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Observation of the $h_c(^1P_1)$ State of Charmonium

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Abstract

The $h_c(^1P_1)$ state of charmonium has been observed in the reaction $\psi(2S) \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ using 3.08 million $\psi(2S)$ decays recorded in the CLEO detector. Data have been analyzed both for the inclusive reaction, where the decay products of the η_c are not identified, and for exclusive reactions, in which η_c decays are reconstructed in seven hadronic decay channels. We find $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV which corresponds to a hyperfine splitting $\Delta M_{hf}(1P) \equiv \langle M(^3P_J)\rangle - M(^1P_1) = +1.0 \pm 0.6 \pm 0.4$ MeV, and $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$.

Over the past thirty years charmonium spectroscopy has provided valuable insight into the quark–antiquark interaction of quantum chromodynamics (QCD). QCD-based potential models have been quite successful in predicting masses, widths, and dominant decays of several charmonium states. The central potential in most of these calculations is assumed to be composed of a vector Coulombic potential ($\sim 1/r$) and a scalar confining potential ($\sim r$). Under these assumptions, the spin-spin interaction in the lowest order is finite only for $L=0$ states. It leads to the hyperfine splittings $\Delta M_{hf}(nS) \equiv M(n^3S_1) - M(n^1S_0)$ between spin-triplet and spin-singlet S-wave states of charmonium, which have been measured as $\Delta M_{hf}(1S) = M(J/\psi) - M(\eta_c) = 115 \pm 2$ MeV [1], $\Delta M_{hf}(2S) = M(\psi(2S)) - M(\eta_c') = 43 \pm 3$ MeV [1, 2]. It also leads to the prediction that the hyperfine splitting $\Delta M_{hf}(\langle M(^3P_J)\rangle - M(^1P_1))$ for P-wave states should be zero. Higher-order corrections are expected to provide no more than a few MeV deviation from this result [3–5]. Lattice QCD calculations [6] predict $\Delta M_{hf}(1P) = +1.5$ to $+3.7$ MeV, but with uncertainties at the few-MeV level. Larger values of $\Delta M_{hf}(1P)$ could result if the confinement potential had a vector component or if coupled channel effects were important. In order to discriminate between these possibilities, it is necessary to identify the $h_c(^1P_1)$ state and to measure its mass to $\mathcal{O}(1$ MeV$)$ as the mass of the ^3P_J centroid is very well known, $\langle M(^3P_J)\rangle = 3525.36 \pm 0.06$ MeV [7],

In this Letter we report the successful identification of h_c in the isospin-violating reaction

$$e^+e^- \to \psi(2S) \to \pi^0 h_c\ ,\ h_c \to \gamma\eta_c\ ,\ \pi^0 \to \gamma\gamma. \tag{1}$$

Two methods are used: one in which the η_c decays are reconstructed (exclusive), which has an advantage in signal purity, and the other in which the η_c is measured inclusively, which has larger signal yield. Together these approaches provide a result of unambiguous significance, and allow a precise determination of the mass of h_c and the branching fraction product $\mathcal{B}_\psi\mathcal{B}_h$, where $\mathcal{B}_\psi \equiv \mathcal{B}(\psi(2S) \to \pi^0 h_c)$ and $B_h \equiv \mathcal{B}(h_c \to \gamma\eta_c)$. Theoretical estimates of the product $\mathcal{B}_\psi\mathcal{B}_h$ vary by nearly two orders of magnitude, $(0.5-40)\times 10^{-4}$ [4, 5].

The Crystal Ball Collaboration at SLAC searched for h_c using the reaction of Eq. (1) but were only able to set a 95% confidence upper limit $\mathcal{B}_\psi\mathcal{B}_h < 16\times 10^{-4}$ in the mass range $M(h_c) = (3515-3535)$ MeV [8]. The FNAL E760 Collaboration searched for h_c in the reaction $p\bar{p} \to h_c \to \pi^0 J/\psi,\ J/\psi \to e^+e^-$, and reported a statistically significant enhancement with $M(h_c) = 3526.2 \pm 0.15 \pm 0.2$ MeV, $\Gamma(h_c) \leq 1.1$ MeV [9]. The measurement was repeated twice by the successor experiment E835 with $\sim 2\times$ and $\sim 3\times$ larger luminosity, but no confirming signal for h_c was observed in $h_c \to \pi^0 J/\psi$ decay [5].

