Hyperfine Splitting of B Mesons and B_s Production at the $\Upsilon(5S)$

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Using the Columbia University–Stony Brook (CUSB-II) detector we have studied the inclusive photon spectrum from 2.9×10^4 $\Upsilon(5S)$ decays. We observe a strong signal due to $B^*\rightarrow B\gamma$ decays. From this we obtain (i) the average B^*-B mass difference, 46.7 ± 0.4 MeV, (ii) the photon yield per $\Upsilon(5S)$ decay, $\langle\gamma/\Upsilon(5S)\rangle=1.09\pm0.06$, and (iii) the average velocity of the B^*'s, $\langle\beta\rangle=0.156\pm0.010$, for a mix of nonstrange (B) and strange (B_s) B^* mesons from $\Upsilon(5S)$ decays. From the shape of the photon line, we find that both B and B_s mesons are produced with nearly equal values for the hyperfine splitting of the B and B_s meson systems.

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Vector mesons carrying b flavor, B^*'s, were first observed by the Columbia University–Stony Brook (CUSB) Collaboration in 1985, detecting the photon signal from $B^*\rightarrow B+\gamma$ decays.[1] B^* mesons were produced in e^+e^- annihilations in the center-of-mass energy (W) range, $10.55<W<11.25$ GeV, resulting in a spread of the velocity β of the B^*'s from 0 up to $\beta\sim0.33$. Because of that reason and the limited energy resolution for photons of the CUSB-I detector, our result $M(B^*)-M(B)=52\pm2\pm4$ MeV applies for an unknown mixture of nonstrange and strange B mesons but we could not determine the hyperfine splitting for nonstrange B mesons ($\Delta M_{\rm ns}$) and strange B_s mesons (ΔM_s). In this paper we report on results obtained with the CUSB-II detector from new data collected from e^+e^- annihilations in the $\Upsilon(5S)$ region, containing $\sim2.9\times10^4$ $\Upsilon(5S)$ decays. We present arguments, based on the study of the photon signal shape, that both B and B_s mesons are produced and that $\Delta M_{\rm ns}\sim\Delta M_s$. We recall that production of a reasonable fraction of B_s mesons on the $\Upsilon(5S)$ is of great interest to the detection of B_s mixing.[2-4]

The CUSB-II detector consists of a bismuth germanate (BGO) electromagnetic calorimeter inserted in the CUSB-I (Ref. 5) NaI–Pb-glass array. With it we have realized the best resolution for photons in the energy range from 30 MeV to 5 GeV.[6] The CUSB-II photon algorithm is optimized, for the energy range of interest, for both photon efficiency and energy resolution. In the present study we achieve an (acceptance)×(efficiency) of $\sim15.5\%$ and a resolution of ~5.2 MeV (FWHM) for 47-MeV photons with an energy dependence $\sigma_{E_\gamma}/E_\gamma=4.7\%/[E_\gamma/(47\text{ MeV})]^{1/4}$. The combined response function of the calorimeter and the search algorithm is not, however, a Gaussian; see Fig. 1. Efficiency, resolution, and scale nonlinearity are determined by searching for monochromatic, 47-MeV Monte Carlo- (MC-) generated photons, including Doppler broadening, merged with real events. Crystal calibration is maintained using ^{60}Co lines and the absolute scale is anchored[7] at 100, 200, and 700 MeV by use of the photon transitions between Υ's via χ_b''s and at ~5 GeV with Bhabha-scattering events. A comparison of the energy scale obtained from the ^{60}Co calibration with that from the sum of the two photon energies in Υ transitions via the χ_b'

