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Observation of a Narrow Resonance of Mass 2.46 GeV/c^2 in the $D_s^{*+}\pi^0$ Final State, and Confirmation of the $D_{sJ}^*(2317)$*

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Abstract

Using 13.5 fb^{-1} of e^+e^- annihilation data collected with the CLEO-II detector, we have observed a new narrow resonance in the $D_s^{*+}\pi^0$ final state, with a mass near 2.46 GeV/c^2. The search for such a state was motivated by the recent discovery by the BABAR Collaboration of a narrow state at 2.32 GeV/c^2, the $D_{sJ}^*(2317)^+$, that decays to $D_s^+\pi^0$. Reconstructing the $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ final states in CLEO data, we observe a peak in each of the corresponding reconstructed mass difference distributions, $\Delta M_{D_s\pi^0} = M(D_s\pi^0) - M(D_s)$ and $\Delta M_{D_s^*\pi^0} = M(D_s^*\pi^0) - M(D_s^*)$, both of them at values near 350 MeV/c^2. These peaks constitute statistically significant evidence for two distinct states, at 2.32 and 2.46 GeV/c^2, taking into account the background source that each state comprises for the other in light of the nearly identical values of ΔM observed for the two peaks. We have measured the mean mass differences $\overline{\Delta M}_{D_s\pi^0} = 350.4 \pm 1.2$ [stat.] ± 1.0 [syst.] MeV/c^2 for the $D_{sJ}^*(2317)^+$ state, and $\overline{\Delta M}_{D_s^*\pi^0} = 351.6 \pm 1.7$ [stat.] ± 1.0 [syst.] MeV/c^2 for the new state at 2.46 GeV/c^2. We have also searched, but find no evidence, for decays of $D_{sJ}^*(2317)$ into the alternate final states $D_s^{*+}\gamma$, $D_s^+\gamma$, and $D_s^+\pi^+\pi^-$. The observations of the two states at 2.32 and 2.46 GeV/c^2, in the $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ decay channels respectively, are consistent with their possible interpretations as $c\bar{s}$ mesons with orbital angular momentum $L = 1$, and spin-parity $J^P = 0^+$ and 1^+.

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The BABAR Collaboration has recently reported [1] evidence for a new narrow resonance with mass near 2.32 GeV/c^2, in the $D_s^+\pi^0$ final state. The BABAR data is consistent with the identification of this state as one of the four lowest-lying members of the $c\bar{s}$ system with orbital angular momentum $L = 1$, and provisionally it has been named the $D_{sJ}^*(2317)$ meson. A natural candidate would be the $^3P_0$ $c\bar{s}$ state with spin-parity $J^P = 0^+$, but other possibilities, including exotic states, are not ruled out. In this paper, we report on a search for the $D_{sJ}^*(2317)$ meson, as well as other, possibly related states, in data collected with the CLEO II detector in symmetric e^+e^- collisions at the Cornell Electron Storage Ring, at center-of-mass energies $\sqrt{s} \sim 10.6$ GeV.

The spectroscopy of P-wave $c\bar{s}$ mesons is summarized in Ref. [2]. Theoretical expectations [3–7] were that: (1) all four states $L = 1$ are massive enough that their dominant strong decays would be to the isospin-conserving DK and/or D^*K final states, (2) the singlet and triplet $J^P = 1^+$ states could mix, and (3) in the heavy quark limit, the two states with $j = 3/2$ would be narrow while the two with $j = 1/2$ would be broad, where j is the sum of the strange quark spin and the orbital angular momentum. Existing experimental evidence [8, 9] for the narrow $D_{s1}(2536)$ and $D_{sJ}^*(2573)$ mesons which decay dominantly to D^*K and DK respectively, and the compatibility of the $D_{sJ}^*(2573)$ with the J^P assignment as 2^+ support this picture.

The observation by BABAR [1] of the new state is surprising because: (1) it is narrow (with intrinsic width $\Gamma < 10$ MeV), (2) it has been observed in the isospin-violating $D_s\pi^0$ channel, and (3) its mass (2316.8 ± 0.4 [stat.] MeV/c^2) is smaller than most theoretical predictions for a 0^+ $c\bar{s}$ state that could decay via this channel. However, points (1) and (2) would be obvious consequences of the low mass, since the $D^{(*)}K$ decay modes would not be allowed kinematically. We also note that at least one theoretical calculation [10] had suggested that in the heavy quark limit the mass splittings between the 0^+ and 0^- states of flavored mesons could be as small as 338 MeV/c^2, which is near the $D_{sJ}^*(2317)^+ - D_s^+$ mass splitting of 348.3 MeV/c^2 measured by BABAR.

Since the initial observation, a number of explanations have appeared [11–15]. Cahn and Jackson [11] apply non-relativistic vector and scalar exchange forces to the constituent quarks. Barnes, Close and Lipkin [12] consider a quark model explanation unlikely and propose a DK molecular state. Similarly Szczepaniak [15] suggests a $D_s\pi$ atom. Bardeen, Eichten and Hill [14], on the contrary, couple chiral perturbation theory with a quark model representation in heavy quark effective theory, building on the model described in Ref. [10]. They infer that the $D_{sJ}^*(2317)$ is indeed the 0^+ $c\bar{s}$ state, predict the existence of the 1^+ partner of this state with a $1^+ - 0^+$ mass splitting equal to the $D_s^*(2112) - D_s$ (*i.e.*, $1^- - 0^-$) mass splitting, and compute the partial widths for decays to allowed final states. Van Beveren and Rupp [13] also present arguments supporting a low mass for the 0^+ $c\bar{s}$ state, by analogy with members of the light scalar meson nonet.

