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Observation of $\Upsilon(4S)$ decays to $\pi^+\pi^-\Upsilon(1S)$ and $\pi^+\pi^-\Upsilon(2S)$

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We present the first measurement of $\Upsilon(4S)$ decays to $\pi^+\pi^-\ \Upsilon(1S)$ and $\pi^+\pi^-\ \Upsilon(2S)$ based on a sample of $230{\times}10^6\ \Upsilon(4S)$ mesons collected with the *BABAR* detector. We measure the product branching fractions $\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))\times\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-) = (2.23{\pm}0.25_{stat}{\pm}0.27_{sys})\times10^{-6}$ and $\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S))\times\mathcal{B}(\Upsilon(2S)\to\mu^+\mu^-) = (1.69{\pm}0.26_{stat}{\pm}0.20_{sys})\times10^{-6}$, from which we derive the partial widths $\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = (1.8{\pm}0.4)$ keV and $\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S)) = (2.7\pm0.8)$ keV.

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The $\Upsilon(4S)$ meson is known to decay predominantly to $B\overline{B}$, with small, but as yet unobserved, decays to other bottomonium states or to light hadrons. Partial widths for hadronic transitions in heavy quarkonia have been extensively studied both experimentally and theoretically over the past decades [1]. In particular, the values of the partial widths for dipion transitions between vector states $\psi(2S)\to\pi^+\pi^-J/\psi$ and $\Upsilon(mS)\to\pi^+\pi^-\Upsilon(nS)$, where the principal quantum number $m>n$, can be related to the radial wave function within the framework of the QCD multipole expansion [2]. This picture may be significantly altered by mixing and coupled channel effects [3] when states are close to the threshold for open charm or bottom production. Hence these states are the ideal laboratory to investigate these effects. Exclusive non-$D\overline{D}$ decays of the $\psi(3770)$ (believed to be predominantly $^3D_1$) have recently been observed [4–6], but only upper limits have been published for exclusive non-$B\overline{B}$ decays of the $\Upsilon(4S)$ [7].

We search for the decays $\Upsilon(4S)\to\pi^+\pi^-\Upsilon(nS)$, where $n=1,\,2$ [8], using a sample of $230\times10^6\ \Upsilon(4S)$ events corresponding to an integrated luminosity of 211 fb^{-1} acquired near the peak of the $\Upsilon(4S)$ resonance with the PEP-II asymmetric-energy e^+e^- storage rings at SLAC. An additional 22 fb^{-1} sample collected approximately 40 MeV below the resonance is used as a control sample.

The *BABAR* detector is described in detail elsewhere [9]; here we summarize only the features relevant to this analysis: charged-particle momenta are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer central drift chamber (DCH), both situated in a 1.5-T axial magnetic field. Charged-particle identification is based on the dE/dx measured in the SVT and DCH, and on a measurement of the photons produced in the synthetic fused-silica bars of the ring-imaging Cherenkov detector (DIRC). A CsI(Tl) electromagnetic calorimeter (EMC) is used to detect and identify photons and electrons, while muons are identified in the instrumented flux return of the magnet (IFR).

An $\Upsilon(mS)\to\pi^+\pi^-\Upsilon(nS)$ transition, denoted by $mS\to nS$, is detected by reconstructing the $\Upsilon(nS)$ meson via its leptonic decay to $\mu^+\mu^-$. The sensitivity to $4S\to nS$ transitions is much smaller in the $\pi^+\pi^-e^+e^-$ final state due to the presence of larger backgrounds, and to a trigger-level inefficiency introduced by the prescaling of Bhabha scattering events. Data collected at a nominal center-of-mass energy $\sqrt{s}$ near 10.58 GeV include $3S\to nS$ ($n=1$, 2) and $2S\to1S$ events from initial state radiation (ISR) production that are used as control samples. The signature for $mS\to nS$ transition events, where the nS decays to muons, is a $\mu^+\mu^-$ invariant mass, $M_{\mu\mu}$, that is compatible with the known mass [10] of the $\Upsilon(nS)$ resonance, $M(nS)$, and an invariant mass difference $\Delta M = M_{\pi\pi\mu\mu}-M_{\mu\mu}$ that is compatible with $M(mS)-M(nS)$. The r.m.s. values of the reconstructed ΔM and $M_{\mu\mu}$ distributions are, respectively, ≈ 7 MeV/c^2 and ≈ 75 MeV/c^2. The center-of-mass momentum p^*_{cand} should be compatible with 0 for $4S\to nS$ candidates, or with $\left(s-M^2(mS)\right)/(2\sqrt{s})$ for $mS\to nS$ candidates from ISR.