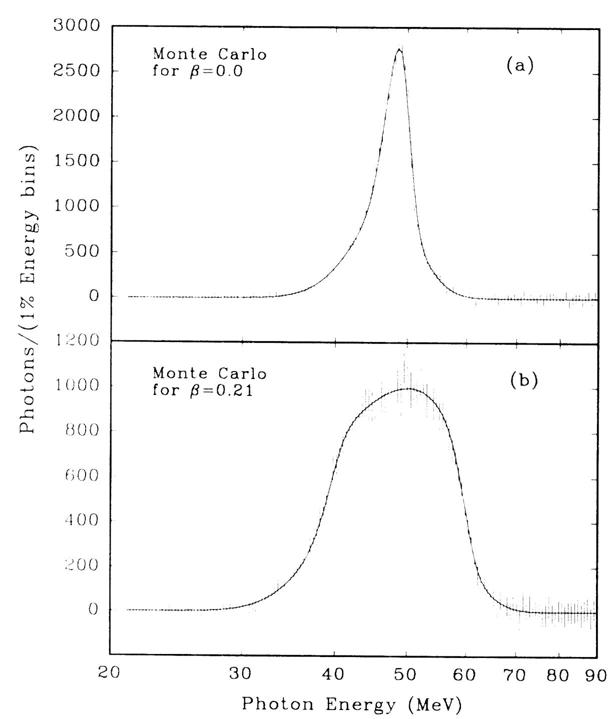

FIG. 1. CUSB-II response to (a) a monochromatic γ line and (b) a Doppler-broadened line with $\beta=0.21$.

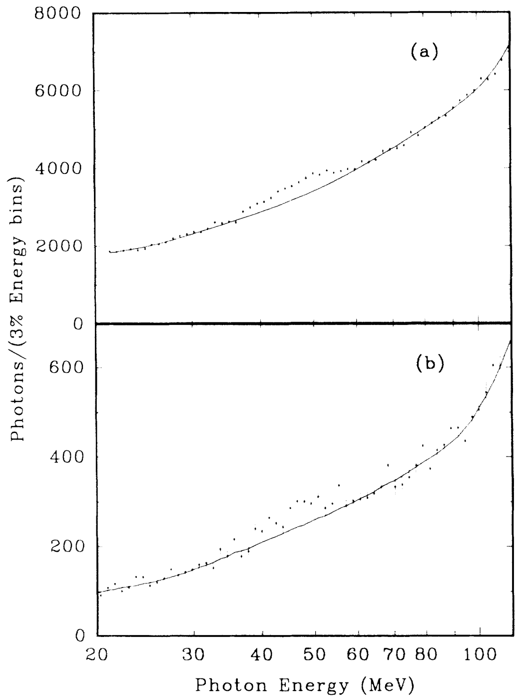

FIG. 2. The inclusive photon spectrum on $\Upsilon(5S)$ (a) for all events and (b) for electron-tagged events. The curves in (a) and (b) are fits to the background photon spectra.

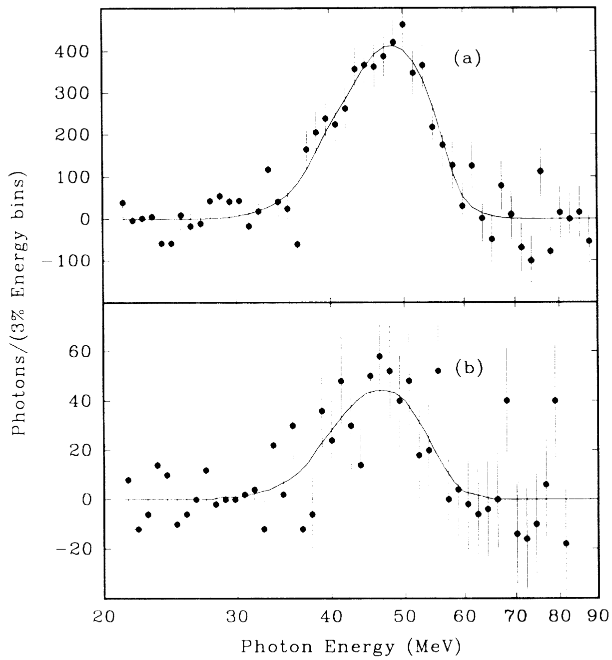

FIG. 3. Inclusive photon spectrum after subtraction of the background curve shown in Fig. 2(a) for all events and (b) for electron-tagged events.

provides an estimate of the systematic error on the energy scale of 0.5%.