A data sample consisting of 3.08×10^6 $\psi(2S)$ decays was obtained with the CLEO III and CLEO-c detector configurations [10–13] at the Cornell Electron Storage Ring. The CLEO III detector features a solid angle coverage for charged and neutral particles of 93%. The charged particle tracking system achieves a momentum resolution of $\sim$0.6% at 1 GeV, and the calorimeter photon energy resolution is 2.2% for $E_\gamma = 1$ GeV and 5% at 100 MeV. Two particle identification systems, one based on energy-loss (dE/dx) in the drift chamber and the other a ring imaging Cherenkov (RICH) detector, are used to distinguish pions from kaons.

Half of the $\psi(2S)$ data were accumulated with a newer detector configuration, CLEO-c [13], in which the silicon strip vertex detector was replaced with an all-stereo six-layer wire chamber. The two detector configurations also correspond to different accelerator lattices. Studies of Monte Carlo simulations and the data reveal no significant differences in the capabilities of the two detector configurations; therefore the CLEO III and CLEO-c datasets are analyzed together.

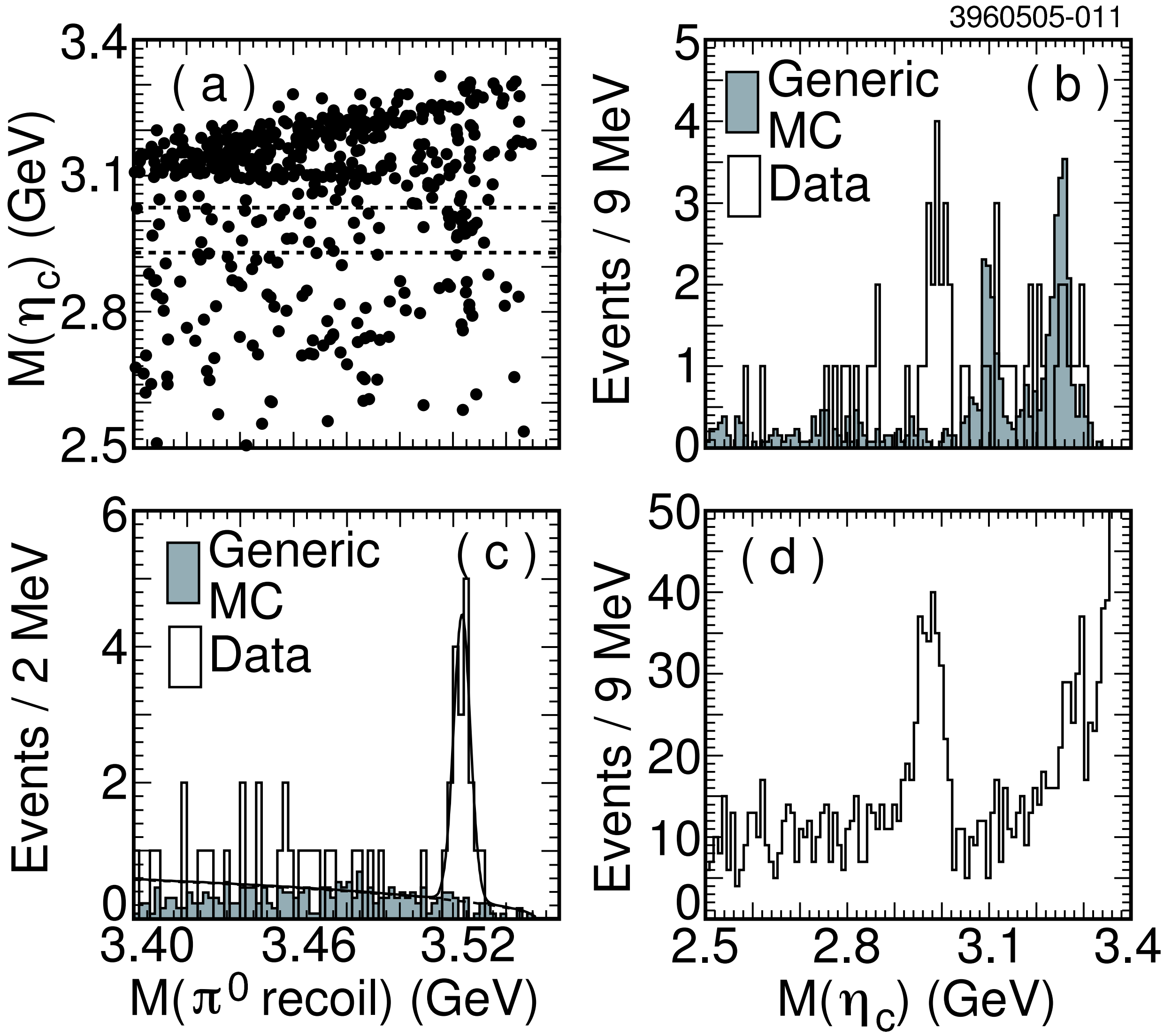

