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Measurement of the Branching Fraction for $\Upsilon(1S) \to \tau^+\tau^-$

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Abstract

We have studied the leptonic decay of the $\Upsilon(1S)$ resonance into tau pairs using the CLEO II detector. A clean sample of tau pair events is identified via events containing two charged particles where exactly one of the particles is an identified electron. We find $B(\Upsilon(1S) \to \tau^+\tau^-) = \left(2.61 \pm 0.12 \,^{+0.09}_{-0.13}\right)\%$. The result is consistent with expectations from lepton universality.

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One of the interesting aspects of heavy quarkonia is that in the lower energy states the electromagnetic decays compete with the strong decays due to OZI suppression. In the $b\bar{b}$ system, the first three Υ resonances all lie below the threshold for strong decay into pairs of B mesons, and the measured leptonic decays are of the order of a few percent. For the $\Upsilon(1S)$, the world average of the branching fraction into tau pairs is $(2.97 \pm 0.35)\%$ [1] based on two measurements, one from CLEO [2] and one from ARGUS [3] . Comparing the tauonic decay rate to the e^+e^- and $\mu^+\mu^-$ rates is an interesting test of lepton universality. The e^+e^- and $\mu^+\mu^-$ branching fractions have been measured and lie about one standard deviation lower than the tau pair branching fraction [1].

We describe here a new measurement of the tauonic branching fraction of the $\Upsilon(1S)$ [4] which is significantly more precise than the two previous determinations. The analysis method also differs significantly from the previous two analyses. The previous CLEO measurement identified taus in their 1-vs.-3 topology[2] and the ARGUS measurement was based upon $\Upsilon(1S)$ mesons produced via $\Upsilon(2S)$ decays. Here we use data taken on the $\Upsilon(1S)$ resonance and look for tau pair events where one tau has decayed into $e\nu\bar{\nu}$ and the other has decayed into a final state having one charged particle which is not an electron (we use the notation $\not e$ below to denote this track, which is a muon, pion, or kaon). This allows us to select a very pure sample of tau pair events and avoid uncertainties associated with the hadronic background. The presence of the electron also improves our understanding of the trigger efficiency of the detector.

The data were recorded with the CLEO II detector which operates at the Cornell Electron Storage Ring (CESR). The CLEO II detector is described in detail elsewhere [5] . Excellent electron identification is provided by the charged particle tracking system and the electromagnetic calorimeter which are inside the solenoidal magnet with a 1.5 T field. The calorimeter consists of 7800 CsI(Tl) crystals providing excellent energy resolution and fine segmentation.

The data sample used in this analysis corresponds to an integrated luminosity of 49 pb^{-1} at the energy of the $\Upsilon(1S)$ resonance. In addition, a 101 pb^{-1} data sample taken in the continuum between the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances is used for subtraction of the non-resonant contribution. The trigger conditions were the same for the two datasets.

In measuring the branching fraction we must make a large subtraction to remove the contribution from the non-resonant process $e^+e^- \to \tau^+\tau^-$ from the $e^+e^- \to \Upsilon \to \tau^+\tau^-$ signal. Because the background continuum process is measured at a different energy from the signal process (E_{beam} of 5.263 GeV vs. 4.730 GeV for the $\Upsilon(1S)$), we try to choose cuts for which the energy dependence of the efficiency is well simulated by our Monte Carlo. Determination of the trigger efficiency is critical, so we insist that each event must fire a specific set of well-understood hardware trigger elements. The set of elements we use combines information from the calorimeter and the central drift chamber to identify events with an electron candidate and at least one other charged track.

There are two aspects to selecting events: electron identification cuts and tau topology cuts. For electron identification, we match the charged track with energy deposited in the CsI calorimeter and insist that this energy be consistent with the measured momentum of the track. In particular, if p is the momentum of the charged track and E is the associated energy in the calorimeter, we require $0.85 \leq E/p \leq 1.1$. Further, we require that there be at most one nearby photon which could overlap with the electron shower and that there be no associated signal in the muon chambers. Tracks that fail any of these criteria are classified as "$\not e$ ".