For the isotropic decay of B^*'s, the laboratory spectrum of the photons is uniform over an energy interval $\Delta E = 2\beta E^*$ centered around γE^*, where β is the parent particles' velocity in the laboratory, γ the corresponding Lorentz factor, and E^* the photon energy in the decaying particle's frame of reference. Examples of MC photon spectra corresponding to $\beta = 0$ and 0.21 are shown in Fig. 1. The photon line shape has been measured using photons from transitions via the χ_b' and agrees well with the MC line shape. The statistical accuracy limits the maximum deviation of the width of the signal shape to 6% of its value. We use this value as an estimate of the systematic error on the MC photon line shape.

From the upper spectrum in Fig. 1 we determine the response function of the CUSB detector and search algorithm combined. This is shown as a solid line in the figure. The solid line superimposed on the lower spectrum is obtained from folding the response function for monochromatic photons with the Doppler broadening; it matches the shape of the recovered signal well.

The data reported here were obtained in a period when the Cornell Electron Storage Ring (CESR) ran at the $\Upsilon(5S)$ region. The integrated luminosity collected by CUSB is ~ 139 pb^{-1} and the luminosity-weighted average energy $\langle W \rangle$ for the data sample is 10870.5 MeV. The energy dependence of

$$R \equiv \sigma_{\text{visible}}(e^+e^- \to \text{hadrons})/\sigma_0(e^+e^- \to \mu\mu)$$

around the $\Upsilon(5S)$ is in very good agreement with a coupled-channel analysis of our previous data above the b-flavor threshold.[8] We confirm our previous finding that the resonance fraction of the total hadronic cross section is about 9% and that a thrust cut $t < 0.84$ retains 80% of the resonance events but only 36% of the continuum. We will use this cut throughout our analysis (except for lepton-tagged events) since it increases the resonance fraction of our samples to $\sim 19\%$ at a negligible loss of events. Our new determination of the $\Upsilon(5S)$ parameters, $M(5S) = 10866 \pm 20$ MeV, $\Gamma(5S) = 101 \pm 13$ MeV, and $\Gamma_{ee}(5S) = 0.30 \pm 0.04$ keV, are in good agreement with our previous findings of 10880 ± 20 MeV, 110 ± 15 MeV, and 0.37 ± 0.06 keV, respectively, where the latter mass includes a correction of 1.0032, due to a recalibration of the CESR energy scale using the $g-2$ depolarizing resonance method.[9] The range in W covered in the present run is only just over ~ 100 MeV.

In Fig. 2(a) we show the inclusive photon distribution in the 20–115-MeV interval, obtained on the $\Upsilon(5S)$ region. There is clearly a broad structure around 50 MeV. New data collected with CUSB-II at the $\Upsilon(4S)$ and in the continuum, just prior to the $\Upsilon(5S)$ run, do not show any low-energy photon signal, confirming previous findings.[10] Using the measured spectra from both continuum and $\Upsilon(4S)$ data we can predict uniquely the "background" photon spectrum in the inclusive photon spectrum taken on the $\Upsilon(5S)$. This is shown as the solid curve in Fig. 2(a). Figure 3(a) shows the subtracted photon spectrum. The curve shown is the best fit to the data using a Doppler-smeared spectrum folded with our resolution. The width of this peak, with a full width at half maximum (FWHM) of 15.7 ± 0.77 MeV, is wider than that expected from the intrinsic resolution of CUSB-II (~ 5.2 MeV FWHM) and is narrower than that resulting from the decay of B^* mesons moving with velocity $\beta = 0.21$, the average velocity of B^* mesons from $\Upsilon(5S) \rightarrow B^*\bar{B}^*$, $B\bar{B}^* + B^*\bar{B}$ in our sample. By unfolding the resolution we can obtain the average velocity $\langle\beta\rangle$ of the mixture of B^* and B_s^* contributing to the signal. From the fitting described we obtain $\langle E_\gamma \rangle = 46.7 \pm 0.4 \pm 0.2$ MeV, $\langle\beta\rangle = 0.156 \pm 0.010 \pm 0.004$ (where the first error is statistical and the second systematic), and $\langle \gamma/\Upsilon(5S) \rangle = 1.09 \pm 0.06$.

