# GAMMA RAY CASCADE DECAYS FROM $\psi^{\prime}(3684)$ TO $\psi(3095)^{*}$ 

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#### Abstract

The consequences of the existence of the gamma ray cascade decay, $\psi^{\prime}(3684) \rightarrow \gamma+\mathrm{X}$ and $\mathrm{X} \rightarrow \gamma+\psi(3095)$, are examined. The kinematics of the resulting two-gamma mass spectrum together with the observed dynamics of the neutral missing mass in $\psi^{\prime}(3684) \rightarrow \psi(3095)+$ neutrals are shown to be of such a form that a stringent upper limit can be placed on the sum of all such transitions.


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[^0]The discovery ${ }^{1}$ of the narrow boson resonances, $\psi(3095)$ and $\psi^{\prime}(3684)$, and the rise ${ }^{2}$ in $R=\sigma_{\mathbf{T}}\left(\mathrm{e}^{+} \mathrm{e}^{-} \rightarrow\right.$ hadrons $) / \sigma\left(\mathrm{e}^{+} \mathrm{e}^{-} \rightarrow \mu^{+} \mu^{-}\right)$near center of mass energies of 4 GeV have focused attention on the possible existence of new hadronic degrees of freedom. An attractive and elegant theory is achieved with the addition of a new quark and associated additive quantum number, charm. ${ }^{3}$ In such a scheme, the $\psi$ and $\psi^{\prime}$ are quark-antiquark (cec) bound states, while the rise in R corresponds to the production of the continuum including pairs of charmed particles.

A most important consequence of such a scheme (and of many related ones) is the existence of a new spectroscopy including, in the case of charm, various charmed particles (containing a charmed quark plus the "ordinary" quarks) as well as additional $c \bar{c}$ bound states. In particular, an examination of the known meson spectra or the use of potential models ${ }^{4,5,6}$ leads one to expect pseudoscalar ( ${ }^{1} \mathrm{~S}_{0}$ ) states to lie just below the $\psi$ and $\psi^{\prime}$ (taken as ${ }^{3} \mathrm{~S}_{1}$ states of $\mathrm{c} \overline{\mathrm{c}}$ ) and a set of p-wave c- $\bar{c}$ states to lie between the $\psi$ and $\psi^{\prime}$. These states would have the ${ }_{\mathrm{J}} \mathrm{PC}_{\text {quantum numbers }} 0^{++}, 1^{++}, 2^{++}$, and $1^{+-}\left({ }^{3} \mathrm{P}_{0},{ }^{3} \mathrm{P}_{1},{ }^{3} \mathrm{P}_{2}\right.$, and ${ }^{1} \mathrm{P}_{1}$ in spectroscopic notation).

The ${ }^{3} \mathrm{P}_{\mathrm{J}}$ states have the appropriate quantum numbers to allow the decay $\psi^{\prime}(3684) \rightarrow \gamma+{ }^{3} \mathrm{P}_{\mathrm{J}}$ and thence ${ }^{3} \mathrm{P}_{\mathrm{J}} \rightarrow \gamma+\psi(3095)$. In fact, in the "charmonium" picture, calculations ${ }^{4,5,7}$ predict a combined width of several hundred keV for $\psi^{\prime}(3684) \rightarrow \gamma+{ }^{3} \mathrm{P}_{\mathrm{J}}(\mathrm{J}=0,1,2)$ via electric dipole transitions, and then ${ }^{3} \mathrm{P}_{\mathrm{J}} \rightarrow \gamma+\psi(3095)$ being the overwhelmingly dominant decay of these p-wave states. ${ }^{8}$ Thus, such gamma ray cascade decays from $\psi^{\prime}(3684)$ to $\psi(3095)$ are predicted to be a major part of the total width of the $\psi^{\prime}(3684)$ which lies in the range ${ }^{9}$

$$
200 \mathrm{keV}<\Gamma\left(\psi^{\prime}(3684) \rightarrow \text { all }\right)<800 \mathrm{keV} .
$$

In the following we show that the two-gamma mass spectrum is of such a form that by measuring the neutral missing mass spectrum in $\psi^{\prime}(3684) \rightarrow \psi(3095)+$ neutrals, one can place stringent upper limits on the sum of all gamma ray cascade decays passing through the p-wave c $\bar{c}$ states or through a pseudoscalar state. This limit does not require detecting gamma rays, but only depends on observing the $\psi$ in a known decay mode like $\mu^{+} \mu^{-}$.

