Upper Limit for $J/\psi \rightarrow \gamma +$ Axion

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A search has been made with the Crystal Ball Detector for axionlike particles in radiative J/ψ decays. An upper limit on the branching ratio $B(J/\psi \rightarrow \gamma + a) < 1.4 \times 10^{-5}$ (90% C.L.) is obtained. This result holds for long-lived, noninteracting pseudoscalar or vector particles of mass less than 1 GeV. Thus, this experiment also places stringent limits on the existence of other possible light bosons such as those arising in supersymmetric theories.

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Gauge theories of the strong interactions have been shown[1] to exhibit potentially large P- and CP-invariance violations, which are unobserved in nature. One way to circumvent these violations consists of adding an extra chiral U(1) symmetry[2] to the total Lagrangian. After symmetry breaking a Goldstone boson appears, dubbed the axion.[3,4]

Predictions[5] on axion production, interaction, and decay stimulated many searches in hadronic[6] and leptonic[7] beam-dump experiments, in the decay of excited nuclei,[8] in reactor experiments,[9] and in the decay of kaons.[10] Most results place quite stringent bounds on the axion's mass or on x, the only free parameter, which is the ratio of the vacuum expectation values of the two Higgs fields present in the theory. Recently, positive evidence for an axion or axionlike particle was reported by Faissner *et al.*[6] but their values for the mass $m_a = 250 \pm 25$ keV and $x = 3.0 \pm 0.3$ seem to be inconsistent with other experiments.[7,8,10]

The main difficulty of many experimental searches for the axion is that additional assumptions (e.g., concerning the relative isoscalar/isovector coupling, the mixing with light quark pseudoscalar mesons, or the number of quark generations) are required to obtain testable predictions. These introduce undesirable model dependences. In particular reactor experiments are subject to multiple uncertainties.[5,9] Purely leptonic experiments, on the other hand, often have an unambiguous interpretation[5,7] but suffer from lower statistics.

In this experiment we test the axion hypothesis by probing the direct coupling of the axion with heavy quarks. The branching ratio for the axion in radiative J/ψ decays is free from model-dependent assumptions and can be calculated quite reliably[4]:

$$\frac{B(J/\psi \rightarrow \gamma + a)}{B(J/\psi \rightarrow \mu^+ + \mu^-)} = \frac{G_F m_c^2 x^2}{\sqrt{2}\pi\alpha}, \qquad (1)$$

where G_F is the Fermi coupling constant, m_c the mass of the charmed quark, x is the free parameter of the theory mentioned above, and α is the fine-structure constant. Using the experimentally determined branching ratio $B(J/\psi \rightarrow \mu^+ + \mu^-) = 0.07 \pm 0.01$ and $m_c = 1.5 \pm 0.3$ GeV we obtain the following prediction:

$$B(J/\psi \to \gamma + a) = (5.7 \pm 1.4) \times 10^{-5} x^2. \qquad (2)$$

The data were collected with the Crystal Ball Detector at the Stanford Linear Accelerator Center e^+e^- storage ring facility SPEAR at the peak of the J/ψ resonance. The detector has been described elsewhere.[11] We summarize here the relevant parameters for this analysis. The main array consists of 672 NaI(Tl) crystals each being 16 radiation lengths long. The solid angle covered is 93% of 4π sr and is extended to 98% with crystals in the end-cap region. The detector offers a photon energy resolution of $\sigma_E/E = 2.6\%/[E(\mathrm{GeV})]^{1/4}$ and an angular resolution of 25 mrad for photons of energy greater than 1 GeV. Rejection of charged particles is achieved with cylindrical magnetostrictive spark chambers and a multiwire-proportional chamber placed around the beam pipe.