We confirm that these photons are associated with B mesons by tagging them with high-energy electrons from their semileptonic decays. We cannot reject here high-thrust events since high-energy electrons make for high thrust. While the semileptonic B branching ratio is only 10.5%,[11] one gains in the signal-to-background ratio because essentially only B semileptonic decays contribute electrons of energy between 1 and 3 GeV. Figure 2(b) shows the inclusive γ distribution for events with an electron tag at the $\Upsilon(5S)$, together with a background curve obtained by an appropriate combination of the $\Upsilon(4S)$ and the continuum data. Note that the reduction in signal is about a factor of 8 while the signal-to-background ratio is enhanced by a factor of about 1.8, with respect to the data with the thrust cut. Figure 3(b) shows the background-subtracted γ peak together with the fit. The fitted position ($\langle E_\gamma \rangle = 46.5 \pm 1.2$ MeV) and width ($\langle\beta\rangle = 0.142 \pm 0.027$), while less accurate, are in agreement with the signal obtained without electron tagging.

Assuming $\Delta M_{\rm ns} \sim \Delta M_s \sim 50$ MeV, $M(B_s) - M(B) \sim M(D_s) - M(D) \sim 100$ MeV (Ref. 12), and since $M(\Upsilon(5S)) - 2M(B) \sim 330$ MeV, six B-meson-pair decay channels are open to the $\Upsilon(5S)$. Of these, $B\bar{B}^* + B^*\bar{B}$, $B^*\bar{B}^*$, $B_s\bar{B}_s^* + B_s^*\bar{B}_s$, and $B_s^*\bar{B}_s^*$ contribute to the observed photon signal. The relative intensity of these channels could be calculated within the coupled-channel formalism with an accurate knowledge of the potential.[8] Most features of the energy dependence of the cross section from the $\Upsilon(4S)$ to the $\Upsilon(5S)$ are determined by the six B-pair thresholds above and therefore by the three mass differences $\Delta M_{\rm ns}$, ΔM_s, and $\Delta M = M(B_s) - M(B)$ [$M(B)$ is known[13] to be 5279.25 ± 0.4 MeV] and the fraction $f = N(B_s)/N(B)$ of strange to nonstrange B's produced at the $\Upsilon(5S)$.

For the above mass differences, the velocities of the B^*'s produced via the $B\bar{B}^* + B^*\bar{B}$ and $B^*\bar{B}^*$ channels are $\beta \sim 0.22$ and 0.20, respectively. Therefore, the photon spectrum would have a FWHM of $\sim$22–20 MeV for isotropic B^* decays; see Fig. 1(b). Including the decay angular distributions for $e^+e^- \rightarrow BB^*$ (pseudoscalar-vector or PV) and $e^+e^- \rightarrow B^*B^*$ (vector-vector or VV) changes the width by 1.07 and by 0.93, respectively.[14] Fitting the measured photon spectrum with pure nonstrange B^*B^* decays ($\beta = 0.20$) results in a fit with a 0.2% confidence level, implying that there are contributions from sources which produce less broadening. Strange B's are produced with considerably smaller velocities and do provide such a source. For the $B_s\bar{B}_s^* + B_s^*\bar{B}_s$ and $B_s^*\bar{B}_s^*$ channels, the velocities are $\beta \sim 0.10$ and 0.045, respectively. The spectrum requires some (10% of the photons) of this narrow-source ($\beta = 0.045$) contribution in order to raise the confidence level to 5%. A more complete fit with no constraints on the four vector-meson fractions shows that the fraction of photons from B_s^* decays is in the range of 20%–55%. This fraction depends weakly on ΔM in the range from 76 to 126 MeV (e.g., the 1σ limits are 30% to 55% at 76 and 126 MeV, and 20% to 55% at 105 MeV). For this region we find $\Delta M_{\rm ns} = 45.4 \pm 1.0$ MeV, $\Delta M_s = 47.0 \pm 2.6$ MeV.

The above results for $\Delta M_{\rm ns}$ and ΔM_s are in agreement with the empirical rule[15] $M_V^2 - M_P^2 \sim 0.54$–0.58 GeV^2. Close equality of the hyperfine strange and nonstrange splittings is also observed in the D system.[12] These results disagree, however, with the naive quark-model prediction that the ratio of the splittings should scale inversely with the light-quark mass,[4] $m_d/m_s \sim 0.7$.