The goals of the analysis presented here are to use CLEO data to shed additional light on the nature of the $D_{sJ}^*(2317)$, to provide independent evidence regarding its existence, and to search for decays of other new, possibly related states. In particular, we address the following questions. Are the electromagnetic decays $D_s\gamma$ or $D_s^*\gamma$ observable in light of the isospin suppression of the strong decay to $D_s\pi^0$? Are other strong decays observable such as $D_s^*\pi^0$, or the isospin-conserving but Okubo-Zweig-Iizuka (OZI) suppressed [16] decay $D_s\pi^+\pi^-$? If the $D_{sJ}^*(2317)$ is the expected 0^+ $c\bar{s}$ state, might the remaining 1^+ state also be below threshold for decay to D^*K, as suggested in Ref. [14], and thus be narrow enough to be observable in its decays to $D_s^*\pi^0$, $D_s\gamma$ or $D_s^*\gamma$?

This article is organized as follows. After describing the detector and data set, we summarize the reconstruction of the $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ decay channel, including efforts to understand and exclude contributions from known background processes. We then report on searches for other possible decay channels as described in the preceding paragraph. We report on the appearance of a statistically significant signal in the $D_s^{*+}\pi^0$ channel, but at a location not compatible with $D_{sJ}^*(2317)^+$. We describe a quantitative analysis of the signals in the $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ channels, leading us to infer the existence of two distinct states. Based on this conclusion, we discuss the properties of these two states, after which we summarize the principal results of the analysis.

The analysis described here is based on 13.5 fb^{-1} of e^+e^- collision data collected between 1990 and 1998. CLEO II is a general-purpose, large-solid-angle, cylindrical detector featuring precision charged-particle tracking and electromagnetic calorimetry, and is described in detail in Refs. [17, 18]. In its initial configuration, the tracking system was comprised of a six-layer straw tube chamber just outside of a 3.2-cm radius beryllium beam pipe, followed by a 10-layer hexagonal-cell drift chamber and a 51-layer square-cell drift chamber, immersed in a 1.5-T magnetic field generated by a superconducting solenoid. In 1995, the beam pipe and straw tubes were replaced by a 2.0-cm radius beam pipe plus three layers of silicon strip detectors each with double-sided readout, and a helium-propane gas mixture replaced the argon-ethane mixture previously used in the main drift chamber.

Beyond the tracking system but within the solenoid were also located a 5-cm thick plastic scintillation counter system for time-of-flight measurement and triggering, as well as a barrel calorimeter consisting of 6144 tapered CsI(Tl) crystals 30-cm in length and arrayed in a projective geometry with their long axis oriented radially with respect to the e^+e^- interaction point. An additional 1656 crystals were deployed in two end caps to complete the solid angle coverage. The excellent energy and angular resolution of the calorimeter is critical for the reconstruction of $\pi^0 \to \gamma\gamma$ decays as well as single low-energy photons such as those emitted in the $D_s^{*+} \to D_s\gamma$ transition.

The search for the $D_{sJ}^*(2317)$ was carried out by reconstructing the $D_s^+\pi^0$ state, using the $D_s^+ \to \phi\pi^+$ channel with $\phi \to K^+K^-$. Charge conjugation is implied throughout this report. Pairs of oppositely-charged tracks were considered as candidates for the decay products of the ϕ if the specific ionization (dE/dx) is measured in the main drift chamber to be within 2.5 standard deviations of expectations for kaons, and if the invariant mass of the K^+K^- system was within ± 10 MeV/c^2 of the ϕ mass. A third track with dE/dx consistent with the expectation for a pion was combined with the K^+K^- system to form a D_s^+ candidate. The observed D_s^+ peak has a Gaussian width (σ) of 6.4 ± 0.2 MeV/c^2 in our data, consistent with CLEO Monte Carlo simulations of D_s production and decay plus a GEANT-3 [19] based simulation of particle propagation and detector response.

Pairs of clusters of energy deposition of greater than 100 MeV apiece, of which one cluster must lie in the central region of the calorimeter ($|\cos\theta| < 0.71$, where θ is measured with respect to the beam axis) were selected as the candidates for photons from π^0 decay if they satisfied $122 < M(\gamma\gamma) < 148$ MeV/c^2. The $M(\gamma\gamma)$ distribution for photon-pairs accompanying a D_s^+ candidate with $M(KK\pi)$ between 1.955 and 1.979 GeV/c^2 has a width of 5.8 ± 0.4 MeV/c^2 in our data, consistent with expectations from the Monte Carlo simulations.

