Observation of B^* Production in e^+e^- Interactions above the b-Flavor Threshold

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We have observed production of monochromatic low-energy photons in e^+e^- interactions between 10.6 and 11.2 GeV/c^2. We show that this signal is associated with the production of b-flavored meson pairs, and interpret it as due to the decay $B^* \to B+\gamma$. This is the first experimental evidence for the existence of vector $b\bar{u}$ or $b\bar{d}$ bound states. We determine the mass difference of the vector and pseudoscalar states, $M(B^*)-M(B)$, to be $52 \pm 2 \pm 4$ MeV.

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The existence of b-flavored mesons (B's), consisting of a b quark bound to a light $\bar{u}$ or $\bar{d}$ quark, was established by the discovery at the Cornell Electron Storage Ring (CESR) of the Υ''', or $\Upsilon(4S)$, with a mass of 10 577 MeV and width of ≈ 20 MeV,[1,2] and by the observation[3] of a large yield of high-energy leptons at the $\Upsilon(4S)$ peak due to the semileptonic decay of a meson of mass $\approx M(4S)/2$. The mass of the B meson was subsequently determined to be 5272.3 ± 2.5 MeV from reconstruction of final states resulting from hadronic decays.[4]

Both spin-singlet (pseudoscalar) and spin-triplet (vector) $b\bar{u}$, $b\bar{d}$, and $b\bar{s}$ S-wave states are expected to exist and, as for lighter mesons, the vector state B^* is expected to be heavier than the pseudoscalar state B. Scaling arguments and potential-model fits,[5] as well as the empirical observation that the difference of the masses squared for the known vector-pseudoscalar pairs ($\rho-\pi$, K^*-K, D^*-D) is approximately constant, suggest that $\Delta M = M(B^*)-M(B) \approx 40$–60 MeV. In this case the dominant decay mode is $B^* \to B+\gamma$, resulting in the emission of a photon with energy equal to ΔM in the B^* rest frame.

Monochromatic photons have not been observed at the $\Upsilon(4S)$ peak,[6,7] establishing that the $\Upsilon(4S)$ decays dominantly into B-meson pairs. Recently CESR has devoted a large amount of running time to the region above the $\Upsilon(4S)$, $10.6 < W < 11.2$ GeV, where W is the total center-of-mass energy. We have previously reported on a measurement of the e^+e^- cross section in this region,[8] using data obtained with the Columbia University–Stony Brook detector. Figure 1 shows our measurment of $R_{\rm vis}$, the ratio of the visible hadronic cross section (not corrected for detector efficiency) to the theoretical muon-pair cross section. The hadronic-event yield increases significantly above the $B\bar{B}$ threshold and shows complicated structure. This excess has been shown to be associated with events having low thrust,[8,9] and with a larger yield of high-energy leptons,[9,10] thus confirming that these events are due to the production and decay of b-flavored meson pairs (hereafter referred to as b-flavored events). In addition to $B\bar{B}$ production the opening of new channels, $B\bar{B}^*$ and $B^*\bar{B}^*$, should also occur. We report here on the result of a search for monochromatic photons from B^* radiative decays.

The nonmagnetic Columbia University–Stony Brook detector, described in more detail elsewhere,[11] is an electromagnetic calorimeter consisting of an array of sodium iodide (NaI) crystals backed by lead-glass blocks. A small tracking system provides a charged-particle veto. The method used to identify photons is similar to that described by Han *et al.*[12] Our rms energy resolution, as described below, is 15% for 50-

