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Precision Measurement of the Mass of the $h_c(^1P_1)$ State of Charmonium

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Abstract

A precision measurement of the mass of the $h_c(^1P_1)$ state of charmonium has been made using a sample of 24.5 million $\psi(2S)$ events produced in e^+e^- annihilation at CESR. The reaction used was $\psi(2S) \to \pi^0 h_c$, $\pi^0 \to \gamma\gamma$, $h_c \to \gamma\eta_c$, and the reaction products were detected in the CLEO-c detector. Data have been analyzed both for the inclusive reaction and for the exclusive reactions in which η_c decays are reconstructed in fifteen hadronic decay channels. Consistent results are obtained in the two analyses. The averaged results of the present measurements are $M(h_c) = 3525.28 \pm 0.19(\text{stat}) \pm 0.12(\text{syst})$ MeV, and $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.19 \pm 0.32 \pm 0.45) \times 10^{-4}$. Using the ^3P_J centroid mass, $\Delta M_{hf}(1P) \equiv \langle M(\chi_{cJ})\rangle - M(h_c) = +0.02 \pm 0.19 \pm 0.13$ MeV.

The large body of experimental data for the spectroscopy of the charmonium ($c\bar{c}$) states has provided detailed information about the QCD interactions between a quark and an antiquark. A convenient and transparent realization of the interaction is in terms of a potential which is generally assumed to consist of a Coulombic part attributed to a vector one gluon exchange, and a less well understood confinement part. In analogy with QED, the spin–dependence of the interaction is attributed to the Breit–Fermi reduction of the one–gluon vector exchange, which leads to spin–orbit ($\mathbf{L}\cdot\mathbf{S}$), tensor ($T$) and spin–spin ($\mathbf{S}_1\cdot\mathbf{S}_2$) potentials. The confinement part is generally assumed to be Lorentz scalar and no spin–spin dependence arises from it. The mass splitting of the triplet $1P$ charmonium states into $\chi_{c0}(^3P_0)$, $\chi_{c1}(^3P_1)$ and $\chi_{c2}(^3P_2)$ is determined by the ($\mathbf{L}\cdot\mathbf{S}$) and ($T$) terms of the potential, and the ($\mathbf{S}_1\cdot\mathbf{S}_2$) term determines the hyperfine or triplet–singlet splitting. If the $q\bar{q}$ hyperfine interaction receives no contribution from the confinement part, and is only due to the Coulombic term in the potential, it is a contact interaction in the lowest order, and it is identically zero for all $L\neq 0$, i.e., $\Delta M_{hf}(1P)\equiv M(^3P)-M(^1P)=0$. The triplet ^3P_J states are well established, and the mass of their spin–weighted centroid is $\langle M(^3P_J)\rangle=[M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2})]/9=3525.30\pm 0.04$ MeV [1]. The singlet state $h_c(^1P_1)$ was not identified until very recently [2, 3]. Although the identification of the triplet centroid mass $\langle M(^3P_J)\rangle$ with the unperturbed triplet mass $M(^3P)$ has been questioned [4], it is necessary to make a precision measurement of the mass of h_c irrespective of how $M(^3P)$ is determined.

Two recent experiments have reported identification of h_c and measured its mass. The CLEO measurement [2] was made by means of the isospin-forbidden reaction

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

using 3 million $\psi(2S)$ produced in e^+e^- annihilations. The h_c was identified as the enhancement in the mass spectrum of recoils against π^0. Two different kinds of analysis of the data were done. In the *inclusive analyses* h_c decays were identified by loose constraints on either the energy of the E1 photon from h_c decay, or the mass of η_c. In the *exclusive analysis* no constraint was placed on $E(\gamma)$. Instead, η_c events were reconstructed in seven different hadronic decay channels of η_c. The combined significance level of the h_c observation was >6 σ, and the quoted mass was $M(h_c)$=3524.4±0.6±0.4 MeV.

The Fermilab E835 measurement [3] made scans of antiproton energy for the reaction, $\bar{p}p\to h_c\to\gamma\eta_c$, $\eta_c\to\gamma\gamma$. The results from the year 1997 scan and the year 2000 scan were combined to obtain $M(h_c)$=3525.8±0.2±0.2 MeV. The significance level of h_c observation was $\sim 3\sigma$. No evidence was found for h_c in the previously reported reaction $\bar{p}p\to h_c\to\pi^0 J/\psi$ [5].