To suppress combinatoric backgrounds, we further required that the momentum of the $D_s^+\pi^0$ candidate be greater than 3.5 GeV/c. We also required that the helicity angle of the $\phi \to K^+K^-$ decay satisfy the requirement $|\cos\theta_h| > 0.3$, where θ_h is the angle between the K^+ momentum vector, as measured in the ϕ rest frame, and the ϕ momentum vector, as

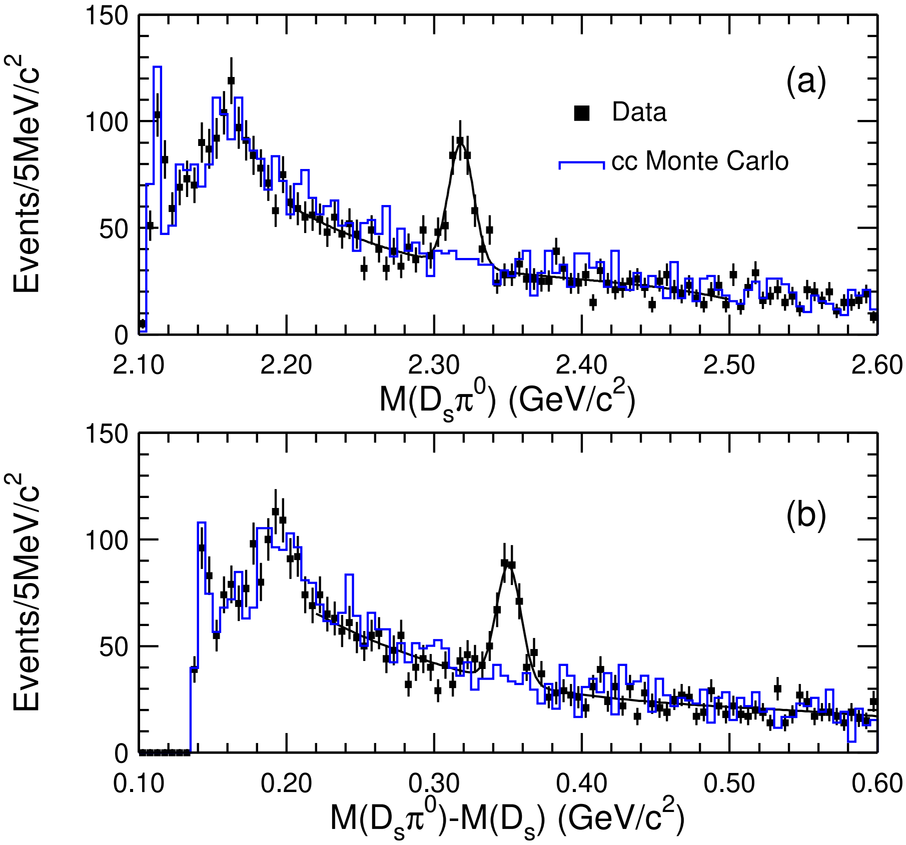

FIG. 1: The $M(KK\pi\pi^0)$ mass and $M(KK\pi\pi^0) - M(KK\pi)$ mass difference for events satisfying cuts on $M(KK\pi)$ consistent with the D_s and $M(\gamma\gamma)$ consistent with the π^0, as described in the text. The points represent the CLEO data, while the solid histogram is the predicted spectrum from the Monte Carlo simulation of $e^+e^- \to c\bar{c}$ events. The predicted spectrum is normalized to the data in the region between 2.50 and 2.60 GeV/c^2. The overlaid curve represents the results from a fit of the data to a Gaussian signal function plus a polynomial background function.

measured in the D_s rest frame. The expected distribution from real ϕ decays varies as $\cos^2\theta_h$, whereas combinatoric backgrounds tend to be flat. For $D_s\pi^0$ combinations satisfying these requirements, we plot the mass $M(KK\pi\pi^0)$ and the mass difference $\Delta M = M(KK\pi\pi^0) - M(KK\pi)$ in Fig. 1. To improve the experimental resolution on $M(KK\pi\pi^0)$, the true D_s mass has been used to determine the energy of the $KK\pi$ system from its measured momentum in Fig. 1(a); this substitution is not done for ΔM in Fig. 1(b), or for the calculation of other mass differences entering this analysis.

The narrow peaks in Fig. 1 at mass near 2.32 GeV/c^2 and ΔM near 350 MeV/c^2 are in qualitative agreement with the BABAR observation. We note that there are no peaks in this region when $KK\pi$ combinations with $M(KK\pi)$ lying in D_s side bands are combined with a π^0. The other features in the spectra shown in Fig. 1, namely the sharp signal from $D_s^{*+} \to D_s^+\pi^0$ [20] near the kinematic threshold and the broad enhancement above this (due primarily to $D_s^{*+} \to D_s^+\gamma$ plus a random photon, as well as a small contribution from $D^+ \to K^-\pi^+\pi^+\pi^0$ with a mass mis-assignment), correspond well with the features present in the BABAR data. In addition, Monte Carlo simulations of inclusive charmed hadron production via $e^+e^- \to c\bar{c}$ give $M(D_s^+\pi^0)$ and ΔM spectra that reproduce the features observed in the data, except for the peak at 2.32 GeV/c^2 and 350 MeV/c^2. This is also illustrated in Fig. 1, where normalizations of each of the $c\bar{c}$ Monte Carlo spectra are fixed so as to match the last 20 bins of the corresponding data spectrum.

We have investigated mechanisms by which a peak at 2.32 GeV/c^2 could be generated from decays involving known particles, either through the addition, omission or substitution of a pion or photon, or through the mis-assignment of particle masses to the observed charged particles. In no cases were narrow enhancements in the $M(D_s^+\pi^0)$ spectrum near 2.32 GeV/c^2 observed. We will discuss the issue of feed down from a possible new resonance at 2.46 GeV/c^2 when we describe our studies of the $D_s^{*+}\pi^0$ final state.

