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TWO-PHOTON COUPLINGS OF QUARKONIA WITH ARBITRARY ANGULAR MOMENTA†

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ABSTRACT

The observation of a large $\gamma\gamma$ width for the $^1D_2$ $q\bar{q}$ state $\pi_2(1670)$ suggests that the $\gamma\gamma$ couplings of many orbitally-excited light $q\bar{q}$ states may be experimentally accessible. In this talk we present $\gamma\gamma$ helicity amplitudes for $q\bar{q}$ states with general angular momenta $^1\ell_J$ and $^3\ell_J$, and note some relations and selection rules that may be useful in spectroscopic classification of orbital excitations.

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Two-photon production of meson resonances has proven to be a very useful experimental technique for studying light mesons with even C-parity. The coupling of photons to the quark charges in $q\bar{q}$ states provides direct evidence of the internal charge structure, for example in the relative $\gamma\gamma$ partial widths of 25:9:2 for $(u\bar{u}+d\bar{d})/\sqrt{2}, (u\bar{u}-d\bar{d})/\sqrt{2}$ and $s\bar{s}$ states within an orbital SU(6) multiplet. Non-$q\bar{q}$ states may also be identified through their two-photon couplings. For example, the $f_0(975)$ and $a_0(983)$ $K\bar{K}$-molecule candidates [1] have anomalously small $\gamma\gamma$ widths [2] of ≈ 0.2 Kev [3], whereas quark model expectations for light, nonstrange $(I=0,1)$ $^3\mathrm{P}_0$ $q\bar{q}$ states are typically several Kev. A much broader $f_0(\sim 1200)$ has recently been identified in $\gamma\gamma \to \pi\pi$ by the Crystal Ball [4] and CELLO [5] collaborations, which has a $\gamma\gamma$ width consistent with quark model estimates for an $\ell=1$ $q\bar{q}$ state.

Until recently only quarkonium states with low orbital angular momenta, $\ell \leq 1$, had been reported in two-photon collisions. The observation of the $^1\mathrm{D}_2$ $q\bar{q}$ state $\pi_2(1670)$ [4-7] with a $\gamma\gamma$ partial width comparable to those of light $\ell=1$ states has dramatically altered this situation, and suggests that two-photon experiments may be useful in the study of other light higher-spin resonances.

It will be important to have theoretical estimates of $\Gamma_{\gamma\gamma}$ and characteristic $\gamma\gamma$ couplings (such as the dominant helicity amplitudes) for orbitally-excited states for comparison with future experimental studies. In this talk I report theoretical $\gamma\gamma$ couplings of nonrelativistic $q\bar{q}$ states with all allowed angular momenta, $(S=0, \ell=even)$ and $(S=1, \ell=odd)$. These results are abstracted from work with E.S.Ackleh, F.E.Close and Z.P.Li [8-11], and complete a theoretical program of nonrelativistic calculations of fermion-antifermion couplings to on-shell $\gamma\gamma$ states begun by Wheeler [12] (for $\ell=0$) and continued by Alekseev [13] $(\ell=1)$, Anderson, Austern and Cahn [14] $(\ell=2)$ and Ackleh and Barnes [9] $(\ell=even)$. Details of the calculation and of relativistic corrections will be presented elsewhere [9-11]. We note in passing that relativistic corrections are actually very important in determining the absolute rate within an (S,ℓ) multiplet, for example in the $\gamma\gamma$ partial width of the $\pi_2(1670)$. We have evaluated relativistic corrections to the $(S=1, \ell=1)$ [8] and $(S=0, \ell=even)$ [9] $\gamma\gamma$ widths, and $(S=1, \ell=odd)$ is in progress [11], but space does not permit discussion of these results here. Helicity selection rules appear to be less sensitive to relativistic effects, at least in the $^3P_2$ case [7,8].

Our result for the nonrelativistic two-photon width of an e^+e^- bound state is of the form

$$\Gamma_{NR}\left({}^{2S+1}\ell_j(e^+e^-) \to \gamma\gamma\right) = \sum_{\lambda=0,2} \hat{\Gamma}_\lambda \cdot \frac{\alpha^2}{m_e^{2\ell+2}} |\psi^{(\ell)}(0)|^2 \;, \tag{1}$$

where $\psi^{(\ell)}(0)$ is the ℓth derivative of the radial wavefunction at contact, which is normalised to $\int_0^\infty r^2 |\psi(r)|^2 dr = 1$. Allowed values of the two-photon helicity λ are 0 and 2 for $S = 1$, $j = \ell \pm 1$, $\lambda = 2$ only for the $S = 1$, $j = \ell$ "middle-of-multiplet" triplet states, and $\lambda = 0$ only for the $S = 0$, $j = \ell$ singlet quarkonium states. We have determined the reduced partial widths $\hat{\Gamma}_\lambda$ in (1) for each two-photon helicity state ($\lambda = 0$ or 2) for given e^+e^- or $q\bar{q}$ angular quantum numbers. (Here we quote coefficients for positronium decay; for the $q\bar{q}$ case one should replace m_e in (1) by m_q and multiply $\hat{\Gamma}_\lambda$ by an overall color factor of 3.)