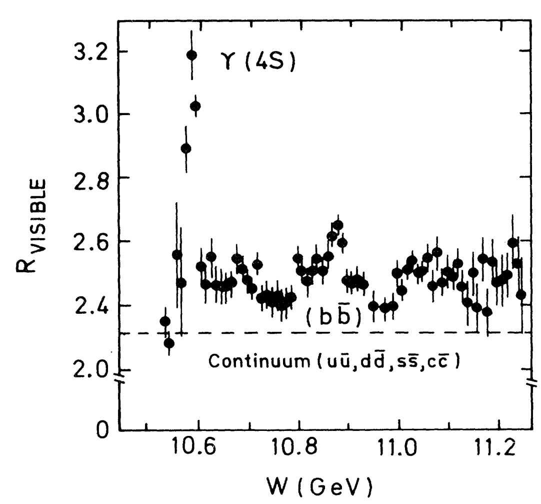

FIG. 1. $R_{\rm vis} = \sigma_{\rm vis}(e^+e^- \to \text{hadrons})/\sigma_{\mu\mu}$ vs W. Dashed line represents the $R_{\rm vis}$ level below the $\Upsilon(4S)$ from continuum production (from Ref. 8).

MeV photons. For photons assumed to come from B^* decay, inclusion of Doppler broadening results in a total spread of 19%.

The data used in our search were collected in a run of 118 pb^{-1} of integrated luminosity in the region $10.62 < W < 11.25$ GeV, yielding 311 437 hadronic annihilations. Data consisting of 6 pb^{-1} on the $\Upsilon(4S)$ peak and 3 pb^{-1} in the continuum below the resonance were collected under the same detector conditions. Because of detector modification a large amount of data previously taken on and below the $\Upsilon(4S)$ could not be combined with the present sample. The continuum data below the $\Upsilon(4S)$ were used to determine the fraction of b-flavored events in the other samples (see Fig. 1).

While the fraction of b-flavored events at the $\Upsilon(4S)$ peak is approximately 30% of the total hadronic cross section, it is only about 8% on average in the region studied here, making the search for photons from B^* decays extremely difficult. The fraction of b-flavored mesons can be substantially enhanced by use of high-energy leptons from semileptonic decays to tag production of pairs of such mesons.[10,13] Consequently, we have separately studied the photon spectra from two independent samples: (1) hadronic events with an observed high-energy lepton in the final state, and (2) all remaining hadronic events not included in the first sample.

In sample (1) we require the presence of an electron whose energy is between 1.3 and 2.5 GeV, or an identified muon of a similar energy range. Our detection efficiency is 12% each for electrons and muons from B decays. This selection yields 2352 hadronic events, of which $(34 \pm 8)\%$ are b-flavored events. We further enhance the b-flavored fraction by using the event topology as measured by a planar thrust variable,[2] hereafter called T, which is bounded between 0.67 for spherical energy-flow events and 1 for two collimated, back-to-back jets. A cut of $T < 0.88$ on lepton-tagged events increases the b-flavored fraction by a factor of 1.5, while losing only 10% of the b-flavored events. The photon energy spectrum for the remaining events is shown in Fig. 2(a). Around 50 MeV a clear enhancement is visible which we attribute to $B^* \to B + \gamma$ decays. We produce an estimate of the photon spectrum in the absence of any possible B^* production by combining the data samples taken on and below the $\Upsilon(4S)$, such that the fraction of b-flavored events is 8%. The same thrust cut is applied as before, but because of the limited statistics no lepton requirement is imposed. The resulting spectrum, normalized to the number of photons outside the region 35–65 MeV, is shown as the dotted histogram in Fig. 2(a). The subtracted photon spectrum is shown in Fig. 2(b), where we observe an excess of 123 ± 28 photons in the region 35–65 MeV. The error includes the uncertainty in the normalization. The good agreement elsewhere between the two spectra of Fig. 2(a) verifies the assumption that in the absence of B^* decays, the photon spectra for events with and without a lepton tag are the same. Fitting a Gaussian of variable height, position, and width to the subtracted spectrum gives a peak position of 46 ± 2 MeV before various energy corrections (described later), and an rms width of 8 ± 2 MeV, in good agreement with our derived resolution of 9 MeV.