From a fit to the ΔM distribution with a Gaussian signal shape and 3rd order polynomial background function, we obtain a yield of 231^{+31}_{-29} events in the peak near 350 MeV/c^2. From Monte Carlo simulations, the detection efficiency associated with the reconstruction of the full $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$, $D_s^+ \to \phi\pi^+$, $\phi \to K^+K^-$ decay chain is $(13.1 \pm 0.7)\,\%$ for the portion of the $D_{sJ}^*(2317)^+$ momentum spectrum above 3.5 GeV/c, where this efficiency does not include the D_s and ϕ decay branching fractions.

The fit returns a mean and Gaussian width for the $D_{sJ}^*(2317)$ peak of $\overline{\Delta M} = 350.3 \pm 1.0$ MeV/c^2 and $\sigma = 8.4^{+1.4}_{-1.2}$ MeV/c^2, respectively, where the errors are due to statistics only. The expected mass resolution is $6.4{\pm}0.4$ MeV/c^2, somewhat smaller than the width returned from the fit to the CLEO data. Further discussions of the broader-than-expected width, as well as of systematic errors in the measurements of the mass and width of the $D_{sJ}^*(2317)$ appear later in this article. However, the mean mass difference and width of the peak are consistent with the corresponding BABAR values [1]. Thus, we confirm the existence of a peak in the $D_s\pi^0$ mass spectrum that cannot be explained as reflections from decays of known particles.

The conclusion that the $D_{sJ}^*(2317)$ is a new narrow resonance decaying to $D_s\pi^0$ leads to two questions: (1) are there other observable decay modes, and (2) might additional new $c\bar{s}$ resonances also exist in which normally suppressed decay modes such as $D_s^{(*)}\pi^0$ are dominant? To answer these questions we have searched in the channels $D_s\gamma$, $D_s^*\gamma$, $D_s^*\pi^0$ and $D_s\pi^+\pi^-$.

If the $D_{sJ}^*(2317)$ is a 0^+ $L=1$ $c\bar{s}$ meson as has been suggested [14], it could decay via S- or D-wave to $D_s^*\gamma$, but would not be able to decay to $D_s\gamma$ due to parity and angular momentum conservation. Consequently, observation of one or the other of these channels would be interesting. On the other hand, if neither channel is seen, this would not be too surprising since these are electromagnetic decays, and the $D_s\pi^0$ decay, while isospin-violating, is not as severely phase-space suppressed as in the case of the corresponding decay of the D_s^* where the electromagnetic decay dominates. The BABAR data show no evidence for either channel, however no upper limits were reported on the branching ratios for these channels.

With regard to strong decays, the $D_s\pi^+\pi^-$ final state is kinematically allowed and isospin-conserving, but would be suppressed by the OZI rule. This is in contrast to the $D_s\pi^0$ channel for which one mechanism would be decay to a D_s plus a virtual η, with production of the π^0 via η-π^0 mixing [21]. Observation of the $D_s\pi^+\pi^-$ channel would be strong evidence against the interpretation of the $D_{sJ}^*(2317)$ as a 0^+ meson.

Finally, it is possible that the remaining $L=1$ $c\bar{s}$ state with $J^P = 1^+$ could also be light enough that decays to D^*K would be kinematically forbidden. In this case, the strong isospin-violating decay of this 1^+ state to $D_s^*\pi^0$ could occur via S-wave (the electromagnetic

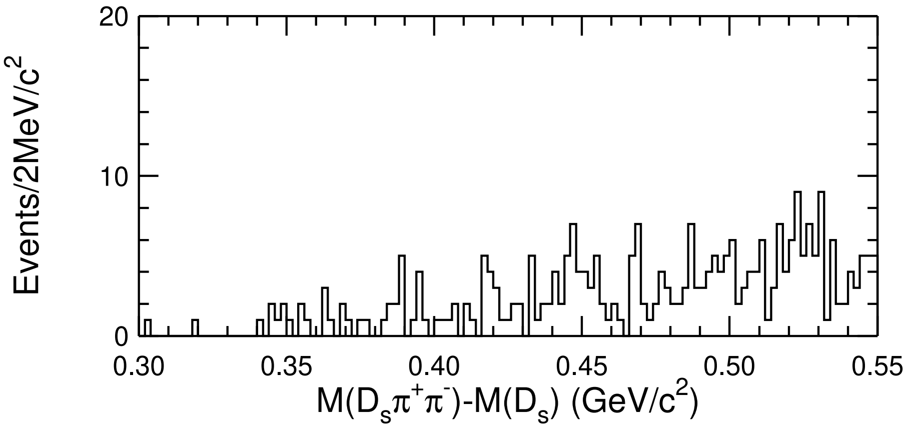

FIG. 2: The mass difference $M(D_s\pi\pi) - M(D_s)$ for $D^*_{sJ}(2317)^+ \to D_s^+\pi^+\pi^-$ candidates, as described in the text.

decays to $D_s\gamma$ or $D_s^*\gamma$ would also be possible), and thus a peak in the $\Delta M_{D_s^*\pi^0} = M(D_s\gamma\pi^0) - M(D_s\gamma)$ spectrum would be a compelling signature of such a state.

To look for these channels we select events containing $D_s^+ \to \phi\pi^+$ candidates as in the $D_s\pi^0$ analysis. For the $D_s\pi^+\pi^-$ channel, we combine the D_s candidates with two oppositely charged tracks, and plot the mass difference $\Delta M_{D_s\pi\pi} = M(D_s\pi\pi) - M(D_s)$, where $M(D_s) = M(KK\pi)$, as shown in Fig. 2. No signal is evident.

