_P = \alpha_V = 21.2$ and $\beta_P = 2.45$ the mass of ψ_P is now $m_{\psi_P} = 2.75$ GeV. The masses and wave functions for these two cases are given in table 2a and 2b. We remark that, contrary to the vector meson multiplet, the parameter β_P must be chosen larger than one in order to have small coefficients $\alpha_C^{(\eta)}, \alpha_C^{(\eta')}, \alpha_\sigma^{(\psi_P)}, \alpha_S^{(\psi_P)}$.

3. Two- Body Decays.

We consider the decays $V \to PP$, $V \to VP$, $V \to \gamma P$ and $P \to \gamma\gamma$, where V and P are members of the vector and pseudoscalar SU(4) multiplets. For the coupling constants of the corresponding three-point vertices we assume SU(4) symmetry as in ref. 2. The radiative decays $V \to \gamma P$ are calculated from $V \to VP$ using vector meson dominance with the direct $V - \gamma$ couplings taken from the known decays $V \to e^+e^-$. The results are shown in table 3a for the strong decays and in table 3b for the radiative decays. The results in the first (second) column refer to pseudoscalar wave functions taken from table 2a (2b). For normalization of the coupling constants we used the known decays[5] $\rho^0 \to \pi^+\pi^-$, $\phi \to \rho^+\pi^-$, $\omega \to \pi^0\gamma$ and $\pi^0 \to 2\gamma$.

The strong decays are almost equal for the two choices of the pseudoscalar wave functions. This is to be expected since the coefficients α_σ and α_S for η and η' are very close in the two versions. In table 3a we compare our results with recent measurements.[3] We see that the width for $\psi \to K^+K^-$ is predicted to be around 1 eV well below the experimental upper limits: 14 eV (SPEAR) [4] and 40 eV (DORIS)[6]. For the calculation of the $\psi \to p\bar{p}$ decay we have taken $g^2_{\omega\bar{p}p}/4\pi = 15$ consistent with information from low energy proton-proton scattering analysis.

From table 3b it can be seen that the radiative decays $\psi \to \eta\gamma$, $\psi \to \eta'\gamma$ and $\psi \to \psi_p\gamma$ are reduced appreciably compared to our old result with $\beta_p = 1$.[2)] Still a problem is the decay $\psi \to \psi_p\gamma$ in version (2). The difference for $\psi \to \psi_p\gamma$ between version (1) and (2) is a pure phase space effect due to the lower mass of m_{ψ_p} in version (2). This cannot be changed appreciably by mixing effects. If it turns out that the recently reported particle around 2.75 GeV [7)] is the ψ_p, then only the SU(4) breaking of the VVP coupling constants could reduce this width in version (2). That such a breaking goes in the right direction follows from a recent paper by Aubrecht and Razmi. [8)]

Finally we remark that the ratio $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma)$ comes out roughly in agreement with the experimental value 6 ± 3 [7)]. However the absolute values of these decay widths are still too large.

In conclusion we have shown that the mass mixing in broken SU(4) is consistent with the existing experimental information about the two-body decays of the ψ with the exception of $\psi \to \psi_p\gamma$, $\psi \to \eta'\gamma$ and $\psi \to \eta\gamma$. Hopefully these decays can be accomodated by introducing SU(4) breaking of the VVP coupling constants.

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2) A. Kazi, G. Kramer and D.H. Schiller, Desy report, Desy 75/11 (May 1975)

3) G.J. Feldman and M.L. Perl, Physics Report (to be published).

4) See J.F. Bolzan, K.A. Geer, W.F. Palmer and S.S. Pinsky, preprint Fermi National Accelerator Laboratory (Fermilab - Pub - 75/62 - THY, August 1975) for a similar discussion in the framework of the O-meson model.

5) Particle Data Group, Physics Letters 50B, (1974) , Number 1

6) W. Braunschweig et al. , Desy report, Desy 75/14 (May 1975)

7) B. Wiik and J. Heintze, reports to the Stanford Conference (August 1975)

8) G.J. Aubrecht and M.S.K. Razmi, preprint Oregon University (March 1975).

Table Captions

Table 1: Predicted masses of charmed vector mesons D^* and F^* and wave functions for the mixed states ω, ϕ and ψ. Masses are in GeV.

Table 2a: The same as table 1 for the pseudoscalar mesons with $\alpha_P = \alpha_V = 21.2359$ and $\beta_P = 2.50$.

