Brief Reports

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Search for $B^* \rightarrow B + \gamma$ in Υ''' decays and the B^*-B mass difference

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The CUSB detector at the Cornell Electron Storage Ring is used to measure the inclusive photon spectrum at the Υ''' peak at 10.58 GeV. In $\approx 50\,000$ Υ''' decays, we do not observe any photon signal from $B^* \rightarrow B + \gamma$ decays for $20 < E_\gamma < 140$ MeV. We obtain an upper limit on the branching ratio for $\Upsilon''' \rightarrow$ monochromatic γ + hadrons of 6% to 9% at 90% confidence level. From the lack of a photon signal and the observed width of the Υ''' we deduce that the reconstructed b-flavored mesons from Υ''' are most likely the pseudoscalar B mesons and that $M(B^*) - M(B) \gtrsim 30$ MeV.

It is well established that the fourth upsilon Υ''' with a mass of 10 575 MeV (Ref. 1) decays into a pair of b-flavored mesons,[2,3] the lightest of which is expected to be the pseudoscalar B meson. The next excited states are vector mesons, called B^*'s.

Theoretical estimates of the B^*-B mass difference ΔM, based on the assumption that the hyperfine interaction is due to the exchange of a single hard gluon, result in the scaling relation

$$\Delta M = (M_c/M_b)(M_{D^*} - M_D) \quad ,$$

where c and b are the charm and bottom quarks, or $\Delta M \approx 52$ MeV.[4] Martin, in the context of potential models and using the π-ρ, K-K^*, and D-D^* splittings, obtains the bound $52 < \Delta M < 57$ MeV.[5] A recent calculation including one-loop QCD corrections finds $\Delta M = 23$ MeV.[6]

If the B^*-B mass difference is less than the mass of the pion the dominant B^* decay mode is $B^* \rightarrow \gamma B$. If in addition the Υ''' is kinematically allowed to decay into B^* mesons then the decay chain $\Upsilon''' \rightarrow B^* \rightarrow B + \gamma$ results in the emission of monochromatic photons ($\gamma_{\rm mon}$) observable in the inclusive photon spectrum from Υ''' decays. We have previously reported[7] a null result in a search for monochromatic photons in ≈ 5000 Υ''' decays, for photon energies of 40 to 70 MeV. Here we extend this search to photon energies in the range 20 to 140 MeV with much improved statistics and obtain a lower bound for ΔM.

b-flavored mesons have recently been observed directly in decays of Υ''' by reconstruction of hadronic decays.[8] Both charged and neutral mesons were reconstructed, with masses of 5274.2 ± 3.9 MeV for the neutral meson and 5270.8 ± 4.3 MeV for the charged meson, the average Q value of the decay is

$$M(\Upsilon''') - M(b\text{-flavored pair}) = 32.4 \pm 5.0 \text{ MeV} \quad .$$

The method used in Ref. 8 for reconstructing these b-flavored states is insensitive to the presence of low energy photons, and the possibility that some or all of the reconstructed particles are B^* mesons rather than B's is not ruled out. Their results therefore cannot distinguish between the following three possibilities: (A) $M_{\Upsilon'''} - 2M_B = 32$ MeV, (B) $M_{\Upsilon'''} - M_B - M_{B^*} = 32$ MeV, and (C) $M_{\Upsilon'''} - 2M_{B^*} = 32$ MeV.

The results presented in the following allows us to distinguish between alternatives A, B, and C. For case A, for instance, a photon signal can be observed in Υ''' decays only if $M(B^*)-M(B)\lesssim 30$ MeV. For cases B and C we would expect to observe a photon signal regardless of the mass difference between B and B^*. The results of our search for monochromatic photons in Υ''' decays then provide information both on the identity of the reconstructed b-flavored mesons and on the hyperfine splitting of the B and B^* states.