FIG. 1: Exclusive analysis: (a) Scatter plot of the reconstructed η_c candidate mass vs. the recoil mass against π^0 for data. The horizontal band in the vicinity of $M(J/\psi)$ and the diagonal band at larger η_c candidate mass correspond to $\psi(2S) \to \pi^0\pi^0 J/\psi$ and $\psi(2S) \to \gamma\chi_{c0}$, respectively. The dashed lines denote the region $M(\eta_c) = 2982 \pm 50$ MeV. Data events (open histograms) and Monte Carlo background estimate (shaded histograms) of (b) reconstructed η_c candidate mass projection for $M(\pi^0 \text{ recoil}) = 3524 \pm 8$ MeV and (c) recoil h_c candidate mass spectrum for $M(\eta_c) = 2982 \pm 50$ MeV. The peaks in b) near M=3.1 GeV and 3.25 GeV correspond to $\psi(2S) \to \pi^0\pi^0 J/\psi$ and $\psi(2S) \to \gamma\chi_{c0}$, respectively. (d) Reconstructed η_c candidate mass for data in the direct decay $\psi(2S) \to \gamma\eta_c$. The peak near $M = 3.4$ GeV is from the direct decay $\psi(2S) \to \gamma\chi_{c0}$.

The inclusive and exclusive analyses share a common initial sample of events and numerous selection criteria. Details of the analyses are provided in a companion paper [14]. Event selection for both analyses require at least three electromagnetic showers and two charged tracks, each selected with standard CLEO criteria. For showers, $E_\gamma > 30$ MeV is required. Candidates for $\gamma\gamma$ decays of π^0 or η mesons satisfy the requirement that $M(\gamma\gamma)$ be

