Further Search for the Two-Photon Production of the Glueball Candidate $f_J(2220)$

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The CLEO II detector at the e^+e^- storage ring CESR has been used to search for two-photon production of the $f_J(2220)$ decaying into $\pi^+\pi^-$. No evidence for a signal is found in 4.77 fb^{-1} of data and a 95% C.L. upper limit on $[\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}]_{f_J(2220)}$ of 2.5 eV is set. If this result is combined with the BES Collaboration's measurement of $f_J(2220) \to \pi^+\pi^-$ in radiative J/ψ decay and the recent CLEO result for $[\Gamma_{\gamma\gamma}B_{K_S^0K_S^0}]_{f_J(2220)}$, a 95% C.L. lower limit on the stickiness of 102 is obtained. This result for the stickiness provides further support for a substantial neutral parton content in the $f_J(2220)$.
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The two-photon width of a resonance is proportional to the fourth power of the constituent parton charges (to lowest order), so a very small two-photon width is an indication of substantial neutral parton content. Within the framework of QCD, a small two-photon width implies that the resonance has substantial glueball content. A quantitative measure of the glueball content of a resonance is the ratio of the probabilities for two-gluon coupling and two-photon coupling for which the resonance's two-gluon coupling is deduced from its production rate in radiative J/ψ decay.

The $f_J(2220)$ is a glueball candidate owing to its observation in radiative J/ψ decay (a glue-rich environment) [1,2], its small two-photon width relative to its two-gluon width [3,4], it small total width [1,2], its flavor independent coupling as evidenced by its similar branching fraction for nonstrange and strange final states [2], and its proximity to the mass obtained in lattice calculations [5,6] for a tensor glueball. CLEO has recently [4] obtained a 95% C.L. upper limit on the product of the two-photon width and the $K_S^0K_S^0$ branching fraction $[\Gamma_{\gamma\gamma}B_{K_S^0K_S^0}]_{f_J(2220)}$ of 1.3 eV using the reaction $e^+e^- \to e^+e^- f_J(2220) \to e^+e^-K_S^0K_S^0$. Earlier, the ARGUS Collaboration [3] obtained a less restrictive limit based upon the K^+K^- decay mode. In the present paper we report on a search for the two-photon production of the $f_J(2220)$ in the reaction $e^+e^- \to e^+e^- f_J(2220) \to e^+e^-\pi^+\pi^-$.

The CLEO II detector [7] is a general purpose detector operating at the Cornell Electron Storage Ring (CESR) [8]. It provides charged particle tracking, precision electromagnetic calorimetry, charged particle identification, and muon detection. Charged particle detection over 95% of the solid angle is provided by three concentric drift chambers in a magnetic field of 1.5 T giving a momentum resolution $\sigma_p/p = 0.5\%$ at $p = 1$ GeV. The drift chambers are surrounded by a time-of-flight system and a CsI electromagnetic calorimeter. A superconducting coil and muon detectors surround the calorimeter. Two-prong events are recorded with three triggers [9] that differ in their requirements on the number of tracks in the drift chambers (and their transverse momentum), the number of hits in the time-of-flight system, and the number of showers (and their energy) in the calorimeter. The different requirements provide some redundancy, compensating for inefficiencies in the elements that form the triggers. The results in this paper are based upon an integrated luminosity of 4.77 fb^{-1} with CESR operating at a center-of-mass energy of approximately 10.6 GeV.

The $f_J(2220)$ is searched for in the two-photon reaction $e^+e^- \to e^+e^- f_J(2220) \to e^+e^-\pi^+\pi^-$ in the untagged mode in which the outgoing e^+ and e^- are undetected. Events are selected that have exactly two tracks of opposite charge whose vector sum of momenta transverse to the beam has a magnitude less than 0.5 GeV. The total energy of the event is required to be less than 6.0 GeV and the energy in the calorimeter not associated with either track must be less than 0.5 GeV.

Two-photon produced final states of charged particle pairs are selected (and backgrounds from Bhabha scattering, muon pair production, and cosmic rays are suppressed) by requiring that the acolinearity of the two tracks is greater than 0.1. In addition, the acoplanarity is required to be less than 0.05. Acolinearity is the deviation from colinearity in three dimensions while acoplanarity is the deviation from colinearity in the plane transverse to the beams [acolinearity $\equiv \arccos(-\vec{p}_1 \cdot \vec{p}_2/|\vec{p}_1||\vec{p}_2|)$ and acoplanarity $\equiv \arccos(-\vec{p}_{T_1} \cdot \vec{p}_{T_2}/|\vec{p}_{T_1}||\vec{p}_{T_2}|)$]. These last two requirements are effective because the photon-photon center of mass generally moves rapidly and at a small angle with respect to the beams.