The inclusive photon spectrum from e^+e^- annihilations into hadrons was obtained using the CUSB NaI-Pb glass electromagnetic-shower detector. For detailed characteristics of the detector, see Ref. 9. For the present search, a special photon-finding algorithm, optimized for finding very low energy photons, was used. The combined acceptance and efficiency for finding photons is 8.4% for photon energies greater than 50 MeV. For $E_\gamma < 50$ MeV, the efficiency is given by

$$\epsilon_\gamma=[6.2+2.2(E_\gamma-20)/30]\%$$

(E_γ in MeV). The energy resolution is given by

$$\sigma(E_\gamma)=0.9\sqrt{E_\gamma}\ \text{MeV}$$

for photon energies $E_\gamma < 150$ MeV. Doppler broadening of the line is less than the resolution and is ignored. The efficiency and resolution are obtained as described previously.[10]

The data sample used consists of 170 000 hadronic events collected at the Υ''' peak ($10.559 < E_{\text{c.m.}} < 10.593$ GeV), of which 50 000 are resonance decays and 120 000 are continuum events. 60 000 continuum events are used as control sample. The inclusive photon spectrum from Υ''' events, with the continuum contribution subtracted for illustration purposes, is shown in Fig. 1. No obvious monochromatic signal is observed. Also shown in Fig. 1 is the expected photon signal in our detector for one γ per Υ''' decay for photon energies of 25, 50, and 70 MeV. Limits for the branching ratio (B_γ) for $\Upsilon'''\to\gamma_{\text{mon}}+$ hadrons are obtained by a maximum-likelihood calculation using a polynomial to represent the background and a Gaussian with a width equal to the detector resolution to represent the expected photon signal. The maximum-likelihood calculation is performed on the photon spectrum obtained at the Υ''' peak, without continuum subtraction. The results are given in Table I. The branching ratio is consistent with zero throughout this energy range, and the upper limit for B_γ varies from 6% to 9% at the 90% confidence level.

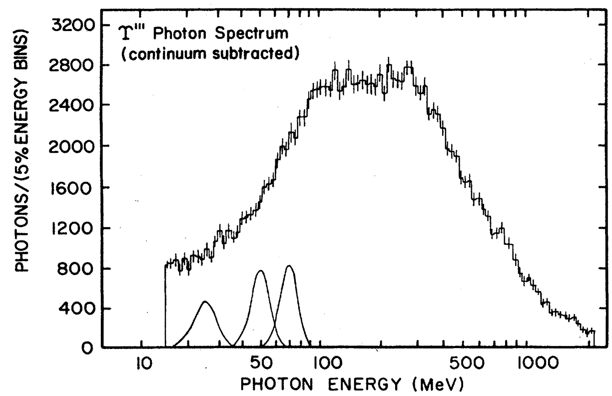

FIG. 1. Inclusive photon spectrum for 50 000 Υ''' events after continuum subtraction. The solid lines show the expected photon signal for one B^* per Υ''' decay for photon energies for (a) 25 MeV, (b) 50 MeV, and (c) 70 MeV.

These results can be compared with the expected rates for $\Upsilon'''\to B\bar{B}\gamma$ as a function of the B^*-B mass difference for cases A, B, and C. The number of monochromatic photons produced per Υ''' decay, $N_\gamma/N_{\Upsilon'''}$, is given by

$$B_\gamma=N_\gamma/N_{\Upsilon'''}=\frac{R(BB^*)+2R(B^*B^*)}{R(BB)+R(B^*B)+R(B^*B^*)}\ .$$

The relative rates $R(ab)$ for $\Upsilon'''\to ab$ are proportional to

$$p_{ab}{}^3|M(p_{ab})|^2S_{ab}\ ,$$

where a,b refer to B or B^*, p_{ab} is their relative momentum, the p^3 factor is for p-wave emission, $M(p_{ab})$ is a matrix element that describes the decay, and S_{ab} is a statistical factor which depends on the spins of the final state particles. The statistical weights S_{ab} are in the ratio 1:4:7 for $B\bar{B}$:$B^*\bar{B}+B\bar{B}^*$:$B^*\bar{B}^*$ (Refs. 4 and 11).