The tau event selection cuts are designed to accept two track tau pair events while minimizing the contribution from other processes. Muon pair and Bhabha events can be eliminated by the particle identification criteria (one e, one $\not e$) and by insisting that there be missing energy in the event. Some additional cuts are implemented to reduce the contamination from radiative Bhabhas (such as (d) and (j) below), hadronic events (cut (h) below), and two-photon processes (cut (g) below). The polar angles of the calorimeter shower and the missing momentum in the event are denoted θ_E, and θ_{miss}, respectively. E_{vis} is the total visible energy, charged and neutral, in the event. ΣE is the summed energy of all the calorimeter showers. The event topology cuts applied are:

(a) Exactly two good charged tracks with a net charge of zero.

(b) Both tracks have good, unique matches to calorimeter showers.

(c) One track must be called "e" and the other "$\not e$" by the electron identification criteria.

(d) At most one track with $p \geq 0.85 E_{beam}$.

(e) Both tracks satisfy $p \geq 0.65$ GeV.

(f) $\cos(\theta_E) \leq 0.707$ for the showers matched to charged particle tracks.

(g) $|\cos(\theta_{miss})| < 0.98$.

(h) At most 10 isolated showers in the calorimeter.

(i) $20\% < E_{vis}/E_{cm} < 90\%$.

(j) $(\Sigma E/E_{cm}) < -0.36(|\vec{p}(\not e)|/E_{beam}) + 0.78$.

(k) $|\vec{p}(e)| < 90\%\ E_{beam}$; $|\vec{p}(\not e)| < 96\%\ E_{beam}$.

These cuts select 4899 events in the $\Upsilon(1S)$ data sample, and 5824 events in the continuum sample. Figure 1a. shows the uncorrected momentum distribution of the electron candidate in our continuum events. Figure 1b. shows the uncorrected momentum distribution for the $\not e$ track for the same data. Figures 2a. and 2b. show the same quantities for the $\Upsilon(1S)$ data sample. The normalized tau Monte Carlo curves shown in the figures include the effect of the cuts, but not any background, misidentification, or trigger efficiency effects. The good agreement with the data, especially at higher momentum, demonstrates that the raw samples have small background and fake contaminations. The trigger efficiency effects are addressed below.

A number of background sources were studied. Cosmic rays, μ pairs, beam-wall and beam-gas interactions were investigated using muon chamber, timing, and vertex information. All of these backgrounds were determined to be negligible. Similarly, no radiative

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[2] The terminology a-vs.-b topology refers to a tau-pair event in which the final decay products of one tau includes a charged particles and the final state of the other tau includes b charged particles.

Bhabha events passed our cuts when Monte Carlo events were examined. The most significant backgrounds could potentially come from hadronic and two-photon processes. No hadronic continuum Monte Carlo events ($e^+e^- \to q\bar{q}$) passed our cuts when a fully simulated sample corresponding to an integrated luminosity of 230 pb^{-1} was examined. In addition, over one million $\Upsilon(1S) \to ggg$ Monte Carlo events were studied and only one event passed our cuts. Thus we find our hadronic background to be less than 0.02% in our tau samples. Two-photon Monte Carlo data corresponding to 1299 pb^{-1} with the final state $e^+e^-\tau^+\tau^-$ were examined. Assuming other two-photon processes produce a negligible background, we found 28.3 ± 1.4 two-photon events in our continuum data, and 13.8 ± 0.7 events in the $\Upsilon(1S)$ data. After the continuum subtraction, this background is therefore also negligible, as the 28.3 events scale to 16.1 in the subtraction.

