Measurement of the Direct Photon Spectrum from the $\Upsilon(1S)$

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We have observed decays of the $\Upsilon(1S)$ into hadronic final states containing high-energy photons. These are interpreted as coming from the decay $\Upsilon(1S) \rightarrow \gamma+\text{gluon}+\text{gluon}$. We compare the shape of the observed photon energy spectrum with several theoretical predictions and deduce the value of the strong-coupling constant α_s and the QCD scale parameter $\Lambda_{\overline{MS}}$ ($\overline{MS}$ denotes the modified minimal-subtraction scheme) associated with each prediction.

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The theory of quantum chromodynamics (QCD) predicts the decay of quarkonium into a photon and two gluons. Predictions have been made for the branching ratio, photon energy spectrum, and photon angular distribution. To lowest order this decay is identical to the dominant decay mode, that into three gluons, except for the replacement of a gluon by a photon. For the $\Upsilon(1S)$, the ratio of these two decay rates is given by[1]

$$B_\gamma = \frac{\Gamma(\Upsilon \to \gamma gg)}{\Gamma(\Upsilon \to ggg)} = \frac{36}{5} q^2 \frac{\alpha_{em}}{\alpha_s} [1 + (2.2 \pm 0.6)\alpha_s/\pi], \quad (1)$$

where α_s is the strong-interaction coupling constant, α_{em} is the electromagnetic coupling constant, and $q = -\frac{1}{3}$ is the b-quark electric charge. The strong-coupling constant is related to $\Lambda_{\overline{MS}}$, the fundamental energy scale of QCD ($\overline{MS}$ denotes the modified minimal-subtraction scheme), by[2]

$$\alpha_s = \frac{4\pi}{\beta_0 \ln(x)} - \frac{4\pi\beta_1 \ln[\ln(x)]}{\beta_0^2 \ln^2(x)}, \quad (2)$$

where $\beta_0 = 11 - 2n_f/3$, $\beta_1 = 102 - 38n_f/3$, $x = Q^2/\Lambda_{\overline{MS}}^2$, n_f is the number of active quark flavors (four in our case), and the energy scale is[3] $Q = 0.157 M_\Upsilon$. The lowest-order perturbative calculation[4] predicts a photon energy spectrum which is nearly linear in the variable $x_\gamma = E_\gamma / E_{beam}$, peaking at $x_\gamma = 1$. A recent calculation by Photiadis[5] gives corrections to this spectrum near the region $x_\gamma = 1$ by summing the leading-logarithmic contributions to all orders in perturbation theory. The result is a softening of the spectrum, still retaining a substantial value at $x_\gamma = 1$. Field[6] has used a cluster-model Monte Carlo simulation to calculate corrections to the lowest-order spectrum due to hadronization effects. He predicts a spectrum that peaks near $x_\gamma = 0.7$ and falls to zero at $x_\gamma = 1$. In this report, we present a measurement of the photon yield and energy spectrum from $\Upsilon(1S)$ decays and compare our results with the above theoretical predictions.

We made our measurement using the CLEO detector at the Cornell Electron Storage Ring (CESR). The CLEO detector has been described in detail elsewhere.[7] Briefly, photons were detected with a lead–proportional-wire-chamber sandwich electromagnetic shower counter, 12 radiation lengths deep, and covering 47% of 4π sr. Using a kinematic fit to determine the photon energy in radiative Bhabha events, we have measured an energy resolution $\sigma_E/E = (21 \text{ GeV}^{1/2})/E^{1/2}$ % over the range of interest. These events were also used to calibrate the detector at all photon energies. Two-photon annihilation events ($e^+e^- \to \gamma\gamma$) were used as a check of the calibration at $E_\gamma = 4.7$ GeV. At high energy the uncertainty in the photon energy calibration is about 1%. The single-photon angular resolution was 10 mrad. We detected charged particles with a 17-layer drift chamber in a 1.0-T magnetic field. The momentum resolution of the system was $\sigma_p/p = [0.7 \ (\text{GeV}/c)^{-1}]p$%.