Events are vetoed if either track is identified as an electron or muon. If E/p, the ratio of a track's energy deposition in the calorimeter and its momentum measured in the drift chambers, is in the range 0.85–1.10, the track is identified as an electron. Muons are identified by the muon detectors. Events must have satisfied at least one of the two-prong triggers.

The event simulation uses the BGMS [10] formalism with the transverse-transverse term (appropriate for untagged two-photon reactions) for the event generation and GEANT [11] for the detector simulation down to the detector component level. The trigger simulation and the event reconstruction use this information to determine the detector response. Photon form factors based upon vector-meson dominance with a mass $m_V = 768.5$ MeV are used. The spin of the $f_J(2220)$ is taken to be 2 as spin 0 is ruled out [12,13] and spin 4 is unlikely. The detection efficiencies for helicity 0 and 2 are found to be 13.1% and 26.9%, respectively. We use a ratio [14] of helicity 0 and helicity 2 of 1:6, giving an efficiency of 24.9%. When the mass m_V in the photon form factors is varied from 768.5 MeV to infinity (corresponding to a form factor equal to 1) the cross section increased by 29.8% while the efficiency dropped by

18.9% and their product increased by 5.5%. A 2.8% systematic uncertainty is assigned to the product of the cross section and efficiency.

Most events are accepted with trigger requirements that demand evidence for two tracks. Although simulations show no azimuthal dependence for the trigger efficiency, variations with a standard deviation of 13% are observed in the tracking trigger efficiency as a function of the azimuthal angle of the two tracks. These variations are used to estimate a 13% systematic uncertainty due to the trigger. Data and simulation are compared to determine smaller systematic uncertainties of 2% per track from track reconstruction efficiency, 3% from the requirement on the energy deposition in the calorimeter, 3% from the transverse momentum requirement, 2% each from the acolinearity and acoplanarity requirements, 5% from the E/p requirement, and 4% from the muon veto. The total systematic uncertainty is the sum in quadrature of the above sources and is 15%.

A pion-pair invariant mass distribution is constructed using all events that pass the selection criteria and assuming that both particles are pions. A plot of $m_{\pi^+\pi^-}$ in the mass region relevant for the $f_J(2220)$ is shown as the data points with statistical error bars in Fig. 1. A possible contribution from K^+K^- is accounted for in the fit to the background described below. The contribution from $p\overline{p}$ is negligible due to the much larger photon-photon center-of-mass energy W required for their production. There is no evidence of an enhancement near the mass of the $f_J(2220)$. The mass distribution is fit with the sum of a signal and a background assuming that there is no interference between the two. The signal shape is represented by a nonrelativistic Breit-Wigner distribution $[f(W) = \frac{1}{\pi}\frac{\Gamma/2}{(W-m)^2+(\Gamma/2)^2}]$ with a mass $m = 2231$ MeV [12] and a width $\Gamma = 23$ MeV [12] convolved with the detector resolution of 12 MeV and is shown as the hatched histogram in Fig. 1. The background is represented by a third order polynomial that is fit to the mass region 2000–2500 MeV excluding the region 2200–2268 MeV. The fit gives a signal of -103 ± 77 events with a $\chi^2 = 35.6$ for 36 degrees of freedom.

An upper limit is obtained by allowing only for a positive number of signal events, N. Given that $m_{f_J(2220)} = 2231.1 \pm 2.5$ MeV [12] and $\Gamma_{f_J(2220)} = 23^{+8}_{-7}$ MeV [12], likelihood functions for N are obtained for a range of the resonance mass and width, spanning $\pm 2.5\sigma$ in each. These functions are then weighted with Gaussian probabilities for the mass and width to obtain a final likelihood function L_N. The product of the two photon partial width and charged di-pion branching fraction, $\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}$, is given by the product of N and P. Here P is the partial width used in the simulation divided by the product of luminosity, cross section, and efficiency; P is assumed to be Gaussian distributed. The likelihood function $L_{\Gamma B}$ is then obtained by numerical integration in the two-dimensional space of N and P. The likelihood function is shown in Fig. 2. From $L_{\Gamma B}$ a 95% C.L. upper limit of 2.5 eV for $\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}$ is obtained. The solid line in the main portion of Fig. 1 is the sum of the fit to the background and a signal that corresponds to this upper limit. The mass region 2150–2310 MeV is shown enlarged in the inset in Fig. 1 with the two curves representing the background fit with and without this level of signal added.

