Limits on axion and light Higgs boson production in Υ(1S) decays

Crystal Ball Collaboration

D. Antreasyan [a], H.W. Bartels [b], D. Besset [c], Ch. Bieler [d], J.K. Bienlein [b], A. Bizzeti [e], E.D. Bloom [f], I. Brock [g], K. Brockmüller [b], R. Cabenda [c], A. Cartacci [e], M. Cavalli-Sforza [h], R. Clare [f], A. Compagnucci [e], G. Conforto [e], S. Cooper [f,1], R. Cowan [c], D. Coyne [h], A. Engler [g], K.H. Fairfield [f], G. Folger [i], A. Fridman [f], D. Gaiser [f], D. Gelphman [f], G. Glaser [i], G. Godfrey [f], K. Graaf [d], F.H. Heimlich [e,d], F.H. Heinsius [d], R. Hofstadter [f], J. Irion [a], Z. Jakubowski [j], H. Janssen [k], K. Karch [b,ℓ], S. Keh [ℓ], T. Kiel [d], H. Kilian [ℓ], I. Kirkbride [f], T. Kloiber [b], M. Kobel [i], W. Koch [b], A.C. König [k], K. Königsmann [ℓ,2], R.W. Krämer [g], S. Krüger [d], G. Landi [e], R. Lee [f], S. Leffler [f], R. Lekebusch [d], A.M. Litke [f], W. Lockman [f], S. Lowe [f], B. Lurz [i], D. Marlow [g], H. Marsiske [b,f], W. Maschmann [d], P. McBride [a], F. Messing [g], W.J. Metzger [k], H. Meyer [b], B. Monteleoni [e], B. Muryn [j,3], R. Nernst [d], B. Niczyporuk [f], G. Nowak [j], C. Peck [m], P.G. Pelfer [e], B. Pollock [f], F.C. Porter [m], D. Prindle [g], P. Ratoff [m], M. Reidenbach [k,b], B. Renger [g], C. Rippich [g], M. Scheer [ℓ], P. Schmitt [ℓ], J. Schotanus [k], J. Schütte [i], A. Schwarz [f], D. Sievers [a], T. Skwarnicki [b], V. Stock [d], K. Strauch [a], U. Strohbusch [d], J. Tompkins [f], H.J. Trost [b], B. van Uitert [f], R.T. Van de Walle [k], H. Vogel [g], A. Voigt [b], U. Volland [i], K. Wachs [b], K. Wacker [f], W. Walk [k], H. Wegener [i], D.A. Williams [a,h] and P. Zschorsch [b]

[a] *Harvard University [4], Cambridge, MA 02138, USA*
[b] *Deutsches Elektronen Synchrotron DESY, W-2000 Hamburg, FRG*
[c] *Princeton University [5], Princeton, NJ 08544, USA*
[d] *Universität Hamburg, I. Institut für Experimentalphysik [6], W-2000 Hamburg, FRG*
[e] *INFN and University of Florence, I-50100 Florence, Italy*
[f] *HEPL, Department of Physics [7] and Stanford Linear Accelerator Center [8], Stanford University, Stanford, CA 94305, USA*
[g] *Carnegie-Mellon University [9], Pittsburgh, PA 15213, USA*
[h] *University of California at Santa Cruz [10], Santa Cruz, CA 95064, USA*
[i] *Universität Erlangen-Nürnberg [11], W-8520 Erlangen, FRG*
[j] *Cracow Institute of Nuclear Physics, PL-30055 Cracow, Poland*
[k] *University of Nijmegen and NIKHEF [12], NL-6525 ED Nijmegen, The Netherlands*
[ℓ] *Universität Würzburg [13], W-8700 Würzburg, FRG*
[m] *California Institute of Technology [14], Pasadena, CA 91125, USA*

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We have searched for axion and light Higgs boson production in the channel $\Upsilon(1S)\to(a^0 \text{ or } h^0)+\gamma$, where the non-interacting axion a^0 and the Higgs boson h^0 do not decay in the detector. We find no evidence for an axion and give an upper limit, $Br(\Upsilon(1S)\to a^0\gamma)<4.0\times10^{-5}$ (90% CL), for long-lived axions. Combining our limit with the previous search in J/ψ decays, we are able to rule out the axion in the standard model with first order QCD corrections. Our Υ(1S) data also rule out a Higgs boson with mass $m_h<86$ MeV.