There is also a "background" from real tau events. We take as the fraction of tau events in our signal process $B(\tau^+\tau^- \to e\not{e}) = 2B_e(B_1 - B_e)$, where B_1 is the one prong topological branching fraction and B_e is the electronic branching fraction. (We use values for these branching fractions taken from the Particle Data Group. [1]) Thus any 1-vs.-3 (or 1-vs.-5) tau-pair event, or a 1-vs.-1 tau event where the e or $\not{e}$ has been misidentified is treated as background. The background is most easily expressed as a fraction of the tau-pair events which are "fakes." Using about 100,000 generic Monte Carlo tau-pair events, we found a fake rate of $(4.1 \pm 1.5)\%$ for the $\Upsilon(1S) \to \tau^+\tau^-$ events. The fake rates for continuum tau production at the beam energies of our two data samples differ only slightly from this and from each other.

In calculating this fake rate we used data to determine the fraction of hadrons passing the critical cut, $0.85 < E/p < 1.1$. Muons are very unlikely to deposit this fraction of their energy in the electromagnetic calorimeter, but hadrons occasionally do. Tracks from K^0_s decays in hadronic events were used to measure, as a function of momentum, the fraction of pions which satisfy our E/p cut. The π^+ and π^- have differing fractions and were treated separately in our analysis. (We assume that any differences between kaons and pions are negligible for this purpose since there are approximately twenty times more pions than kaons in our tau events.) A very clean sample of $K^0_s \to \pi^+\pi^-$ candidates was selected by taking oppositely charged tracks from a secondary vertex and requiring that the K^0_s momentum vector point back to the primary vertex. Pion candidates were chosen from those K^0_s candidates with an invariant mass between 0.48 and 0.51 GeV/c^2. If the $p\pi$ invariant mass was consistent with the process $\Lambda \to p\pi^-$, the tracks were rejected to avoid proton contamination. The calculated event selection efficiency for tau-pair events from $\Upsilon(1S)$ decay is $(26.69 \pm 0.21)\%$; this value also depends somewhat upon these fake rates.

Trigger efficiencies were determined from the data. The CLEO II trigger has been described in detail elsewhere [6]. There are three levels to the hardware trigger and each level has several elements associated with different subsystems of the CLEO II detector. We required in our event selection a specific set of four elements, each coming from a different detector subsystem: time-of-flight, barrel calorimeter, central drift chamber, and vertex detector. All trigger element efficiencies were studied using radiative Bhabha events except for the time-of-flight efficiency which was studied in the tau events themselves. Radiative Bhabha events were selected from the same $\Upsilon(1S)$ dataset. The strategy was to look at events which fired a different trigger line which does not involve the detector subsystem under study and measure the fraction of those events that fire the given element. The efficiencies of all but the calorimeter element are found to be independent of momentum in the momentum region of interest (that is, the region $p > 0.60$ GeV/c). The efficiency of the calorimeter element is 100% when the momentum of the electron is greater than 0.95 GeV/c, but decreases with decreasing momentum below that value, down to an efficiency of 86% at $p = 0.65$ GeV/c, the lowest momentum allowed by our selection criteria. We obtained a function giving the trigger efficiency versus momentum by fitting our data. Then taking the fitted function and a Monte Carlo generated momentum distribution for the electrons in our tau events, we calculated a momentum integrated trigger efficiency. Momentum distributions were generated for continuum produced taus at beam energies of 5.263 GeV and 4.730 GeV and for $\Upsilon(1S) \to \tau^+\tau^-$. The three momentum distributions are slightly different and give slightly different efficiencies. For $\Upsilon(1S) \to \tau^+\tau^-$, the trigger efficiency is $(95.1 \pm 1.2)\%$. The error was determined from the statistical errors on the measurements and the spread in values obtained by using different fitting functions. The ratio of the continuum trigger efficiencies at the two beam energies ($\epsilon^{4.730}/\epsilon^{5.263}$) was seen to be quite insensitive to the method of integration over momentum, and is found to be 0.998 ± 0.002.

