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


(CLEO Collaboration)

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 $3.08 \times 10^6 \psi(2S)$ decays recorded in the CLEO detector. Data have been analyzed both for the inclusive reaction, where the decay products of the $\eta_c$ are not identified, and for exclusive reactions, in which $\eta_c$ 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 $\Delta M_{hf}(1P) = (M(1P_1) - M(1P_0)) = +1.0 \pm 0.6 \pm 0.4$ MeV, and $B(h_c \to \pi^0 h_c) \times B(h_c \to \gamma \eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$.

Over the past 30 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 (∝ 1/r) and a scalar confining potential (∝ 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 ΔM_{hf}(nS) = M(nS_J) - M(nS_{0}) between spin-triplet and spin-singlet S-wave states of charmonium, which have been measured as ΔM_{hf}(1S) = M(J/ψ) - M(η_c) = 115 ± 2 MeV [1], ΔM_{hf}(2S) = M(ψ(2S)) - M(η_c^+) = 48 ± 5 MeV [1,2]. It also leads to the prediction that the hyperfine splitting ΔM_{hf}(M(1P_J)) - M(1P_{I}) 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 ΔM_{hf}(1P) = +1.5 to +3.7 MeV, but with uncertainties at the few-MeV level. Larger values of ΔM_{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_J) state and to measure its mass to O(1 MeV) as the mass of the 3P_J centroid is very well known, ⟨M(1P_J)⟩ = 3525.36 ± 0.06 MeV [7].

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

\[ e^+ e^- → ψ(2S) → π^0 h_c, \quad h_c → γη_c, \quad π^0 → γγ. \] (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 B_{ψ/π}B_{h_c}, where B_{ψ/π} = B(ψ(2S) → π^0 h_c) and B_{h_c} = B(h_c → γη_c). Theoretical estimates of the product B_{ψ/π}B_{h_c} vary by nearly 2 orders of magnitude, (0.5–40) × 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 B_{ψ/π}B_{h_c} < 16 × 10^{-4} in the mass range M(h_c) = (3515–3535) MeV [8]. The FNAL E760 Collaboration searched for h_c in the reaction p̅p → h_c → π^0 J/ψ, J/ψ → e^+ e^−, and reported a statistically significant enhancement with M(h_c) = 3526.2 ± 0.15 ± 0.2 MeV, Γ(h_c) ≤ 1.1 MeV [9]. The measurement was repeated twice by the successor experiment E835 with ~2× and ~3× larger luminosity, but no confirming signal for h_c was observed in h_c → π^0 J/ψ decay [5].

A data sample consisting of 3.08 × 10^6 ψ(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 ~0.6% at 1 GeV, and the calorimeter photon energy resolution is 2.2% for E_γ = 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 ψ(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.

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 requires at least three electromagnetic showers and two charged tracks, each selected with standard CLEO criteria. For showers, E_γ > 30 MeV is required. Candidates for γγ decays of π^0 or η mesons satisfy the requirement that M(γγ) be within 3 standard deviations (σ) of the known π^0 or η mass, respectively. These candidates are kinematically fit, constraining M(γγ) 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 ψ(2S) → π^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 ψ(2S) → π^+ π^- J/ψ, with J/ψ → π^0 + hadrons and π^0 J/ψ, with J/ψ → any. The recoil spectra against M(π^+ π^-) (both analyses) and M(π^0 π^0) (inclusive only) show prominent peaks for J/ψ; these events are removed by appropriate selection around M(J/ψ).

In the exclusive analysis, η_c are reconstructed in seven channels: K^0_L K^+ π^−, K^0_S K^+ π^−, K^+ K^- π^0 π^0, π^+ π^- π^0 π^0, K^- K^0 π^0, π^+ π^- η(→ γγ), and π^+ π^- η(→ π^+ π^- π^0). The sum of the branching fractions is (9.7 ± 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_c decays to π^+ π^- π^0, the three-pion invariant mass is required to be within 20 MeV of the nominal η mass. The K^0_L candidates are selected from pairs of oppositely charged and vertex-constrained...
tracks with invariant mass within 10 MeV, roughly 4σ, of the \(K^0_L\) mass. A kinematically constrained 4C fit is performed for each event. A 1C fit is performed for the \(\eta_c \rightarrow K^0_L K^+ K^- \pi^0\) 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 \(h_c \rightarrow \gamma \eta_c\) is required. The final selection is on the \(\eta_c\) candidate mass; however, to improve resolution, the \(h_c\) mass is calculated from the four momentum of the \(\psi(2S)\) and the \(\pi^0\) instead of the invariant mass of its decay products.

