Limits on Higgs bosons, scalar-quarkonia, and η_b's from radiative upsilon decays

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We have searched for monochromatic photon signals in the reaction $\Upsilon(9460)\rightarrow X+\gamma$ in a sample of 420 000 Υ decays observed in the CUSB detector. From the absence of signal we obtain upper limits for Higgs-boson production in Υ decay which approach the minimal-standard-model expectations, including QCD radiative corrections, for low Higgs-boson masses. For two Higgs-boson models we obtain bounds on the ratio of the vacuum expectation values of the two neutral Higgs fields as a function of the Higgs-boson mass. We do not confirm the $\zeta(8.3)$ and find no evidence for a nearby bound scalar-quark—anti-scalar-quark state. We obtain a lower bound for the η_b mass using potential-model predictions.

SEARCH FOR HIGGS BOSONS

The search for Higgs scalars in radiative decays of heavy vector mesons was first suggested by Wilczek[1] and Weinberg[2] in conjunction with the possible existence of the "axion." The decay rate for $V\rightarrow\gamma+H$, where V is a 1^{--} bound state of a heavy $Q\bar{Q}$ pair, is given in terms of the two-muon rate by

$$\Gamma(V\rightarrow\gamma+H)/\Gamma(V\rightarrow\mu\mu)=\frac{G_F M_Q{}^2}{\alpha\pi\sqrt{2}}(1-M_H{}^2/M_V{}^2)x^2 ,$$

exhibiting the coupling of the Higgs boson to the quark mass M_Q. x is unity in the standard model where only one physical, neutral Higgs state survives. For models with more Higgs bosons, $x=\langle\phi_1\rangle/\langle\phi_2\rangle$, where $\langle\phi_{1,2}\rangle$ are vacuum expectation values of the Higgs fields. Interest in the search for Higgs bosons in Υ (and ψ) decays was stimulated by supersymmetric models in which it appears natural to have Higgs bosons with a few-GeV mass.[3] The above formula for Γ gives, for the case of Υ decays, $B(\Upsilon\rightarrow H+\gamma)\approx 2.5\times 10^{-4}(1-M_H{}^2/89.5)x^2$, M_H in GeV. Tantalizing experimental results were presented some time ago by the Mark III Collaboration,[4] suggesting the existence[5] of a Higgs boson of 2.2-GeV mass, called $\xi(2.2)$. In 1984 the Crystal Ball Collaboration reported evidence[6] for $\Upsilon\rightarrow\gamma+X$, with $M(X)=8.3$ GeV and a branching ratio around 0.5%. This state, named ζ, was also considered as a possible candidate for the Higgs vacuum. The CUSB Collaboration had also searched for $\Upsilon\rightarrow\gamma+X$ with null result,[7] reporting an upper limit for the branching ratio of $\approx 0.1\%$ for Higgs-boson masses between 2.5 and 5 GeV and from a new analysis[8] a limit of $\approx 0.2\%$ for $M=8.3$ GeV. Other searches have also yielded null results.[9] One should note that if ξ and ζ were indeed Higgs bosons, they would require x^2 factors of >10 and >100, respectively.

It clearly appears worthwhile to reexamine the whole situation, both with respect to whether these objects exist at all and are indeed Higgs bosons, and improve the sensitivity of Higgs-boson searches until the standard-model branching ratio is approached. This in general requires vastly increased statistics and improved detector performance. The Cornell Electron Storage Ring (CESR) provided us (CUSB) with 420 000 Υ's, the largest single sample collected contiguously to date. We had also significantly improved the performance of CUSB over part of its coverage. CUSB has underway an upgrade program,[10] which consists of inserting a cylindrical array of bismuth germanate (BGO), 12 radiation lengths (λ_0) thick, subdivided into $2\times 36\times 5$ elements in θ, ϕ and r. Since only a fraction of the BGO crystals were available to us initially, we installed a partial array covering 110 degrees in ϕ, and only the first four elements in depth (i.e., $\sim 9\lambda_0$). Also thin scintillators were installed in front of all BGO *and* NaI sectors of the detector to provide additional charged particle veto. It is this partially upgraded detector that was used to collect the data presented here. The BGO array improved the CUSB energy resolution by a factor of 2. We wish to point out that at 4.7 GeV we have measured (with electrons from Bhabha scattering) a resolution σ_E/E of 1.2%. This is the best resolution achieved yet by any electromagnetic calorimeter in actual running of a high-energy physics experiment. This partial upgrade provided us essentially with two independent spectrometers: the familiar NaI—Pb-glass CUSB spectrometer[11] of many years' usage and the similarly longitudinally segmented BGO array with improved resolution.