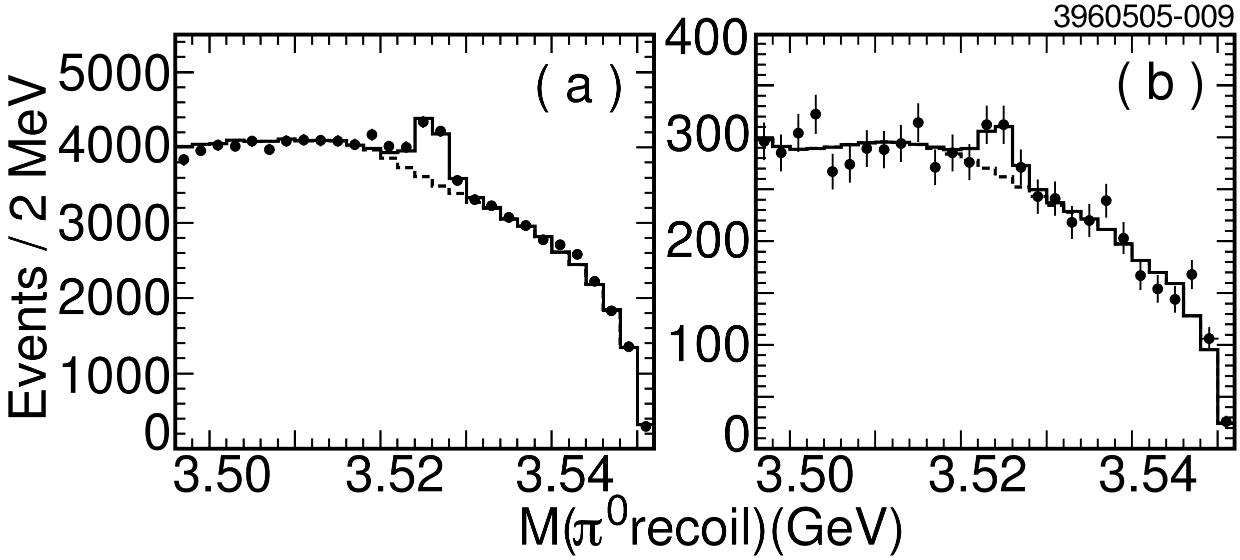

FIG. 2: Inclusive analysis: Recoil mass against π^0 for (a) Monte Carlo sample for 39.1 million $\psi(2S)$ and (b) data for 3 million $\psi(2S)$. See text for details.

within 3 standard deviations (σ) of the known π^0 or η mass, respectively. These candidates are kinematically fit, constraining $M(\gamma\gamma)$ to the appropriate mass to improve π^0/η energy resolution. Charged tracks are required to have well-measured momenta and to satisfy criteria based on the track fit quality. They must also be consistent with originating from the interaction point in three dimensions.

Both techniques identify h_c as an enhancement in the spectrum of neutral pions from the reaction $\psi(2S) \to \pi^0 h_c$ [15]. For this purpose, it is useful to remove neutral pions originating from any other reaction. It is easy to remove most of the π^0 arising from $\psi(2S) \to \pi^+\pi^- J/\psi$, with $J/\psi \to \pi^0$ + hadrons and $\pi^0\pi^0 J/\psi$, with $J/\psi \to$ any. Since the recoil spectra against $M(\pi^+\pi^-)$ (both analyses) and $M(\pi^0\pi^0)$ (inclusive only) show prominent peaks for J/ψ; these events are removed by appropriate selection around $M(J/\psi)$.

In the exclusive analysis, η_c are reconstructed in seven channels: $K^0_S K^\pm \pi^\mp$, $K^0_L K^\pm \pi^\mp$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\eta(\to \gamma\gamma)$, and $\pi^+\pi^-\eta(\to \pi^+\pi^-\pi^0)$. The sum of the branching fractions is $(9.7 \pm 2.7)\%$ [7]. The decay chain in Eq. (1) as well as these η_c decays are identified from reconstructed charged particles, π^0 and η mesons. For η decays to $\pi^+\pi^-\pi^0$, the three-pion invariant mass is required to be within 20 MeV of the nominal η mass. The K^0_S candidates are selected from pairs of oppositely charged and vertex-constrained tracks with invariant mass within 10 MeV, roughly 4σ, of the K^0_S mass. A kinematically constrained 4C fit is performed for each event. A 1C fit is performed for the $\eta_c \to K^0_L K^\pm \pi^\mp$ decay because the K^0_L is not detected. It is required that $M(\eta_c) = 2980 \pm 50$ MeV. No explicit selection of the energy of the photon from $h_c \to \gamma\eta_c$ is required. The final selection is on the η_c candidate mass; however, to improve resolution, the h_c mass is calculated from the 4-momentum of the $\psi(2S)$ and the π^0 instead of the invariant mass of its decay products.

In addition to $\psi(2S) \to \pi\pi J/\psi$ decays discussed above, a fraction of $\psi(2S)$ decays proceed through $\psi(2S) \to \pi^0 J/\psi$ and $\psi(2S) \to \gamma\chi_{cJ} \to \pi^0 X$. To suppress the π^0 background, each signal photon candidate is paired with all other photons in that event. If the invariant mass of any pair is within the π^0 mass requirement, the event is removed.

Fig. 1(a) shows the scatter plot of the η_c candidate mass versus π^0 recoil mass (sum of all channels). Many events are seen in the vicinity of $M(J/\psi)$. In the mass band $M(\eta_c) = 2980\pm50$ MeV an enhancement of events is observed at larger π^0 recoil mass. The projection of the events in this band and the Monte Carlo background estimate is shown in Fig. 1(c). A prominent peak is clearly visible over a very small background. The projection of the events in the mass band $M(\pi^0$ recoil$) = 3524 \pm 8$ MeV and the Monte Carlo background estimate, shown in Fig. 1(b), indicate that most of these events arise from η_c decay. The π^0 recoil mass spectrum, in Fig. 1(b), is fit using a double Gaussian shape determined from Monte Carlo simulation and an ARGUS function background [16]. The maximum likelihood fit yields 17.5 ± 4.5 counts in the peak and $M(h_c) = 3523.6 \pm 0.9$ MeV.

