Search for Invisible Decay of the Υ(1S)

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We report results of a search for the invisible decay of the $\Upsilon(1S)$ via the $\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S)$ transition using a data sample of 2.9 fb^{-1} at the $\Upsilon(3S)$ resonance. The data were collected with the Belle detector at the KEKB asymmetric-energy $e^+ e^-$ collider. No signal is found, and an upper limit for the branching fraction at the 90% confidence level is determined to be $\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 2.5 \times 10^{-3}$.

An invisible particle decay mode is defined as one where the final state particles interact so weakly that they are not observable in a detector. The standard model (SM) predicts that there are no invisible particles except neutrinos. If the invisible decay rate is observed to have a larger branching fraction than the SM prediction, it implies physics beyond the SM. One possibility is a decay into dark matter particles, χ, whose existence is strongly suggested by several astronomical observations [1]. In the SM, quarkonium decay to the two-neutrino final state is predicted to have a branching fraction $\mathcal{B}(\Upsilon(1S) \to \nu\bar{\nu}) = (9.9 \pm 0.5) \times 10^{-6}$ [2]. A much larger invisible branching fraction $\mathcal{B}(\Upsilon(1S) \to \chi\chi)) \simeq 6 \times 10^{-3}$ is predicted [3] for dark matter particles that are lighter than the b quark. Here, the pair annihilation cross section of dark matter particles to a SM quark pair $\sigma(\chi\chi \to q\bar{q})$ is estimated based on cosmological arguments, and the time-reversed reaction is assumed to have the same cross section, i.e., $\sigma(q\bar{q} \to \chi\chi) = \sigma(\chi\chi \to q\bar{q})$. The previous upper limits for the invisible $\Upsilon(1S)$ branching fraction were reported by ARGUS (23×10^{-3} with 90% confidence level) [4] and CLEO (50×10^{-3} with 95% confidence level) [5], which are about 1 order of magnitude above the prediction [3].

In this Letter, we present the result of a search for the invisible decay of the $\Upsilon(1S)$. The data sample used consists of 2.9 fb^{-1} collected on the $\Upsilon(3S)$ resonance [11×10^6

$\Upsilon(3S)$] with the Belle detector [6] at the KEKB asymmetric-energy $e^+ e^-$ [3.4 on 7.8 GeV on $\Upsilon(3S)$] collider [7]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electro-magnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

For this search, we use the $\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S)$ decay where only the cascade $\pi^+ \pi^-$ pair is detected. If an $\Upsilon(1S)$ decay into an invisible final state does occur, it would appear as a peak at the $\Upsilon(1S)$ mass (9.46 GeV/c^2) in the distribution of recoil mass against the $\pi^+ \pi^-$ system ($M_{\pi^+\pi^-}^{\text{recoil}}$) without any detected decay products from the $\Upsilon(1S)$. To provide a clean sample of $\Upsilon(1S)$ decays, we choose to run at the $\Upsilon(3S)$ resonance. Although the $\Upsilon(2S) \to \pi^+ \pi^- \Upsilon(1S)$ branching fraction is about 4 times larger, the low energy of the cascade pions results in a low trigger efficiency. The effective cross section on the $\Upsilon(4S)$ resonance, $\sigma(e^+ e^- \to \Upsilon(4S) \to \pi^+ \pi^- \Upsilon(1S))$, is much smaller than that at the $\Upsilon(3S)$ resonance ($\sim 1/1000$ [8]). To understand the reconstruction efficiency, it is essential

to check that our Monte Carlo (MC) simulation reproduces well the properties of the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ transition. This is confirmed by using a control sample, $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, followed by $\Upsilon(1S) \to \mu^+\mu^-$.