If it is assumed that $M(^3P)$=$\langle M(^3P_J)\rangle$, the above two measurements lead to $\Delta M_{hf}(1P)$=+0.9±0.6±0.4 MeV (CLEO), and $\Delta M_{hf}(1P)$=–0.5±0.2±0.2 MeV (FNAL). While both results are statistically consistent with the prediction of $\Delta M_{hf}(1P)$=0, it is important to understand any deviation from it, and its origin.

In this Letter we report a much improved measurement of the reaction in Eq. (1) using nearly an order of magnitude larger sample of $N(\psi(2S))=24.5\pm 0.5$ million [6] obtained at the Cornell Electron Storage Ring with e^+e^- annihilations at a center of mass energy corresponding to the $\psi(2S)$ mass of 3686 MeV [1]. The CLEO-c detector was used for the detection of the reaction products.

The CLEO-c detector [7], which has a cylindrical geometry, consists of a CsI electromagnetic calorimeter, an inner vertex drift chamber, a central drift chamber, and a ring-imaging

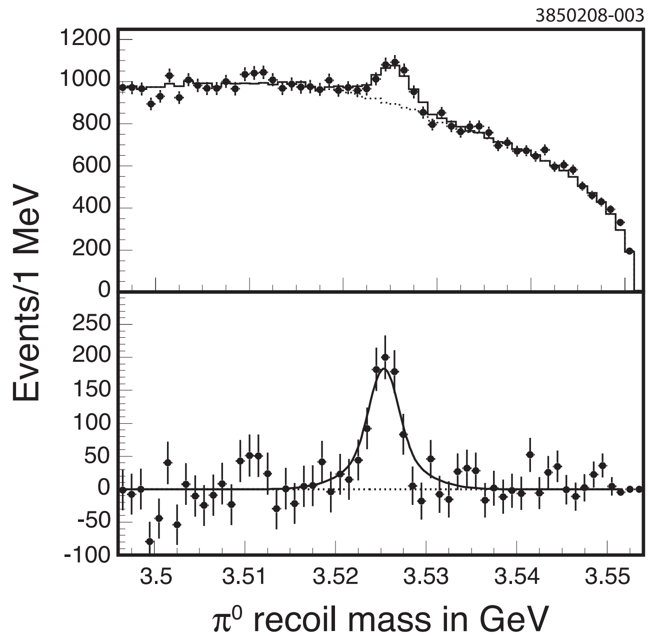

FIG. 1: Spectra of recoil masses against π^0 in the inclusive analysis: (top) full spectrum, (bottom) background subtracted spectrum.

Cherenkov (RICH) detector, inside a superconducting solenoid magnet with a 1.0 T magnetic field. The detector has a total acceptance of 93% of 4π, photon energy resolutions of 2.2% at E_γ=1 GeV, and 5% at 100 MeV, and charged particle momentum resolution of 0.6% at 1 GeV.

The event selection criteria common to both the inclusive and exclusive analyses are the following. The events were required to have at least three electromagnetic showers and two charged tracks meeting the standard CLEO quality and vertex criteria [8]. The acceptance region was defined as $|\cos\theta| \leq 0.93$, except that recoil π^0 candidates were reconstructed using photons only in the good barrel region, $|\cos\theta| \leq 0.81$. For showers it was required that E_γ(barrel) > 30 MeV, and E_γ(endcaps) > 50 MeV, where the endcap region is defined as $0.85 < |\cos\theta| < 0.93$. The events accepted for $\gamma\gamma$ decays of π^0 and η were required to have $M(\gamma\gamma)$ within ± 15 MeV of $M(\pi^0)$=135.0 MeV and $M(\eta)$=547.5 MeV, respectively [1] . It was further required that there be only one π^0 in the event with the recoil mass in the expected region of h_c mass, 3526 ± 30 MeV. These candidates were fit kinematically with $M(\gamma\gamma)$ constrained to the π^0 and η masses to improve energy resolution. To distinguish charged pions, kaons and protons a log-likelihood criterion including dE/dx and information from the RICH detector was used.

