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Observation of $\Upsilon(4S)$ Decays Into non-$B\overline{B}$ Final States Containing ψ Mesons

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Abstract

We report on the observation of ψ mesons from $\Upsilon(4S)$ decays which are too energetic to come from B mesons. These events provide evidence for non-$B\bar{B}$ decays of the $\Upsilon(4S)$. The measured rate is $B(\Upsilon(4S)\to\psi X)=0.22\pm0.06\pm0.04\%$ for ψ momentum above 2 GeV/c.

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The $\Upsilon(4S)$ resonance is the third radial excitation of the $b\bar{b}$ system. It is massive enough to be above threshold for decay into B^-B^+ or $B^0\bar{B}^0$ and is thought to decay dominantly into these modes. Other vector meson resonances decay into final states which do not contain the explicit flavors of the constituent quarks. For example, the ϕ, an $s\bar{s}$ state, decays 13% of the time into $\rho\pi$[1] and the $\psi(3770)$, a $c\bar{c}$ state, has recently been observed to decay into non-charm final states.[2]

A previous search for non-$B\bar{B}$ final states in $\Upsilon(4S)$ decay investigated the inclusive charged particle momentum spectrum. No statistically significant signal was observed for particles above the kinematic limit for B decay.[3] The resulting upper limits on the non-$B\bar{B}$ decay fraction depend on the assumed shape of the non-$B\bar{B}$ spectrum. For a spectrum with the shape of continuum e^+e^- annihilations, the upper limit is 3.8%, while for a shape similar to three-gluon decays of the $\Upsilon(1S)$, the limit is 13%, both at 90% confidence level.

In this analysis we investigate the production of ψ mesons from the $\Upsilon(4S)$ in the momentum range above the kinematic limit allowed for ψ's from B decay. Low momentum ψ's have previously been seen in $\Upsilon(4S)$ decay and were assumed to arise solely from B decays.[4] The inclusive branching ratio for $B\to\psi X$ was found to be 1.1%. Some fully reconstructed $B\to\psi K$ and $B\to\psi K^*$ events have been seen.

We use data taken with the CLEO detector using the Cornell Electron Storage Ring (CESR). The luminosities used consist of $212pb^{-1}$ accumulated at the $\Upsilon(4S)$ resonance, $102pb^{-1}$ taken at a center-of-mass energy 60 MeV below the $\Upsilon(4S)$ and $116pb^{-1}$ taken at the $\Upsilon(5S)$ resonance. There are 240,000 $\Upsilon(4S)$ decays and 35,000 $\Upsilon(5S)$ decays. The CLEO detector is described in detail elsewhere.[5] This analysis uses the charged particle tracking system and the electron and muon identification systems. The tracking chambers consist of a set of three drift chambers and have a charged particle momentum resolution of $(\delta p/p)^2 = (0.007p)^2 + (0.0023)^2$, with p in units of GeV/c. Electrons are identified by a combination of devices. Energy loss (dE/dx) is measured in the 51 layer inner tracking chamber where the dE/dx resolution is 6.5% (rms) on Bhabha electrons. This measurement is used in combination with two other measurements from devices placed outside the 0.7 radiation length thick solenoid magnet coil. These devices include wire proportional chambers which also determine dE/dx and a 12 radiation length thick lead-wire proportional chamber calorimeter which gives a measurement of electromagnetic energy. The muons system consists of segmented steel plates whose total thickness varies between 1.0 and 1.5 meters. Wire chambers inside and outside of the steel record hits made by muon candidate tracks.

The event sample is selected by using standard CLEO hadronic event selection criteria.[6] In order to suppress electromagnetic and two-photon backgrounds, we impose the additional requirement that at least 5 charged tracks be found. ψ's are identified via the di-electron or di-muon modes. One muon must either penetrate all the iron and make two hits (a "cross") in orthogonal layers of the outer muon chambers, or produce a single hit in the outer chambers and a cross in the inner muon chambers. The second muon candidate is required only to make a cross in the inner layer or have at least one hit in the outer layer. Electrons are identified either by ionization loss (dE/dx) in the drift chamber or a combination of the former with outer dE/dx information and shower counter information, if the track points to the outer octant detectors. At least one of the two electrons must be identified using shower counter information.