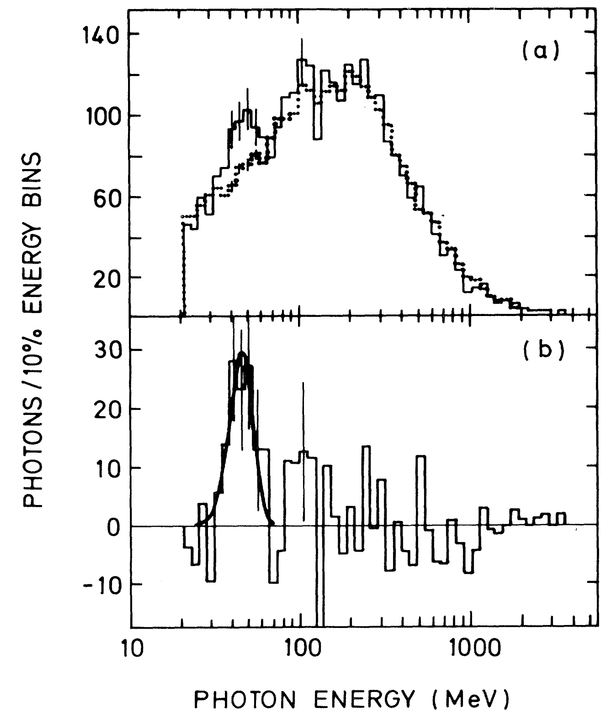

FIG. 2. (a) Solid histogram: photon energy spectrum in the region $10.62 < W < 11.25$ GeV, for hadronic events with an observed high energy electron or muon (sample 1) and with thrust $T < 0.88$. Dotted histogram is an estimated spectrum from a mixture of continuum and $\Upsilon(4S)$ peak events, normalized to the same area outside the region 35–65 MeV. Energy scale is uncorrected. (b) Subtracted photon spectrum. Error bars are those from data and estimated spectrum, combined.

We now consider the photon spectrum for sample (2). In this sample we apply more stringent transverse shower-shape and isolation requirements to the detected photons, thereby obtaining a photon spectrum with fewer misidentified or poorly measured showers, at the expense of a smaller detection efficiency. (The events from semileptonic decays are substantially cleaner because a significant fraction of energy is carried away by the neutrino.) The photon spectrum for the interval $20 < E_\gamma < 150$ MeV is shown in Fig. 3(a). Next we enhance the b-flavored fraction, first by applying a