In the *inclusive analysis*, in order to remove neutral pions from J/ψ decays following $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\pi^0\pi^0 J/\psi$, events were rejected with $\pi^+\pi^-$ recoil mass in the range $M(J/\psi) = 3097 \pm 15$ MeV and $\pi^0\pi^0$ recoil mass in the range $M(J/\psi) = 3097 \pm 40$ MeV. Similarly, events with the invariant mass of all charged particles, M(all charged) > 3050 MeV, as well as events with recoil mass against $\gamma\gamma$ in the range $M(J/\psi) = 3097 \pm 40$ MeV, were rejected to remove decays through the χ_J states.

For the inclusive analysis it is required that the energy of the E1 photon in $h_c \to \gamma\eta_c$ be in the expected range $E(\gamma) = 503 \pm 35$ MeV. It is also required that there be only one such photon in the event. Further, this candidate photon was rejected if it made either a π^0 or η

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, $\mathcal{B}_1 \times \mathcal{B}_2$ for the exclusive analysis is based on 165 ± 19 counts.

	Inclusive	Exclusive
Counts	1146 ± 118	136 ± 14
Significance	10.0σ	13.2σ
$M(h_c)$, MeV	3525.35±0.23±0.15	3525.21±0.27±0.14
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$	$4.22 \pm 0.44 \pm 0.52$	$4.15 \pm 0.48 \pm 0.77$

with any other photon in the event.

The mass spectra of π^0 recoils are shown in Fig. 1, with the full spectrum in the top panel, and the background subtracted spectrum in the bottom panel. When the requirement $E(\gamma) = 503 \pm 35$ MeV is not imposed, a spectrum of the background is obtained with nearly twenty times larger yield and no apparent h_c enhancement, as is expected because of the small product branching fraction $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) \approx 4\times10^{-4}$. To remove the small h_c contribution in the above background, events were removed if they had a photon with $E(\gamma) = 503 \pm 50$ MeV. In the fit of the h_c spectrum in Fig. 1 (top) this background shape was mapped to the full spectrum with just one normalization parameter. The peak shape used consists of a Breit–Wigner function with an assumed width of 0.9 MeV (same as $\Gamma(\chi_{c1})$), convolved with the instrumental resolution function obtained by fitting the Monte Carlo (MC) simulation of the data. The χ^2/d.o.f. of the fit is 54/52. In the MC simulations the angular distribution for the E1 photon was assumed to be $(1 + \cos^2\theta)$. The overall efficiency determined from the MC sample is ϵ=11.1%. The results of the fit, and $\mathcal{B}_1 \times \mathcal{B}_2 = N(h_c)/(\epsilon \times N(\psi(2S)))$ are listed in Table I.

In the *exclusive analysis* no constraint on $E(\gamma)$ was imposed. Instead, for the decays $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to X$, η_c candidates were reconstructed in fifteen different decay modes, X, with multiplicities of 2 to 6. These modes were used because they had significant yields in the direct decays $\psi(2S) \to \gamma\eta_c$. Several of them, marked with (*), were utilized for the first time. These decay channels are: $p\bar{p}$, $\eta\pi^+\pi^-$ $(\eta \to \gamma\gamma)$, $\eta\pi^+\pi^-$ $(\eta \to \pi^+\pi^-\pi^0)$, $K_S K^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$, $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-\pi^+\pi^-$, (*)$\eta K^+K^-(\eta \to \gamma\gamma)$, (*)$p\bar{p}\pi^0$; (*)$\pi^+\pi^-\pi^0\pi^0$, (*)$p\bar{p}\pi^+\pi^-$, (*)$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$.

The decay chain in Eq. (1) as well as the above η_c decays were identified from the reconstructed charged particles, and π^0's and η's. For η decays to $\pi^+\pi^-\pi^0$, it was required that the invariant mass be within 30 MeV of the nominal mass $M(\eta)$=547.5 MeV [1]. For K^0_S decaying into a $\pi^+\pi^-$ pair, it was required that the invariant mass of the pair be within 10 MeV of the nominal mass $M(K^0_S)$=497.6 MeV [1], and information about vertex displacement was used to reject random $\pi^+\pi^-$ combinations. The $\psi(2S) \to \pi^+\pi^- J/\psi$ events were rejected with $\pi^+\pi^-$ recoil mass in the range $M(J/\psi) = 3097 \pm 15$ MeV.

The entire decay sequence was reconstructed for each η_c decay channel. A kinematically constrained fit was done for each event to take advantage of energy-momentum conservation, and it was required that the χ^2 of the 4C fit be less than 15. The mass of the η_c candidates was required to be within 30 MeV of the nominal mass of $M(\eta_c)$=2980 MeV [1]. If multiple η_c candidates were found in an event, only the one with the smallest χ^2 was retained.