Several different methods have been utilized to estimate the statistical significance s of the signal [14], including the fit to the recoil mass spectrum just described, Poisson fluctuations of MC-predicted backgrounds inside the signal window, and a binomial statistics calculation using the assumption that the events in the recoil mass distribution are uniformly distributed. Using the difference between the likelihood values of the fit with and without the signal contribution, we obtain $s = 6.1\sigma$; similar calculations with different η_c mass ranges yield $s = 5.5 - 6.6\sigma$. The probability that Poisson fluctuations of the background, estimated from the generic MC sample, completely account for the observed events in the signal region is 1×10^{-9} ($s = 6.0\sigma$). The binomial probability that the number of data events in Fig. 1(b) and 1(c) fluctuate to be greater than the number of events in the signal region is 2.2×10^{-7}, corresponding to $s \sim 5.2\sigma$.

To test our ability to reconstruct η_c decays and provide normalization for the branching fraction measurement, $\mathcal{B}_\psi \mathcal{B}_h$, the direct radiative decay $\psi(2S) \to \gamma\eta_c$ is studied. Events are reconstructed in the same η_c decay channels as for the h_c search, but with much better yields. Relative yields among the various channels are similar to previous results [7] and the η_c peak shape was verified for each channel. Figures 1(b) and 1(d) show the reconstructed mass spectra for the η_c candidates from h_c and direct $\psi(2S)$ decay, respectively. The η_c mass resolution in the photon recoil mass spectrum is identical for all seven channels. This distribution summed over all channels (not shown) is fit using a peak shape which consists of a Monte Carlo-derived double Gaussian convolved with a Breit-Wigner function (with $M(\eta_c) = 2979.7$ MeV, $\Gamma(\eta_c) = 27$ MeV). It yields 220 ± 22 counts. The efficiency-corrected ratio of h_c decays to direct decays, which corresponds to $\mathcal{B}_\psi \mathcal{B}_h/\mathcal{B}_\mathcal{D}$, where $\mathcal{B}_\mathcal{D} \equiv \mathcal{B}(\psi(2S) \to \gamma\eta_c)$, is determined to be 0.178 ± 0.049. The CLEO [17] and PDG [7] values are combined to obtain $\mathcal{B}_\mathcal{D} = (0.296\pm0.046)\%$. Multiplying these two results yields $\mathcal{B}_\psi \mathcal{B}_h = (5.3\pm1.5)\times10^{-4}$ from the exclusive analysis.

In the inclusive analysis, we explore two methods to enhance the selection of neutral pions which are part of the chain $\psi(2S) \to \pi^0 h_c \to \pi^0\gamma\eta_c$. One way is to specify that there be only one photon in the event with energy for the transition $h_c \to \gamma\eta_c$, $E_\gamma \approx 503$ MeV (corresponding to $M(h_c) \approx 3526$ MeV). Another way is to specify that the mass recoiling against the photon and π^0 for the event should be near the mass of η_c. Both approaches are investigated, leading to consistent results, as detailed in Ref. [14].

A combined sample of generic $\psi(2S)$ decay and signal Monte Carlo events is used to optimize the criteria for the final event selection. The resulting selection criteria determined were $E_\gamma = 503\pm35$ MeV for hard photon acceptance in one approach and $M(\eta_c) = 2980\pm35$ MeV in the other. As a result of the Monte Carlo studies, a number of selection criteria, in which the two approaches occasionally differ, are made. These include requiring only one π^0 in the signal region, removing hard photons that reconstruct η mesons with any other