The reaction $B\to\psi\pi$ gives the most energetic ψ's possible from B decay; the ψ momentum is 1.73 GeV/c. Although this decay mode is Cabbibo suppressed with respect to the ψK mode, it is still allowed. We do not expect many of these decays; the measured $B\to\psi K$ branching ratio[4] is about 0.1% and $\psi\pi$ should be suppressed by the sine squared of the Cabbibo angle. To find the kinematic limit we need to Lorentz-boost the ψ, since the B is moving with velocity $\beta=0.06$. This results in a Doppler smearing about the endpoint, with the maximum possible momentum now being 1.94 GeV/c. There is an additional Gaussian momentum smearing of 30 MeV/c (rms) due to our momentum resolution. Therefore, 2 GeV/c is a conservative upper limit for ψ momenta from B decay. This translates into a maximum allowed x of $x_B=0.378$ at the $\Upsilon(4S)$, where x is the momentum divided by the beam energy.

The $\ell^+\ell^-$ mass spectrum for the $\Upsilon(4S)$ sample is shown in Fig. 1a for $x > x_B$ and in Fig. 1b for $x < x_B$. To suppress random background combinations and better define the lepton acceptance, we require that the absolute value cosine of the decay angle of the leptons in the dilepton mass frame with respect to the dilepton direction in the laboratory be < 0.9. The ψ peaks are fitted with Gaussians centered at the known ψ mass and with fixed width of 25 MeV rms as determined by Monte Carlo simulation. We find 150 ± 14 events in the $x < x_B$ sample and $15.2^{+4.9}_{-4.5}$ for $x > x_B$. In the latter sample, we have 17 total events in the two bins centered on the ψ mass including a background of 5.0 events. The probability of the signal at the ψ mass being caused by a background fluctuation is 2×10^{-5}. There are approximately equal numbers of di-electron and di-muon candidates. As these events cannot be from B decay, they are either evidence of non-$B\bar{B}$ decays of the $\Upsilon(4S)$, or arise from the continuum under the $\Upsilon(4S)$ resonance. We have investigated two samples of continuum-rich data in order to see which is more likely.

The first continuum sample comes from data taken 60 MeV in center-of-mass energy below the $\Upsilon(4S)$. The $\ell^+\ell^-$ mass plot is shown in Fig. 1c for $x > x_B$ and in Fig. 1d for $x < x_B$. There is no signal in either x range. The probability that the excess in the $\Upsilon(4S)$ data for $x > x_B$ is due to a continuum fluctuation is 2.8%, after we take into account that the $\Upsilon(4S)$ sample is 2.08 times larger. The lack of a signal in the low x data adds support to the idea that the signal on the $\Upsilon(4S)$ is not due to a continuum fluctuation. Summing the high x and low x samples together and fitting the resulting distribution gives a yield of $1.6^{+2.4}_{-3.8}$ events. This can be expressed as an upper limit on continuum ψ production of $R_\psi = \sigma(e^+e^- \to \psi X)/\sigma(e^+e^- \to \mu^+\mu^-) < 1.9 \times 10^{-3}$ at 90% confidence level for events with at least 3 charged tracks in addition to the ψ. We have previously published an upper limit at 90% confidence level of $R_\psi < 2.3 \times 10^{-3}$, requiring only one charged track in addition to the ψ.[7] Theoretical estimates[8] of R_ψ range from 3×10^{-4} to 7×10^{-4}.