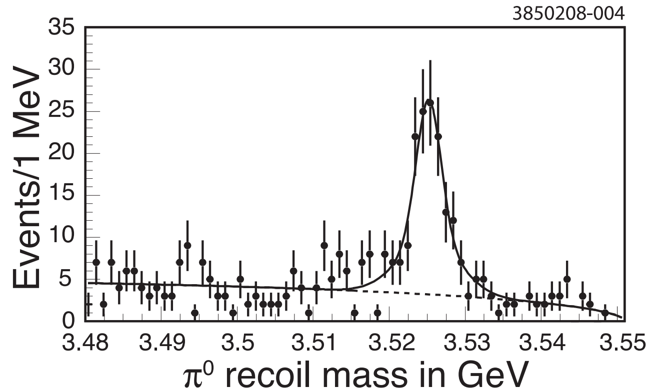

FIG. 2: Summed distribution of recoil masses against π^0 in the exclusive analysis with 15 decays channels of η_c. See text for details.

The π^0 recoil mass distribution for each decay channel was fitted separately using the instrumental resolution shape determined from MC simulation, convolved with a Breit–Wigner function of assumed width $\Gamma(h_c)$=0.9 MeV. The ARGUS shape [9] was used to parameterize the background. The fitted number of counts from individual decays range from 1 to 30. The summed distribution was fitted in the same way. The fit is shown in Fig. 2.

The product branching ratio $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ is related to the observed counts in the different decay channels $\eta_c \to X$ as the average

$$\left\langle \frac{N(X,h_c)/\epsilon(X,h_c)}{N(X,\mathrm{direct})/\epsilon(X,\mathrm{direct})} \right\rangle_X = \frac{\mathcal{B}_1 \times \mathcal{B}_2}{\mathcal{B}(\psi(2S) \to \gamma\eta_c)} \tag{2}$$

In order to minimize systematic errors in the evaluation of Eq. (2) it is desirable to construct $\eta_c \to X$ decays in the same manner for η_c from h_c and η_c from direct decay of $\psi(2S)$. We do so by placing a window of $\pm$7 MeV around $M(h_c)$ in π^0 recoil. The spectrum for the hadronic system mass for each individual decay channel was then reconstructed and fitted in the same manner for decays through h_c as for the direct decays. The fits were done using a Breit–Wigner function with $\Gamma(\eta_c)$=26.5 MeV [1], convoluted with the experimental resolution function as determined by the MC simulation for that channel, and parametrized as a double Gaussian. The background in each case was parametrized using a polynomial. The number of counts in individual decays ranged from 37$\pm$11 ($p\bar{p}$) to 1052$\pm$74 ($\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$), with a total $\Sigma N(X,\mathrm{direct})$=4043$\pm$127. The corresponding total $\Sigma N(X,h_c)$ was 165$\pm$19. This is larger than $\Sigma N(X,h_c)$ obtained by fitting the π^0 recoil spectrum for $M(h_c)$ measurement, and has correspondingly larger efficiency.

The efficiencies $\epsilon(X,h_c)$ and $\epsilon(X,\mathrm{direct})$ were determined from MC simulations separately for each channel. As expected, it was found that the ratios of efficiencies, $R(X) = \epsilon(X,\mathrm{direct})/\epsilon(X,h_c)$ were essentially independent of X, and had the average value $\langle R \rangle = 2.36 \pm 0.17$. This allows us to obtain from Eq. 2.

$$\frac{\mathcal{B}_1 \times \mathcal{B}_2}{\mathcal{B}(\psi(2S) \to \gamma\eta_c)} = \frac{\sum N(X,h_c)}{\sum N(X,\mathrm{direct})} \times \langle R \rangle = 0.096 \pm 0.013. \tag{3}$$

Using the summed counts above, and the recently measured CLEO value, $\mathcal{B}(\psi(2S) \to \gamma\eta_c)$=(4.32$\pm$0.67)$\times 10^{-3}$ [10], we obtain $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c)$= (4.15$\pm$0.48(stat))$\times 10^{-4}$.