In our trigger system [9], a charged track is required to have hits in more than half the layers of the CDC. Tracks that reach the outermost layer of the CDC are called "long tracks." To suppress beam-induced background events, the trigger system requires two or more charged tracks in an event, and at least one of them should be a long track. The trigger system also requires that the opening angle of the two tracks in the transverse plane be larger than a certain value for the purpose of identifying tracks being different particles. Careful evaluation of the trigger efficiency is important for this analysis. The signal events contain only two charged tracks with relatively small transverse momentum (p_t); the available energy for the signal is 0.89 GeV, which is shared between the two pions. To evaluate the trigger efficiency, we took 1.7 fb^{-1} of data with a trigger condition that required a single long track in an event with a 1/500 prescale rate.

Charged tracks that are reconstructed in the CDC are required to originate from the interaction point: the nearest approach of the trajectory to the collision point is required to satisfy $dr < 1$ cm and $|dz| < 3$ cm, where dz is measured along the direction opposite to the positron beam and dr in the plane perpendicular to it. We also require that the polar angle of the reconstructed track be within the detector acceptance, $17° < \theta < 150°$. Charged kaons are distinguished from pions based on TOF, ACC, and CDC dE/dx measurements. Electron candidates are identified based on the ratio of the energy detected in the ECL to the track momentum, the ECL shower shape, the energy loss in the CDC, and the response of the ACC. Identification of muons is based on track penetration depth and the hit pattern in the KLM system.

To reconstruct events for the control sample, we require four charged tracks in an event, μ^+, μ^-, π^+, and π^-. The $\Upsilon(1S) \to \mu^+\mu^-$ candidates are selected by requiring 9.2 GeV/$c^2 < M_{\mu^+\mu^-} < 9.7$ GeV/c^2 with muon identification for both tracks. For the pions, we reject tracks that are positively identified as electrons or muons. Figure 1 shows the distribution of the mass difference $\Delta M = M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-}$. The signal yield in the control sample is extracted from an unbinned maximum likelihood fit in ΔM. The signal shape is modeled with a triple Gaussian while the background shape is modeled with a first order polynomial whose slope is floated in the fit. We obtain $4902 \pm 71(87 \pm 15)$ signal (background) events in the range of 0.65 GeV/$c^2 < \Delta M < 1.15$ GeV/c^2. Using a detection efficiency of 39.7% for the control sample, which is determined from MC calculations, we estimate that $498 \times 10^3 \, \Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ decays are present in our data set. We compare properties of the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ decay with MC calculations using events in
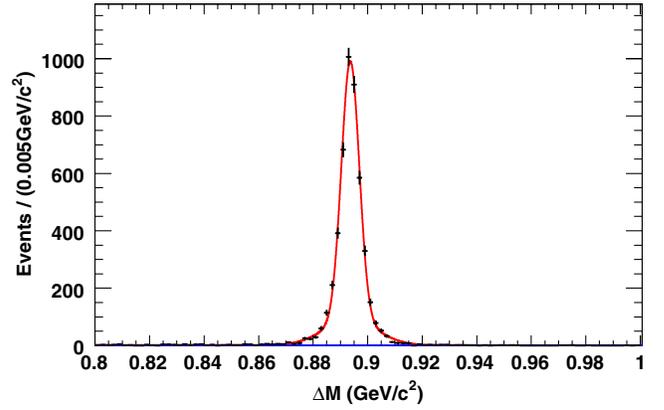
FIG. 1 (color online). Mass difference $\Delta M = M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-}$ distribution where $M_{\mu^+\mu^-}$ lies in the $\Upsilon(1S)$ mass region. The solid curve shows the fits to signal plus background distribution.

the region of 0.875 GeV/$c^2 < \Delta M < 0.910$ GeV/c^2, where the signal purity is 99.9%. The distribution of $\pi^+\pi^-$ invariant masses, $M_{\pi^+\pi^-}$, is well reproduced by the MC calculations as shown in Fig. 2, and the shape is consistent with CLEO results [10] and theoretical models [11]. We also confirm that the MC calculations reproduces well the distributions for other variables in the data such as p_t of pion tracks, the opening angle of the pions in the transverse plane ($\varphi_{\pi\pi}$), the transverse momentum of the $\pi^+\pi^-$ system ($p_t^{\pi\pi}$), the polar angle of the $\pi^+\pi^-$ system ($\cos\theta_{\pi\pi}$), and the polar angle of the muons.