Another data sample we can use to search for continuum ψ production was taken on the $\Upsilon(5S)$ resonance. To insure that ψ mesons are not coming from Doppler shifted B decays, we increase the x cut to 0.48, as the B mesons are moving faster when produced at the $\Upsilon(5S)$ than at the $\Upsilon(4S)$. The only possible non-continuum source of real ψ mesons above 0.48 would be direct $\Upsilon(5S)$ decays. However, since the $\Upsilon(5S)$ cross-section is a factor of 3.8 smaller than the $\Upsilon(4S)$ and the x range is smaller we would expect only 1.2 ± 0.4 direct $\Upsilon(5S) \to \psi X$ events if the decay width was the same as on the $\Upsilon(4S)$, while for $x < 0.48$ we expect 19 ± 2 events from B decay by scaling from the observed low x $\Upsilon(4S)$

signal. We find 21.6 ± 6.4 events for $x < 0.48$ and no evidence for a signal for $x > 0.48$. (See Figs. 1e and 1f.) In Fig. 2 we compare $\Upsilon(4S)$ with continuum plus $\Upsilon(5S)$ data for $x > 0.48$. This summed sample is equal in size to the on $\Upsilon(4S)$ sample; the scaling factor of the summed distribution accounting for the energy squared dependence of the cross-section is 1.00. In the summed distribution there are 2 events in the two bins at the ψ mass including 0.8 background events. In estimating the probability that this distribution can come from the same population as the one we see on the $\Upsilon(4S)$ we have not included any allowance for direct $\Upsilon(5S) \to \psi X$ decays. The probability of this joint $\Upsilon(5S)$-continuum sample being consistent with the observation on the $\Upsilon(4S)$ is 1.4%

Global event shape characteristics can help discriminate between continuum events and events arising from different, less jet-like, production mechanisms. The Fox-Wolfram moment $R_2 = H_2/H_0$ is one such measure.[9] Fig. 3 shows the R_2 distribution for the high momentum ψ's from the $\Upsilon(4S)$ sample as well as three other samples for comparison: events with continuum dileptons of mass exceeding 2.5 GeV, the two continuum events at near the ψ mass (shaded), and $\Upsilon(4S)$ events containing a lepton with momentum greater than 1.4 GeV/c. The high momentum ψ events in the $\Upsilon(4S)$ sample have a spherical shape, not unlike that for $B\bar{B}$ decays with a lepton. They are very different from the above mentioned continuum samples.[10] The two continuum events near the ψ mass have only a 6% probability of coming from the same R_2 distribution as the $\Upsilon(4S)$ ψ's, while they have a 95% probability of coming from the continuum dilepton sample.[11] These considerations provide additional evidence that it is much less probable that the high momentum ψ signal is due to continuum production than due to direct $\Upsilon(4S)$ decay.[12]

After correcting for acceptances including our ψ detection efficiency, 20% for electrons and 28% for muons, and the $\psi \to \ell^+\ell^-$ branching ratio (13.8%), we find $B(\Upsilon(4S) \to \psi\ X) = (0.22 \pm 0.06 \pm 0.04)\%$ for $x > 0.378$. The momentum spectrum is shown in Fig. 4. The high momentum events are not concentrated near the kinematic limit from B decay, nor do they peak at any unique momentum.

We have searched for other indications of non-$B\bar{B}$ $\Upsilon(4S)$ decays. We have redone the charged particle momentum spectrum analysis in our new data sample. However, because of the sensitivity to the error in the relative $\Upsilon(4S)$ and continuum luminosities, the upper limits are almost the same as those given in ref. 3.

The discovery of non-$B\bar{B}$ ψ production naturally points to the possibility of high momentum charm production. It is possible that open charm is produced with a much higher rate than hidden charm. Thus, we have also searched for $D^{*\pm}$ above the endpoint allowed from B decay. The kinematic limit is 2.5 GeV/c, or x = 0.473. However, there is copious continuum charm production and we expect to have much less sensitivity than in the case of ψ's. We use the decay $D^{*+}\rightarrow\pi^+D^0$ and the subsequent decay of the D^0 into $K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$, and the charge conjugate reactions for D^{*-}. We find $B(\Upsilon(4S)\rightarrow(D^{*+}X + D^{*-}X)/2 = 1\pm2\%$ for $x > 0.473$. This translates into a 90% confidence upper limit of 3.7%. The limit is more than one order of magnitude larger than the measurement of the branching ratio to ψ's.

