Experimental Limit on $\iota \to \gamma\gamma$ and the Interpretation of the Iota as a Glueball

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By observing the reaction $\gamma\gamma \to K_S^0 K^{\pm}\pi^{\mp}$, the TPC/Two-Gamma experiment at the SLAC e^+e^- storage ring PEP has obtained a 95%-confidence-level limit of $\Gamma_{\iota\to\gamma\gamma} B(\iota \to K\bar{K}\pi) < 1.6$ keV for the $\iota(1450)$ meson. If, as is likely, the ι decays predominantly into $K\bar{K}\pi$, the resulting $\Gamma_{\iota\to\gamma\gamma}$ limit appears to conflict with previous assignments of an observed $\rho\gamma$ decay to ι and also with many analyses of η-η'-ι mixing. The contrast of this small $\gamma\gamma$ width with the large rate for $J/\psi \to \gamma\iota$ is evidence that the ι is a glueball with little admixture of $q\bar{q}$ states.

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The iota meson, $\iota(1450)$, is a likely candidate[1-3] for a long-sought bound state of gluons (glueball), the existence of which is a consequence of the non-Abelian nature of quantum chromodynamics. That the ι is likely to have a large gluonic content is indicated by its copious production in J/ψ radiative decay, which is dominated in perturbation theory by $J/\psi \to \gamma + 2$ gluons. A strong additional constraint can be placed on the nature of the ι by a determination of its two-photon width, $\Gamma_{\gamma\gamma}$, and a stringent new limit on that quantity is presented here.

The J/ψ radiative decays into the iota have been observed in several experiments, first by Scharre *et al.*[4] (the Mark II Collaboration) in the $K_S^0 K^{\pm}\pi^{\mp}$ final state. Its spin and parity were determined to be 0^- by Edwards *et al.*[5] (the Crystal Ball Collaboration) (using the $K^{\pm}K^{\mp}\pi^0$ decay) and confirmed by Richman *et al.*[6] (the Mark III Collaboration) and Augustin *et al.*[7] (DM2 Collaboration). From the four experiments the mass of the iota is 1454 ± 5 MeV and its width 85 ± 11 MeV.

The TPC/Two-Gamma experiment at the SLAC e^+e^- storage ring PEP has observed from e^+e^- collisions the reaction $\gamma\gamma \to K_S^0 K^{\pm}\pi^{\mp}$. The final-state particles, $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$, were identified by momentum and energy loss (dE/dx) in the time projection chamber (TPC), and the e^{+} and e^{-} were not detected. The apparatus is described elsewhere.[8,9] The data sample used here corresponds to an integrated $e^{+}e^{-}$ luminosity of 70 pb^{-1} at 29-GeV center-of-mass energy. Events were recorded with a trigger which required at least two charged tracks in the TPC. Off line, events were selected with exactly four charged tracks in the TPC projecting back to the $e^{+}e^{-}$ vertex within distances sufficient to keep K_S^0 candidates.

Between 30 and 183 samples of the specific ionization rate were taken for each track, with dE/dx defined as the mean of the lowest 65% of the samples. This yielded a typical dE/dx resolution of 3.7%, while the momentum resolution for full-length tracks was $(\sigma/p)^2 \simeq (0.06)^2 + (0.035p)^2$ for p in GeV/c. The expected dE/dx values for different mass hypotheses (e, π, K, p) at the measured monentum were compared with the measured dE/dx by using an empirically determined formula, and a confidence level for each hypothesis was found.

Each event was required to have one track identified as a charged kaon and three tracks consistent with being pions, such that the total charge added to zero. To avoid background from $K^{+}K^{-}\pi^{+}\pi^{-}$ events, any pion candidate of charge opposite to that of the identified K had to satisfy the additional requirement that its probability for being another K was small. Each track had to be more than 0.35 rad from the beam direction and had to have a momentum uncertainty less than 30%. For the pions the momentum had to be greater than 120 MeV/c and for the kaon greater than 310 MeV/c. To avoid events with undetected particles, the requirement was imposed that the sum of the transverse momenta for all tracks be less than 200 MeV/c. This cut also eliminated events with a recoil $e^{\pm}$ tagged in the forward spectrometer.