Simulated Monte Carlo (MC) events are generated using the EvtGen package [11]. The angular distribution of generated dilepton decays incorporates the $\Upsilon(nS)$ polarization, while dipion transitions are generated according to phase space. These events are passed through a detector simulation based on GEANT4 [12], and analyzed in the same manner as data. The events in the data sample whose values of ΔM and $M_{\mu\mu}$ are within 60 MeV/c^2 and 300 MeV/c^2, respectively, of the values expected for any known $mS\to nS$ transition were not examined until the event selection criteria were finalized. Events outside these regions were used to understand the background.

We select events having at least 4 charged tracks with a polar angle θ within the fiducial volume of the tracking system ($0.41<\theta<2.54$ rad). Each muon candidate is required to have a center-of-mass momentum greater than 4 GeV/c, and to be compatible with the muon hypothesis based on the energy deposited in the EMC and the hit pattern in the IFR along the track trajectory. A dipion candidate is formed from a pair of oppositely charged tracks. The two pion candidates are each required to have a transverse momentum greater than 100 MeV/c. The dimuon and the dipion are constrained to a common vertex, and the vertex fit is required to have a χ^2 probability larger than 10^{-3}.

A large fraction of the background is due to $\mu^+\mu^-\gamma$ events where a photon converts in the detector mate-

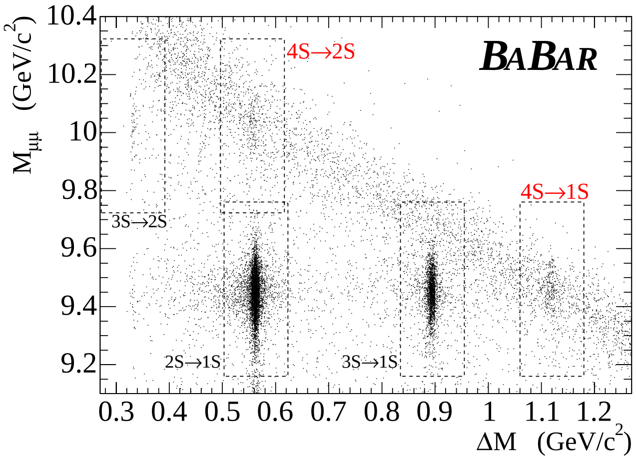

FIG. 1: The $M_{\mu\mu}$ vs. ΔM distribution. Dashed lines delimit the regions where ΔM and $M_{\mu\mu}$ are within ± 60 MeV/c^2 and ± 300 MeV/c^2, respectively, of the values expected for an $mS \to nS$ transition. The remaining region is used to model background. The text discusses the features seen in the data.