Our measurement used 12 pb^{-1} of data taken on the peak of the $\Upsilon(1S)$ resonance and 4.1 pb^{-1} taken at an energy just below the resonance. This sample includes 223 000 observed $\Upsilon(1S)$ hadronic decays. We required hadronic events to have at least three charged tracks with a vertex coinciding with the e^+e^- interaction region. Additional criteria that were imposed during event selection are described in detail elsewhere.[8]

A photon was defined as any shower contained within the fiducial region of the shower counter which was not matched to a drift-chamber track. To reduce the background from π^0 decays, we eliminated from our sample every photon that was within 0.32 rad of another photon in the event.

There are three main sources of background present in our photon sample. First, there is a contribution from nonresonant hadron production. We subtracted this directly by using our sample of data taken on the continuum below the $\Upsilon(1S)$ resonance, accounting for differences in luminosity and center-of-mass energy.

Second, there is a contribution from the electromagnetic decay $\Upsilon(1S) \to q\bar{q}$. We have estimated that, out of our full sample of 223 000 observed $\Upsilon(1S)$ hadronic events, 24 000 result from the process $\Upsilon(1S) \to q\bar{q}$.[8] This background differs from the continuum data only in that there is no contribution to the photon spectrum from initial-state radiation. We calculated the spectrum of photons expected from initial-state radiation using a Monte Carlo event simulation,[9] then adjusted the continuum data to account for the $\Upsilon(1S) \to q\bar{q}$ component of our background.

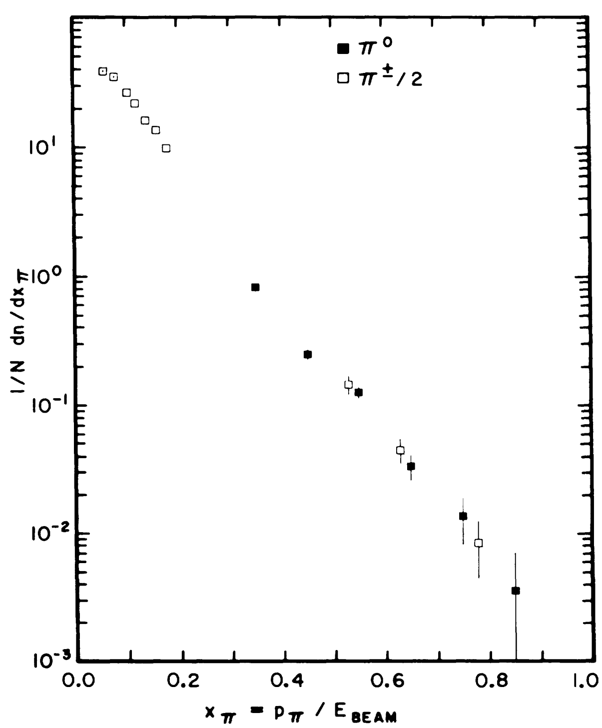

FIG. 1. Comparison of neutral-pion and charged-pion spectra. The charged-pion spectrum has been scaled by $\frac{1}{2}$.

Third, there are photons from decays of π^0 and η mesons produced in the strong decay of the $\Upsilon(1S)$. At low energy this source of photons dominates all others and limits our measurement to values of x_γ greater than 0.55. To correct for this background it is necessary to know the neutral-pion momentum spectrum from $\Upsilon(1S)$ decays. We performed the analysis using two different spectra: a measured neutral-pion spectrum and one-half the measured charged-pion spectrum.[10] Figure 1 shows the two spectra. The difference in the two results is incorporated into our systematic error. Using these π^0 momentum spectra and a momentum-dependent π^0 angular distribution obtained from $\Upsilon(1S) \rightarrow ggg$ Monte Carlo events, we calculated the single-photon spectrum that should be observed in our detector taking into account the possibility that the two photons from the π^0 appear as a single shower. The probability that this occurs is negligible for $x_\pi < 0.2$ ($x_\pi = p_\pi / E_{\text{beam}}$) and rises linearly to 70% at $x_\pi = 1$. We included background from η decay by assuming the η production rate to be 0.32 times the π^0 rate.[11] The probability that the two photons from η decay merge to form a single shower is negligible. Photons from η's account for the about 10% of the background photons in the region $x_\gamma > 0.05$.