The present data were collected with a trigger threshold of ≈ 500 MeV, using a very loose event-selection criterion, which was essentially satisfied by the presence in the detector of two energy clusters or one energy cluster plus one track, assuring $\sim 100\%$ triggering efficiency for events within the detector acceptance. In the analysis of the data collected we arranged the photon search codes so that for $\frac{1}{3}$ of the solid-angle photon energies are measured in BGO. The collected sample is equivalent therefore to 140 000 Υ decays having their decay photons detected in BGO and 280 000 in NaI. Because of the superior resolution in BGO, the present sample is equivalent to 530 000 Υ decays collected with the old CUSB detector. The search codes used with the present data are mostly an adaptation of the ones used previously. In addition to clustering and isolation criteria used to reject merged π^0's we require that the shower centroids measured in the four BGO layers and the five NaI layers agree within the expected spread. This requirement is very efficient at removing showers contaminated by other close-by photons and nuclear interactions, particularly in BGO, because of true projective boundaries and the absence of azimuthal cracks, and is responsible for the different shapes of the photon spectra at high energy.

Figures 1 and 2 show the inclusive photon spectra from 740 to 4740 MeV from $\Upsilon \rightarrow \gamma + X$ decays (including $\approx 15\%$ continuum events) as observed in BGO and NaI, respectively. Both spectra are smooth, featureless, and in good agreement with what one expects: mostly photons from π^0 decays with small contaminations from hadronic interactions. The efficiency$\times$acceptance product for the BGO array ranges smoothly from 8% to 13% for photon energies from 740 to 4740 MeV and is twice as large as that for the NaI array. The efficiency$\times$acceptance is computed from Monte Carlo calculations assuming that X decays into $q\bar{q}$ and $l\bar{l}$ within the detector, with their usual couplings to the Higgs boson.[12] In the absence of any monochromatic signal one cannot prove the existence of any Higgs bosons, and thus we present upper limits for $B(\Upsilon \rightarrow \gamma + X)$ at 90% confidence level (C.L.). Although Figs. 1 and 2 do not show fine details, the data have been scrutinized in fine detail and fitted in various energy regions with polynomials plus Gaussians with the proper, energy-dependent, resolution given by $\sigma_E/E = 0.039/[E\ (\text{GeV})]^{1/4}$ for NaI and by $\sigma_E/E = 0.018/[E\ (\text{GeV})]^{1/4}$ for BGO. The energy resolution and its energy dependence of the NaI spectrometer has been checked in numerous previous experiments.[13] That of the BGO spectrometer was computed in the same manner and checked at high energy using Bhabha scatterings at 4.73 GeV. No signal (positive or negative) of significance greater than one standard deviation is observed in this way. Nor is a one-standard-deviation signal ever observed at the same energy in the two samples. In particular, a negative signal of 47 ± 51 counts is observed at 1090 MeV, corresponding to $M_X = 8300$ MeV. Since the spectra are so smooth we feel it is appropriate to apply the procedure described to the locally averaged count. This is equivalent to computing the error of the (vanishingly small) area of the Gaussian as