The resulting 63 events were then scanned to remove events with calorimeter energy depositions not associated with charged tracks, or with extra charged tracks not detected by the analysis program, leaving a total of 36 events. All of the events which were rejected by scanning were treated separately as if they were good $K\bar{K}\pi$ data to see their effect on the final result. Had these events been included, they would have changed the limit reported below by only 12%.

$K_S^0 \rightarrow \pi^{+}\pi^{-}$ candidates were then sought in the 36-event sample. The K_S^0 mass was calculated by utilizing pion four-momenta at the position of closest approach of the π^{+} and π^{-} tracks. Each event gave two opposite-sign pion pairs, the invariant masses of which are plotted as a solid histogram in Fig. 1. Despite there being two entries per event, a K_S^0 signal is apparent. To indicate the shape of the background, equal-sign pion pairs are plotted as a dotted histogram. After the pion pair with mass closest to the K_S^0 mass was chosen, the peak displayed a mass resolution of 23 MeV, a value also obtained in higher-statistics measurements made in this apparatus using $e^{+}e^{-}$ annihilation events.[10] In order to avoid the loss of potential ι candidates, a loose cut of 498 ± 70 MeV was applied to the invariant $\pi^{+}\pi^{-}$ mass. To show that the resulting 24 events had properly identified pions and charged kaons, the dE/dx and momentum of each of these tracks is plotted in Fig. 2, along with curves expected for several particle types.

In evaluating a possible ι signal, the systematic error has to be determined. The largest uncertainties ($\sim 10\%$ each) are in the effective luminosity, the simulation of the trigger efficiency, and in the effect of kinematic cuts. Smaller errors are ascribed to scanning uncertainties, the identification of particles by dE/dx and the loss of particles by nuclear interactions. These systematic errors when added in quadrature total 20%.

The $K_S^0 K^{\pm}\pi^{\mp}$ invariant-mass spectrum, shown in Fig. 3, does not exhibit any enhancement in the $\iota(1450)$ region. To determine how many events could be ascribed to the ι, we have used a Monte Carlo simulation based on the fit the Mark III Collaboration made to their ι decay data.[6] Our simulation included effects of nuclear interactions, energy loss and multi-

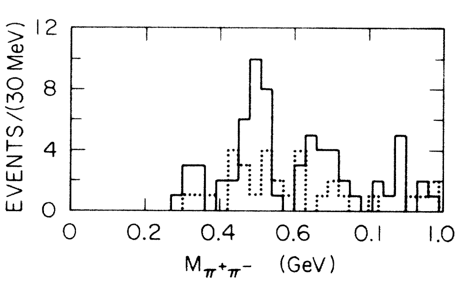

FIG. 1. Invariant $\pi^{+}\pi^{-}$ masses from the $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ events. Equal-sign pairs are plotted as a dotted histogram, while both opposite-sign pairs from each event are shown as a solid histogram.

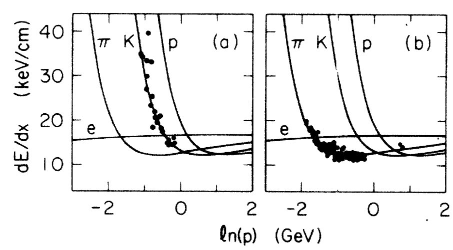

FIG. 2. The truncated mean energy loss as function of momentum for the final sample of $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ events with tracks identified as $K^{\pm}$ plotted in (a) and those identified as $\pi^{\pm}$ plotted in (b). The solid lines represent the expected curves for the various particle types.

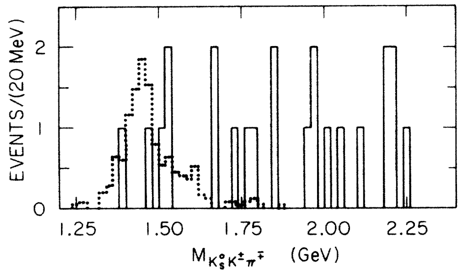

FIG. 3. Invariant $K_S^0 K^{\pm}\pi^{\mp}$ mass specturm; the dotted histogram has the shape of an ι signal which should have been seen if $\Gamma_{\iota\to\gamma\gamma}B(K\bar{K}\pi) = 1.6$ keV.

