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Search for $B^* \to B + \gamma$ and limits on the B-meson mass

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The CUSB detector at the Cornell Electron Storage Ring was used to measure the inclusive photon spectrum at the $\Upsilon'''(10.55)$. In $\sim$5000 Υ''' events we see no obvious $\sim$50-MeV photon signal from $B^* \to B + \gamma$ decays and obtain an upper limit on the branching ratio for $\Upsilon''' \to BB^*$ of $\sim$10% with a 90% confidence level. From the lack of a photon signal and the observed width of the Υ''', we deduce limits on the B-meson mass of $[M(\Upsilon''')/2 - 25 \text{ MeV}] < M_B < [M(\Upsilon''')/2 - 10 \text{ MeV}]$.

In April, 1980 both the CUSB and the CLEO[1,2] collaborations discovered at the Cornell Electron Storage Ring (CESR) a fourth enhancement in the cross section for $e^+e^- \to$ hadrons at a c.m. energy of 10.547 GeV. Both its excitation energy above the Υ ($\sim$1113 MeV) and its leptonic width ($\Gamma_{ee} \sim 0.23$ keV), when compared to results from potential-model calculations, make it plausible to identify this new state as the fourth radial excitation of a triplet s-wave $b\bar{b}$ system.[3] This state is referred to as the Υ''' or $\Upsilon(4S)$. In contrast to the first three Υ's, whose total widths[4] range from 40 to 20 keV, the Υ''' is observed at CESR with a width of $\sim$24 MeV (see Fig. 1). The machine energy spread at 10.6 GeV is $\sim$11 MeV (full width at half maximum) and therefore the Υ''' has a total width of about 20 MeV.[4] This enormous change in total width is taken as proof that the mass of the Υ''' is greater than twice the mass of the lightest bound state of a b quark and a $\bar{u}$ or $\bar{d}$ antiquark. These bound $(b,\bar{u})$, $(b,\bar{d})$ states and their charge-conjugate states are called the B mesons and are new stable particles of mass $\sim$5 GeV. The lightest states are expected to be the pseudoscalar $B^0,\bar{B}^0,B^+,B^-$ mesons, in analogy to the K mesons. The next excited states are vector mesons, called B^*'s. The hyperfine splitting of the B^* and B is predicted[5] to be about 50 MeV, with only a few-MeV uncertainty[6]; therefore production of B^* mesons at rest should result in the observation of monochromatic $\sim$50-MeV photons from the decay $B^* \to B + \gamma$. We report in this paper on a search for this decay which we do not observe, and on limits on the B-meson mass which one can derive from such negative results.

From the values of Γ_{ee} and Γ_{tot} we infer that the Υ''' decays by annihilation of the $b\bar{b}$ pair with a branching ratio to leptons of $< 10^{-4}$ and we will therefore assume that $\Upsilon''' \to B$-meson pairs 100% of the time. For this reason the Υ''' is sometimes called

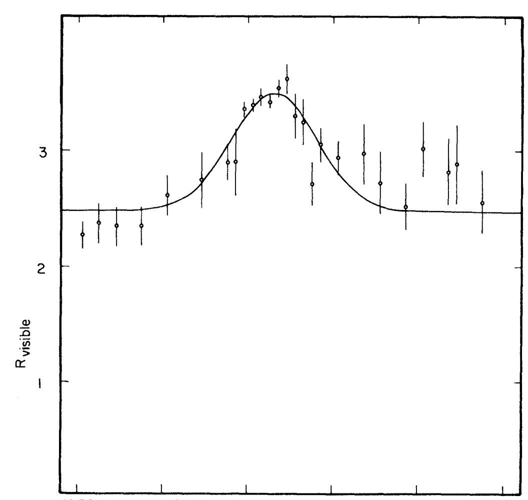

FIG. 1. Visible R near the Υ''' resonance. The solid line is a fit to a constant plus a single Gaussian. Although a change in the continuum level is expected and has been observed (Ref. 13), the shape of the continuum near threshold is not known and therefore no change in continuum level has been included.