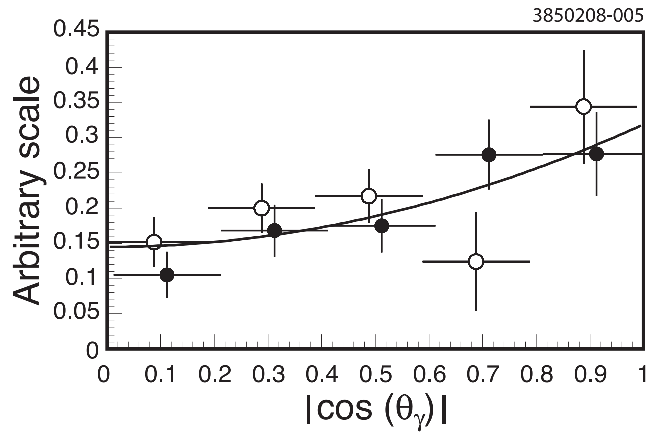

FIG. 3: Angular distributions of the photons from $h_c \to \gamma\eta_c$. Circles and solid points denote results from inclusive and exclusive analyses, respectively. The curve shows $N(1+\alpha\cos^2\theta)$ distribution, corresponding to α=1.20, as explained in the text.

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

	$M(h_c)$, MeV		$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$	
Systematic uncertainty in	Incl.	Excl.	Incl.	Excl.
$N(\psi(2S))$	N/A	N/A	0.08	N/A
$\mathcal{B}(\psi(2S) \to \gamma\eta_c)$	N/A	N/A	N/A	0.66
Background shape	0.10	0.01	0.26	0.15
π^0 energy calibration	0.08	0.08	N/A	N/A
π^0 signal shape	0.03	0.01	0.14	N/A
h_c width	0.03	0.02	0.27	<0.01
efficiency	N/A	N/A	0.20	0.22
Binning, fitting range	0.03	0.03	0.08	0.27
MC input/output	0.05	0.11	N/A	N/A
η_c decays	N/A	N/A	0.18	<0.01
η_c width	N/A	N/A	0.16	<0.01
η_c line shape	N/A	N/A	N/A	0.09
Sum in quadrature	$\pm$0.15	$\pm$0.14	$\pm$0.52	$\pm$0.77

The angular distributions of the E1 photons in both inclusive and exclusive analyses were obtained by fitting separately the h_c peak in the data for different angular ranges. The results are shown in Fig. 3. The distributions were fitted with the function $N(1+\alpha\cos^2\theta)$. The fits give α_{incl}=0.87$\pm$0.65 (χ^2/dof=3.9/3) and α_{excl}=1.89$\pm$0.94 (χ^2/dof=1.8/3). In order to take the average of the results from inclusive and exclusive analyses, the exclusive events were removed from the inclusive sample. The average of the values from inclusive and exclusive analyses is $\alpha_{average}$=1.20$\pm$0.53, and the curve in Fig. 3 illustrates it. This is consistent with α=1 expected for an E1 transition from $h_c(J^{PC}=1^{+-})$ to $\eta_c(J^{PC}=0^{-+})$.

Systematic errors in the two analyses due to various possible sources were estimated by varying the parameters used. These include choice of background parameterization, $\Gamma(h_c) = 0.5 - 1.5$ MeV, π^0 line shape (varied by $\pm 10\%$), bin size (varied between 0.5 and 2 MeV), π^0 energy calibration (varied energy of photon daughters by 0.2% to 1.0% depending on photon energy). In the branching ratio for $\psi(2S) \to \gamma\eta_c$ [10] the dominant systematic uncertainty is due to the line shape of the η_c which propagates into our product branching fraction analysis. An additional 2% systematic uncertainty is included to account for the possibility that line shape for the E1 transition $h_c \to \gamma\eta_c$ differs from that for the M1 transition in direct $\psi(2S) \to \gamma\eta_c$ in a way that does not cancel in Eq. (2). It was determined that the results were stable well within statistical errors for the variations of event selection criteria.

The individual contributions to systematic errors, as well as their sum in quadrature, are listed in Table II.

When the exclusive events are removed from the inclusive spectrum, and the data are refitted, we obtain $M(h_c) = 3525.35 \pm 0.27$(stat). The average of this result for the (inclusive–exclusive) events and the result in Table 2 for the exclusive events gives our final result as

$$M(h_c) = 3525.28 \pm 0.19(\text{stat}) \pm 0.12(\text{syst}) \text{ MeV}, \tag{4}$$

$$\begin{aligned} &\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\ \eta_c) \\ &= (4.19 \pm 0.32 \pm 0.45) \times 10^{-4}. \end{aligned} \tag{5}$$

These results represent a large improvement over our earlier results. The significance of h_c identification is 10 σ for the inclusive measurements, and 13 σ for the exclusive measurements. The present results from the exclusive measurements are based on twice as many decay channels of η_c as before, and are in excellent agreement with the results from the inclusive measurements.