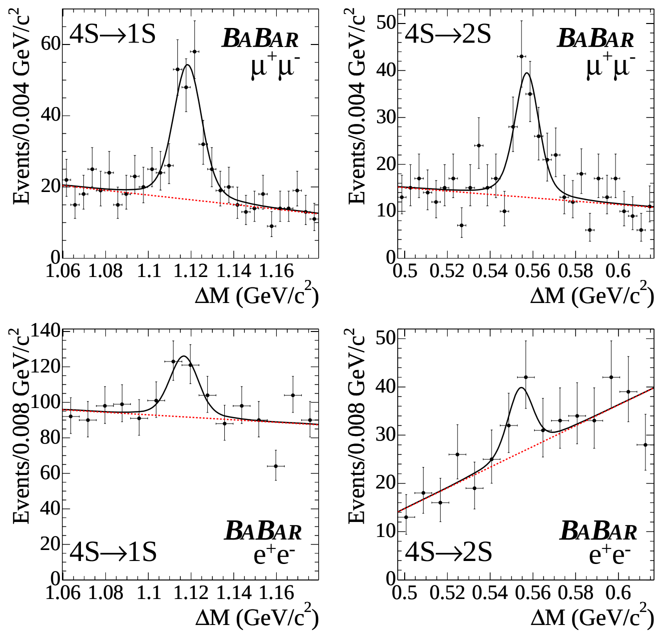

FIG. 2: The ΔM distribution for events with $|M_{\ell^+\ell^-} - M(1S)| < 200\,\mathrm{MeV}/c^2$ (left) and $|M_{\ell^+\ell^-} - M(2S)| < 150\,\mathrm{MeV}/c^2$ (right). The solid lines show the best fit to the data. Dashed lines show the background contribution. The two upper plots are for $\pi^+\pi^-\mu^+\mu^-$ candidates and the two lower plots for $\pi^+\pi^-e^+e^-$ candidates.

rial. To reduce this background we apply an "electron veto", rejecting events where any of the following is true: either of the two pion candidates is positively identified as an electron; the e^+e^- invariant mass of the two charged tracks associated with the pion candidates satisfies $M_{ee} < 100$ MeV/c^2; or the dipion opening angle satisfies $\cos\theta_{\pi^+\pi^-} > 0.95$. The distribution of ΔM vs $M_{\mu\mu}$ for the final sample is shown in Fig. 1. The clusters of events in the boxes centered at $(\Delta M, M_{\mu\mu}) = (1.120, 9.460)$ GeV/c^2 and $(0.558, 10.023)$ GeV/c^2 constitute, respectively, the first observation of $4S \to 1S$ and of $4S \to 2S$ transitions. We also observe signals for $2S \to 1S$, $3S \to 2S$, and $3S \to 1S$ from ISR at $(\Delta M, M_{\mu\mu}) = (0.563, 9.460)$ GeV/c^2, $(0.332, 10.023)$ GeV/c^2, and $(0.895, 9.460)$ GeV/c^2 respectively. The diagonal band is predominantly due to $\mu\mu\gamma$ events, while the cluster at $(\Delta M, M_{\mu\mu}) = (0.332, 9.460)$ GeV/c^2 is due to $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ decays, where $\Upsilon(2S) \to \Upsilon(1S)\,X$.

The number of signal events N_{sig} is extracted by an unbinned extended maximum likelihood fit to the ΔM distribution for events with $p^*_{cand} < 200$ MeV/c and $|M_{\mu\mu} - M(1S)| < 200$ MeV/c^2 for the $4S \to 1S$ mode or $|M_{\mu\mu} - M(2S)| < 150$ MeV/c^2 for the $4S \to 2S$ mode (Fig. 2). In each case, the background is parametrized as a linear function, and the signal as the convolution of a Gaussian with standard deviation σ and a Cauchy function with width Γ, which is found to adequately describe the non-Gaussian tails of the ΔM distribution. The values for σ and Γ are, for each mode, fixed to the values determined from a fit to a MC signal sample subjected to the detector simulation and reconstruction algorithms. We verify that the experimental ΔM resolution is well described by the MC for $2S \to 1S$ and $3S \to nS$ ($n = 1, 2$) ISR samples. The values of ΔM returned by the fit, 1.1185 ± 0.0009 GeV/c^2 and 0.5571 ± 0.0010 GeV/c^2, where the errors are statistical only, are in excellent agreement with the world averages $M(4S) - M(1S) = 1.1197 \pm 0.0035$ GeV/c^2 and $M(4S) - M(2S) = 0.5567 \pm 0.0035$ GeV/c^2 [10]. These values cannot be interpeted as a new measurement of the $\Upsilon(4S)$ mass, since data come from the peak of the resonance and not from a scan of it. The cuts described above are also applied to $\pi^+\pi^-e^+e^-$ candidates, with the additional requirement on the polar angle of the electron, $\theta(e^-) > 0.75$ radians, to reject Bhabha events. The fits to the electron samples are also shown in Fig. 2, and give yields and ΔM values consistent with expectations based on the fits to the muon samples.