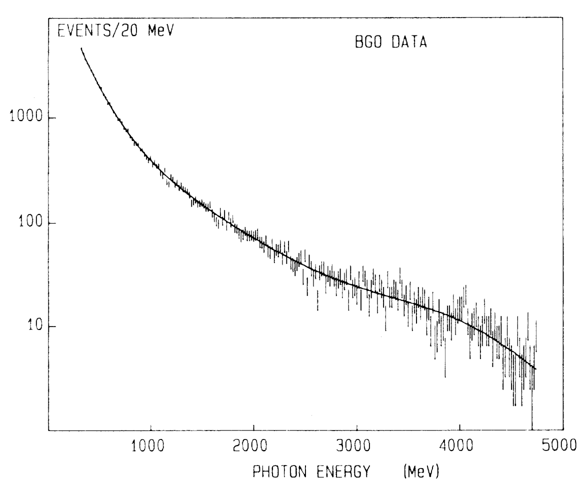

FIG. 1. Inclusive photon spectrum for photons in the BGO array for $740 < E_\gamma < 740$ MeV.

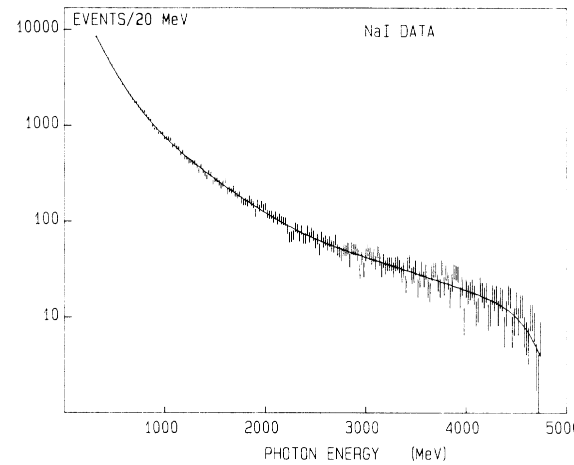

FIG. 2. Inclusive photon spectrum for photons in the NaI array for $740 < E_\gamma < 4740$ MeV.

$$\delta N\ (\text{counts}) = \{(\text{counts/MeV}) \times [\sigma_E\ (\text{MeV})] \times 3.7\}^{1/2} .$$

Finally, the 90%-C.L. upper limit to the branching ratio is given by $B < \delta N \times 1.65 / N_\Upsilon \epsilon$ where ϵ is the (energy-dependent) photon-finding efficiency. Note that it is common practice to use 2.36 and 1.28 instead of 3.7 and 1.65, respectively, resulting in upper limits which are optimistically lower by a factor 0.62.

Since we have two independent samples of data from the NaI and BGO spectrometers, we combine their limits and the results of this negative labor are shown in Fig. 3. The dashed line indicates the original Wilczek-Weinberg expectation for the minimum standard model. Note that for the first time upper limits lower than the original predictions have been obtained for masses between 2 and 5.5 GeV. The sensitivity of our search is limited at high Higgs-boson masses by the large number of photons from π^0 decays and at the very low Higgs-boson masses by the low multiplicity in Higgs-boson decay. Because of the calorimetric nature of our detector, the sensitivity of our search does not have abrupt changes at specific values of the Higgs-boson mass.

Strictly speaking, the computed limit applies to $B(\Upsilon \rightarrow \gamma + X) B(X \rightarrow \text{anything detectable})$. For Higgs bosons of conventional properties and the data analyzed, the second branching ratio is unity. Concerning the $\zeta(8.3)$, our limit for its branching ratio in Υ decays is 0.09%.