It has been more than a decade since Peccei and Quinn [1] first proposed their elegant solution to the problem of *P* and *CP* violation in the QCD lagrangian with the introduction of a weakly coupled $U(1)_{PQ}$ chiral symmetry. Shortly afterwards, Wilczek [2] and Weinberg [3] pointed out that the breaking of $U(1)_{PQ}$ leads to a light, neutral, pseudoscalar boson – the axion, a^0. They proposed a number of possible decay channels in which to search for this new particle. One such channel is the decay of a heavy vector meson to an axion plus photon, $V \to a^0\gamma$. We present here a new search by the Crystal Ball for such axion production in $\Upsilon(1S)$ decays, and for similar production of the Higgs boson.

The search for axions and Higgs bosons in Υ and J/ψ decays is attractive for several reasons. First, their couplings to quarks are proportional to the masses of the quarks and are therefore enhanced for these heavy vector mesons. Second, the theoretical predictions are more reliable [4] for their production in heavy meson decays than in most K or π decays. Third, *light* axions and Higgs bosons are very long-lived, giving a rather striking signature: $V \to a^0\gamma$ or $V \to h^0\gamma$, in which the a^0 or h^0 escapes detection, leaving a single, high-energy photon in the final state.

[1] Present address: Max-Planck-Institut für Physik und Astrophysik, W-8000 Munich 40, FRG.

[2] Present address: CERN, CH-1211 Geneva 23, Switzerland.

[3] Permanent address: Institute of Physics and Nuclear Techniques, AGH, PL-30055 Cracow, Poland.

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The mass of the axion is given by [3,5] $m_a \simeq 25N(x+1/x)$keV, which has a minimum of 150 keV at $x=1$ for $N=3$ generations; x is the ratio of the vacuum expectation values of the two Higgs fields. For $0.074 < x < 13.5$, m_a is less than $2m_e$ and the only available decay is $a^0 \to \gamma\gamma$, which proceeds rather slowly [4,5]: $\tau_{a\to\gamma\gamma} \simeq 6.7\times10^{-6}\,(\text{MeV}/m_a)^5$s. Such a light axion escapes undetected from a relatively small detector like the Crystal Ball. For $m_a > 2m_e$, the axion can also decay to e^+e^-, with a partial lifetime [2] $\tau_{a\to ee} \simeq 3.8\times10^{-9}x^2\,(\text{MeV}/m_a)/\sqrt{1-(2m_e/m_a)^2}$s, assuming that the axion couples to lepton doublets as it does to quark doublets. It is also possible [3] that the coupling is reversed, in which case x^2 is replaced by $1/x^2$ in the expression for $\tau_{a\to ee}$. In either case, there is a range of $m_a > 2m_a$ for which the lifetime remains long enough so that the axion escapes undetected.

A similar situation holds for a light scalar Higgs boson in the minimal model with one Higgs doublet [6]. For a mass $m_h < 2m_e$ the lifetime [7] is again very long, $\tau_{h\to\gamma\gamma} = O(10^{-4}\text{s})(\text{MeV}/m_h)^3$. If $m_h > 2m_e$ the decay into e^+e^- dominates with $\tau_{h\to e^+e^-} = 3.8\times 10^{-9}(\text{MeV}/m_h)\times[1-(2m_e/m_h)^2]^{-1.5}$s. For example, a Higgs boson with mass $m_h = 91.5$ MeV produced in $\Upsilon(1S)$ decays would have a mean decay length of $\beta\gamma c\tau = 0.66$ m, equal to the distance from the interaction point to the outer radius of the Crystal Ball detector.