The number of photons produced per $\Upsilon(5S)$ decay depends on the relative rates for the six channels, $B\bar{B}$, $B\bar{B}^* + B^*\bar{B}$, $B^*\bar{B}^*$, $B_s\bar{B}_s$, $B_s\bar{B}_s^* + B_s^*\bar{B}_s$, and $B_s^*\bar{B}_s^*$, with the PV final states contributing one photon and the VV states two. The relative contributions of the six channels can be obtained using a coupled-channel calculation, requiring good knowledge of the potential. As mentioned, we had performed such a calculation using $\Delta M = 100$ MeV, $\Delta M_{\rm ns} = \Delta M_s = 50$ MeV.[8] The same calculation gives the relative rates or $\Delta R_{\rm visible}$ for $\Upsilon(5S)$ decay into the six channels as 0.055, 0.11, 0.082, 0.017, 0.008, and 0.097, respectively, yielding $f = 33\%$, consistent with the B_s contribution necessary to obtain agreement with the observed photon spectrum. It also gives $\langle \gamma/\Upsilon(5S) \rangle = 1.3$ compared with the measurement of $\langle \gamma/\Upsilon(5S) \rangle = 1.09$. Encouraged by this agreement, we have searched (using the parametrization of Ref. 8) in the four-dimensional space ΔM, $\Delta M_{\rm ns}$, ΔM_s, and f for the values which maximize the probability of observing the spectrum of Fig. 3(a) and for hypersurfaces of constant likelihood. In this way we obtain the same results as above for $\Delta M_{\rm ns}$ and ΔM_s. We also find two solutions for ΔM and f:

$$\Delta M = 82.5 \pm 2.5 \text{ MeV}, \quad f = 0.36 \pm 0.12,$$

$$\Delta M = 121 \pm 9 \text{ MeV}, \quad f = 0.24 \pm 0.12.$$

The 1σ and 2σ contours are shown in Fig. 4 as the solid and dashed curves, respectively. The two solutions that are observed correspond to regions where the parametrization of Ref. 8 leads to small $B_s^*\bar{B}_s^*$ contributions. We have performed the same search using the coupled-channel potential model calculation of Martin and Ng,[4]

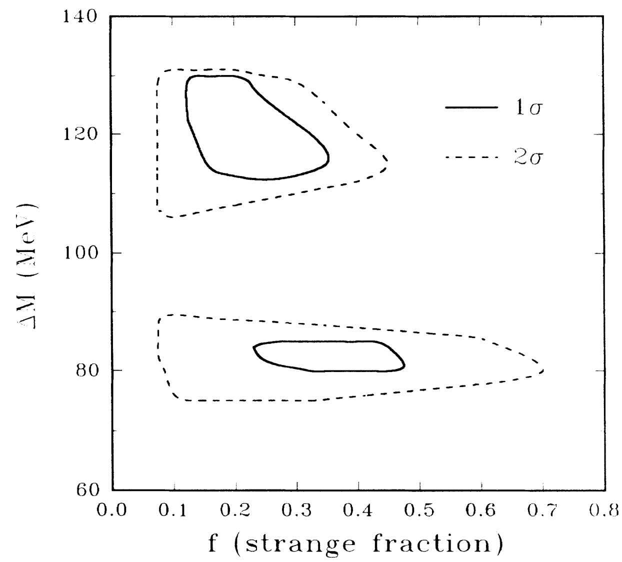

FIG. 4. The 1σ (solid curve) and 2σ (dashed curve) contours in the $(\Delta M, f)$ plane corresponding to the signal of Fig. 3(a).

and found similar results. The stability of the results when the actual potential is changed within values allowed by other and independent experimental constraints gives added confidence in the analysis performed.

In conclusion, from a study of the shape of the photon signal from $B^* \to B + \gamma$ and $B_s^* \to B_s + \gamma$ transitions from $\Upsilon(5S)$ decays we determine the hyperfine splitting of nonstrange and strange B mesons to be $\Delta M_{ns} = 45.4 \pm 1.0$ MeV, $\Delta M_s = 47.0 \pm 2.6$ MeV. In the context of a coupled-channel analysis, we find $M(B_s) - M(B)$ to be between 80 and 130 MeV and the fraction of strange B mesons to be between 12% and 48%, at the 1σ extremes.

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