Figure 2 shows our observed signal and the various backgrounds. Note that at $x_\gamma = 0.55$ the ratio of the background from π^0 decay to the signal with all backgrounds subtracted is approximately 1.0; at $x_\gamma = 0.95$ this ratio drops to 0.07. Our good spatial resolution therefore reduces our sensitivity to backgrounds due to π^0 decay relative to that of the previous analysis of this process.[12] Although the photons are kinematically limited to $x_\gamma < 1.0$, we measured values in excess of this limit because of the finite resolution of our shower counter.

To calculate the efficiency for detecting the photon in $\Upsilon(1S) \rightarrow \gamma gg$ events as a function of photon energy, we used a Monte Carlo simulation of the events, incorporating the QCD predictions for the photon and gluon energy and angular distributions.[13] For $0.3 < x_\gamma < 0.9$ the net efficiency for event selection and photon detection is constant at 33%. Above $x_\gamma = 0.9$ the net efficiency drops sharply because of the low charged multiplicity of the hadronic system recoiling against the photon. As a check on our event simulation, we compared the multiplicity distributions from Monte Carlo events and data for various values of x_γ. We found good agreement between the two, in particular, at $x_\gamma > 0.9$, where the efficiency is most sensitive to the multiplicity.

In order to compare our results with theory we modified the theoretical spectra to reflect the resolution and efficiency of our detector. We used these smeared spectra to fit the background-subtracted photon spectrum. The only free parameter in each fit was the overall normalization. Figure 3 shows the observed background-subtracted spectrum and the best

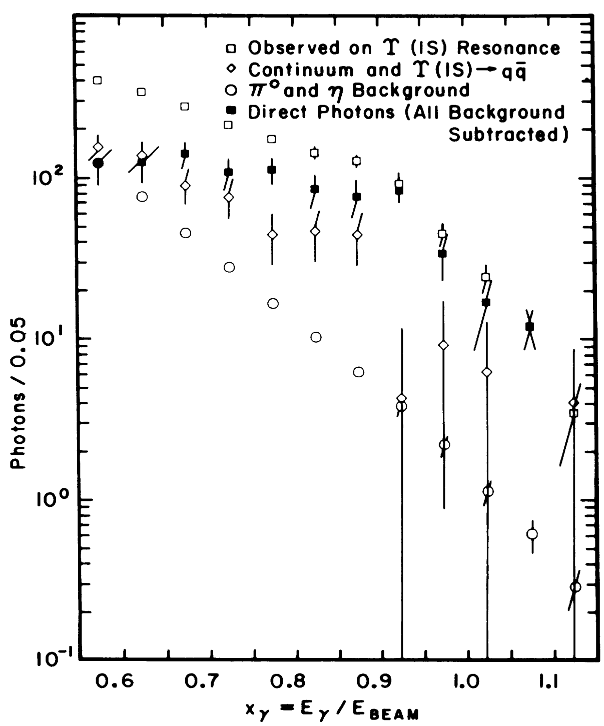

FIG. 2. Photon spectrum and various background contributions.

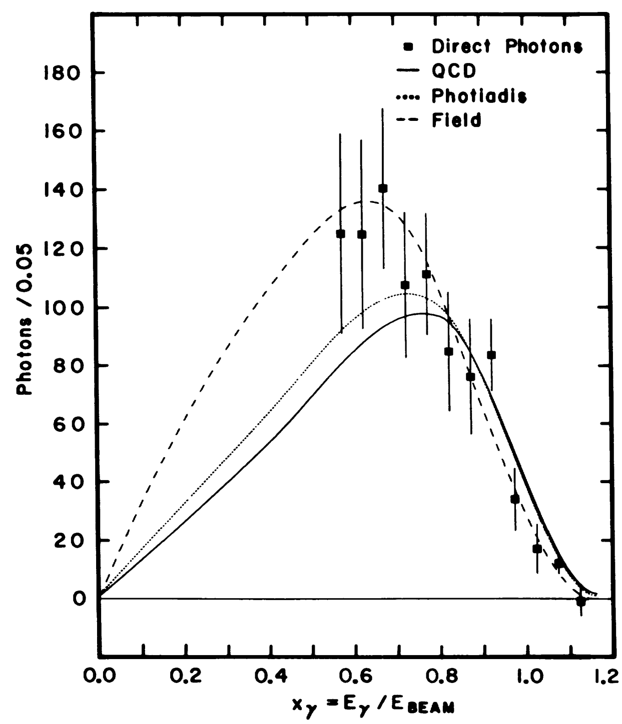

FIG. 3. Background-subtracted photon spectrum and fits to the various theoretical spectra. Errors are statistical only.