The nearly one order of magnitude larger statistics available in the present measurements has enabled us to determine the systematic errors presented in Table II with much greater precision than in our earlier publication [2]. This allows us to average the present results with the previous ones. The resulting average results are:

$$M(h_c)_{\text{AVG}} = 3525.20 \pm 0.18 \pm 0.12 \text{ MeV}, \tag{6}$$

$$(\mathcal{B}_1 \times \mathcal{B}_2)_{\text{AVG}} = (4.16 \pm 0.30 \pm 0.37) \times 10^{-4}. \tag{7}$$

To put our results in perspective, we wish to make two further observations.

It is expected that the E1 radiative transitions $\chi_{c1} \to \gamma J/\psi$ and $h_c \to \gamma\eta_c$ should be similar. Also, the total widths of $\Gamma(\chi_{c1})$ and $\Gamma(h_c)$ should be similar. If we assume them to be identical, it follows that $\mathcal{B}_2(h_c \to \gamma\eta_c) = \mathcal{B}(\chi_{c1} \to \gamma J/\psi) \approx 0.36 \pm 0.02$ [1]. Our product branching fraction then leads to $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \approx (1.13 \pm 0.15) \times 10^{-3}$. Incidentally, this is nearly equal to that for the only other isospin forbidden decay measured within the charmonium family, $\mathcal{B}(\psi(2S) \to \pi^0 J/\psi)$=$(1.26\pm0.13)\times10^{-3}$. A recent theoretical prediction [11] gives the range $\mathcal{B}(\psi(2S) \to \pi^0 h_c)$=$(0.4$–$1.3)\times10^{-3}$.

If the mass of the centroid of ^3P_J states, $\langle M(^3P_J)\rangle$ is used as a measure of $M(^3P)$, the present measurement of $M(h_c)$ in Eq. 4 leads to

$$\begin{aligned} &\Delta M_{hf}(1P) \equiv \left\langle M(^3P_J)\right\rangle - M(^1P_1) \\ &= +0.02 \pm 0.19(\text{stat}) \pm 0.13(\text{syst}) \text{ MeV}. \end{aligned} \tag{8}$$

The CLEO average mass in Eq. (6) leads to

$$\Delta M_{hf}(1P) = +0.08 \pm 0.18(\text{stat}) \pm 0.12(\text{syst}) \text{ MeV}. \tag{9}$$

These results are consistent with the lowest order expectation of $1P$ hyperfine splitting being zero. We notice that the triplet mass used above was obtained as $\langle M(^3P_J)\rangle = (M(^3P_0) + 3M(^3P_1) + 5M(^3P_2))/9$, which is the evaluation of $M(^3P)$ in the lowest order, when the spin–orbit splitting is perturbatively small. It has been pointed out [4] that with $(M(^3P_2) - M(^3P_0)) \approx 140$ MeV, the validity of the perturbative determination of $M(^3P)$ is questionable. Indeed, the perturbative prediction that $M(^3P_1) - M(^3P_0) = \frac{5}{2}[M(^3P_2) - M(^3P_1)] = 113.9 \pm 0.3$ MeV disagrees with the experimental result, 95.9 ± 0.4 MeV, by 18 MeV. This necessarily implies that the true $M(^3P)$ is different from the centroid value $\langle M(^3P_J)\rangle$. Since $\Delta M_{hf}(1P)$ is expected to be small ($\sim$ few MeV), if not identically zero, it is important that higher order effects should be taken into account in deducing $M(^3P)$ from the known masses of ^3P_J states [4], so that a true measure of $\Delta M_{hf}(1P)$ can be obtained. Only then can the present measurement of $M(h_c)$ be used to distinguish between the different potential model calculations, whose predictions for $\Delta M_{hf}(1P)$ vary over a large range because of the different assumptions they make about relativistic effects, the Lorentz nature of the confinement potential, and smearing of the spin–spin contact potential [12]. Although the presently available lattice calculations do not have the required precision [13], it may be expected that future unquenched lattice calculations will resolve these problems.

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