We have estimated the photon branching ratio in two

TABLE I. Results from a maximum-likelihood analysis of the photon spectrum (see text for details). The first column is the assumed photon energy in MeV, the second is the most likely value for the branching ratio $B(\Upsilon'''\to B\bar{B}^*$ or $\bar{B}B^*)$, constrained to be positive, and the third is the 90%-confidence-level upper limit for the branching ratio.

Photon Energy (MeV)	$B(\Upsilon'''\to$ monochromatic $\gamma)$	90%-C.L. upper limit
20	0.00	0.07
30	0.00	0.07
40	0.00	0.07
50	0.00	0.07
60	0.01	0.09
70	0.00	0.08
80	0.00	0.06
90	0.00	0.08
100	0.01	0.09
110	0.01	0.09
120	0.01	0.09
130	0.00	0.08
140	0.00	0.08

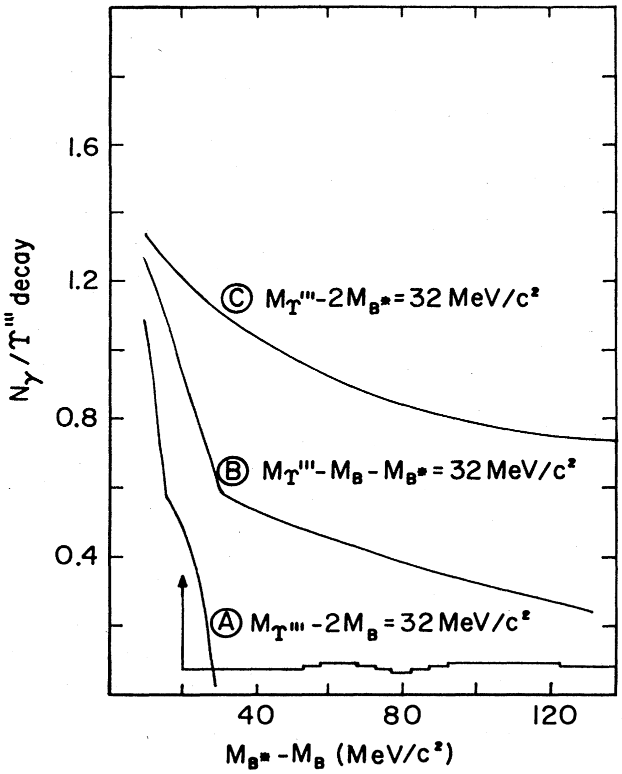

FIG. 2. The expected yield of monochromatic photons per Υ''' decay, computed using method 1, vs the B^*-B mass difference for cases A, B, and C, as described in the text and defined in the figure. Also shown is the 90%-confidence-level experimental upper limit (histogram near the bottom of the figure) as a function of a photon energy equal to the mass difference. Note that this method ignores the Υ''' wave-function structure and therefore underestimates the photon yield.