The predicted widths for axion production in $V \to a^0\gamma$ are given by [2]

$$\Gamma(\Upsilon \to a^0\gamma) = \Gamma(\Upsilon \to \mu^+\mu^-)\,\frac{G_F m_b^2}{\sqrt{2}\pi\alpha}\,C_\Upsilon \frac{1}{x^2}, \qquad (1)$$

$$\Gamma(J/\psi \to a^0\gamma) = \Gamma(J/\psi \to \mu^+\mu^-)\,\frac{G_F m_c^2}{\sqrt{2}\pi\alpha}\,C_{J/\psi}\, x^2, \qquad (2)$$

where $\Gamma(V \to \mu^+\mu^{-1})$ are the leptonic decay widths in lowest order QED. The factors C_Υ and $C_{J/\psi}$ contain QCD radiative and relativistic corrections. The radiative corrections [8] to first order in α_s large, ~ 0.5, and they may have large uncertainties due to higher order terms. Relativistic corrections [9] may be of a similar size, but cannot be reliably separated from the radiative corrections [10]. In the following we use $C_\Upsilon = C_{J/\Psi} = 0.5$ as an estimate, but also give our results as a function of C.

We calculate the predicted branching ratios to $a^0\gamma$

from eqs. (1) and (2) and the measured branching ratios to lepton pairs [11] [#1]:

$$\mathrm{Br}(\Upsilon(1S)\to a^0\gamma)$$
$$=(19.0\pm1.8)\times10^{-5}\cdot C_\Upsilon/x^2$$
$$>16.7\times10^{-5}\cdot C_\Upsilon/x^2 \quad (90\%\ \mathrm{CL}), \qquad (3)$$

$$\mathrm{Br}(J/\psi\to a^0\gamma)$$
$$=(5.3\pm1.5)\times10^{-5}\cdot C_{J/\psi}\cdot x^2$$
$$>3.4\times10^{-5}\cdot C_{J/\psi}\cdot x^2 \quad (90\%\ \mathrm{CL}), \qquad (4)$$

where the errors arise from the uncertainties in the quark masses [13], $m_c=1.5\pm0.2$ GeV and $m_b=4.7\pm0.2$ GeV, and the measured leptonic branching fractions.

The predictions for the corresponding decays of $\Psi(1S)$ and J/ψ into a light Higgs boson plus a photon are given by setting $x=1$ in the above equations [14]. The QCD radiative corrections are of about the same size [15] as for the axion. We consider first the decay to the axion and return to the Higgs boson at the end of the paper.

Several groups [16–20] have previously searched for $V\to a^0\gamma$. The only upper limit from J/ψ decays is from the Crystal Ball at SPEAR [16], $\mathrm{Br}(J/\psi\to a^0\gamma)<1.4\times10^{-5}$ (all limits quoted are at the 90% CL). The CUSB group has published the best limit in the upsilon family using $\Upsilon(3S)$ decays [18], $\mathrm{Br}(\Upsilon(3S)\to a^0\gamma)<12\times10^{-5}$, where the corresponding prediction is $(11.8\times3.1)\times10^{-5}\cdot C_\Upsilon/x^2$, or $>7.8\times10^{-5}\cdot C_\Upsilon/x^2$. For $C=0.5$, the J/ψ search requires $x<0.9$, while the $\Upsilon(3S)$ search requires $x>0.6$, leaving room for a standard Peccei–Quinn axion near $x=0.7$.

We have analyzed data taken on the $\Upsilon(1S)$ resonance with the Crystal Ball detector at DORIS II. The data sample consists of 44 pb^{-1} corresponding to $(460\pm20)\times10^3$ produced $\Upsilon(1S)$ mesons. The Crystal Ball [21] is an ideal detector to search for the single-photon final state produced in $\Upsilon\to a^0\gamma$. It consists of a spherical array of 672 NaI(Tl) crystals which cover 93% of the solid angle, and are housed in two sealed hemispherical containers. In addition, endcap arrays of NaI(Tl) crystals extend the solid angle coverage to 98%. The measured energy resolution for electromagnetically showering particles is $\sigma_E/E=(2.7\pm0.2)\%/(E/\mathrm{GeV})^{1/4}$, while the angular resolution for photons of energy greater than 2 GeV is about 2°. A tracking chamber of four cylindrical double layers of proportional tubes separates charged and neutral particles.