The significance, estimated from the likelihood ratio $n\sigma \simeq \sqrt{2\log\left[\mathcal{L}(N_{sig})/\mathcal{L}(0)\right]}$ between a fit that includes a signal function and a fit with only a background hypothesis, is 10.0σ for the $4S \to 1S$ and 7.3σ for the $4S \to 2S$ in the $\pi^+\pi^-\mu^+\mu^-$ final states. The significance of the signals in the $\pi^+\pi^-e^+e^-$ final states is 3.6σ and 2.5σ for $4S \to 1S$ and $4S \to 2S$, respectively.

The event selection efficiency ϵ_{sel} is determined using the MC samples. The largest source of systematic uncertainty (10%) is due to the unknown distribution of the dipion invariant mass in the $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$

TABLE I: Number of signal events, significance, efficiency and measured values of the products of branching ratios for the $4S \to nS$ transitions. The error on the efficiency is obtained adding in quadrature the systematic uncertainties. The errors on the product branching fractions are statistical and systematic respectively

Transition	N_{sig}	significance	ε_{sel} (%)	$\mathcal{B}_{4S\to nS} \times \mathcal{B}_{nS\to\mu\mu}$ (10^{-6})
$4S \to 1S$	167±19	10.0σ	32.5±3.9	2.23±0.25±0.27
$4S \to 2S$	97±15	7.3σ	24.9±3.0	1.69±0.26±0.20

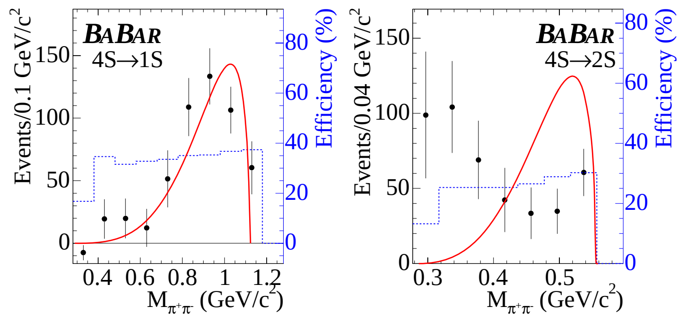

FIG. 3: The efficiency-corrected $M_{\pi^+\pi^-}$ distribution for $4S \to 1S$ transition (left) and $4S \to 2S$ transition (right). The solid line shows the distribution predicted in Ref. [2]. The dotted histogram shows the selection efficiency in each bin. The experimental resolution in $M_{\pi^+\pi^-}$ is less than 5 MeV/c^2, much smaller than the bin size.

transition, and is estimated by comparing the acceptance for a phase space distribution to that obtained using the QCD multipole model [2]. The second largest source of systematic uncertainty is due to uncertainty in the track reconstruction efficiency, which is 1.3% per track, resulting in a 5.2% uncertainty in ϵ_{sel}. The systematic uncertainties associated with the event selection (4.3%) and muon identification (1.4%) criteria are estimated by comparing the efficiency of each selection criterion determined from MC samples to the corresponding efficiency measured with the ISR control samples. We have also considered the systematic uncertainties due to the choice of signal and background parametrizations by using different functions or different parameters, and the systematic uncertainties due to the choice of the fit range. The contributions from these sources are negligible in comparison to the previously mentioned sources.