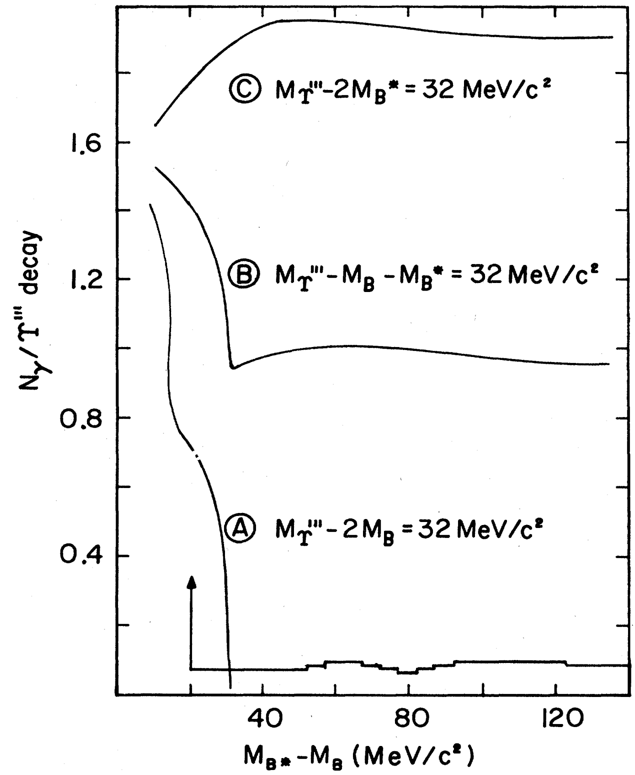

FIG. 3. Same as Fig. 2, but using method 2. Potential-model wave functions for the Υ''' (Refs. 4 and 12) have been used, resulting in a more realistic estimate for the photon yield.

ways. Method 1 assumes $|M(p_{ab})|^2=1$, which gives a $p_{ab}{}^3$ dependence for the partial rates for $\Upsilon''' \rightarrow ab$ and underestimates the production of B^*'s because the structure of the Υ''' wave function in momentum space is ignored. Method 2 uses the Υ''' decay amplitude of Ref. 12 to estimate the momentum dependence of the matrix element, thereby taking into account the effect of the nodes in the wave function of the Υ'''. Mixing with other ^3S states is negligible, due to the small width of the Υ'''. The relative momentum p_{ab} is determined by the Q value for decay $\Upsilon''' \rightarrow ab$ and is different for case A, B, and C. The expected number of photons per Υ''' from B^* decays is shown in Fig. 2 for method 1, and in Fig. 3 for method 2. The three curves correspond to cases A, B, and C. Both methods predict a large photon signal (> 0.4 photon/Υ''' for method 1, > 1.0 photon/Υ''' for method 2) for cases B and C. Therefore we conclude that the mesons reconstructed by the CLEO collaboration are the pseudoscalar B mesons. Our results also allow us to set a bound on the B^*-B mass difference. The 90%-C.L. experimental upper limit on B_γ is less than the rate estimated with method 1 for $\Delta M > 29$ MeV, and less than the rate estimated with method 2 for $\Delta M > 31$ MeV.

We conclude therefore that $\Delta M \geqslant 30$ MeV; in particular $\Delta M \approx 23$ MeV appears to be excluded.

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[1]We use the so-called VEPP-4 mass scale [A. S. Artamanov *et al.*, Phys. Lett. **118B**, 225 (1982)]. See also W. W. MacKay *et al.*, Phys. Rev. D **29**, 2483 (1984). For the masses of the other upsilons, see P. Franzini and J. Lee-Franzini, Annu. Rev. Nucl. Part. Sci. **33**, 1 (1983).
[2]G. Finocchiaro *et al.*, Phys. Rev. Lett. **45**, 222 (1980); D. Andrews *et al.*, Phys. Rev. Lett. **45**, 219 (1980).
[3]C. Bebek *et al.*, Phys. Rev. Lett. **46**, 84 (1981); L. J. Spencer *et al.*, Phys. Rev. Lett. **47**, 771 (1981).
[4]E. Eichten *et al.*, Phys. Rev. D **17**, 3090 (1978); **21**, 203 (1980).
[5]A. Martin, Phys. Lett. **103B**, 55 (1980).
[6]S. N. Gupta, S. F. Radford, and W. W. Repko, Phys. Rev. D **28**, 1716 (1983).
[7]R. D. Schamberger *et al.*, Phys. Rev. D **26**, 720 (1982).
[8]S. Behrends *et al.*, Phys. Rev. Lett. **50**, 881 (1983).
[9]P. Franzini and J. Lee-Franzini, Phys. Rep. **81**, 239 (1982).
[10]K. Han *et al.*, Phys. Rev. Lett. **49**, 1612 (1982); C. Klopfenstein *et al.*, Phys. Rev. Lett. **51**, 160 (1983).
[11]K. Lane and S. Weinberg, Phys. Rev. Lett. **17**, 717 (1976).
[12]E. Eichten, Phys. Rev. D **22**, 1819 (1980).