THE $1^-$ STATE AND $\psi$ SPECTROSCOPY

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ABSTRACT

We suggest that $\psi' \rightarrow \psi_H \eta^0$ (where the $\psi_H$ is the $1^-$ state) may be an important decay mode of the $\psi'(3685)$ and $\psi'' \rightarrow \psi_H \eta$ of the $\psi''(4414)$. We also discuss ways to test the magnitude of the $\eta - \eta^0$ transition in the $\psi$ system.

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There seems to be a puzzle in accounting for the decays of the $\psi'(3685)$ \(^1\). Approximately 57\% of the decays are to $\psi(3095)$+ anything. Taking the total width as 220 keV \(^2\) (it is $220 \pm 56$ keV) leave approximately 90 keV to be explained, of which about five are the $e^+e^-$ and $\mu^+\mu^-$ final states. It seems that the hadronic decay modes of the $\psi'$ give a $\Gamma_{\psi'}$ hadronic less than half of $\Gamma_{\psi}$ hadronic; this then gives us another $\sim 30$ keV and we are left with $\sim 55$ keV still to be explained. This is the puzzle: where are the remaining decays? The limits on photon transitions of the $\psi'$ suggest it is not $\pi^0 + \gamma$ states \(^3\),\(^4\), though this issue is still not settled. Decays involving the $\eta_c$ \(^5\) such as an $\eta_c\pi^0$ final state do not appear sufficient either \(^6\).

In this note we would like to suggest a completely different mechanism which seems capable of resolving the puzzle of the missing $\psi'$ decays. It involves decays to a final $^1P_1$ state $J^{PC} = 1^{+-}$, which we label $\psi_H$ in analogy to the $\phi$ meson in the conventional quark model. No such state has been seen as of yet, but we believe that whatever the explanation of the $\psi$, $\psi'$, $\pi^0\gamma$ states is, the evidence is strong for it having the nature of fermion-anti-fermion bound states and hence the $\psi_H$ should exist. A first guess for the value of its mass would place it in the 3400-3500 MeV region with the other $\pi^0$ states, but the apparent strong spin-spin forces which lead to the $\eta_c$ ($^3S_1$) being $\sim 300$ MeV lower \(^5\) than the $\psi'$ probably lead to the $\psi_H$ having a lower mass. The actual value is not crucial to our calculation; for argument's sake we take it to be 3300 MeV.

The mechanism we suggest for the missing $\psi'$ decays is that the $\psi'$ decays into a $\psi_H$ plus a virtual $\eta$ or $\eta'$ which then converts electromagnetically or otherwise into a $\pi^0$

$$\psi' \rightarrow \psi_H + \pi^0 (\eta, \eta') \quad (1)$$

At first sight one would imagine this to be hopelessly small because of the virtual electromagnetic transition but two factors are at work:

1) it is a two-body $S$ wave decay, whereas competing mechanisms involve either $P$ waves ($\psi\eta$) or three-body phase space ($\psi\pi\pi$);

2) the $\eta\pi^0$ transition is probably anomalously large, in fact many \(^7\)-\(^13\) authors believe there is strong evidence for a non-electromagnetic isospin violating term in the interaction Hamiltonian.
We need to know the magnitude of the $\eta(\eta') - \pi^0$ transition. If we take this as due to an isospin violating scalar density interaction term, $\varepsilon_3 u_3$, we have the parameter

$$\frac{\langle \eta(\eta') | \varepsilon_3 u_3 | \pi^0 \rangle}{m_{\eta}^2 - m_{\pi^0}^2} = \lambda_{\eta}$$

A reasonable estimate \(^7\)-\(^{13}\) is that $0.02 \leq \lambda_{\eta} \leq 0.05$. We expect $\lambda_{\eta}$ to be somewhat smaller since $m_{\eta'} = 3 m_{\eta}$.

The decay width for $\psi' - \psi_H^0$ is

$$\Gamma_{\psi' \rightarrow \psi_H^0 \pi^0(\eta')} = \frac{1}{2} \frac{g_1^2}{4\pi} \frac{\lambda_{\eta}^2}{2} \left(1 + \frac{P_3}{3 M_{\psi_H^0}}\right) \frac{P_H}{M_{\psi'}} M_{\psi'}$$

as contrasted to the $\psi' - \psi$ width

$$\Gamma_{\psi' \rightarrow \psi_H^0 \pi^0(\eta')} = \frac{1}{3} \frac{g_1^2}{4\pi} \left(\frac{P_3}{M_{\psi'}}\right)^3 M_{\psi'}$$