We look for candidate events having a single high-energy photon in the detector, and nothing else. Selected events must have been triggered by the "total energy" trigger. It is fully efficient above 2 GeV of deposited energy in the "main Ball", that is, the spherical array of crystals, excluding those crystals which border the openings for the beam pipe. There must be exactly one neutral energy deposition in the event with 2 GeV$\leqslant E_\gamma\leqslant E_{\mathrm{Beam}}(1+3\sigma_E)$ and no charged tracks. The upper energy limit rejects interacting cosmic rays that may deposit considerably more than the beam energy in the main Ball. There may be no other energy depositions in the event having more than 100 MeV. The high-energy photon must satisfy fiducial requirements which reduce background from $e^+e^-\to\gamma\gamma$, which which one of the photons is lost through the gap between the upper and lower hemispheres of the Ball. Finally, the pattern of lateral energy deposition of the photon candidate must be consistent with that expected for an electromagnetic showering particle. The efficiency to call the photon candidate neutral was determined from an analysis of $e^+e^-\to e^+e^-$ and $e^+e^-\to\gamma\gamma$ data, while the efficiency of the other cuts was determined from a detailed Monte Carlo simulation of the detector and its reponse to single photons. The overall detection efficiency for single photons with $E_\gamma\geqslant2.0$ GeV was determined to be 0.34 for the $(1+\cos^2\theta)$ angular distribution of the axion, and 0.39 for the isotropic distribution of the Higgs boson. The largest factor in the efficiency is the effect of the fiducial cuts, 0.55 for the former, and 0.63 for the latter angular distribution. The relative error on the efficiency of 2% arises mostly from variations in the chamber performance and from uncertainties in the neutrals efficiency and the geometric cuts.

[#1] We use lepton universality to average the vector meson decays to muon and electron pairs. In order to correspond to the calculations of eqs. (1) and (2), which are to lowest order in QED, the measured branching ratios to e^+e^- and $\mu\mu$ need to be multiplied by 0.958 (0.932) for charmonium (bottonium) to remove the vacuum polarization contribution which is included in the experimental determination of these branching ratios. See ref. [12].

The above criteria select a total of 37 single-photon events with $E_\gamma \geqslant 2.0$ GeV, whose energy distribution is shown in fig. 1a. There is an evident peaking of events with E_γ near the beam energy, which is the signature expected for a light axion. In order to estimate the background, we have also applied the above analysis to 93 pb^{-1} of data taken on the $\Upsilon(4S)$ resonance, which decays $\approx 100\%$ to $B\bar{B}$ pairs [#2]. The results are shown in fig. 1b, where the number of $\Upsilon(4S)$ events has been scaled by the ratio of luminosities for the two data sets and where the photon energy of the $\Upsilon(4S)$ data has been scaled by the ratio of beam energies to the $\Upsilon(1S)$ energy. The $\Upsilon(4S)$ data exhibit the same peaking of events near the beam energy as is seen in the $\Upsilon(1S)$ data, from which we conclude that these events are due to assorted background processes including beam–gas interactions and the QED interaction $e^+e^- \to \gamma\gamma$, where one of the photons escapes detection by passing through the small gap between crystals. It is impossible to calculate a priori the absolute loss of photons, as this would require an exact knowledge of the shape and size of these small gaps. Therefore we use the $\Upsilon(4S)$ data as an estimate of the non-axion background.

[#2] Assuming equal partial widths for $\Gamma(\Upsilon \to a^0\gamma)$ for the $\Upsilon(1S)$ and $\Upsilon(4S)$ resonances, our limit for axion production on the $\Upsilon(1S)$ corresponds to a branching ratio of $Br(\Upsilon(4S) \to a^0\gamma) = 8 \times 10^{-8}$, which is unobservable with our statistics.