For the selection of the invisible decay candidates, we require two oppositely charged tracks in the event, i.e., $\pi^+\pi^-$ tracks. The total visible energy in the ECL is required to be less than 3 GeV to reject $\Upsilon(1S)$ decays into final states consisting of neutral particles. To minimize any possible trigger bias, we require $\varphi_{\pi\pi} > 30°$, $p_t > 0.17$ GeV/c for the tracks, and $p_t > 0.30$ GeV/c for at least one of the tracks. Most combinatorial background is
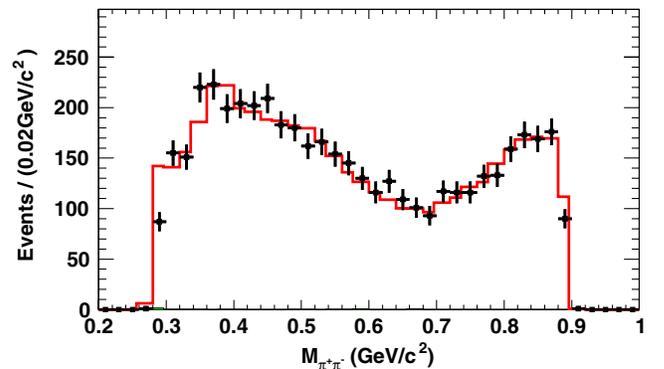
FIG. 2 (color online). Invariant mass distribution of the two cascade pions for the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ cascade decay candidates. The open histogram shows the same distribution for MC calculations events.

from the two-photon processes $e^+ e^- \rightarrow e^+ e^- X$, where the incident e^+ and e^- escape detection and $X \rightarrow \pi^+ \pi^-$, $\mu^+ \mu^-$, $\pi^+ \pi^- \pi^0$ or other states. We reject tracks that are positively identified as electrons, muons, or kaons. We require that no π^0 candidates are observed in the event; we form π^0 candidates using pairs of photons having energies greater than 20 MeV, and requiring a pair invariant mass within ± 16 MeV/c^2 ($\sim 3\sigma$) of the π^0 mass. Events from two-photon process are typically boosted along the beam direction so that the vector p_t sum tends to be small. For further background suppression, a Fisher discriminant variable $\mathcal{F}$ is constructed with the linear combination of $|\cos\theta_{\pi\pi}|$, $p_t^{\pi\pi}$, and the maximum energy of the γ candidates in the event ($E_\gamma^{\max}$), $\mathcal{F} = 0.87 \times |\cos\theta_{\pi\pi}| - 2.4 \times p_t^{\pi\pi} + 1.43 \times E_\gamma^{\max}$, where coefficients are optimized by using MC calculations signal events and background events in the $\pi^+ \pi^-$ recoil mass sideband (9.42 GeV/c^2 < $M_{\pi^+\pi^-}^{\text{recoil}}$ < 9.44 GeV/c^2 or 9.48 GeV/c^2 < $M_{\pi^+\pi^-}^{\text{recoil}}$ < 9.50 GeV/c^2). We require $\mathcal{F} < -0.7$; this requirement is determined using the figure of merit, $S/\sqrt{B}$, where S is the number of signal events in MC calculations and B is the number of background events as mentioned above. The overall detection efficiency, which is the product of the event reconstruction efficiency (9.1%) and the trigger efficiency (89.8%), is 8.2%; thus, we expect 244 signal events in our data sample for $\mathcal{B}(\Upsilon(1S) \rightarrow \chi\chi) = 6 \times 10^{-3}$. The event reconstruction efficiency is obtained from MC calculations.