To calculate the number of tau pair events from $\Upsilon(1S)$ decays, N_τ, we subtract fakes from the raw tau event yields, scale the continuum value (by relative luminosities, cross sections, and efficiencies), subtract it from the $\Upsilon(1S)$ value, and divide by the efficiencies and $B(\tau^+\tau^- \to e\not{e})$. We obtain: $N_\tau = 25100 \pm 1300 \pm 800$. We calculate that 31% of the tau pairs observed at 4.730 GeV are from the $\Upsilon(1S)$ resonance. The quoted systematic error comes from the uncertainties in the trigger efficiencies and fake rates discussed previously, the uncertainties in B_1 and B_e, a 0.5% error in the ratio of luminosities [7], and uncertainties in the ratio of continuum tau-pair cross sections at the two beam energies. The cross sections were calculated from α^3 QED [8]. We found the ratio of the cross sections to be independent of the cutoff energy of the photon and to have an uncertainty of 0.5% [9]. We also studied the sensitivity of the result to the lower bound on the track momenta by varying that cut from 0.65 GeV to 1.0 GeV. This caused N_τ to change by less than 0.5%.

We normalize the number of tau events to the number of hadronic events from the $\Upsilon(1S)$. Hadronic events were selected by requiring three or more charged tracks, $E_{vis} \geq 0.30E_{cm}$, and $\Sigma E \geq 0.12E_{cm}$. The primary event vertex was also required to be consistent with the beam position. From Monte Carlo, we find the efficiency for hadrons from the $\Upsilon(1S)$ resonance is 98.8% with these cuts. The efficiency for continuum hadronic events is 94.0% at the $\Upsilon(1S)$ energy and 94.4% at $E_{beam} = 5.263$ GeV. The continuum subtracted hadronic event yield is found to be $N_{hadron} = 886600 \pm 1100$ events where the error is statistical only. A Monte Carlo calculated tau background of 7300 events was subtracted to arrive at this number. The dominant systematic error comes from the determination of the efficiency for hadrons from the $\Upsilon(1S)$. We examined the agreement between the Monte Carlo simulation and the continuum subtracted hadronic data. The data show an excess at low multiplicity, leading to a possible overestimation of the efficiency. Because the discrepancy tends to produce a lower efficiency and because one cannot have an efficiency in excess of 100%, we assign an asymmetric systematic error of $^{+11,200}_{-36,000}$ events to the number of hadrons.

In obtaining our branching fraction, we first define $\bar{B}$ as the ratio of N_τ to N_{hadron}. Then, assuming lepton universality:

$$B(\Upsilon(1S) \to \tau^+\tau^-) = \frac{\bar{B}}{1 + 3\bar{B}}. \qquad (1)$$

Using the numbers of taus and hadrons we observed gives: $\bar{B} = 0.0283 \pm 0.0014^{+0.0010}_{-0.0015}$, which yields:

$$B(\Upsilon(1S) \to \tau^+\tau^-) = \left(2.61 \pm 0.12 \; ^{+0.09}_{-0.13}\right)\%. \qquad (2)$$

We can test lepton universality by comparing this number to previous measurements of the mu-pair and electron-pair branching fractions. These values are [1]: $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.48 \pm 0.07)\%$, and $B(\Upsilon(1S) \to e^+e^-) = (2.52 \pm 0.17)\%$.[3] We see that our measurement is in closer agreement with lepton universality than the previous world average.

In conclusion, we have measured the tauonic branching fraction of the $\Upsilon(1S)$ resonance. The value we obtain is more precise than previous measurements and is consistent with expectations from lepton universality.

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[3] One can also obtain a branching fraction by assuming only electron-muon universality. Using the muon pair branching fraction quoted above we obtain $B(\Upsilon(1S) \to \tau^+\tau^-) = \left(2.62 \pm 0.13 \; ^{+0.09}_{-0.13}\right)\%$.