We determine the upper limit on the number of $\Upsilon(1S) \to a^0\gamma$ events with photons of beam energy from the difference between the $\Upsilon(1S)$ and $\Upsilon(4S)$ data. We first fit each spectrum with a linear function and a gaussian peak. This results in 13.3 ± 4.3 and 19.6 ± 3.3 events for the $\Upsilon(1S)$ and $\Upsilon(4S)$ spectra, respectively, where the latter number is scaled to the $\Upsilon(1S)$ luminosity. Widths and means of the gaussians are consistent with resolution and beam energy. Thus we fix the gaussian mean and width and the linear function to the values obtained in the fits, and calculate the likelihood as a function of the peak amplitude. The likelihood as a function of the difference in the number of events in the peaks of the $\Upsilon(1S)$ and $\Upsilon(4S)$ spectra is then calculated from the convolution of the corresponding likelihood functions. Integrating this function from 0 to 90% of its area yields 6.2 events. Note that we would obtain 5.6 events at 90% CL when allowing the linear function to vary in the determination of the likelihood. We then convolute this likelihood function with that for the efficiency and the number of produced $\Upsilon(1S)$ mesons and obtain an upper limit of $Br(\Upsilon(1S) \to a^0\gamma) < 4.0 \times 10^{-5}$ at the 90% confidence level.

To set limits on heavier particles we repeat the above fits for photon energies down to 2 GeV in steps of 2% of the photon energy, a step size comparable to our resolution. We find that the upper limit on the

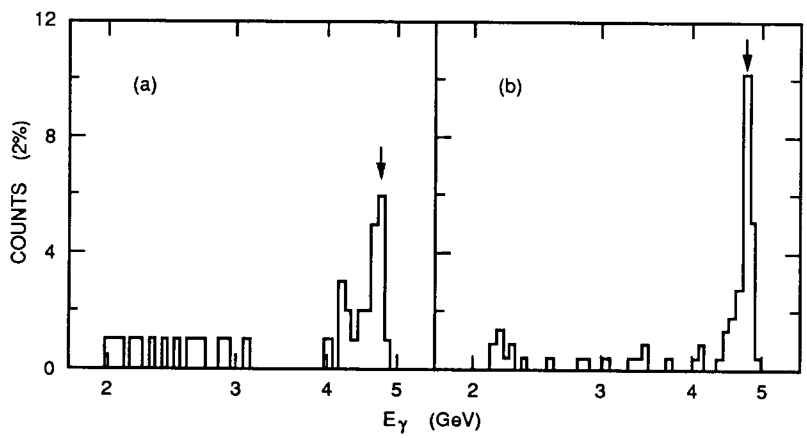

Fig. 1. Distribution of photon energy, E_γ, for (a) $\Upsilon(1S)$ data, and (b) $\Upsilon(4S)$ data. The number of entries in (b) has been scaled by the ratio of luminosities of the two data sets, while the photon energy in (b) has been scaled by the ratio of beam energies. Arrows indicate the beam energy.

radiative branching ratio is always $\leqslant 5.6\times10^{-5}$ at 90% CL. The largest value is obtained for a photon energy of 4.34 GeV, corresponding to a recoil mass of 2.7 GeV.

Together with eq. (3), our upper limit on axion production requires $x>1.44$ for $C_\Upsilon=0.5$, thus closing the window near $x=0.7$. The product of eqs. (3) and (4) is independent [22] of x. Comparing it to the product of our limit on $\mathrm{Br}(\Upsilon(1\mathrm{S})\to a^0\gamma)$ and the previous limit on $\mathrm{Br}(J/\psi\to a^0\gamma)$ we rule out a standard axion with $m_a<2m_e$ as long as $c_\Upsilon C_{J/\psi}>0.09$.

For $m_a>2m_e$ we need to consider the possibility of the axion decay to e^+e^-. We compare our upper limit to the predicted effective branching ratio, which includes the probability for the axion not to decay within the detector volume: $\mathrm{Br}(\Upsilon(1\mathrm{S})\to a^0\gamma)\times\exp(-r_{\mathrm{CB}}/\beta\gamma c\tau)$, where $r_{\mathrm{CB}}=0.66$ m is the outer radius of the Crystal Ball calorimeter.