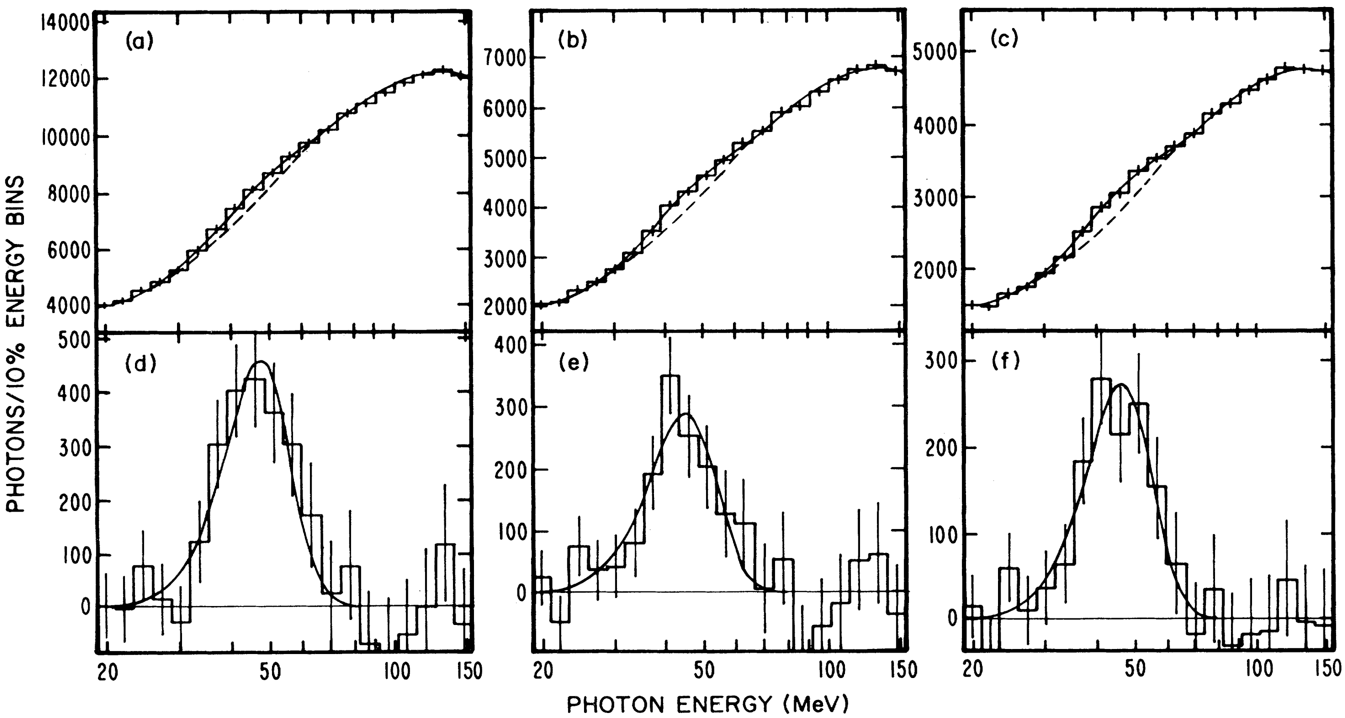

FIG. 3. (a) Photon spectrum for events of sample (2), in the region $10.62 < W < 11.25$ GeV. (b) Photon spectrum for events with $T < 0.83$. (c) Photon spectrum for events with $T < 0.83$ and with c.m. system energy $10.62 < W < 10.72$, $10.78 < W < 10.90$, or $11.00 < W < 11.12$ GeV. The solid curve is a fit to the data with a Gaussian plus a cubic polynomial (dashed line). (d),(e),(f) The background-subtracted photon signals of (a),(b), and (c), respectively.

thrust cut of $T < 0.83$, then by selecting those energy regions where the b-flavored event yield is largest (see Fig. 1), that is, $10.62 < W < 10.72, 10.78 < W < 10.90$, and $11.00 < W < 11.12$ GeV. The resulting spectra are shown in Figs. 3(b) and 3(c), respectively. As the background-data sample is too small to be useful here, instead we employ a method similar to that used in previous photon searches.[12,14] That is, we fit the spectra to a third-order polynomial plus a Gaussian of 9-MeV fixed width which represents our computed resolution. The results of these fits are shown as continuous lines in Fig. 3. The fraction of the signal from the photon line relative to the polynomial background increases with successive cuts, thus confirming that the signal can be attributed to b-flavored events. Figure 3 also shows the same three spectra after subtraction of the cubic polynomial. The area of the fitted Gaussian gives the number of photons in the signal. Table I shows the observed count, along with the observed yield of photons per b-flavored event. For all three samples we find good agreement in the peak positions and approximately constant fractional photon yield. The fits yield a χ^2 of 8.2, 11.2, and 7.2, respectively, for 14 degrees of freedom. A fit by a cubic polynomial alone yields a χ^2 of 36, 31, and 33, respectively, for 16 degrees of freedom. From the fit shown in Fig. 3(a) we obtain an uncorrected photon peak energy of 46 ± 2 MeV, coinciding exactly with that observed in sample (1).