Another particle that is related to the $c\bar{c}$ ψ state is the $s\bar{s}$ ϕ state. We search for ϕ's above the kinematic limit for the reaction $B\rightarrow\phi\pi$, which is 2.75 GeV/c or an x of 0.52. The upper limit on the $\Upsilon(4S)$ branching fraction to ϕ's above x=0.52 is 0.23% at 90% confidence level.

We have also searched for $\Upsilon(1S)$ production from the $\Upsilon(4S)$ using the dilepton decay of the $\Upsilon(1S)$. A statistically significant signal was not observed, yielding an upper limit $B(\Upsilon(4S)\rightarrow\Upsilon(1S)+X) < 0.4\%$ at 90% confidence level, where X contains at least one charged track.

The high momentum ψ events provide direct evidence for non-$B\bar{B}$ decays of the $\Upsilon(4S)$. Other such decays must be present. We have tried to find D^{*+}, ϕ and $\Upsilon(1S)$ signals without success. Lipkin has argued[13] that non-$B\bar{B}$ decays of the $\Upsilon(4S)$ are to be expected. He explains the $\phi\rightarrow\rho\pi$ decay by a two step mechanism where ϕ goes to an intermediate $K\bar{K}$ which then annihilate into $\rho\pi$. He proposed this two step mechanism as a way for the ψ'' to decay into non-$D\bar{D}$ final states, which have been observed.[2] However, Lipkin's predictions are not quantitative and therefore it is difficult to ascertain the validity of his assertions. There are other intriguing explanations. Marciano has suggested that transitions to lower lying 4-quark states are possible. He points out that there is a large, 18%, Coulomb enhancement of $\Upsilon(4S)\rightarrow B^+B^-/\Upsilon(4S)\rightarrow B^0\bar{B}^0$ which may help generate a bound state which could in turn decay into such a 4-quark state.[14] This state could be a 0^+ state which decays via 2-gluon emission. Because of helicity arguments, the 2-gluons would decay preferentially to charm. It is also interesting to note that Ono et al. can explain the mass splittings between the $\Upsilon(3S)$, $\Upsilon(4S)$ and $\Upsilon(5S)$ and the total e^+e^- cross-section above the $\Upsilon(4S)$ by postulating that the $\Upsilon(4S)$ has a mixture of pure $b\bar{b}$ and $b\bar{b}g$ hybrid state in the wave function.[15] The $b\bar{b}g$ part cannot decay into $B\bar{B}$.[16]

None of these predictions is quantitative and we still need to determine the decay mechanism. Whatever processs is responsible for producing ψ's on the $\Upsilon(4S)$, it is different from that on the $\Upsilon(1S)$. The width[7] on the $\Upsilon(1S)$ is 50 eV while on the $\Upsilon(4S)$ it is in excess of 50 KeV.[1]

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FIGURE CAPTIONS

1) $m(\ell^+\ell^-)$ for various data samples. The curves are fits to the data using a Gaussian with fixed mass and width and a third order polynominal to describe the background. x_B is the maximum allowed (.378) for $B \to \psi\pi$ decay on the $\Upsilon(4S)$. For $\Upsilon(4S)$ data (a) $x > x_B$ and (b) $x < x_B$. For continuum data (c) $x > x_B$ and (d) $x < x_B$. For $\Upsilon(5S)$ data (e) $x > 0.48$ and (f) $x < 0.48$.
2) $m(\ell^+\ell^-)$ for $x > 0.48$, (a) on $\Upsilon(4S)$, (b) continuum plus $\Upsilon(5S)$.
3) The R_2 distribution for $x > x_B$ ψ's from the $\Upsilon(4S)$ shown as crosses, continuum with dilepton masses > 2.5 GeV (from Fig. 1c). The two continuum events close to the ψ mass are shaded. The dashed curve is the measured distribution for $B\overline{B}$ with a lepton > 1.4 GeV/c which has been normalized to the large x ψ data.
4) The ψ momentum distribution for $\Upsilon(4S)$ decays. Note, that the bin size changes above 2 GeV/c.