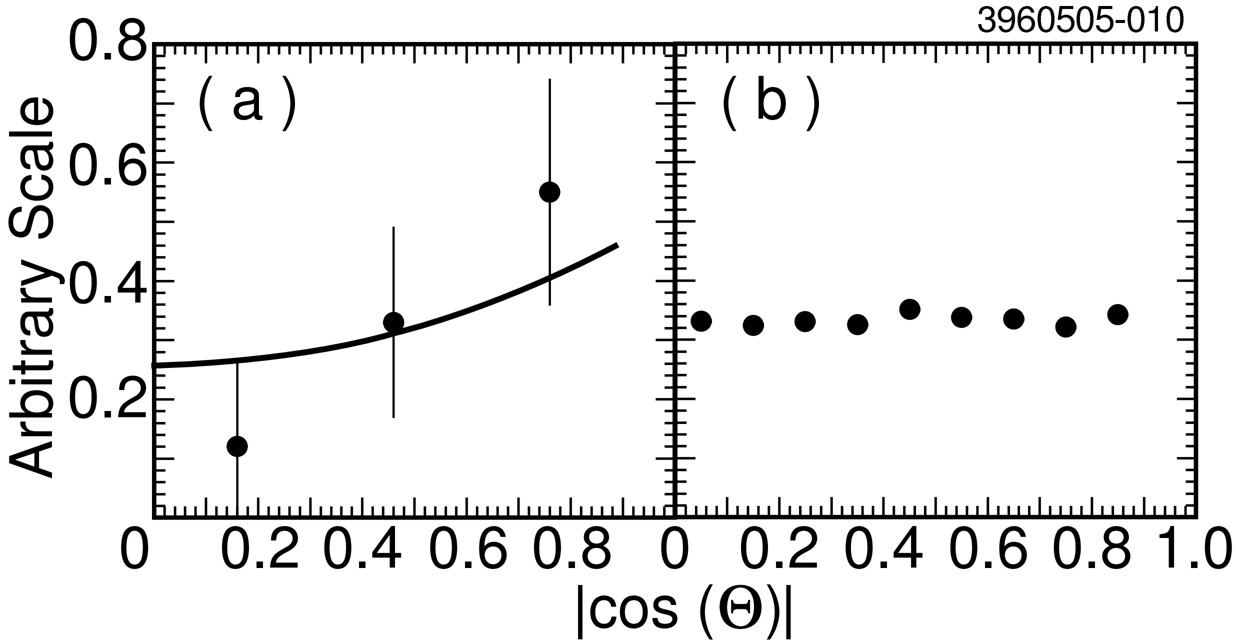

FIG. 3: Inclusive analysis: Efficiency-corrected fit yields versus $|\cos\theta|$ for data with $E_\gamma = 503 \pm 35$ MeV, (a) for h_c yield, the curve corresponds to the best fit $\propto (1+\cos^2\theta)$ and (b) for the nearly isotropic background yield.

TABLE I: Results for the inclusive and exclusive analyses for the reaction $\psi(2S) \to \pi^0 h_c \to \pi^0 \gamma \eta_c$. First errors are statistical, and the second errors are systematic, as described in the text and Table II.

	Inclusive	Exclusive
Counts	150±40	17.5±4.5
Significance	$\sim$3.8σ	6.1σ
$M(h_c)$ (MeV)	3524.9±0.7±0.4	3523.6±0.9±0.5
$\mathcal{B}_\psi \mathcal{B}_h$ (10^{-4})	3.5±1.0±0.7	5.3±1.5±1.0

photon, accepting photons in the calorimeter endcaps, removing photons from the cascade reaction $\psi(2S) \to \gamma\chi_J \to \gamma\gamma J/\psi$, and the choice of the background shape.

The recoil spectrum for the total Monte Carlo sample of 39.1 million $\psi(2S)$ (13 times the size of the data sample), obtained in the E_γ-selection approach with its optimized selection criteria, is shown in Fig. 2(a). A product branching fraction $\mathcal{B}_\psi \mathcal{B}_h = 4 \times 10^{-4}$ was assumed. The corresponding plot from the other approach is very similar. The h_c signal is evident. The overall efficiencies determined from the Monte Carlo sample are 13.4% and 14.6% for the two inclusive approaches. Input values of $M(h_c)$ and $\mathcal{B}_\psi \mathcal{B}_h$ are well reproduced. Results of Monte Carlo studies lead to the conclusion that the resonance fits to the data may be expected to have significance levels of $\sim 4\sigma$, statistical error on the mass of $\sim\pm 0.6$ MeV, and central values of the mass are reproduced within $\sim\pm 0.6$ MeV of the generated $M(h_c)$.