To search for states decaying to $D_s^+\gamma$, as well as to select D_s^{*+} candidates for use in other searches, we have formed $D_s^+\gamma$ combinations by selecting photons of energy greater than 150 MeV. We ignore photons that can be paired with another photon such that $M(\gamma\gamma)$ is consistent with π^0 decay. The inclusive $\Delta M_{D_s\gamma} = M(KK\pi\gamma) - M(KK\pi)$ spectrum for this sample is plotted in Fig. 3(a), illustrating that a large D_s^* sample can be obtained. For decay modes with a D_s^* in the final state, We select $D_s\gamma$ combinations where $M(D_s\gamma)$ is reconstructed to be between 2.090 and 2.130 GeV/c^2.

Also visible in Fig. 3(a), are regions of the $\Delta M_{D_s\gamma}$ spectrum where decays of the $D^*_{sJ}(2317)$ (or of a possible higher mass state) into $D_s\gamma$ would appear. There is no evidence for a signal corresponding to a $M(D_s\gamma)$ in the vicinity of 2.32 GeV/c^2, or elsewhere in the plotted region.

The same conclusion holds for the $D_s^*\gamma$ final state, shown in Fig. 3(b), where we combine selected D_s^* candidates with photons of energy above 200 MeV. The peak in the $\Delta M_{D_s^*\gamma}$ spectrum in Fig. 3(b) near 150 MeV is due to real $D_s^{*+} \to D_s^+\gamma$ decays in which a random photon has been combined with the D_s^+ candidate to form the D_s^* candidate, and the actual photon from this transition is combined with this system to form the D^*_{sJ} candidate. There is no sign of any additional structure in this spectrum.

We have also searched in the $D_s^{*+}\pi^0$ channel for D^*_{sJ} states. This analysis was carried out with different selection criteria than the channels described above. Fig. 4(a) shows the mass difference plot for events with candidate $D_s^+ \to \phi\pi^+$, $D_s^{*+} \to \gamma D_s^+$ and di-photon combinations consistent with being π^0 candidates. Other requirements are similar to those described in preceding sections of this paper, except that all photon candidates are required to be in the central region of the calorimeter, and we do not veto extra photons consistent with π^0 decay to maintain efficiency. As before, the $D_s^*\pi^0$ candidates are required to have momenta above 3.5 GeV/c. A signal is apparent at a ΔM of 350.6 ± 1.2 MeV/c^2, with

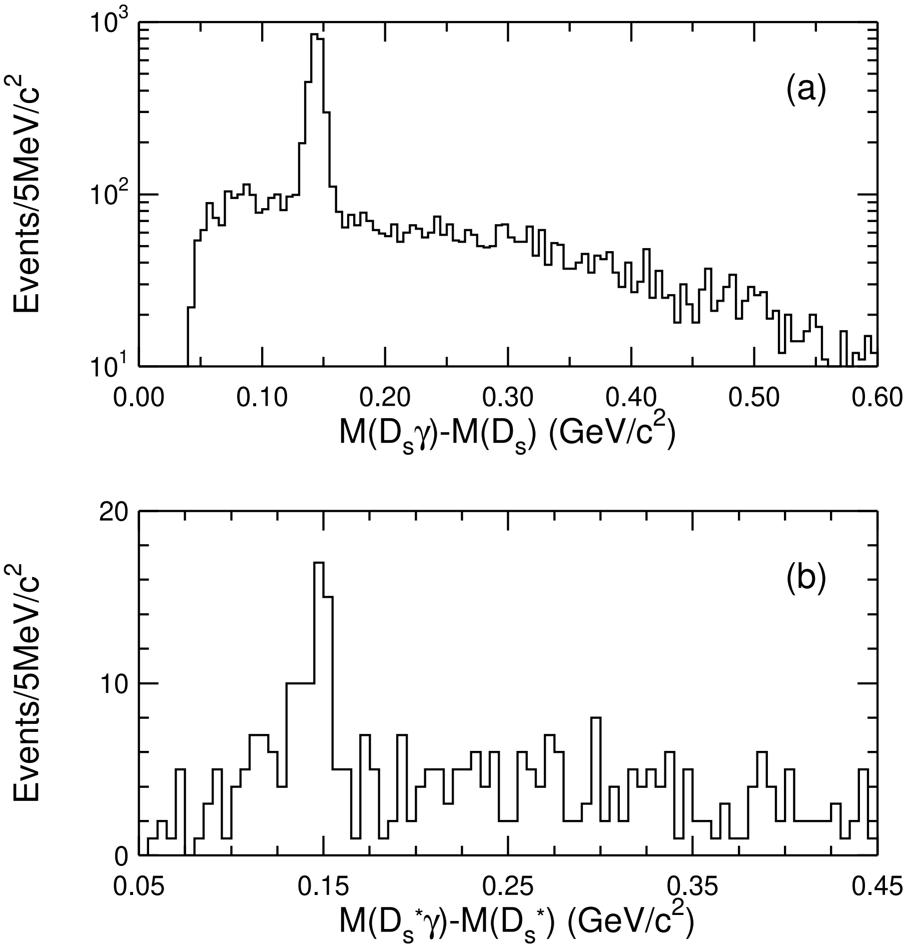

FIG. 3: (a) Spectrum of the mass difference $M(KK\pi\gamma) - M(KK\pi)$, plotted on a logarithmic scale. The peak is due to the transition $D_s^{*+} \to D_s^+\gamma$. (b) Spectrum of the $M(D_s^*\gamma) - M(D_s^*)$ mass difference for $D_s^*\gamma$ candidates.