In searching for the axion we assume the validity of the standard model,[2,3] i.e., that the axion is light, its interaction cross section is semiweak ($\propto G_F$), and it has a long decay time ($\tau \gg 10^{-9}$ sec). Therefore the signature for the decay $J/\psi \to \gamma + a$ is a single photon of energy $E_\gamma = (M_\psi^2 - m_a^2)/2M_\psi$. We select events with one and only one neutral track in the main detector and demand the energy deposition in the end caps to be less than 20 MeV. We require the photon to have $|\cos\theta_\gamma| < 0.8$, where θ_γ is the polar angle of the photon with respect to the beam axis. In addition the lateral energy deposition pattern must be consistent with that expected for electromagnetically showering particles. Finally the events are required to be in time with the beam crossing. Events outside the expected timing window will be used to estimate the contamination due to cosmic-ray events.

The resulting energy spectrum of 454 events is shown in Fig. 1. The hardware trigger threshold was set at 1 GeV which causes the sharp fall in the spectrum below this energy. No significant bump is seen above 1 GeV. Figure 2(a) shows the scatter plot of the photon energy versus $\cos\alpha$ of each track, where α is the angle between the track and the vertical axis. The event cluster near $\cos\alpha = 1$ indicates the cosmic-ray origin of most events. This behavior is further exhibited in the $\cos\alpha$ distribution of all events [Fig. 2(b)]. The solid curve shows the angular distribution expected for cosmic-ray events[12]: $dN/d\cos\alpha \propto \mathrm{const} + \cos^2\alpha$, for $\cos\alpha > 0$. Selecting events in the lower hemisphere of the Crystal Ball ($\cos\alpha < 0$) yields Fig. 2(c). The dashed rectangle indicates the $\pm 2\sigma$ window for the resolution of a photon with beam energy, $E_\gamma = 1.55$ GeV. Within these limits we find 5 events. Using the same cuts we find 11 events outside the expected timing peak in a window three times larger. From this we calculate an upper limit of 6.2 events (90% C.L.). The same limit is obtained for photon energies down to 1.3 GeV, which translates into

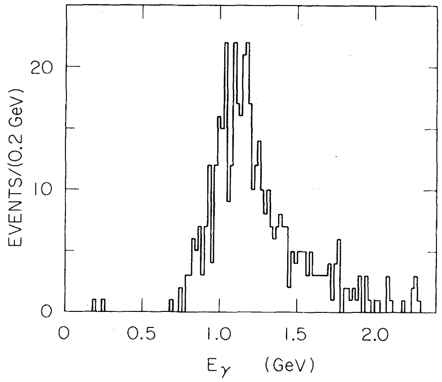

FIG. 1. Photon energy distribution for all one-photon events.

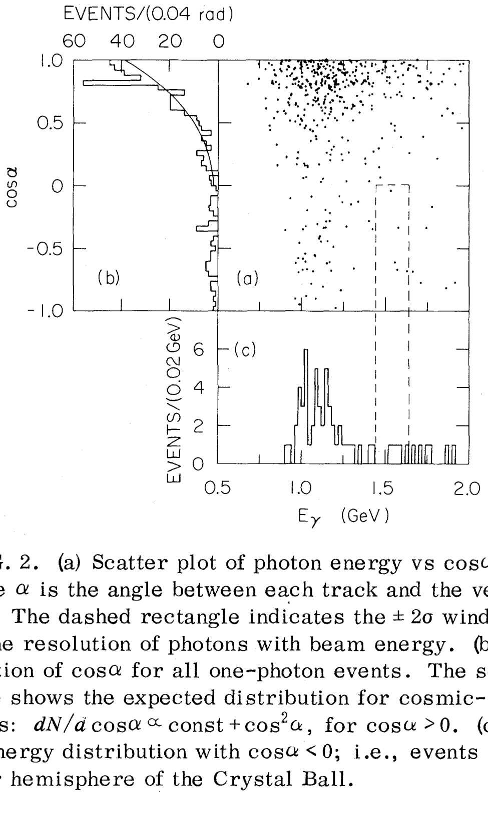

FIG. 2. (a) Scatter plot of photon energy vs $\cos\alpha$, where α is the angle between each track and the vertical axis. The dashed rectangle indicates the $\pm 2\sigma$ window for the resolution of photons with beam energy. (b) Distribution of $\cos\alpha$ for all one-photon events. The solid curve shows the expected distribution for cosmic-ray events: $dN/d\cos\alpha \propto \mathrm{const} + \cos^2\alpha$, for $\cos\alpha > 0$. (c) Photon energy distribution with $\cos\alpha < 0$; i.e., events in the lower hemisphere of the Crystal Ball.

axion masses of up to 1 GeV.