The upper limit can be specified without the assumption of a 1:6 ratio for helicity 0 and 2 as

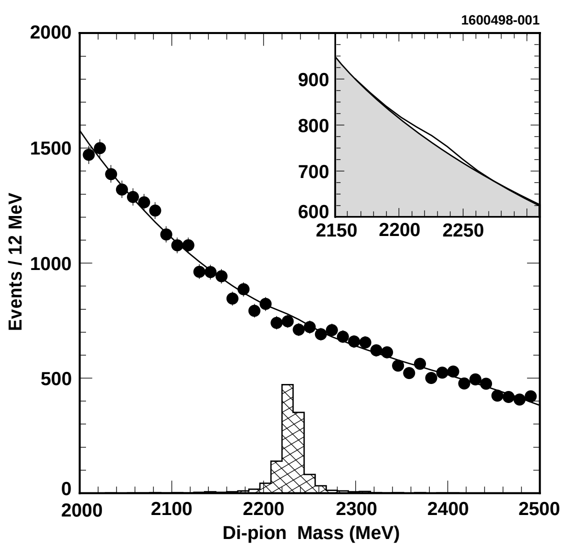

FIG. 1. The $\pi^+\pi^-$ invariant mass distribution for the data in the region of the $f_J(2220)$. The hatched histogram is the expected signal shape with arbitrary normalization. The solid curve is the sum of a fit to the background and a signal corresponding to the 95% C.L. upper limit on $\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}$ of 2.5 eV. In the inset the two curves are the background fit with and without this level of signal added.

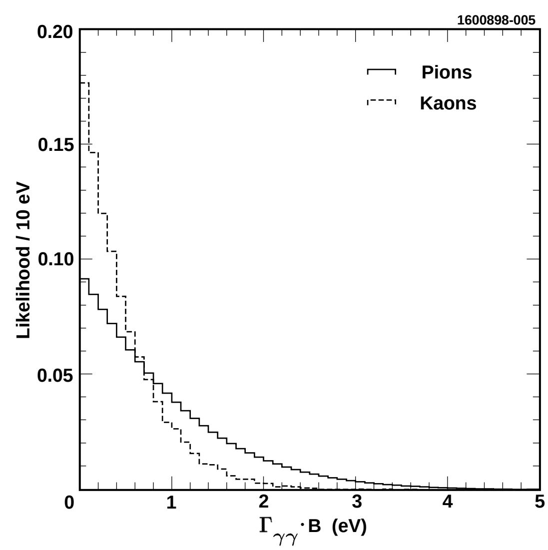

FIG. 2. The likelihood distributions, normalized to unit integral, for $\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}$ (solid line) and $\Gamma_{\gamma\gamma}B_{K^0_SK^0_S}$ (dashed line).

$(0.53\Gamma_{\gamma\gamma}^{2,0} + 1.08\Gamma_{\gamma\gamma}^{2,2})B_{\pi^+\pi^-} < 2.5$ eV at 95% C.L. The superscripts indicate spin and helicity. The ratio of the coefficients is equal to the ratio of the efficiencies for helicity 0 and ± 2 while the overall normalization is determined by the result given above.

The upper limit on $\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}$ can be interpreted in terms of the stickiness, S [15]. Stickiness is the ratio of the probabilities for two-gluon and two-photon coupling of a resonance, which in the present case can be written as [f_J denotes $f_J(2220)$]:

$$S_{f_J} = \frac{|\langle f_J \,|\, gg\rangle|^2}{|\langle f_J \,|\, \gamma\gamma\rangle|^2} = C_\ell \left(\frac{m_{f_J}}{k_\gamma}\right)^{2\ell+1} \times \frac{\Gamma_{J/\psi} B(J/\psi \to \gamma f_J) B(f_J \to \pi^+\pi^-)}{\Gamma(f_J \to \gamma\gamma) B(f_J \to \pi^+\pi^-)}. \quad (1)$$

The parameter k_γ is the energy of the photon (745 MeV) produced in the radiative J/ψ decay as calculated in the J/ψ rest frame, and $\Gamma_{J/\psi}$ is the total width of the J/ψ. The factor with $2\ell + 1$ in the exponent removes the trivial phase space dependence of the stickiness upon the f_J mass. The quantum number ℓ is the relative angular momentum between the two gluons or photons, with $\ell = 0$ for $J = 2$. $C_0 = 20.5$ is a normalization factor chosen such that the stickiness is unity for a resonance thought to be a $q\bar{q}$ resonance with the same J^{PC} as the f_J. The $f_2(1270)$ was chosen for this purpose. The BES result [2] and J/ψ properties from the Particle Data Group [12] are combined with the upper limit on $\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}$ to obtain a likelihood distribution for the stickiness of the f_J via a Monte Carlo technique. In this procedure the $L_{\Gamma B}$ obtained previously was used and all other uncertainties were taken to be Gaussian distributed. A lower limit on S_{f_J} of 73 is found at 95% C.L.