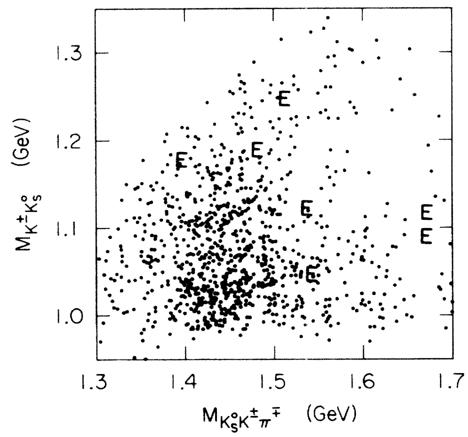

FIG. 4. Scatter plot of $K_S^0 K^{\pm}\pi^{\mp}$ mass vs $K_S^0 K^{\pm}$ mass for the simulated ι decays (dots) and for the data events (denoted by the symbol E).

ple scattering in the detector material, decay of the final-state particles, detector resolution, and trigger efficiency. The dotted histogram in Fig. 3 displays the expected shape of an iota signal. Even those few events close to this Monte Carlo peak do not have appropriate $K\bar{K}$ masses, as is seen clearly in Fig. 4, which shows the correlation in $K\bar{K}\pi$ and $K\bar{K}$ masses for data and Monte Carlo events. The distribution of $K\bar{K}$ masses for ι decay is distinctive, having a threshold enhancement which has sometimes led to interpreting the ι decay as proceeding through the $\delta(980)$ state. While our data events are consistent with background, a conservative upper limit can be obtained by assuming that there is no background in the ι region. To obtain an upper limit on the two-photon width of the ι times its branching ratio into $K\bar{K}\pi$, $\Gamma_{\iota\to\gamma\gamma}B(\iota \to K\bar{K}\pi)$, or ΓB for brevity, the unseen decay modes involving π^0 or K_L^0 had to be taken into account for the $I=0$ ι. ΓB was determined by generating many independent sets of N events according to a probability density, $f(M_{KK\pi}, M_{KK})$, derived from the Monte Carlo distribution of Fig. 4. N was Poisson distributed about $\bar{N}$, with $\bar{N}$ derived from ΓB, taking into account the 20% systematic error. ΓB was then adjusted so that 95% of these sets of events, $\sum_N f(M_{KK\pi}, M_{KK})$, exceeded the corresponding sum for the data events in Fig. 4. The resulting limit is

$$\Gamma_{\iota\to\gamma\gamma}B(\iota K\bar{K}\pi) < 1.6 \text{ keV} \quad (95\% \text{ C.L.}). \qquad (1)$$

This result is not sensitive to the details of the assumed mechanism for iota decay. Other Monte Carlo simulations employing $K_S^0 K^{\pm}\pi^{\mp}$ phase space, $\iota \to K^{\pm}K^{*\mp}$, and $\iota \to \delta^{\pm}\pi^{\mp}$ with $\delta^{\pm} \to K_S^0 K^{\pm}$ yield limits of <1.4, 1.5, and 1.7 keV, respectively.

If the iota contribution to the data were actually as large as given by (1), it would look much like the dotted histogram shown in Fig. 3, which has $\bar{N} = 6.9$ events. That this limit is conservative is further indicated by the fact that if the $K\bar{K}$ "delta cut" used by the Mark II Collaboration[4] and the Crystal Ball Collaboration[5] were employed, all but one of the "ι" events in Fig. 4 would be eliminated. Limit (1) may be compared with the published[11] value $\Gamma_{\iota\to\gamma\gamma}B(\iota \to K\bar{K}\pi) < 8$ keV. However, improved limits have been reported recently. The Mark II Collaboration has given[12] a 90%-C.L. limit of <2.0 keV. For comparison, at that confidence level our limit is <1.3 keV. The new 95%-C.L. limit of Althoff *et al.*[13] (TASSO Collaboration) of <2.2 keV was obtained by use of a phase-space decay, which in our case would give a limit of <1.4 keV.