To determine the efficiency for one-photon events we use a Monte Carlo program based on the shower simulation program EGS.[13] If one assumes a $1+\cos^2\theta$ distribution for the radiated photon an efficiency of 0.30 is obtained. Given our total sample of 1.8×10^6 J/ψ events, and including all statistical and systematic errors, we obtain the following upper limit on the branching ratio:

$$B(J/\psi\rightarrow\gamma+a)<1.4\times10^{-5}\quad(90\%\ \text{C.L.}).$$

This limit is valid for any noninteracting, long-lived, pseudoscalar or vector particle in the mass range from 0 to 1 GeV.

Comparing our result with the theoretical prediction [Eq. (2)] yields an upper limit on the free parameter x:

$$x<0.6\quad(90\%\ \text{C.L.}).$$

Such a small value of x is inconsistent with the experiment of Faissner *et al.*[6] which measures $x=3.0\pm0.3$, if interpreted as indicating an axion. Our result, together with a recent nuclear deexcitation experiment[8] and an electron beam-dump experiment,[7] reduces the allowed range of x to $0.42<x<0.6$. In the standard theory this restricts the mass of the axion to 170 keV $<m_a$ <210 keV (for three generations of weak isospin doublets).

A definitive test of the standard axion model which eliminates any dependence on x has been proposed[14] in the simultaneous search for $J/\psi\rightarrow\gamma+a$ and $\Upsilon\rightarrow\gamma+a$ decays. Our present result implies that a sensitivity for $\Upsilon\rightarrow\gamma+a$ of only 10^{-3} will be sufficient to complete this test. If this test fails, we may have to retreat to an even more elusive axion.[15] Such an axion arises naturally in grand unified theories, where the chiral symmetry is broken at the grand unification scale. As a result the axion couples even more weakly to matter and is extremely light.

It has been shown[16] that some supersymmetric theories lead to the existence of another light particle, a neutral spin-1 gauge boson U. This boson is expected to also show up in radiative J/ψ decays[16] with

$$B(J/\psi\rightarrow\gamma+U)\geqslant3\times10^{-5},$$

where either the U decays so slowly that its decay products are not detected or only $\nu\bar{\nu}$ final states are considered. Given our measured upper limit we can rule out the existence of such a supersymmetric boson in the mass range 0 to 1 GeV. It should be noted, however, that on introduction of additional Higgs fields into these supersymmetric theories, the prediction will depend on an unknown parameter $r<1$. In this case we obtain an upper limit $r<0.6$ (90% C.L.).

In conclusion we have searched for the decay J/ψ into a photon plus a long-lived, noninteracting axion. The derived upper limit on the branching ratio restricts the allowed range of the free parameter of the theory to less than 0.6.

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Search for Structure in $\sigma(e^+e^- \to \text{hadrons})$ between $\sqrt{s} = 10.34$ and 11.6 GeV

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The CUSB detector at the Cornell Electron Storage Ring has been used to measure $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ in the c.m. energy regions between the Υ'' and the Υ''', and above the Υ''' up to $\sqrt{s} = 11.6$ GeV, with integrated luminosities of 5000 and 2100 nb^{-1}, respectively. No narrow resonances are observed, and limits on the leptonic widths are presented. The average value of R increases by 0.31 ± 0.06 across the flavor threshold.

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The measured properties[1] of the $\Upsilon(9.4)$, $\Upsilon'(10.0)$, and $\Upsilon''(10.3)$ are consistent with models which associate these resonances with the 1^3S, 2^3S, and 3^3S states of a bound $b\bar{b}$ quark pair which decay mostly by annihilation of the heavy quark pair.[2] The $\Upsilon'''(10.5)$ has been identified with the 4^3S level, and lies above the threshold for the decay to B mesons containing isolated b quarks,[3,4] which