the B factory. One should remember, however, that the cross section for Υ''' production is about half that of the continuum hadronic cross section. Therefore, at best, one produces one Υ''' for every three hadronic events. This constitutes a severe background since the large charged multiplicity and the many neutral particles from both B decays and continuum events make it all but impossible to isolate B mesons from other final states on an event-by-event basis. Since no B meson has yet been reconstructed one has to infer its mass by indirect methods. An obvious bound for the mass is $M(\Upsilon'') < 2M_B < M(\Upsilon''')$ since the Υ'' has a total width of about 20 keV. From the measured width one can, in principle, determine the Q value of the reaction $\Upsilon''' \rightarrow B + \bar{B}$, where $Q = M(\Upsilon''') - 2M_B$, and improve the above bound. The lower bound given above for M_B corresponds, however, to $Q < 233$ MeV, in which case, as for the $\psi(4030, 4160, 4415)$ which decay mostly into D^* mesons, the Υ''' would decay dominantly into B^* mesons almost at rest, resulting in the production of 50-MeV γ's.

We discuss here a search for these photons using the CUSB NaI–Pb-glass electromagnetic shower detector.[7] For detailed characteristics of the detector see Ref. 3. Several algorithms for photon search were constructed and tested extensively on photons from π^0 decays and Monte Carlo photons sent through our apparatus. They differ in the compromise between resolution and efficiency. We report here the results from an algorithm chosen for its good acceptance and adequate resolution. The photon energy resolution at 50 MeV ($\sigma \sim 17\%$) is dominated by the overlap contamination allowed in order to optimize photon acceptance, and is about twice the resolution at 100 MeV. Doppler broadening of the line is smaller than the resolution and can be ignored.

We have searched for such 50-MeV photons in a data sample consisting of ~17 000 hadronic events in the Υ''' peak (10.530 to 10.564 GeV), of which ~12 000 are continuum events and ~5000 are resonance events. In addition, ~7000 continuum events were recorded between the Υ'' and the Υ''' and serve as our continuum sample. The inclusive photon spectrum for Υ''' events, after subtraction of the continuum contribution for illustration purposes, is shown in Fig. 2. No obvious signal is observed. Also shown in Fig. 2 is the expected photon signal in our detector for one B^* per Υ''' decay.

The combined efficiency of the detector and the photon-search code, as well as the resolution function of the detector and the photon-search code, are obtained by generating the energy deposited in the elements of our array by photons of energies between 50 and 5000 MeV, using the EGS Monte Carlo program. The shower thus produced is superimposed with isotropic distribution on real events from e^+e^- collisions.

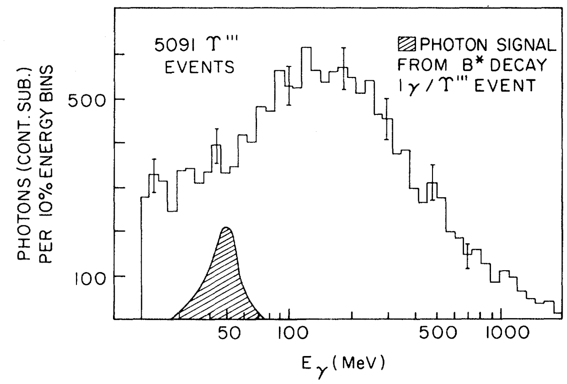

FIG. 2. Inclusive photon spectrum for 5091 Υ''' events after continuum subtraction. The shaded area represents the photon spectrum expected for one $B^* \rightarrow B + \gamma$ decay per Υ''' event. Typical error bars are shown.

The new events are then processed through the same photon-search code. By subtraction, the photon-recovery efficiency is obtained (including solid angle, nominally 65% of 4π) as well as the resolution function. This procedure is at worst slightly pessimistic in that more confusion is added to an already busy detector. The validity of this method has been checked by comparing with Bhabha-scattering events for which we observe an rms resolution of 2.4% as predicted and the width of the mass spectrum of reconstructed π^0's from hadronic events. The rms resolution for the π^0 mass is ~15%, part of which is due to the photon-energy measurement resolution and part to the measurement of the photon angles, in agreement with calculations. Studies were also made of the photon-search code using Monte Carlo–generated π^0 decays, again obtaining good agreement with expected energy and angular resolution of the photon-search code.