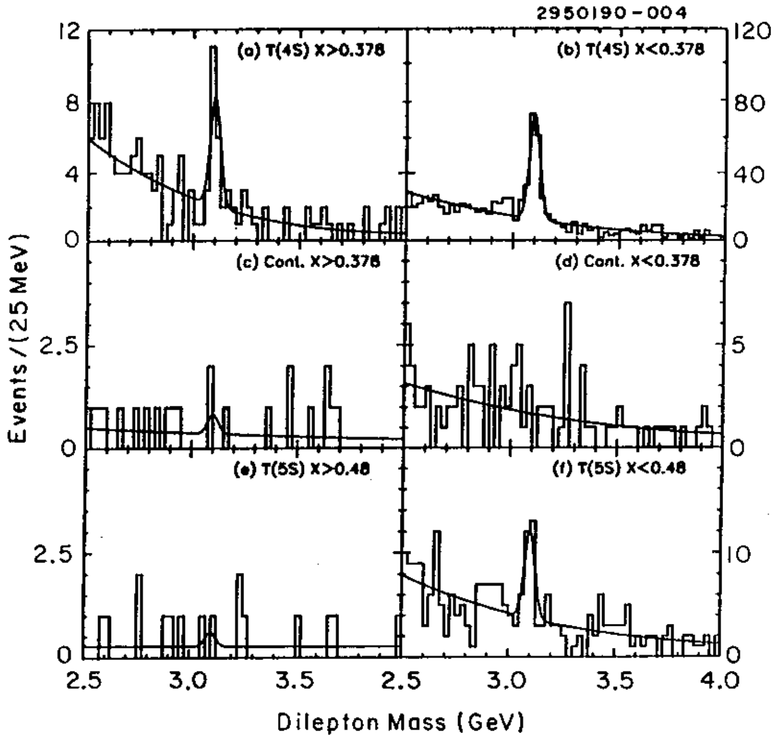


Figure 1

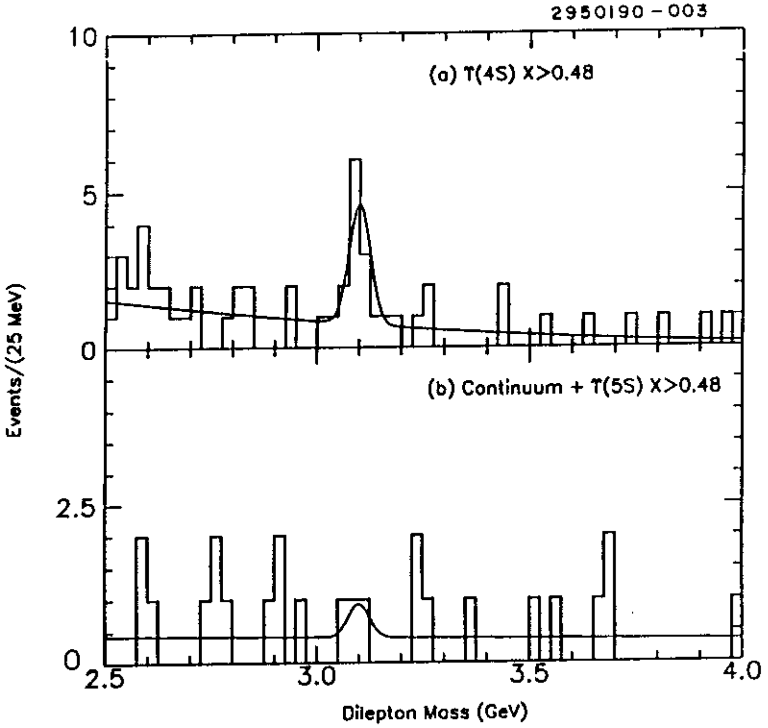


Figure 2

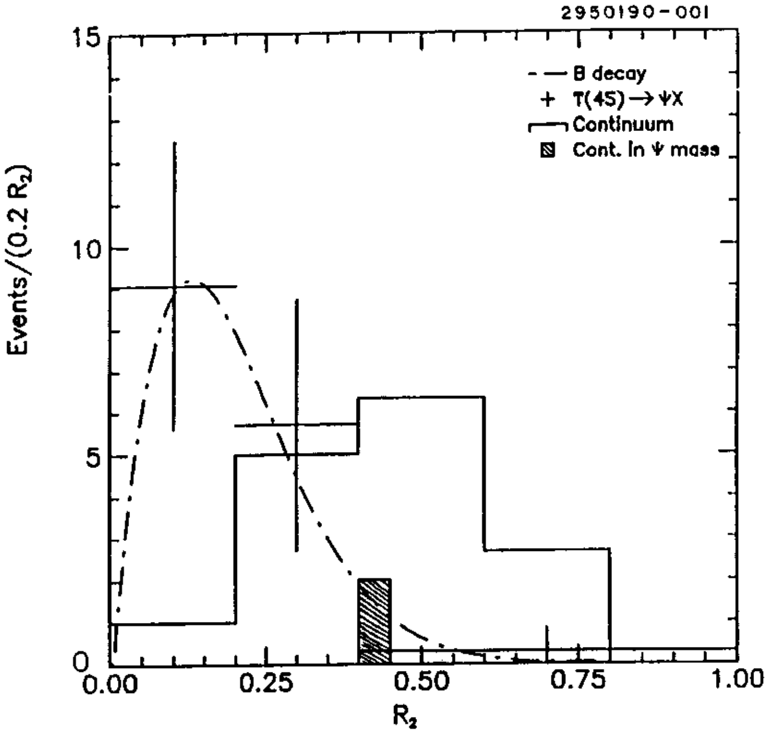
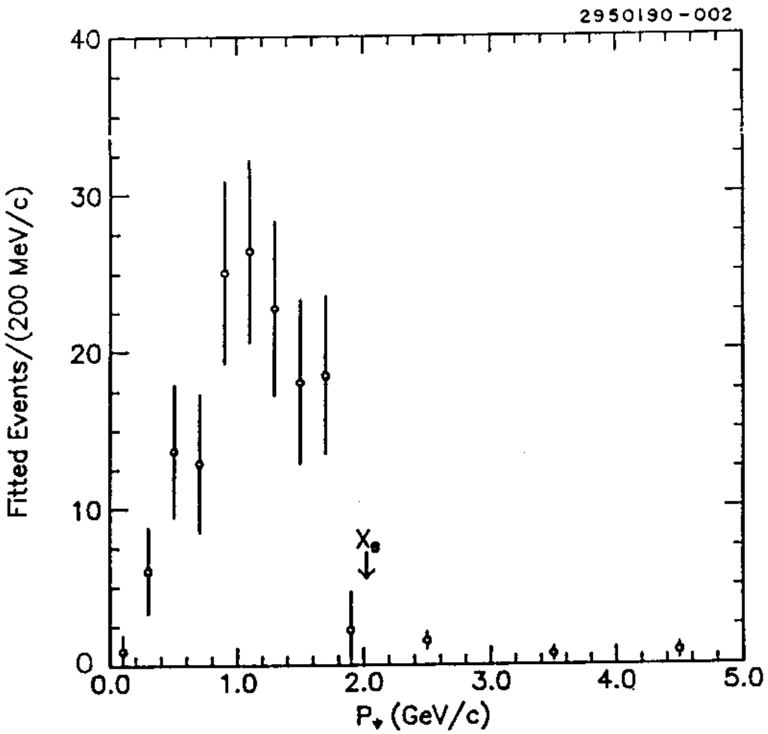


Figure 3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Fitted Events/(200 MeV/c)
40
30
20
10
0
0.0
1.0
2.0
3.0
4.0
5.0
P_ψ (GeV/c)
X_s

Figure 4