The photon detection efficiency, the energy resolution, and corrections to the energy scale as established from calibrations with radioactive sources are determined by Monte Carlo (MC) calculations. Photon showers generated with the electron-gamma shower MC code[15] are produced isotropically in the laboratory frame and superimposed on hadronic events, which are then processed with the analysis program. The

TABLE I. The number and fraction of b-flavored (BF) events, the fitted number of photons in the signal, the yield of photons per b-flavored event, and the corrected peak position for the data samples shown in Fig. 3 and discussed in the text.

	All data	T cut	T cut, W cut
N_{BF}	25100 ± 3180	20620 ± 2050	15400 ± 1420
N_{BF}/N_{tot}	0.081	0.149	0.158
N_γ	2112 ± 424	1405 ± 350	1286 ± 272
N_γ/N_{BF}	0.084 ± 0.020	0.068 ± 0.018	0.084 ± 0.019
E_γ^{corr} (MeV)	51.6 ± 1.7	49.1 ± 2.0	50.5 ± 1.8

Doppler broadening of the signal is included in the generation. We find that on average 16% of the shower energy is lost in the inactive material between NaI layers for photon energies around 50 MeV. Furthermore, the shower-finding algorithm adds an average of 3 MeV to the shower energy. This additional energy is due to small leakage from other showers and interactions in the detector. A final 2% upward adjustment of the energy scale is obtained from a study of reconstructed π^0's. Multiplication by 0.98 then yields the photon peak energy in the B^* rest frame. The photon-detection efficiency is determined separately in the $\Upsilon(4S)$ peak sample and in the continuum sample below the $\Upsilon(4S)$, in order to obtain the efficiency in $B\bar{B}$ decays alone. The combined solid angle and photon-finding efficiency is $(11.4 \pm 3.0)\%$ and $(6.0 \pm 1.5)\%$ for samples (1) and (2), respectively.

After including all corrections, we obtain $52 \pm 2 \pm 4$ MeV for the energy of the observed photon signal in both data sets. The systematic error of 4 MeV is an estimate of the uncertainty in the various calculated corrections. From the observed photon excess in the two data samples of Figs. 2 and 3(a), we infer that the number of B^* mesons produced per b-flavored event is 1.4 ± 0.5 and 1.5 ± 0.6, respectively, where the errors are the combination of statistical and systematic uncertainties. This is in agreement both with the expectation from spin counting[16] and with model calculations of the cross section.[8,17] Using the CLEO measurement[4] for $M(B)$ we obtain a B^* mass of 5325 ± 5 MeV. From the B and B^* masses it follows that the threshold for B^* production is $10\,597 \pm 6$ MeV, thus slightly above the $\Upsilon(4S)$. This is consistent with our previously reported upper limit for the branching ratio $R_B(\Upsilon(4S) \to B\bar{B}^*) < 0.07$ (90% confidence level).[7] We also point out that in the data taken above the $\Upsilon(4S)$ there should be some $B_S\bar{B}_S$, $B_S\bar{B}_S^*$, and $B_S^*\bar{B}_S^*$ production, where B_S represents a $b\bar{s}$ bound state. Model calculations of the cross section[8,17] predict the production of B_S and B_S^* mesons to be small compared to that for B and B^* mesons. If the B_S^*-B_S mass difference is close to that for B^*-B, then the observed photon excess may contain some fraction of B_S^* radiative decays. Given our observed large production rate for monochromatic photons per b-flavored event, however, we conclude that they originate dominantly from B^* mesons.

In conclusion, we have observed a monochromatic photon signal which, either by cuts in thrust and in W or by a high-energy lepton tag, is shown to be associated with the presence of b-flavored meson pairs in the final state. We take this as evidence that we have observed the decay $B^* \to B + \gamma$. The B^*-B mass difference is $52 \pm 2 \pm 4$ MeV, for an unkown mixture of neutral and charged mesons. The value of ΔM is in agreement with many theoretical estimates,[5,18] but not with a calculation which obtained $\Delta M = 23$ MeV.[19]

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