Fig. 2a shows the excluded regions of x versus the correction factor C, making the usual assumption that τ_{ee} is proportional to x^2. For $C_\Upsilon=C_{J/\psi}=0.5$ our results from the $\Upsilon(1\mathrm{S})$ and J/ψ data together rule out the region $0.02<x<260$. These limits are nearly independent of the Cs because of the strong influence of the x-dependent τ and γ factors appearing in the exponent in the effective branching ratio. For small x, searches for axions decaying inside the detector [20] become relevant. The best limit is from ARGUS: $\mathrm{Br}(\Upsilon(1\mathrm{S})\to a^0\gamma)\mathrm{Br}(a^0\to e^+e^-)<3.1\times10^{-4}$ for short-lived axions with $m_a<1.5$ GeV. For $C=0.5$ and the ARGUS radius of 1.2 m, this rules out $5\times10^{-5}<x<0.07$. Thus for this axion–e^+e^- coupling and for $C_\Upsilon=C_{J/\psi}=0.5$, the region $5\times10^{-5}<x<260$ is explicitly excluded. Outside this region the predicted $\mathrm{Br}(\Upsilon(1\mathrm{S})\to a^0\gamma)$ becomes [#3] larger than 0.99997 and 0.53 for the lower and upper x limits respectively. While we know of no explicit limit on these, such a dominant decay rate, especially that of the $\Upsilon(1\mathrm{S})$, is unlikely to have gone unnoticed.

If, instead, τ_{ee} is proportional to $1/x^2$, our $\Upsilon(1\mathrm{S})$ and J/ψ data together rule out $0.003<x<44$ for $C=0.5$ (fig. 2b). The ARGUS limit [20] quoted above is also valid for $a^0\to\gamma\gamma$ if $m_a<100$ MeV, extending the excluded region to $0.00075<x<44$. The lower bound on x would lead to $\mathrm{Br}(\Upsilon(1\mathrm{S})\to a^0\gamma\to\gamma\gamma\gamma)>0.993$, which again seems unlikely to have gone unnoticed. In the region $x>44$ the axion decays