a width of 6.1 ± 1.0 MeV/c^2 consistent with our mass resolution of 6.6 ± 0.5 MeV/c^2. A fit to a Gaussian signal plus polynomial background yields 53.3 ± 9.7 signal events. If the $D_{sJ}^*(2317)^+$ were to decay to the $D_s^{*+}\pi^0$ final state, a peak would be expected at a ΔM of ~ 205 MeV/c^2. The existence of a peak at 351 MeV/c^2 leads us to investigate the possibility of a second narrow resonance with a mass near 2463 MeV/c^2 that decays to $D_s^{*+}\pi^0$. We note that a similar peak is also present in the $M(D_s^*\pi^0)$ spectrum observed by BABAR [1], although BABAR does not claim this as evidence for a new state. For ease of notation, we refer to the postulated particle as the $D_{sJ}^*(2463)^+$.

The kinematics of the $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ decays are quite similar, and it is possible that they can reflect into one another, as noted in Ref. [1]. For example, taking $D_s^{*+}\pi^0$ events and ignoring the photon we find that essentially all the putative signal events form a peak in the $D_s^+\pi^0$ mass spectrum in the same location as the $D_{sJ}^*(2317)$ signal described in previous sections of this report. It is also possible that the $D_s^+\pi^0$ signal can pick up a random photon such that the $D_s^+\gamma$ combination accidentally falls in the D_s^{*+} signal region described earlier. In this case, $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ decays would reflect into the $D_{sJ}^*(2463)^+ \to D_s^{*+}\pi^0$ signal region. A Monte Carlo simulation of $D_{sJ}^*(2317)^+$ production and decay to $D_s^+\pi^0$ shows that

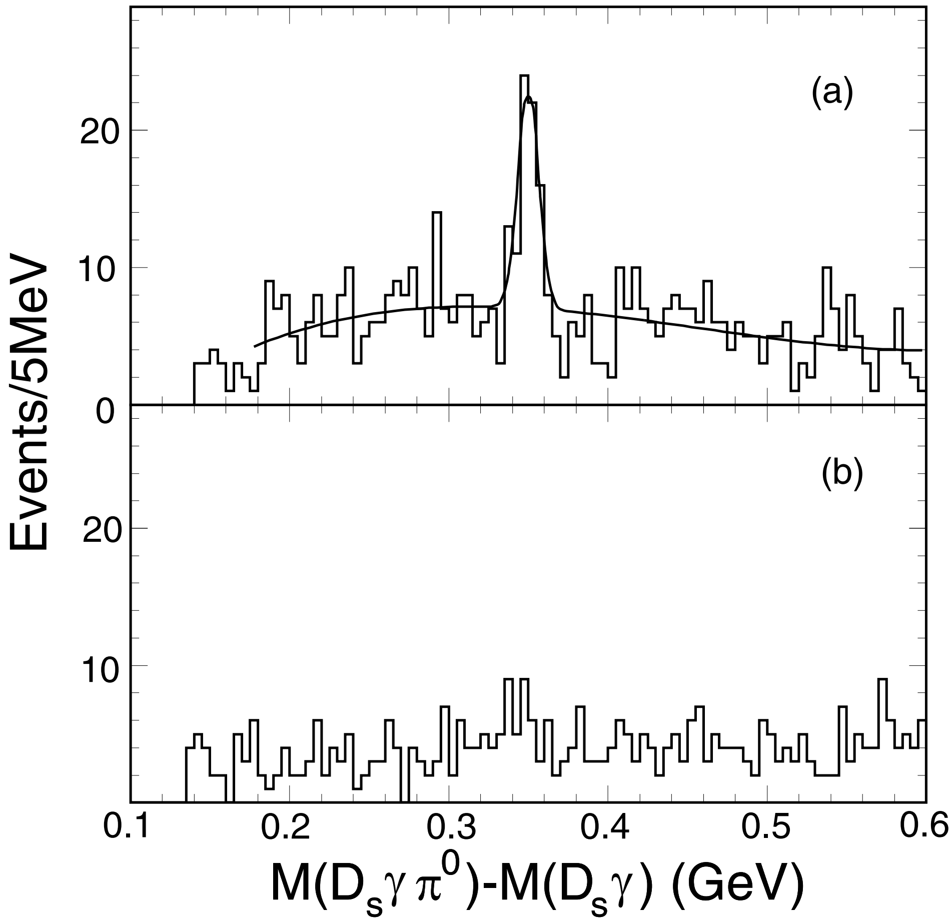

FIG. 4: (a) The mass difference spectrum $\Delta M_{D_s^*\pi^0} = M(D_s\gamma\pi^0) - M(D_s\gamma)$ for combinations where the $D_s\gamma$ system is consistent with D_s^* decay, as described in the text. (b) The corresponding spectrum where $D_s\gamma$ combinations are selected from the D_s^* side band region.

this does happen, but only for approximately 9% of the reconstructed events. By applying the same selection criteria as described in the preceding paragraph, except without selecting the photon from the $D_s^* \to D_s\gamma$ transition, we obtain 160.2 ± 18.5 candidates for the decay $D_{sJ}^*(2317) \to D_s\pi^0$.