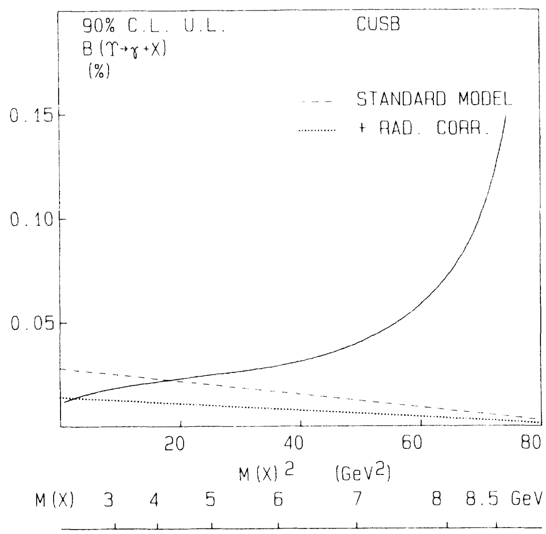

FIG. 3. The 90%-C.L. upper limit branching ratio for radiative ϒ decays (solid curve); NaI and BGO results are combined. The dashed line indicates the standard-model prediction, and the dotted line is the standard-model prediction including radiative corrections, which lowers the branching ratio by $\sim 50\%$.

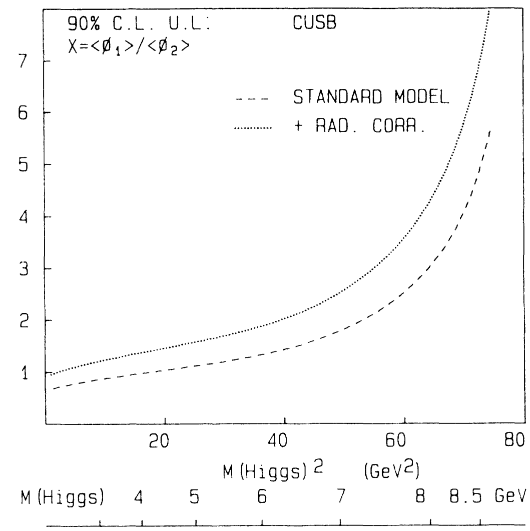

FIG. 4. The 90%-C.L. upper limit for x, the ratio of the vacuum expectation values of the two neutral Higgs fields vs M_{Higgs}, for the standard model (dashed line) and for the standard model including radiative corrections (dotted curve).

Conversely had the branching ratio been $\approx 0.5\%$ as claimed by the Crystal Ball Collaboration we should have observed a signal of 660 ± 72 counts while we observe -40. Our upper limit for ξ production in ϒ decay is $\approx 0.016\%$. Scaling only according to the c- and b-quark mass ratio our limit is more than an order of magnitude less than the branching ratio obtained by the Mark III group. Scaling from ϒ to ψ is of course a bit murky.

According to Vysotsky,[14] QCD radiative corrections, which contain relativistic corrections,[15] reduce the branching ratio for $V \rightarrow \Upsilon + \gamma$ by approximately a factor of 2. This result has been confirmed by other authors.[16] While this implies that we have not excluded Higgs bosons of low masses[17] in the minimal model, we still exclude with our results a large region in the x-M_{Higgs} plane, as shown in Fig. 4.

SEARCH FOR SCALAR-QUARKONIUM STATES IN RADIATIVE DECAYS AT THE ϒ ENERGY

Tye and Rosenfeld[18] have proposed that there may exist scalar-quark bound states (scalar quarkonium) for which the $3P$ states of that system coincidentally overlaps with the usual triplet S ground state of the $b\bar{b}$ system, the ϒ. Under these conditions they conclude that there would be an "apparent" branching ratio for radiative decays of events with the ϒ mass (since some fraction would be scalar-quarkonium $3P$ states that decay via $E1$ transitions to lower-lying triplet scalar-quarkonium S states). We have searched for these states by looking for monochromatic photons, which are predicted to have energies of 1.08, 0.52, and 0.18 GeV with apparent $B(\Upsilon + 3P \rightarrow \gamma + nS)$ of 0.3%, 0.3%, and 0.5%, respectively (unless the $3P$-state mass was sufficiently separated from the ϒ). The inclusive photon spectra in the energy range between 150 and 1325 MeV from the NaI and BGO spectrometers gave no evidence for the existence of such states. Following the same procedure outlined above we obtain the upper limit shown in Fig. 5. Also shown in the figure are the Tye-Rosenfeld predictions for the branching ratios for emission of the three lines, which are clearly excluded by the data.