In the above $P_3$ and $P_\eta$ are, respectively, the pion and $\eta$ momenta. As a first estimate we take $g_1 \approx g_2$. For $0.02 \leq \lambda_{\eta} \leq 0.05$, we then obtain, using the published value \(^{14}\) for (4) to determine $g_2$, that

$$5 \text{ keV} \lesssim \Gamma_{\psi' \rightarrow \psi_H^0 \pi^0(\eta')} \lesssim 30 \text{ keV}$$

The largeness of this result can be intuitively understood by realizing that in the $\eta$ decay mode $p_\eta = 198$ keV so $(p_\eta/M_{\psi'})^2 \approx \lambda_{\eta}^2$. We emphasize that we have only made a crude estimate: there is no a priori reason for relating $g_1$ and $g_2$. In particular, in a Lagrangian picture, the $S$ wave coupling has a mass in the numerator whereas the $P$ wave coupling has a mass in the denominator. We have taken both masses equal to $M_{\psi'}$. This might suggest taking $g_1$ smaller than $g_2$ would be more appropriate; on the other hand we have neglected the contribution due to the $\eta'$, which may be even greater than the $\eta$ contribution, the reason being that although $\lambda_{\eta'}$ is smaller than $\lambda_{\eta}$, the $\psi' \psi_H^0$ coupling violates SU(3) whereas the $\psi' \psi_H^0$ does not (in the limit of no $\eta - \eta'$ mixing). We note that although $\psi' \rightarrow \psi_H^0$ is present, if $M_{\psi_H^0} < 3400$ MeV, the decay is $P$ wave and hence presumably very small ($\Gamma \ll 1$ keV).
The $\psi$ system also allows us to have a direct and new important measurement of a potential isospin violating interaction by looking directly at the decay $\psi' \rightarrow \eta \pi^0$. The present published upper limit \cite{14} on the width of this decay mode is $\approx 0.3$ keV. We estimate the contribution of the $\eta$ pole to this process as

$$\Gamma_{\psi' \rightarrow \eta \pi^0} = \Gamma_{\psi' \rightarrow \eta \eta} \lambda^2 \left( \frac{P_{\eta^0}}{P_{\eta}} \right)^3$$ \hspace{1cm} (6)

and, for $0.02 \leq \lambda \leq 0.05$, we have

$$0.01 \text{ keV} \leq \Gamma_{\psi' \rightarrow \eta \pi^0} \leq 0.65 \text{ keV}$$ \hspace{1cm} (7)

Barring unforeseen cancellations between the $\eta$ and the $\eta'$ pole contributions, the upper limit \cite{14} of $0.3$ keV already seems to exclude $\lambda \eta \geq 0.035$. An improved upper limit would probably rule out the $u_3$ isospin violating mechanism altogether.

Returning now to the $\psi' \rightarrow \eta \pi^0$ decay mode, let us see what its signal would be. Since the $\psi_H$ has $P = 1^+$ pionic final states would involve at least one $\pi^0$; the $\eta \pi^0$ is probably an important decay mode. Some suggested modes that could be detected are

$$\psi_H \rightarrow \eta \phi, \bar{p}p, K^+K^0\pi^-$$ \hspace{1cm} (8)

We would also like to point out that the $\psi_H$ may play an important role in the decay of higher $\psi$ states \cite{6} such as the $\psi''(4414)$. For instance

$$\psi'' \rightarrow \psi_{H}\pi$$ \hspace{1cm} (9)

is an allowed $S$ wave decay, and a naive estimate is that this has a width in the MeV range. There are other allowed $S$ wave two-body decay modes for the $\psi''$ such as the decay into $P_0(0^+) + \omega$. Since the $\psi''$ width is relatively narrow ($\sim 30$ MeV), this raises the intriguing possibility that the dominant decay modes of the $\psi''$ are into lower mass $\psi$ like states, i.e., we have not passed a threshold for $\eta$ constituents.
In conclusion we would like to reiterate the four main points of this paper. They are:

1) the $\bar{\psi}$ system allows us to test the magnitude of the $\eta - \pi^0$ transition by studying $\bar{\psi}' \rightarrow \pi^0$;

2) a mechanism has been suggested for finding the $^1P_1$ state, $\psi_H$;

3) the decay $\psi' \rightarrow \psi_H \pi^0$ may account for the "missing" $\psi'$ decays;

4) two-body decays such as $\psi'' \rightarrow \psi_H \eta$ may be a substantial fraction of the total $\psi''$ decays.

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REFERENCES

1) See, e.g.:  
F.J. Gilman - "New Particle Spectroscopy and Decays", Invited talk at Orbis Scientiae 1976, University of Miami (January 1976), for a review of this situation.