To derive the result, we work in the rest frame of the intermediate ( ${ }^{1} S_{0}$ or $3^{P_{J}}$ ) state, whose mass we denote by m. The invariant mass-squared of the two gammas is simply

$$
\begin{equation*}
M_{\gamma \gamma}^{2}=2 \mathrm{E}_{1} \mathrm{E}_{2}\left(1-\cos \theta{ }_{\gamma \gamma}\right) \tag{1}
\end{equation*}
$$

where $\mathrm{E}_{1}$ and $\mathrm{E}_{2}$ are the gamma energies and $\theta_{\gamma \gamma}$ the angle between them. The energies $\mathrm{E}_{1}$ and $\mathrm{E}_{2}$ are given by

$$
\begin{equation*}
E_{1}=\frac{M_{r^{2}}-m^{2}}{2 m} \tag{2a}
\end{equation*}
$$

and

$$
\begin{equation*}
\mathrm{E}_{2}=\frac{\mathrm{m}^{2}-\mathrm{M}^{2}}{2 \mathrm{~m}} \tag{2b}
\end{equation*}
$$

if $M$ and $M^{\prime}$ are the $\psi$ and $\psi^{\prime}$ masses, respectively.
$M_{\gamma \gamma}^{2}$ ranges between 0 and $4 E_{1} E_{2}=\left(M^{2}-m^{2}\right)\left(m^{2}-M^{2}\right) / m^{2}$. It is easily shown that

$$
\begin{equation*}
4 E_{1} E_{2}=\frac{\left(M^{2}-m^{2}\right)\left(m^{2}-M^{2}\right)}{m^{2}} \leq\left(M^{1}-M\right)^{2}, \tag{3}
\end{equation*}
$$

with the equality occuring when $\mathrm{m}^{2}=\mathrm{MM}^{1}$.
Now, parity conservation demands that the distributions in $\theta_{\gamma \gamma}$ be such that they are symmetrical under $\cos \theta_{\gamma \gamma} \rightarrow-\cos \theta_{\gamma \gamma}$, i. e., only involve even powers of $\cos \theta_{\gamma \gamma}$. Therefore, Eq. (1) immediately shows that the distribution in $M_{\gamma \gamma}^{2}$
will be symmetrical about the midpoint, $2 \mathrm{E}_{1} \mathrm{E}_{2} \leq \frac{1}{2}\left(\mathrm{M}-\mathrm{M}^{\prime}\right)^{2}$. Thus very generally half or more of any two-gamma cascade events have $M_{\gamma \gamma}^{2}$ below $\frac{1}{2}\left(M-M^{\prime}\right)^{2}$. Since it is already known ${ }^{10}$ that the invariant mass-squared of the neutrals in the $\approx 25 \%$ of $\psi^{\prime}$ decays ${ }^{11}$ of the type

$$
\psi^{\prime}(3684) \rightarrow \psi(3095)+\text { neutrals }
$$

is strongly peaked above the midpoint in mass-squared, we see that only a small fraction of these possible candidates for

$$
\psi^{\prime}(3684) \rightarrow \psi(3095)+\gamma+\gamma
$$

can be actual cascade decays. 12
An even tighter restriction follows from consideration of the distributions in $\theta_{\gamma \gamma}$. For electric dipole transitions into and out of the intermediate states under consideration we find ${ }^{13}$