With this information, we can extract the number of real $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ events in our data, denoted as R_0, as well as the number of real $D_{sJ}^*(2463)^+ \to D_s^{*+}\pi^0$ events, denoted as R_1, taking into account that the real signal events can both feed each other. The observed numbers of events are $N_0 = 160.2 \pm 18.5$ $D_s\pi^0$ events and $N_1 = 53.3 \pm 9.7$ $D_s^*\pi^0$ events. The following equations relate the real to observed numbers:

$$N_0 = R_0 + R_1 * f_1 \tag{1}$$

$$N_1 = R_1 + R_0 * f_0 \tag{2}$$

where R_x is number of real events produced times the efficiency to observe them as signal, and f_x is the probability to feed up or feed down relative to the reconstruction efficiency for the respective signal modes. We note that these relations represent first-order approximations; the higher-order corrections are negligible in the present case. From our simulation we measure $f_0 = 0.0910 \pm 0.0072$ for the probability that a reconstructed $D_{sJ}^*(2317) \to D_s\pi^0$ can be combined with a random photon so as to mimic a $D_{sJ}^*(2463)$ candidate. We also obtain $f_1 = 0.840 \pm 0.044$, which includes the probability of feed down as well as the photon finding efficiency.

Solving these equations we find that $R_0 = 124.9 \pm 22.5$ events and $R_1 = 41.9 \pm 10.7$ events, where the uncertainties include both statistical and systematic sources. The result for R_1 provides strong evidence for the existence of a state at 2463 MeV/c^2. The statistical significance of the signal is estimated to be in excess of $5\,\sigma$ by computing the probability for the combinatoric background plus the feed up background to fluctuate up so as to give the observed yield of 53.3 events in the peak in Fig. 4(a).

We have also carried out a direct estimate of the background in Fig. 4(a) due to $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ plus random photon combinations, by selecting events in D_s^* side band regions in the $D_s\gamma\pi^0$ sample. The ΔM distribution for this sample, shown in Fig. 4(b), shows only a small enhancement in the region of the $D_{sJ}^*(2463)$, thereby demonstrating that the background from $D_{sJ}^*(2317)$ decays indeed constitutes only a small fraction of the 53.3 events observed in the $D_{sJ}^*(2463)$ peak. Performing a χ^2 fit to the D_s^*-side-band-subtracted version of Fig. 4, we obtain consistent results with $R_1 = 40.8 \pm 11.3$ events and a value for the $D_{sJ}^*(2463) - D_s^*$ mass difference of 351.6 ± 1.7 MeV/c^2. By comparing the values of χ^2 obtained with and without the $D_{sJ}^*(2463)$ signal contribution, we infer that the statistical significance of the signal is $4.4\,\sigma$. From our fits to data and Monte Carlo ΔM distributions, we also infer a 90 % confidence level (C.L.) upper limit on the natural width (Γ) of the $D_{sJ}^*(2463)^+$ state to be 7 MeV.

Based on the event yields and detection efficiencies given above, we can determine the production rate times branching fraction for the $D_{sJ}^*(2463)$ state to that of the $D_{sJ}^*(2317)$. We find this to be approximately 40 %.

Unlike the case of the 0^+ state, the $D_s\pi^+\pi^-$ decay mode is allowed by parity and angular momentum conservation for a state with $J^P = 1^+$. In the model of Ref. [14], it is predicted to occur with a branching fraction of 19 % relative to that for $D_s^*\pi^0$. We have fit the $\Delta M_{D_s\pi\pi}$ spectrum plotted in Fig. 2 for a signal corresponding to a transition from the $D_{sJ}^*(2463)$. Such a signal would peak with a $\Delta M_{D_s\pi\pi}$ near 495 MeV/c^2 and a Gaussian width of 3.4 ± 0.2 MeV/c^2 assuming a natural width of zero. No evidence for a signal is found, and we obtain an upper limit on the relative branching fraction of 8.1 % at the 90% C.L.

Having obtained evidence for the $D_{sJ}^*(2463)$ state, and having characterized the background that it contributes in the $D_s\pi^0 - D_s$ mass difference spectrum, we are now able to further address properties of the $D_{sJ}^*(2317)$ state. We recall that our measurement of the Gaussian width of the peak in Fig. 1, $8.4^{+1.4}_{-1.2}$ MeV/c^2, is somewhat larger than our mass difference resolution, 6.4 ± 0.4 MeV/c^2. This difference is consistent with predictions from Monte Carlo simulations where we include both $D_{sJ}^*(2463)$ and $D_{sJ}^*(2317)$ production, since roughly one third of the observed $D_s^+\pi^0$ events in the $D_{sJ}^*(2317)$ signal peak enter as a reflection from the $D_{sJ}^*(2463)$ state, this 'background' peak having an expected Gaussian width of 14.9 ± 1.0 MeV/c^2.