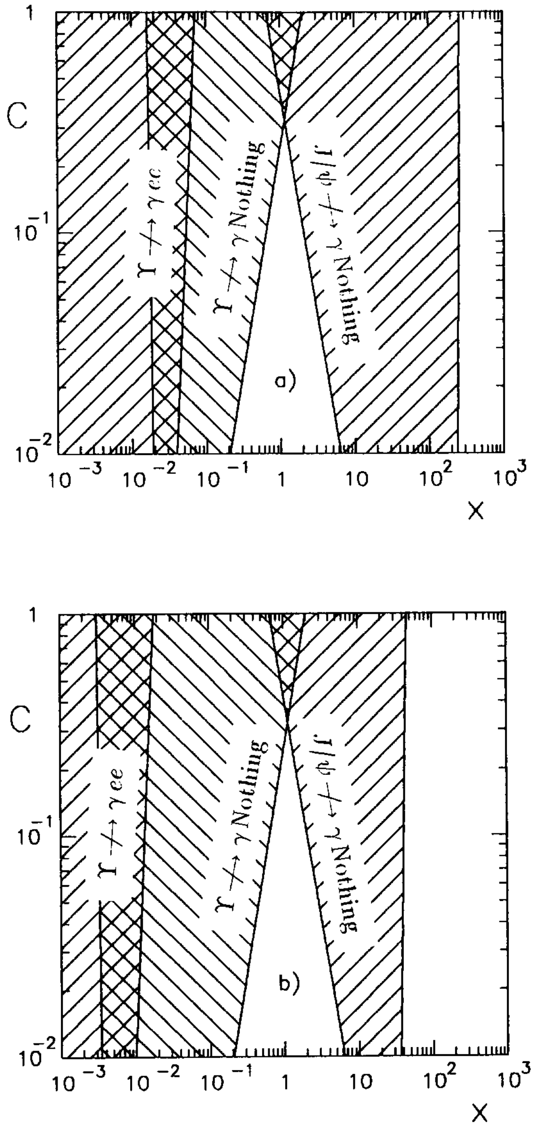

Fig. 2. The hatched area indicates the excluded regions of the parameter x as a function of the QCD correction factor, C, at the 90% CL for (a) $\tau_{ee}\propto x^2$ and (b) $\tau_{ee}\propto 1/x^2$. Note that the lowest order calculation corresponds to $C=1$. We include limits for $\Upsilon(1\mathrm{S})\to\gamma+\text{nothing}$, from this paper, for $J/\psi\to\gamma+\text{nothing}$, from Crystal Ball at SPEAR [15], and for $\Upsilon(1\mathrm{S})\to\gamma e^+e^-$ or $\gamma\gamma\gamma$ from ARGUS [19].

[#3] When the branching ratio to $a^0\gamma$ becomes large, eqs. (3) and (4) must be corrected for the fact that $B_{\mu\mu}$ was measured with the assumption that the $\Upsilon(1\mathrm{S})$ and J/ψ decay to hadrons and leptons only. The corrected branching ratio is $\mathrm{Br}'=\mathrm{Br}/(1+\mathrm{Br})$, where Br is the result of eqs. (3) or (4).

dominantly to e^+e^- and $Br(J/\psi \to a^0\gamma) > 0.03$, so a new search of J/ψ data should easily be sensitive to this less-standard axion.

Previous searches have also ruled out the standard axion [11]. For example, K decays rule out a long-lived axion, while π decays and nuclear transitions have been used to search for short-lived axions. The present results on heavy meson decays have the advantage that the theoretical predictions are more reliable [4].

Light Higgs bosons produced in radiative $\Upsilon(1S)$ or J/ψ decays will give the same signature of a single high-energy photon in the final state, if they do not decay in the detector volume. The present analysis yields a 90% CL upper limit on the $\Upsilon(1S) \to h^0\gamma$ branching ratio of 3.5×10^{-5}, which is smaller than the upper limit on axion production due to the higher efficiency to detect isotropically produced photons. This limit clearly rules out a non-decaying light Higgs boson for which the predicted branching ratio with $C_\Upsilon = 0.5$ is greater than 8.4×10^{-5}. For $m_h > 2m_e$ we include the probability for the e^-e^+ decay to occur outside the detector, and obtain a 90% CL lower limit on the Higgs boson mass of $m_h > 86$ MeV for $C_\Upsilon = 0.5$. If C_Υ would turn out to be as low as 0.25, then our lower limit on the mass of the Higgs mass would be reduced to 39 MeV.

A Higgs boson with mass below 6 MeV has been ruled out by experiments investigating muonic atoms, nuclear decays and neutron scattering off nuclei; for a recent review see Cahn, ref. [7]. Larger Higgs masses can be tested in K decays, but the interpretation of the experimental results is subject to larger theoretical uncertainties. Nevertheless, K decay data appear to rule out [7] a Higgs boson with mass below 360 MeV. Recently, studies of Z^0 decays to Higgs bosons and lepton pairs have excluded [25] Higgs bosons with masses between 0 GeV and 24 GeV.

In conclusion, we have searched for decays $\Upsilon(1S) \to a^0\gamma$ and have found no significant signal above background. We give a new upper limit, $Br(\Upsilon(1S) \to a^0\gamma) < 4.0 \times 10^{-5}$ (90% CL) for axions not decaying in the detector. Taken together with other results obtained from $\Upsilon(1S)$ and J/ψ data, this rules out the standard axion model with first-order QCD corrections throughout the range $5 \times 10^{-5} < x < 260$. For a less-standard coupling $\tau(a \to e^+e^-) \propto 1/x^2$, the excluded range is $0.0075 < x < 44$. Our limit also rules out a light Higgs boson with mass $m_h < 86$ MeV (90% CL). Furthermore no signal is observed for photons recoiling against heavier particles and we find an upper limit for such decays of $Br(\Upsilon(1S) \to X\gamma) < 5.6 \times 10^{-5}$ (90% CL), which is valid for any two-body $\Upsilon(1S)$ decay into γ plus a non-interacting long-lived particle with $M_X < 7.2$ GeV.

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