$$
\begin{align*}
& { }^{1} \mathrm{~S}_{0}: \mathrm{N}\left(\theta_{\gamma \gamma}\right)=\text { constant }  \tag{4a}\\
& { }^{3} \mathrm{P}_{0}: \mathrm{N}\left(\theta_{\gamma \gamma}\right)-\text { constant }  \tag{4b}\\
& { }^{3} \mathrm{P}_{1}: \mathrm{N}\left(\theta_{\gamma \gamma}\right) \propto 5+\cos ^{2} \theta_{\gamma \gamma}  \tag{4c}\\
& 3^{3} \mathrm{P}_{2}: \mathrm{N}^{2}\left(\theta_{\gamma \gamma}\right) \propto 73+21 \cos ^{2} \theta_{\gamma \gamma} \tag{4~d}
\end{align*}
$$

Since the angular distributions all have zero or positive coefficients of $\cos ^{2} \theta_{\gamma \gamma}$, the corresponding $\mathrm{N}\left(\mathrm{M}_{\gamma \gamma}^{2}\right)$ distributions will be maximal at $\mathrm{M}_{\gamma \gamma}^{2}=0$ and $4 \mathrm{E}_{1} \mathrm{E}_{2}$ and a minimum at the midpoint, $2 \mathrm{E}_{1} \mathrm{E}_{2}$. But then greater than or equal to one third of any two gamma events will have $M_{\gamma \gamma}^{2} \leq \frac{1}{3}\left(M^{\prime}-M\right)^{2}=(340 \mathrm{MeV})^{2}$ and one fifth or more will have $\mathrm{M}_{\gamma \gamma}^{2} \leq \frac{1}{5}\left(\mathrm{M}^{\boldsymbol{\gamma}}-\mathrm{M}\right)^{2}=(263 \mathrm{MeV})^{2}$, etc. This last mass
region is already below the threshold for any possible contribution to the neutral missing mass spectrum from $\psi^{\top} \rightarrow \psi+2 \pi^{\circ}$.

The dynamics of strong peaking of the neutral mass spectrum in $\psi^{\prime} \rightarrow \psi+$ neutrals (and the $\pi^{+} \pi^{-}$mass in $\psi^{\prime} \rightarrow \psi+\pi^{+}+\pi^{-}$) toward the highest possible masses and the predicted (essentially kinematic) form of $M_{\gamma \gamma}^{2}$ then allow one to use low values of the neutral mass-squared spectrum in $\psi^{r} \rightarrow \psi+$ neutrals to place very strong limits on gamma ray cascade decays. In that this method: (a) does not rely on detecting gamma rays at all, especially low energy ones from p-wave states nearby in mass to the $\psi^{\prime}$ (3684); (b) depends only on observing the $\psi$ (3095) in a known decay like $\mu^{+} \mu^{-}$; and (c) puts a limit on the sum of all such decays independent of whether the contributing intermediate states are nearby to one another in mass and difficult to resolve; it is complementary to, and in some ways more powerful than, the direct search for gamma rays from particular cascade decays. In the near future, it should be possible to achieve upper limits using this method which are at least an order of magnitude below naive theoretical expectation.

## References

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12. If it is assumed that the dipion system in $\psi^{\prime}(3684) \rightarrow \psi(3095)+\pi^{+}+\pi^{-}$has $\mathrm{I}=0$, then $\psi^{\prime}(3684) \rightarrow \psi(3095)+2 \pi^{0}$ has one-half the width of the charged pion mode for each dipion invariant-mass value. Subtracting one-half the charged pion mass spectrum from the neutrals spectrum in $\psi^{\prime}(3684) \rightarrow \psi(3095)+$ neutrals results in fewer candidates for $\psi^{\prime}(3684) \rightarrow \psi(3095)+\gamma+\gamma$ and a correspondingly reduced upper limit.
13. The last two angular distributions disagree with those given in Table II of Ref. 5, but the results given here agree with a corrected version of their calculation. We thank T. M. Yan for discussions on this point.

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