To better determine the mass and natural width of this state, we carry out a binned likelihood fit of the peak in the ΔM spectrum in Fig. 1(b) to a sum of two Gaussians, one for the $D_{sJ}^*(2317)$ signal, and one to account for the feed down from the $D_{sJ}^*(2463)$. Allowing the means and widths of both Gaussians to float, we measure $\overline{\Delta M}$ for the $D_{sJ}^*(2317)$ to be 350.4 ± 1.2 MeV/c^2 with a width of 5.5 ± 1.3 MeV/c^2. The mean and width for the feed

TABLE I: 90% CL upper limits on the ratio of branching fractions for $D_{sJ}^*(2317)$ to the the channels shown relative to the $D_s^+\pi^0$ state. Also shown are the theoretical expectations from Ref. [14], under the assumption that the $D_{sJ}^*(2317)$ is the lowest-lying 0^+ $c\overline{s}$ meson.

Final State	Yield	Efficiency	Limit (90% CL)	Prediction
$D_s^+\pi^0$	180 ± 46	$(13.1 \pm 0.7)\,\%$	—	
$D_s^+\gamma$	-22 ± 13	$(18.4 \pm 0.9)\,\%$	< 0.054	0
$D_s^{*+}\gamma$	-2.0 ± 4.1	$(5.3 \pm 0.4)\,\%$	< 0.078	0.08
$D_s^+\pi^+\pi^-$	1.6 ± 2.6	$(19.6 \pm 0.7)\,\%$	< 0.020	0

down contribution are 349.2 ± 3.6 MeV/c^2 and 15.3 ± 4.1 MeV/c^2, respectively. Both widths are consistent with predictions from Monte Carlo simulations in which the two states are modeled as having a natural width of zero.

We have also carried out fits in which one or both of the widths of the Gaussians were fixed to values determined by the Monte Carlo. In all cases the results were consistent with the results from the fit described above. These two-Gaussian fits return similar values for $\overline{\Delta M}$ for the $D_{sJ}^*(2317)$ to the value given above. We have also tried to obtain a purer $D_{sJ}^*(2317)$ sample by vetoing events with photons that can be combined with the D_s candidate to form a D_s^*, thereby removing some of the feed down background from the $D_{sJ}^*(2463)$. This veto marginally improves the $D_s\pi^0$ signal when we fit with two Gaussians, and the mass and width change by only a small fraction of the statistical uncertainty. The systematic uncertainty on $\overline{\Delta M}$ receives contributions from uncertainties in the characterization of the $D_{sJ}^*(2463)$ feed down and from uncertainties in the modeling of the energy resolution of the calorimeter. Conservatively, we estimate the total systematic error to be 1.0 MeV/c^2, however further study should allow the size of the estimated error to be decreased. Based on these studies, we limit the natural width of the $D_{sJ}^*(2317)$ to be $\Gamma < 7$ MeV at 90% C.L.

With regard to the alternate $D_{sJ}^*(2317)$ decay channels described earlier, in which no signals were observed, we summarize the limits on the branching fractions relative to the $D_s^+\pi^0$ mode in Table I. The normalization for these limits is based on the determination that $78.1 \pm 13.9\,\%$ of the observed yield of 231^{+31}_{-29} events in the peak of the $\Delta M(D_s\pi^0)$ spectrum in Fig. 1 are attributable to $D_{sJ}^*(2317) \to D_s\pi^0$ decay after accounting for the feed down from decays of the $D_{sJ}^*(2463)$ state to $D_s^*\pi^0$. The event yields are obtained by fitting the mass difference distributions to a Gaussian with mean fixed to the result from the $D_s^+\pi^0$ channel and width specified by the resolution determined from the simulation of the corresponding decay mode. Uncertainties are dominated by the statistical error on the unseen yields and limits on the relative rates are calculated assuming a Gaussian distribution with negative values not allowed.

In summary, data from the CLEO II detector provides confirming evidence for the existence of a new narrow resonance decaying to $D_s^+\pi^0$, with a mass near 2.32 GeV/c^2. This state is consistent with being the 0^+ member of the lowest-lying P-wave $c\overline{s}$ multiplet. We have not observed other decay modes of this state, as summarized in Table I. We have measured the mass splitting of this state with respect to the D_s meson to be 350.4 ± 1.2 [stat.] $\pm$ 1.0 [syst.] MeV/c^2, and we find its natural width to be $\Gamma < 7$ MeV at 90% C.L.

We have observed a second narrow state with a mass near 2.46 GeV/c^2, decaying to $D_s^{*+}\pi^0$. The measured properties of this state are consistent with its interpretation as the

1^+ partner of the 0^+ state in the spin multiplet with light quark angular momentum of $j = 1/2$. We have measured the mass splitting of this state with respect to the D_s^* meson to be 351.6 ± 1.7 [stat.] ± 1.0 [syst.] MeV/c^2. The natural width of this state is also found to be $\Gamma < 7$ MeV at 90% C.L. Since the $D_{sJ}^*(2463)$ mass lies above the kinematic threshold for decay to DK (but not for D^*K), the narrow width suggests that this decay does not occur. This is additional evidence for the compatibility of the $D_{sJ}^*(2463)$ with the $J^P = 1^+$ hypothesis.

In the model of Bardeen, Eichten and Hill, a $J^P = 1^+$ state is predicted with the same mass splitting ΔM with the 1^- state as that between the 0^+ and 0^- states. Taking the difference between the two mean mass differences reported above, we obtain $\delta(\Delta M) = (351.6 \pm 1.7) - (350.4 \pm 1.2) = 1.2 \pm 2.1$ MeV/c^2 for the difference between the $1^+ - 1^-$ and $0^+ - 0^-$ mass splittings, where the dominant uncertainty is due to statistics. Thus our observations are consistent with these predictions.

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