TABLE I. Values of B_γ, α_s, and $\Lambda_{\overline{MS}}$ for various assumptions about the shape of the photon energy spectrum. The errors are statistical and systematic, respectively.

	B_γ (%)	α_s	$\Lambda_{\overline{MS}}$ (GeV)
QCD	$1.88 \pm 0.14 \pm 0.17$	$0.40^{+0.04}_{-0.03}{}^{+0.06}_{-0.05}$	$0.37^{+0.05}_{-0.05}{}^{+0.07}_{-0.06}$
Photiadis	$2.03 \pm 0.15 \pm 0.16$	$0.36^{+0.04}_{-0.03}{}^{+0.04}_{-0.04}$	$0.32^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$
Field	$2.54 \pm 0.18 \pm 0.14$	$0.27^{+0.03}_{-0.02}{}^{+0.03}_{-0.02}$	$0.19^{+0.04}_{-0.03}{}^{+0.04}_{-0.04}$

fits to the three theoretical spectra mentioned above. For the lowest-order QCD spectrum, the Photiadis spectrum, and the Field spectrum, we obtain χ^2's of 14.2, 10.8, and 8.1, respectively, for eleven degrees of freedom.

To obtain B_γ we used the number of photons determined from the fit to each model in the region $0.55 < x_\gamma < 1.15$, correcting for the inefficiencies due to the geometry of our detector and for the effect of this energy cut. The latter correction depends on the shape of the assumed energy spectrum. In Table I we present the values of B_γ, α_s, and $\Lambda_{\overline{MS}}$ obtained from fits to the three theoretical spectra we have considered.

In our calculation of B_γ, we included a systematic error of 4.1% due to uncertainties in the characteristics of the π^0 spectrum and in the effect of our photon-selection criteria. The efficiency for passing our event-selection criteria is least reliably known for the region $0.9 < x_\gamma < 1.0$. Since the three theoretical spectra differ in the fraction of events that fall in this region, the systematic error in the efficiency calculation varies depending on the choice of spectrum. We estimated this error to be 7.7%, 6.2%, and 3.3% for the spectra from lowest-order QCD, Photiadis, and Field, respectively. The systematic error resulting from the uncertainty in the branching fraction for $\Upsilon(1S) \rightarrow q\bar{q}$ was 1.7%. The effect of the uncertainty in the η/π ratio was 1.3%. Finally, there was a systematic error of 5.5% in the determination of α_s due to the theoretical uncertainty expressed in Eq. (1). We added these errors in quadrature to obtain our total systematic error.

Schamburger *et al.* (the CUSB Collaboration)[12] have measured B_γ for $x_\gamma > 0.4$. We compare our results with those of CUSB in the limited region $x_\gamma > 0.55$, where neither measurement depends on the extrapolation to low x_γ. Integrating their spectrum, one finds $B_\gamma(x_\gamma > 0.55) = (1.93 \pm 0.38)\%$. We measured B_γ in this same region to be $(1.40 \pm 0.11 \pm 0.12)\%$. Although our data favor the (softer) Field spectrum, we cannot rule out the (harder) QCD spectra. In contrast, the CUSB data favor QCD and disagree with the Field prediction.

Our determinations of α_s and $\Lambda_{\overline{MS}}$ are consistent with measurements in e^+e^- annihilation and deep-inelastic scattering experiments.[14] Other methods of determining these quantities, however, are often subject to large uncertainties due to nonperturbative effects. In our case, the major uncertainty is due to the assumption for the shape of the photon energy spectrum, an ambiguity which in principle can be resolved experimentally.

In conclusion, we have measured B_γ, α_s, and $\Lambda_{\overline{MS}}$ in the context of three distinct theoretical models for the decay $\Upsilon(1S) \rightarrow \gamma gg$. Our data are not of sufficient precision to choose definitely among these models although the data favor a spectrum softer than that predicted by lowest-order QCD.

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