This lower limit and the one obtained in the $K_S^0K_S^0$ channel [4] can be merged, again using a Monte Carlo procedure, to obtain a combined lower limit [16] on the stickiness of 102, also at 95% C.L. This result can be compared with the stickiness of the $f_2'(1525)$, a resonance thought to be predominantly an $s\bar{s}$ bound state. Using the properties of the $f_2'(1525)$ from the Particle Data Group [12], a stickiness $S_{f_2'} = 14.7 \pm 3.9$ is calculated, considerably smaller than the lower limit of 102. A linear superposition of $q\bar{q}$ states can be constructed such that its two-photon width is negligible; the coefficients would have to take on very specific values, so this possibility is considered unlikely.

The relation between production of a $q\bar{q}$ resonance in photon-photon collisions and in radiative J/ψ decay has been studied [13] using a model motivated by perturbative QCD as applied to the nonrelativistic quark model. Results in Ref. [13] can be cast in the form of a ratio G (for gluiness) of quantities that are measured in radiative J/ψ decay and photon-photon interactions with calculable prefactors

$$G_{f_J} = C\, e_q^4 \left(\frac{m_{J/\psi}^2}{m_{f_J}}\right)\left(\frac{\alpha}{\alpha_s}\right)^2 \times \frac{B(J/\psi \to \gamma f_J) B(f_J \to \pi^+\pi^-)}{\Gamma(f_J \to \gamma\gamma) B(f_J \to \pi^+\pi^-)}, \quad (2)$$

with $C = 1.3 \times 10^{-3}$ for $J^{PC} = 2^{++}$, $\alpha_s = 0.37 \pm 0.03$ evaluated at a mass scale of $(m_{f_J}/2)$ [13], and using m_{f_J}, $m_{J/\psi}$, and Γ in eV. C is slightly different for tensor resonances other than the f_J, varying by less than 10% for the mass range 1.0–2.3 GeV. As opposed to stickiness, which is a relative measure, gluiness is normalized and is expected to be near 1 for a $q\bar{q}$ resonance within the precision afforded by the approximations made in Ref. [13]. For example, using the published properties [12] of the $f_2(1270)$ (assumed to have equal $u\bar{u}$ and $d\bar{d}$ contributions) and the $f_2'(1525)$ (assumed to be $s\bar{s}$) and Eq. (2), their values of G are calculated to be 1.8 ± 0.6 and 2.5 ± 0.9, respectively. The BES result [2] and the CLEO upper limits can be used, taking into account the uncertainties as in the case of the stickiness, to obtain 95% C.L. lower limits for the gluiness of the $f_J(2220)$ of 48 for the $\pi^+\pi^-$ final state and 66 for the combined $\pi^+\pi^-$ and $K_S^0K_S^0$ final states. The factor e_q^4 was calculated assuming equal amplitudes for $u\bar{u}$ and $d\bar{d}$. The large lower limits on the stickiness and the gluiness of the $f_J(2220)$ are an indication of substantial neutral parton or glueball content.

In this Letter a restrictive 95% C.L. upper limit on $[\Gamma_{\gamma\gamma}B_{\pi^+\pi^-}]_{f_J(2220)}$ of 2.5 eV is presented. Using the BES Collaboration's result for $f_J(2220) \to \pi^+\pi^-$ in radiative J/ψ decay, this upper limit leads to a lower limit on its stickiness of 73 at 95% C.L. When these results are combined with an earlier CLEO result [4], a lower limit on the stickiness of 102 at 95% C.L. is obtained. A comparison of the two-photon production of the $f_J(2220)$ and its production in radiative J/ψ decay leads to 95% C.L. lower limits on the gluiness of 48 from the $\pi^+\pi^-$ final state and 66 from the combined $\pi^+\pi^-$ and $K_S^0K_S^0$ final states.

These results are difficult to understand if the valence partons of the $f_J(2220)$ are quarks and antiquarks only; therefore, the $f_J(2220)$ is likely to have a substantial neutral parton or glueball content.

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[16] In this report and in Ref. [4] the uncertainty on C_0 is not included because the stickiness could have been normalized to any $J^{PC} = 2^{++}$ resonance that is thought to have light quarks as valence partons, leading to different values for the stickiness. If that uncertainty is included, the 95% C.L. lower limits on the stickiness of the $f_J(2220)$ are 69 and 67 for the $K_S^0 K_S^0$ and $\pi^+\pi^-$ channels respectively (instead of 76 and 73) while the combined 95% C.L. lower limit is 94 (instead of 102).