The product branching fraction (Table I) is determined from the $\pi^+\pi^-\mu^+\mu^-$ sample using:

$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)\right) \times \mathcal{B}\left(\Upsilon(nS) \to \mu^+\mu^-\right) = \frac{N_{sig}}{\varepsilon_{sel}\, N(4S)}, \quad (1)$$

where $N(4S) = (230.0 \pm 2.5) \times 10^6$ is the total number of $\Upsilon(4S)$ mesons produced.

The event yields observed for $3S \to nS$ and $2S \to 1S$ are compatible with PDG-averaged values of the ISR cross section and branching fractions for those resonances. The number of signal events observed in the $\pi^+\pi^-e^+e^-$ final state is compatible with the branching fractions we measure in the $\pi^+\pi^-\mu^+\mu^-$ sample. No $4S \to nS$ signal is observed for $\pi^+\pi^-\mu^+\mu^-$ or $\pi^+\pi^-e^+e^-$ final states in the data collected at center of mass energies 40 MeV below the $\Upsilon(4S)$ resonance.

The dipion invariant mass distribution, $M_{\pi^+\pi^-}$ (Fig. 3), is determined by fitting the ΔM distribution in equal intervals of $M_{\pi^+\pi^-}$, and dividing the number of signal events in each interval by the corresponding selection efficiency. The measured distribution for the $4S \to 1S$ transition has a shape similar to the prediction of the Kuang-Yan model [2]. This model provides a good description of the observed distributions for $2S \to 1S$, $3S \to 2S$, and also $\psi(2S) \to \pi^+\pi^- J/\psi$, but fails to describe the $3S \to 1S$ distribution. Our measured distribution for the $4S \to 2S$ transition has a marked enhancement at low $M_{\pi^+\pi^-}$ that is incompatible with this model.

The $4S \to nS$ branching ratios and partial widths can be derived using the world average values for $\mathcal{B}\left(\Upsilon(nS) \to \mu^+\mu^-\right)$ [10] and a recent *BABAR* measurement of $\Gamma(\Upsilon(4S))$ [13]. We obtain

$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)\right) = (0.90 \pm 0.15) \times 10^{-4},$$
$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)\right) = (1.29 \pm 0.32) \times 10^{-4},$$
$$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (1.8 \pm 0.4)\ \text{keV},$$

and

$$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)) = (2.7 \pm 0.8)\ \text{keV}.$$

We add in quadrature the statistical and systematic uncertainties on the derived quantities. With the most recent CLEO measurement of $\mathcal{B}\left(\Upsilon(2S) \to \mu^+\mu^-\right)$ [14], we obtain smaller values: $\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)\right) = (0.83 \pm 0.16) \times 10^{-4}$ and $\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)) = (1.7 \pm 0.5)$ keV.

The branching fractions are compatible with previous upper limits on these decays [7]. The $\Upsilon(4S)$ partial widths are within the range spanned by other dipion transitions in the $b\bar{b}$ system [10]: $\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)) = (8.1 \pm 2.1)$ keV; $\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)) = (1.2 \pm 0.2)$ keV; $\Gamma(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)) = (0.6 \pm 0.2)$ keV.

In conclusion, we measure

$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)\right) \times \mathcal{B}\left(\Upsilon(1S) \to \mu^+\mu^-\right) = (2.23 \pm 0.25 \pm 0.27) \times 10^{-6}$$

and

$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)\right) \times \mathcal{B}\left(\Upsilon(2S) \to \mu^+\mu^-\right) = (1.69 \pm 0.26 \pm 0.20) \times 10^{-6} \quad .$$

The dipion invariant mass distribution is measured for $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$ transitions; the latter is found to be incompatible with predictions from QCD multipole expansions.

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