The result of the calculations described is that a signal of 840 photons of ~50 MeV are expected, distributed as the shaded area in Fig. 2 for the case $B(\Upsilon''' \rightarrow B\bar{B}^*$ or $\bar{B}B^*) = 100\%$. Limits for the branching ratio for $\Upsilon''' \rightarrow B\bar{B}^*$ or $\bar{B}B^*$ are obtained by a maximum-likelihood calculation using a polynomial to represent the background and the expected photon signal. The maximum-likelihood calculation is performed on the photon spectrum obtained at the Υ''' peak, without subtraction of the continuum, since the errors are better defined in this way.

The results of the calculation are given in Table I for photon energies from 45 to 60 MeV. All the values are consistent with zero and typically less than ~10% at 90% confidence level. The negative result of this search establishes that the decay channels $\Upsilon''' \rightarrow B^*B$, etc., are not yet fully open as expected for $Q \sim 200$ MeV. To obtain more stringent bounds for the B-meson mass, one has to be guided by

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)	$B(\Upsilon''' \to B^*B)$	90%-C.L. upper limit
45	0.00	0.12
50	0.00	0.09
55	0.00	0.09
60	0.00	0.11

model calculations. In general, for decays of a vector meson to two pseudoscalars, a vector plus a pseudoscalar, and two vectors, one expects for each channel $\Gamma \propto p^3 \propto Q^{3/2}$ for $p << 1/\langle r(\Upsilon''')\rangle$ and Γ to vanish for $p > 1/\langle r(\Upsilon''')\rangle$, where p is the relative momentum of the B-meson pair and $\langle r(\Upsilon''')\rangle$ is the rms radius. In addition, it was noted[5,8] that because of the nodes of the radial wave function of the Υ''' the decay rate for each channel vanishes when its Q value is $\sim$100 MeV. Eichten[9] has performed calculations using the model of Ref. 5, which successfully explains the D,D^* production in e^+e^- annihilations in the 4-GeV region. In particular, he obtains $\Gamma_{tot} \sim 10$ MeV for $Q = 20$ MeV, $\Gamma_{tot} \sim 20$ MeV for $Q = 50$ MeV, and $\Gamma_{tot} \sim 45$ MeV for $Q = 70$ MeV. For $Q \sim 100$ MeV the total width is again $\sim$20 MeV because of the suppression of the $B\bar{B}$ decay channel, $B\bar{B}^*$ and $\bar{B}B^*$ being the only available decay modes. These results together with the absence of 50-MeV photons establish the bound $20 < Q < 50$ MeV or $5248 < M_B < 5263$ GeV. The 0.3% uncertainty on the Υ''' mass due to the absolute calibration of the CESR energy scale does not effect the bounds on Q but is fully reflected in the B-meson mass which is given here in the so-called "CESR energy scale." Also, the bound on Q is not dependent on the B^*-B mass difference. Bigi and Ono,[10] using a different model, fitted our preliminary results on the observation of the Υ''' (Ref. 11) and report $Q = 9$ MeV. This result is certainly in agreement with the nonobservation of B^* decays but it requires an extremely rapid growth of Γ with Q, somewhat at odds with the charm case. Moreover, the data in Fig. 1 show a 10-standard-deviation disagreement with the resonance shape of Eq. (3) in Ref. 10, computed for $Q = 9$ MeV after folding the machine energy spread as a Gaussian with $\sigma = 4.8$ MeV. (The radiative corrections do not significantly change this shape.) Finally, we wish to remark that the bound established above results in a Doppler broadening of the decay products of B mesons, such as electrons, of $\pm$7.7% to $\pm$10%, of significance in the study of B semileptonic decays.[12]

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