Table 2b: The same as table 2a, but for $\alpha_P = 18.1075$ and $\beta_P = 2.45$

Table 3a: The strong decays $V \to PP$ and $V \to VP$ compared to experimental data. In version (1) the wave functions of P from table 2a, and in version (2) those from table 2b are used. The data in column (3) are from refs. 3 and 5.

Table 3b: The radiative decays $V \to P\gamma$ and $P \to \gamma\gamma$ for the same two versions as in table 3a. The experimental data are from refs. 5 and 7.

Table 1

$m_\omega = 0.7827$, $m_\phi = 1.0197$, $m_\psi = 3.095$, $m_{K^*} = 0.89435$

$m_\rho = 0.7605$

$\alpha_V = 21.2359$, $\beta_V = 0.99610$, $m_{D^*} = 2.255$ $m_{F^*} = 2.304$

	α_σ	α_s	α_c
ω	0.99833	-0.05777	-0.000100
ϕ	0.05777	0.99833	-0.000032
ψ	0.000102	0.000026	1.00 000

Table 2a

$m_\pi = 0.13803$, $m_K = 0.4957$, $m_\eta = 0.5488$, $m_{\eta'} = 0.9576$

$\alpha_p = 21.2359$ $\beta_p = 2.50$

$m_{\psi_p} = 2.981$ $m_D = 2.152$ $m_F = 2.204$

	α_σ	α_s	α_c
η'	0.70017	0.71384	0.01397
η	0.71395	-0.70018	-0.00480
ψ_p	-0.00635	-0.01333	0.99989

Table 2b

$m_\pi = 0.13803$, $m_K = 0.4957$, $m_\eta = 0.5488$, $m_{\eta'} = 0.9576$

$\alpha_p = 18.1075$ $\beta_p = 2.45$

$m_{\psi_p} = 2.75$ $m_D = 1.991$ $m_F = 2.047$

	α_σ	α_s	α_c
η'	0.70044	0.71355	0.01520
η	0.71369	-0.70044	-0.00595
ψ_p	-0.00640	-0.01502	0.99987

Table 3a

	(1)	(2)	(3)
$\rho^0 \to \pi^+\pi^-$	150.4 MeV	150.4 MeV	(150.4 ± 2.9) MeV
$\phi \to K^+K^-$	1.75 MeV	1.75 MeV	(1.94 ± 0.19) MeV
$\psi \to K^+K^-$	0.7 eV	0.7 eV	<14 eV
$\phi \to \rho^+\pi^-$	223 KeV	223 KeV	(223 ± 6) KeV
$\psi \to \rho^+\pi^-$	332 eV	332 eV	(299 ± 120) eV
$\psi \to K^{*+}K^-$	131 eV	131 eV	(107 ± 33) eV
$\psi \to \omega\eta'$	25 eV	25 eV	
$\psi \to \omega\eta$	40 eV	40 eV	
$\psi \to \phi\eta'$	4 eV	4 eV	
$\psi \to \phi\eta$	3 eV	3 eV	
$\psi \to p\bar{p}$	152 eV	152 eV	(145 ± 60) eV
$\psi \to \Lambda\bar{\Lambda}$	87 eV	87 eV	(110 ± 80) eV

Table 3b

	(1)	(2)	(3)
$\omega \to \pi^0\gamma$	870 KeV	870 KeV	(870 $\pm$ 86) KeV
$\phi \to \pi^0\gamma$	4.54 KeV	5.03 KeV	(5.9 $\pm$ 2.1) KeV
$\psi \to \pi^0\gamma$	0.1 eV	0.1 eV	$<$ 350 eV
$\omega \to \eta\gamma$	5.6 KeV	5.6 KeV	$<$50 KeV
$\phi \to \eta'\gamma$	0.5 KeV	0.5 KeV	
$\phi \to \eta\gamma$	118.3 KeV	118.4 KeV	(123 $\pm$ 52) KeV
$\psi \to \eta'\gamma$	3.0 KeV	3.6 KeV	$\sim$1.2 KeV
$\psi \to \eta\gamma$	0.43 KeV	0.67 KeV	(94 $\pm$ 30) eV
$\psi \to \psi_p\gamma$	7.90 KeV	196 KeV	
$\pi^0 \to 2\gamma$	7.71 eV	7.71 eV	(7.71 $\pm$ 0.89) eV
$\eta' \to 2\gamma$	5.30 KeV	5.31 KeV	$<$19 KeV
$\eta \to 2\gamma$	0.459 eV	0.458 KeV	(0.374 $\pm$ 0.060) KeV
$\psi_p \to 2\gamma$	11.4 KeV	8.94 KeV	