We estimate the trigger efficiency for signal events by selecting two-pion candidates in the single track trigger data under the same condition as for the signal. We examine the trigger bits that are activated in each of the selected events. The track-finding efficiency of the trigger system is the ratio of number of signal candidates that satisfy the two-track trigger requirement to those that satisfy the single track trigger requirement. We evaluate the track-finding efficiency as a function of p_t requiring a large opening angle $\varphi_{\pi\pi} > 70°$ (the possible bias for two-track separation is negligible in this case). The efficiency for

finding the long track is evaluated with a further requirement that both tracks are long tracks. The efficiency of the long track finding is 97.1% for $p_t > 0.30$ GeV/c. We also evaluate the two-track separation efficiency as a function of $\varphi_{\pi\pi}$, where we require $p_t > 0.30$ GeV/c for the long track and $p_t > 0.17$ GeV/c for the other track. The efficiency for the $\varphi_{\pi\pi} > 30°$ requirement is 92.5%. The detection efficiency for the two-pion signal in the trigger system, which is the product of 97.1% and 92.5%, is 89.8%.

The systematic uncertainties are summarized in Table I. The uncertainty related to the track selection is estimated from the difference of the signal yield in data and MC calculations for the control sample when the dr, dz, particle identification, and other requirements are varied. The error for the π^0 veto, Fisher discriminant, and other requirements are also estimated in a similar way. Uncertainties associated with the modeling of the $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ decay process are estimated by distorting the $M_{\pi^+\pi^-}$ distribution within the statistical error; possible differences in other distributions are also considered. The error for the trigger efficiency is obtained from the quadratic sum of uncertainties for the track-finding efficiency and the two-track separation efficiency. They are conservatively assigned as the differences from 100% efficiencies. Various deviations are evaluated by changing the minimum p_t criteria or polar angle dependences. They are negligibly small.

For those cases where all of the $\Upsilon(1S)$ decay products go outside of the detector acceptance, the $M_{\pi^+\pi^-}^{\text{recoil}}$ distribution still peaks at the $\Upsilon(1S)$ mass and becomes a background to the invisible decay signal. The largest sources of this "peaking background" are from decays to oppositely charged pairs such as $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ or $e^+ e^-$, where the two tracks tend to be back to back, so that when one track escapes into the forward acceptance hole, the other track tends to escape into the backward acceptance hole. The estimated contributions from different decay modes, based on MC calculations, are summarized in Table II. The total number of peaking background events is $133.2^{+19.7}_{-14.6}$, where both statistical and systematic errors are included.

The systematic errors for the peaking background estimation can come from uncertainties in the detection efficiency, branching fractions, MC calculations statistics, and the track-finding efficiency for the tracks from the $\Upsilon(1S)$ decay. For the contribution from the track-finding effi-

TABLE I. Systematic uncertainties for $\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible})$ except for that from peaking background.

Source	(%)
Track selection	5.6
π^0 veto	2.4
Fisher discriminant	6.1
Other selection requirements	1.1
$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$	7.6
Trigger efficiency	8.7
Fit bias	0.2
Statistics of control sample	1.4
$\mathcal{B}(\Upsilon \rightarrow \mu^+ \mu^-)$	2.0
Total	14.7

TABLE II. Expected number of peaking background events.

$\Upsilon(1S) \rightarrow \nu\bar{\nu}$	0.4 ± 0.1
$\Upsilon(1S) \rightarrow \mu^+ \mu^-$	77.3 ± 12.0
$\Upsilon(1S) \rightarrow e^+ e^-$	50.3 ± 8.2
$\Upsilon(1S) \rightarrow \tau^+ \tau^-$	5.2 ± 1.0
Other $\Upsilon(1S)$ decay modes	$0.0 + 2.8$
Other possible contributions	$0.0 + 12.9$
Total	$133.2^{+19.7}_{-14.69}$
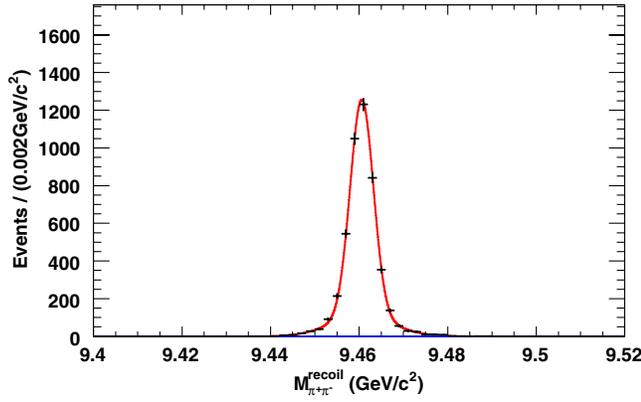
FIG. 3 (color online). $M_{\pi^+\pi^-}^{\text{recoil}}$ distribution for the control sample $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ decay candidates. The solid curve shows the fit results.