For the spin-singlet case, $j^{PC} = even^{-+}$, the reduced partial width [9] is

$$\hat{\Gamma}_{\lambda=0}({}^1\ell_{j=\ell}) = 1 \tag{2a}$$

for all ℓ; this reproduces the well-known ${}^1S_0$ parapositronium width [12] and the recent $\ell = 2$ result of Anderson, Austern and Cahn [14] as special cases. (Although we agree with the nonrelativistic formula of [14], we find that large relativistic corrections and other effects [9] lead to a numerical value much closer to experiment for the $\pi_2(1670)$ than was reported in [14].) The previously unpublished results presented in this talk are for spin-triplet states, $S = 1$ and $\ell = odd$. For these states the coefficients $\{\hat{\Gamma}_\lambda\}$ have nontrivial j, ℓ and λ dependence; our general results [10] are

$$\hat{\Gamma}_{\lambda=2}({}^3\ell_{j=\ell+1}) = \frac{(\ell+2)(\ell+3)}{\ell(2\ell+3)} \;; \tag{2b}$$

$$\hat{\Gamma}_{\lambda=0}({}^3\ell_{j=\ell+1}) = 0 \;; \tag{2c}$$

$$\hat{\Gamma}_{\lambda=2}({}^3\ell_{j=\ell}) = \frac{(\ell-1)(\ell+2)}{\ell^2} \;; \tag{2d}$$

$$\hat{\Gamma}_{\lambda=2}({}^3\ell_{j=\ell-1}) = \frac{(\ell-2)(\ell-1)(\ell+1)}{\ell^2(2\ell-1)} \left(1+\chi\right)^2 \;; \tag{2e}$$

$$\hat{\Gamma}_{\lambda=0}({}^3\ell_{j=\ell-1}) = \frac{(2\ell+1)^2}{\ell(2\ell-1)} \;, \tag{2f}$$

where χ is

$$\chi = \begin{cases} 0, & \ell = 1 \;; \\ \frac{\ell(2\ell+1)}{2(\ell-2)(\ell-1)}, & \ell \geq 3 \end{cases} . \tag{2g}$$

Spin-triplet decays of current interest are $\ell = 1$ and $\ell = 3$. For $\ell = 1$ we recover the well-known *relative* widths of

$$\left[\,\hat{\Gamma}_{\lambda=2}(^3\mathrm{P}_2)\;:\;\hat{\Gamma}_{\lambda=0}(^3\mathrm{P}_2)\,\right]\;:\;\hat{\Gamma}_{\lambda=2}(^3\mathrm{P}_1)\;:\;\hat{\Gamma}_{\lambda=0}(^3\mathrm{P}_0)\;=\;\left[\,1\;:\;0\,\right]\;:\;0\;:\;\frac{15}{4}\;. \qquad (3)$$

The light $\ell = 3$ $q\bar{q}$ states will probably be the first $\ell > 2$ states to be detected in $\gamma\gamma$, and the theoretical partial widths and helicity couplings we find are rather novel and may be useful as experimental signatures. For a nonrelativistic $\ell = 3$ orbital multiplet we find relative $\gamma\gamma$ widths (summed over helicities, with $\hat{\Gamma}_{tot} = \hat{\Gamma}_{\lambda=2} + \hat{\Gamma}_{\lambda=0}$) of

$$\hat{\Gamma}_{tot}(^3\mathrm{F}_4)\;:\;\hat{\Gamma}_{tot}(^3\mathrm{F}_3)\;:\;\hat{\Gamma}_{tot}(^3\mathrm{F}_2)\;=\;1\;:\;1\;:\;\frac{919}{100}\;. \qquad (4)$$

These nonrelativistic two-photon couplings evidently favor the 2^{++} $^3\mathrm{F}_2$ state by about an order of magnitude in the partial width (but somewhat less in the cross section, due to $(2j+1)$ factors), so the 2^{++} state should be the easiest member of the $\ell = 3$ multiplet to observe. (Assuming of course that relativistic corrections do not qualitatively alter the relative rates.) Note that we expect very similar $\gamma\gamma$ widths for 3^{++} and 4^{++} $^3\mathrm{F}_j$ states; this is in marked contrast to the analogous states in the $\ell = 1$ case, in which the $j = \ell$, 1^{++} state is forbidden to on-shell photons by the Landau-Yang theorem.

One might be concerned about the difficulty of distinguishing a $^3\mathrm{F}_2$ $q\bar{q}$ state from a radially-excited $^3\mathrm{P}_2$ state or a more exotic possibility such as a hybrid. Fortunately, we find that the helicity couplings of the $^3\mathrm{F}_2$ are quite characteristic, as $\lambda = 2$ and $\lambda = 0$ couplings are both present in the nonrelativistic decay with comparable amplitudes;

$$\frac{\hat{\Gamma}_{\lambda=0}(^3\mathrm{F}_2)}{\hat{\Gamma}_{\lambda=2}(^3\mathrm{F}_2)} = \frac{294}{625}\;. \qquad (5)$$

In contrast, in the $^3\mathrm{P}_2$ states the $\lambda = 2$ amplitude is known to be dominant [7,8]. This helicity-two dominance is expected to apply to all triplet $j = \ell + 1$ states (2b,c), whereas the $j = \ell - 1$ states with $\ell \geq 3$ should all have significant couplings to both $\lambda = 2$ and $\lambda = 0$ $\gamma\gamma$ final states (2e,f). These may prove to be useful signatures for higher-ℓ $q\bar{q}$ states in future experimental studies.

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