To obtain a limit for $\Gamma_{\iota\to\gamma\gamma}$ it is necessary to estimate the $K\bar{K}\pi$ branching fraction. The Mark III Collaboration had made a coupled-channel analysis,[14] which ascribes $\rho\rho$ and $\omega\omega$ peaks at 1.55 and 1.8 GeV, respectively, to the ι, and which would make $B(\iota \to K\bar{K}\pi) \simeq 0.7$. If the upper limits the Mark III Collaboration[6] has set on ι decays to $\eta\pi\pi$, $K\bar{K}\pi\pi$, $\rho\pi\pi$, $\gamma\phi$, and $\gamma\omega$ are included, $B(\iota \to K\bar{K}\pi) \simeq 0.6$. The possible decay to $\rho\gamma$ ($\sim 2\%$) will be discussed below. The one remaining likely decay channel is $\eta'\pi\pi$, and hence it is improbable that $B(\iota \to K\bar{K}\pi)$ could be smaller than 0.5.[15] Using the reasonable value $B(\iota \to K\bar{K}\pi) = 0.7$ implies that

$$\Gamma_{\iota\to\gamma\gamma} < 2.2 \text{ keV}. \qquad (2)$$

The limit (2) appears to be incompatible with assigning observed[5–7] $J/\psi \to \gamma(\rho\gamma)$ decays to the ι, which would give a weighted average value of $\Gamma_{\iota\to\rho\gamma} = 1.5 \pm 0.4$ MeV, using $B(\iota \to K\bar{K}\pi) = 0.7$. This result, together with the ratio $\Gamma_{\iota\to\rho\gamma}/\Gamma_{\iota\to\gamma\gamma}$ predicted by either vector-meson dominance[15] or a bag-model calculation,[16] would predict that $\Gamma_{\iota\to\gamma\gamma} \simeq 11$ keV. It has already been noted[6,14] that the observed $J/\psi \to \gamma(\rho\gamma)$ might not be associated with ι because the mass is 50 ± 15 MeV too low and the width is a factor of 1.9 ± 0.4 too large. However, many calculations[16–21] predict $\Gamma_{\iota \to \rho\gamma}$ to be in the range of 0.4 to 3.5 MeV, assuming ι is a glueball mixed with η and η'. A much smaller value for $\Gamma_{\iota \to \rho\gamma}$ implied by our $\Gamma_{\iota \to \gamma\gamma}$ limit would favor interpreting the ι either as a radial excitation,[19] or as a glueball with very small $q\bar{q}$ mixing. The explanation[19] of the suppression of $\Gamma_{\iota \to \rho\gamma}$ for a radial excitation—the orthogonality of the excited and ground states—does not apply to $\Gamma_{\iota \to \gamma\gamma}$, so this mechanism cannot explain a small $\Gamma_{\iota \to \gamma\gamma}$.

The other alternative, that the iota is a glueball with small $q\bar{q}$ mixing, can be checked by comparing the limit in (2) with predictions based on η-η'-ι mixing, for which the parameters are set by other experimental observations. A large amount of theoretical work has gone into this mixing problem; recent predictions for $\Gamma_{\iota \to \gamma\gamma}$ are ~ 1,[20] 2.5,[21] 4.3,[22] 5,[23] 12,[24] and 16[25] keV. All of these models assume the ι is a glueball before mixing, and hence the limit given in (2) indicates that the ι has even less mixing with $q\bar{q}$ mesons than many of these models predict.

The combination of a large $J/\psi \to \gamma\iota$ rate with a small $\iota \to \gamma\gamma$ rate provides a strong constraint[2] on the nature of the iota. If the ι were a radial excitation, its J/ψ radiative decay rate would be suppressed,[19,21] whereas very special cancellations are required to suppress the coupling of photons to charged quarks.[26] These statements can be made more quantitative using the property "stickiness,"

$$S \propto (m_X / k^*_{\psi \to \gamma X})^3 \Gamma(\psi \to \gamma X) / \Gamma(X \to \gamma\gamma) \qquad (3)$$

suggested by Chanowitz.[27] Here $k^*_{\psi \to \gamma X}$ is the photon energy in the ψ center of mass, and the first factor removes phase-space effects. Note that S is independent of the branching ratio, $B(\iota \to K\bar{K}\pi)$. Relatively, if S is unity for the η, it is 5 for the η', and, based on (1), at least 65 for the ι. Such an unusually big value for S indicates a large gluon-to-quark ratio for the iota. Thus the result presented here provides further evidence that the iota is a glueball with very little $q\bar{q}$ admixture.

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