FIG. 4 (color online). Recoil mass distribution against two pions, $M_{\pi^+\pi^-}^{\text{recoil}}$. The solid curve shows the result of the fit to signal plus background distributions, the shaded area shows the total background contribution, the dashed line shows the combinatorial background contribution, and the dot-dashed line shows the expected signal for $\mathcal{B}(\Upsilon(1S) \to \chi\chi) = 6 \times 10^{-3}$.

ciency, we evaluate the polar angle dependence of the track-finding efficiency by using the control sample data. Even if we select only one muon and two pions, we can calculate the momentum of the other muon track. We compare the data and corresponding MC calculations. The amount of the peaking background differs by 3.5% between data and MC calculations. The peaking background due to $\Upsilon(1S) \to e^+e^-$ is somewhat lower than that due to $\Upsilon(1S) \to \mu^+\mu^-$. This is due to the fact that the polar angle acceptance of the ECL ($12.4°$–$155.1°$) is larger than that of the CDC ($17.0°$–$150.0°$) and large ECL energy deposits from an electrons can be present in the event, and can veto the event. Other two-body decays, such as $\Upsilon(1S) \to \pi^+\pi^-$ and $p\bar{p}$, are not observed, and their contributions are included systematic error using upper limits from the PDG [12]. We do not observe any background contribution in MC calculations for other $\Upsilon(1S)$, $\Upsilon(3S)$ decays, or modes originating from initial state radiation. The upper limits corresponding to MC calculations statistics are assigned as uncertainties.

The signal extraction is performed by an unbinned extended maximum likelihood fit to the $M_{\pi^+\pi^-}^{\text{recoil}}$ distribution in the range $9.40 \text{ GeV}/c^2 < M_{\pi^+\pi^-}^{\text{recoil}} < 9.52 \text{ GeV}/c^2$. The signal shape is modeled with a double Gaussian that is calibrated using the control sample shown in Fig. 3. In the fit, the amount of peaking background is fixed at the estimated value and the same shape as the signal is used. The shape of the combinatorial background is modeled with a first order polynomial whose slope is floated. Figure 4 shows the $M_{\pi^+\pi^-}^{\text{recoil}}$ distribution. The extracted signal yield, 38 ± 39 events, is consistent with zero observed events. A χ^2 test is performed for the $M_{\pi^+\pi^-}^{\text{recoil}}$ distribution; we obtain $\chi^2/ndf = 23.4/27$. The upper limit for the branching fraction is determined by the Feldman-Cousins frequentist approach [13], taking into account both statistical and systematic uncertainties. We obtain $\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 2.5 \times 10^{-3}$ at the 90% confidence level.

In summary, a search for the invisible decay of the $\Upsilon(1S)$ was performed via the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ transition. In a 2.9 fb^{-1} data sample taken at the $\Upsilon(3S)$ resonance, no signals were found. We obtain an upper limit of 2.5×10^{-3} at the 90% confidence level for $\mathcal{B}(\Upsilon(1S) \to \text{invisible})$. This result disfavors the prediction in Ref. [3] for the $\Upsilon(1S)$ decay to a pair of dark matter particles that are lighter than the b quark.

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