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

Figure 1(a) shows the scatter plot of the \(\eta_c\) candidate mass versus \(\pi^0\) recoil mass (sum of all channels). Many events are seen in the vicinity of \(M(J/\psi)\). In the mass band \(M(\eta_c) = 2980 \pm 50\) MeV an enhancement of events is observed at larger \(\pi^0\) 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 \(M(\pi^0\text{recoil}) = 3524 \pm 8\) MeV and the Monte Carlo background estimate, shown in Fig. 1(b), indicate that most of these events arise from \(\eta_c\) decay. The \(\pi^0\) recoil mass spectrum, in Fig. 1(b), is fit using a double Gaussian shape determined from Monte Carlo simulation (MC) and an ARGUS function background [16]. The maximum likelihood fit yields \(17.5 \pm 4.5\) 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 \(s \approx 6.1\sigma\); similar calculations with different \(\eta_c\) 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 \(1 \times 10^{-9} (s = 6.0\sigma)\). The binomial probability that the number of data events in Figs. 1(b) and 1(c) fluctuate to be greater than the number of events in the signal region is \(2.2 \times 10^{-7}\), corresponding to \(s \approx 5.2\sigma\).

To test our ability to reconstruct \(\eta_c\) decays and provide normalization for the branching fraction measurement, \(B_{\psi B_h}\), the direct radiative decay \(\psi(2S) \rightarrow \gamma \eta_c\) is studied. Events are reconstructed in the same \(\eta_c\) 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 \(\eta_c\) peak shape was verified for each channel. Figs. 1(b) and 1(d) show the reconstructed mass spectra for the \(\eta_c\) candidates from \(h_c\) and direct \(\psi(2S)\) decay, respectively. The \(\eta_c\) 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 \(B_{\psi B_h}/B_{D}\), where \(B_D \equiv B(\psi(2S) \rightarrow \gamma \eta_c)\), is determined to be 0.178 ± 0.049. The CLEO [17] and PDG [7] values are combined to obtain \(B_D = 0.296 \pm 0.046\)%. Multiplying these two results yields \(B_{\psi B_h} = (5.3 \pm 1.5) \times 10^{-4}\) 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 \(\psi(2S) \rightarrow \pi^0 h_c \rightarrow \pi^0 \gamma \eta_c\). One way is to specify that there be only one photon in the event with energy for the transition \(h_c \rightarrow \gamma \eta_c\), \(E_\gamma \approx 503\) MeV [corresponding to
M(h_c) = 3526 MeV]. Another way is to specify that the mass recoiling against the photon and π⁰ 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 ψ(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_γ = 503 ± 35 MeV for hard photon acceptance in one approach and M(η_c) = 2980 ± 35 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 π⁰ in the signal region, removing hard photons that reconstruct η mesons with any other photon, accepting photons in the calorimeter end caps, removing photons from the cascade reaction ψ(2S) → γχ_cJ → γγJ/ψ, and the choice of the background shape.

The recoil spectrum for the total Monte Carlo sample of 39.1 × 10⁶ ψ(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 B_ψB_h = 4 × 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 B_ψB_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 ~4σ, statistical error on the mass of ~ ±0.6 MeV, and central values of the mass are reproduced within ~ ±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 the same inclusive approach as in Fig. 2(a). Features in the Monte Carlo scheme 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 B_ψB_h of ±0.05 × 10⁻⁴. The average results are listed in Table I.

The h_c yield from the recoil mass against π⁰ in the inclusive analysis is studied as a function of the angular distribution. The h_c yield, shown in Fig. 3(a), is found to follow a 1 + cos²θ distribution (χ²/degrees of freedom = 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 cosθ. The h_c yield in the inclusive 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 (Γ = 0.5–1.5 MeV), π⁰ line shape, bin size, and fitting range. The uncertainty in the branching ratio for ψ(2S) → γη_c enters the systematic uncertainty for the exclusive analysis only while the uncertainty on the number of psiphi(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 ±0.7(1.0) × 10⁻⁴ in B_ψB_h. The largest systematic error for the exclusive analysis, B(ψ(2S) → γη_c), cancels in the ratio and we obtain B_ψB_h/B_D = 0.178 ± 0.049 ± 0.018.

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<thead>
<tr>
<th>Inclusive</th>
<th>Exclusive</th>
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<tr>
<td>Counts</td>
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<tr>
<td>Significance</td>
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<td>M(h_c) (MeV)</td>
<td>3524.9 ± 0.7 ± 0.4</td>
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<tr>
<td>B_ψB_h (10⁻⁴)</td>
<td>3.5 ± 1.0 ± 0.7</td>
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To summarize, we have observed the $h_c$ state, the $^2P_1$ state of charmonium, in the reaction $\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$, in exclusive and inclusive analyses. The significance of our observation is greater than $5\sigma$ 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 $\mathcal{B}(\psi(2S) \rightarrow \pi^0 h_c) \times \mathcal{B}(h_c \rightarrow \gamma \eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$. The following value is obtained for the hyperfine splitting:

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

Thus, the combined result for $M(h_c)$ is consistent with the spin-weighted average of the $\chi_{cJ}$ states and with the (nonrelativistic) bound [18] $\Delta M_{hf} \leq 0$.

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