Figure 2(b) shows the data and the fit using the Monte Carlo optimized criteria for

TABLE II: Summary of estimated systematic uncertainties and their sums in quadrature. N/A means not applicable.

	$M(h_c)$ (MeV)		$\mathcal{B}_\psi \mathcal{B}_h \times 10^4$	
Systematic Uncertainty	Incl.	Excl.	Incl.	Excl.
Number of $\psi(2S)$	N/A	N/A	0.1	N/A
$\mathcal{B}(\psi(2S) \to \gamma\eta_c)$	N/A	N/A	N/A	0.8
Background shape	0.3	0.2	0.2	0.3
π^0 energy scale	0.2		$\sim$0	0.1
Signal shape	0.1	0.1	0.3	0.2
h_c width	0.1	0.1	0.3	0.2
π^0 efficiency	$\sim$0	$\sim$0	0.1	0.3
photon efficiency	$\sim$0	$\sim$0	0.2	0.2
Binning, fitting range	0.1	0.1	0.3	0.2
Modeling of h_c decays	0.1	0.3	0.3	$\sim$0
η_c mass	0.1	0.2	0.1	0.1
η_c width	$\sim$0	$\sim$0	0.2	0.1
η_c branching ratios	N/A	~ 0	N/A	0.1
Sum in quadrature	$\pm$0.4	$\pm$0.5	$\pm$0.7	$\pm$1.0

the same inclusive approach as in Fig 2(a). Features in the Monte Carlo such as signal width, signal to background ratio, and approximate background shape mirror the data faithfully. The recoil spectrum and the fit for the other inclusive approach are very similar. Fit significance is approximately 3.8σ. Results from the two inclusive approaches differ by small amounts, with differences from the averages in $M(h_c)$ of ± 0.5 MeV and in $\mathcal{B}_\psi \mathcal{B}_h$ of $\pm 0.05 \times 10^{-4}$. The average results are listed in Table I.

The h_c yield from the recoil mass against π^0 in the inclusive analysis is studied as a function of the angular distribution of the $h_c \to \gamma\eta_c$ photon. The h_c yield, shown in Fig. 3(a), is found to follow a $1+\cos^2\theta$ distribution ($\chi^2/d.o.f. = 1.7/2$) as expected for an E1 transition from a spin 1 state. The background yield, shown in Fig. 3(b), is uniform in $\cos\theta$. The h_c yield in the exclusive analysis is not sufficient to draw any conclusions regarding the corresponding angular distribution.

Systematic uncertainties in the two analyses due to various possible sources have been estimated. Many sources are common, such as choice of background parameterization, h_c resonance intrinsic width ($\Gamma = 0.5 - 1.5$ MeV), π^0 line shape, bin size, and fitting range. The uncertainty in the branching ratio for $\psi(2S) \to \gamma\eta_c$ enters the systematic uncertainty for the exclusive analysis only while the uncertainty on the number of $\psi(2S)$ decays applies to the inclusive analysis only. The estimated contributions are listed in Table II. For the inclusive (exclusive) analysis they sum in quadrature to ± 0.4 (0.5) MeV in $M(h_c)$ and $\pm 0.7\,(1.0) \times 10^{-4}$ in $\mathcal{B}_\psi \mathcal{B}_h$. The largest systematic error for the exclusive analysis, $\mathcal{B}(\psi(2S) \to \gamma\eta_c)$, cancels in the ratio and we obtain $\mathcal{B}_\psi \mathcal{B}_h / \mathcal{B}_\mathcal{D} = 0.178 \pm 0.049 \pm 0.018$.

To summarize, we have observed the h_c state, the $^1P_1$ state of charmonium, in the reaction $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, in exclusive and inclusive analyses. The significance of our observation is greater than 5σ under a variety of methods to evaluate this quantity. We combine the results of the exclusive and inclusive analyses to obtain $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV and $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$. The following value is obtained for the hyperfine splitting:

$$\Delta M_{hf}(\left\langle M(^3P_J)\right\rangle - M(^1P_1)) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}.$$

Thus, the combined result for $M(h_c)$ is consistent with the spin-weighted average of the χ_{cJ} states.

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