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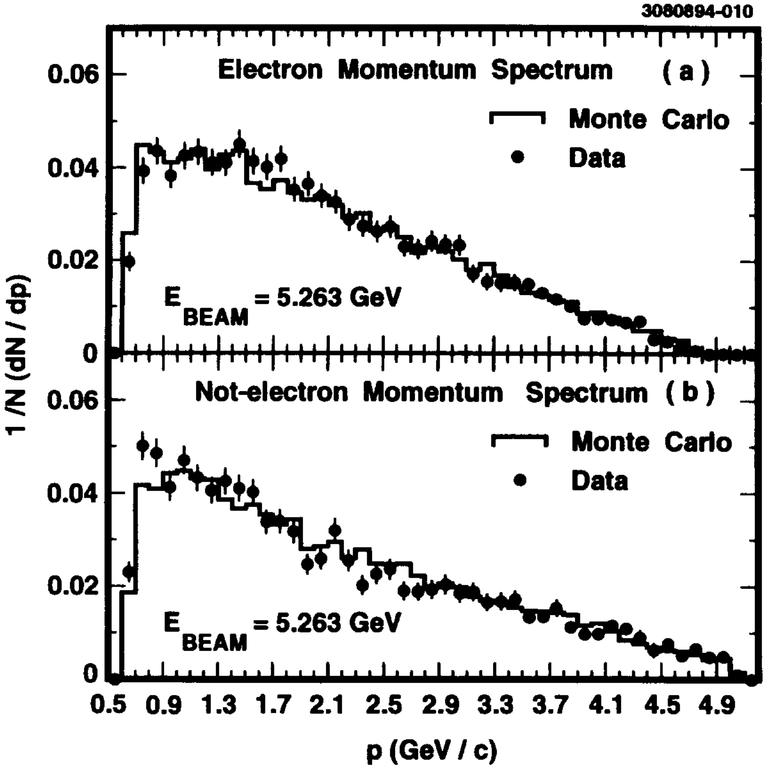

FIG. 1. Momentum distribution of a) the electron candidate and b) the $\not p$ candidate in the continuum data sample. The data are shown by the solid circles and the histogram is from a tau Monte Carlo simulation.

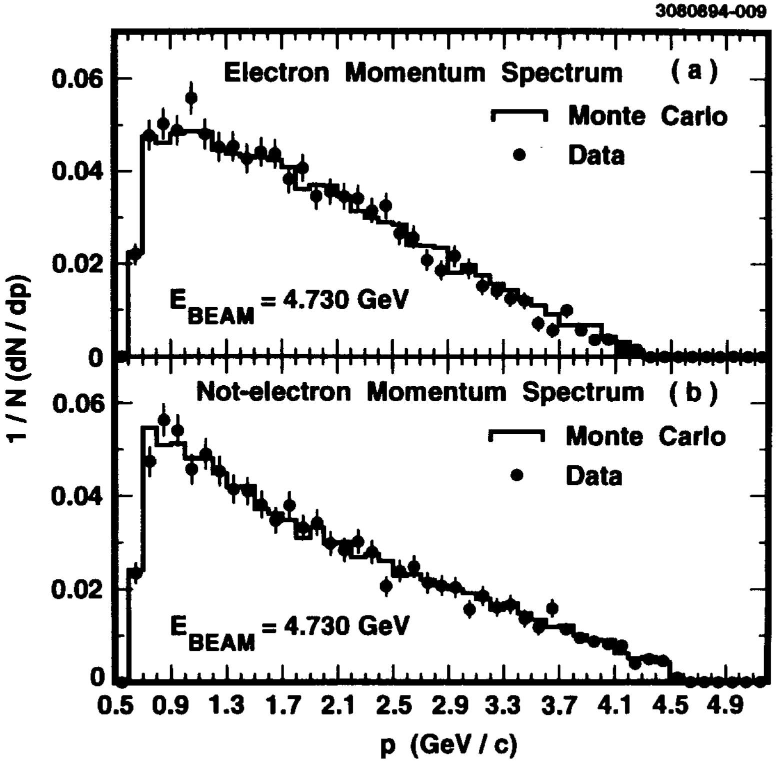

FIG. 2. Momentum distribution of a) the electron candidate and b) the $\not p$ candidate in the $\Upsilon(1S)$ data sample. The data are shown by the solid circles and the histogram is from a tau Monte Carlo simulation.