SEARCH FOR THE η_b

Potential models have been very successful in describing heavy-quark bound-state spectra. The richest system to date has been the ϒ system, composed of bound $b\bar{b}$ quarks. The most precise results on level spacing have

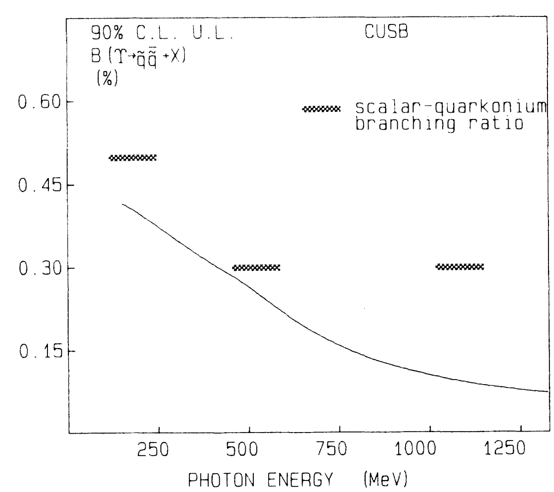

FIG. 5. The 90%-C.L. upper limit for $B(\Upsilon + 3P \rightarrow \gamma + nS)$ after combining the results for the NaI and BGO. The cross hatches represent the predictions for scalar quarkonium from Ref. 18.

come from e^+e^- accelerators, where the $n\,^3S_1$ states are directly produced. Six triplet P states, have also been observed[19] and their fine structure measured. Observation of the singlet states, in particular the $1\,^1S_0$ state, or η_b, would allow measurement of the hyperfine structure in the Υ system.

The most direct way to search for the η_b is to search for the $M1$ transitions from triplet S states to the singlet S states via photon emission. All standard potential models (those with no η—Higgs-boson mixing) predict the hyperfine splitting to be of the order of 50—120 MeV, and give the branching ratio[20] as $\approx 4\times 10^{-8}\times[k_\gamma\ (\mathrm{MeV})^3/\Gamma_\Upsilon\ (\mathrm{keV})]$. The inclusive photon spectra from BGO and NaI were examined in the energy range from 30 to 500 MeV and no signal corresponding to the decay $\Upsilon\rightarrow\eta_b+\gamma$ is observed in either data set. The 90%-C.L. upper limits for the $B(\Upsilon\rightarrow\gamma+\eta_b)$ from the combined data are shown in Fig. 6. The dashed curve is the theoretical prediction for $B(\Upsilon\rightarrow\gamma+\eta_b)$ as a function of energy. We find that $E_\gamma<168$ MeV at the 90% C.L. assuming the above theoretical branching ratio and therefore $M_{\eta_b}>9292$ MeV.

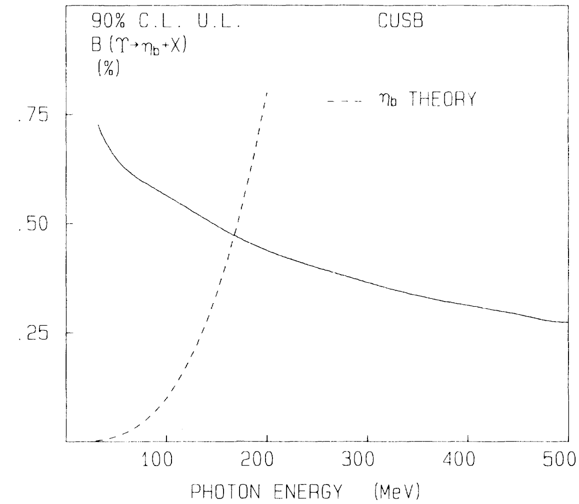

FIG. 6. The 90%-C.L. upper limit on the branching ratio (B) for Υ radiative transitions to the ground-state singlet S state for the combined BGO and NaI results. The dashed curve is the theoretical prediction from Ref. 20.

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