*Physics*

*Physics Research Publications*

*Purdue University* *Year* 2008

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

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(Received 28 May 2008; published 31 October 2008)

A precision measurement of the mass of the $h_c(^1P_1)$ state of charmonium has been made using a sample of $24.5 \times 10^6$ $\psi(2S)$ events produced in $e^+e^-$ annihilation at the Cornell Electron Storage Ring (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 $\eta_c$ decays are reconstructed in 15 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.

DOI: 10.1103/PhysRevLett.101.182003 PACS numbers: 14.40.Gx, 12.38.Qk, 13.25.Gv

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

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

using $3 \times 10^6$ $\psi(2S)$ produced in $e^+e^-$ annihilations. The $h_c$ was identified as the enhancement in the mass spectrum of recoils against $\pi^0$. Two different kinds of analysis of the data were done. In the *inclusive analysis* $h_c$ decays were identified by loose constraints on either the energy of the electric dipole (E1) photon from $h_c$ decay, or the mass of $\eta_c$. In the *exclusive analysis* no constraint was placed on $E(\gamma)$. Instead, $\eta_c$ events were reconstructed in seven different hadronic decay channels of $\eta_c$. The combined significance level of the $h_c$ observation was $>6\sigma$, and the quoted mass was $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ 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 $M(h_c) = 3525.8 \pm 0.2 \pm 0.2$ 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 $\Delta M_{hf}(1P) = +0.9 \pm 0.6 \pm 0.4$ MeV (CLEO), and $\Delta M_{hf}(1P) = -0.5 \pm 0.2 \pm 0.2$ 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 Cherenkov (RICH) detector, inside a superconducting solenoid magnet with a 1.0 T magnetic field. The detector has a total acceptance of 93% of $4\pi$, photon energy resolutions of 2.2% at $E_\gamma = 1$ 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 $\pi^0$ candidates were reconstructed using photons only in the good barrel region, $|\cos\theta| \leq 0.81$. For showers it was required that $E_\gamma(\text{barrel}) > 30$ MeV, and $E_\gamma(\text{end caps}) > 50$ MeV, where the end cap region is defined as $0.85 < |\cos\theta| < 0.93$. The events accepted for $\gamma\gamma$ decays of $\pi^0$ and $\eta$ were required to have $M(\gamma\gamma)$ within $\pm 15$ 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 $\pi^0$ in the event with the recoil mass in the expected region of $h_c$ mass, $3526 \pm 30$ MeV. These candidates were fit kinematically with $M(\gamma\gamma)$ constrained to the $\pi^0$ and $\eta$ 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 $J/\psi$ 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, $M(\text{all charged}) > 3050$ 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 $\chi_J$ 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 $\pi^0$ or $\eta$ with any other photon in the event.

The mass spectra of $\pi^0$ 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 require-

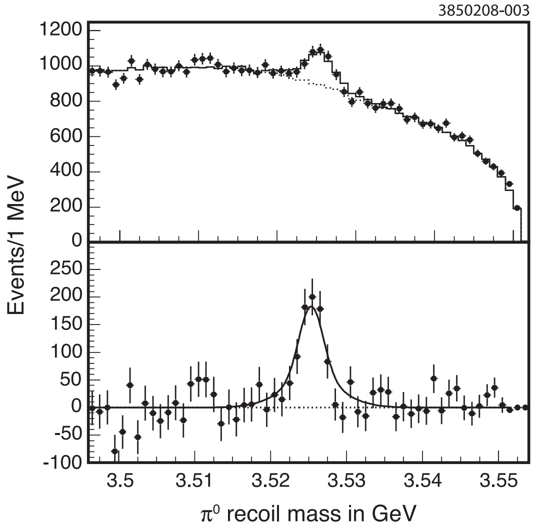


FIG. 1. Spectra of recoil masses against $\pi^0$ in the inclusive analysis: (top) full spectrum, (bottom) background subtracted spectrum.

ment $E(\gamma) = 503 \pm 35$ MeV is not imposed, a spectrum of the background is obtained with nearly 20 times larger yield and no apparent $h_c$ enhancement, as is expected because of the small product branching fraction $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) \approx 4 \times 10^{-4}$. In order to get a background spectrum free of even the small contribution of $h_c$, we only retain those events in it which do not have a photon in the range $E_\gamma = 503 \pm 50$ MeV of the E1 photon from $h_c$. 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 $\chi^2$/(degrees of freedom, 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 $\epsilon = 11.1\%$. The results of the fit are listed in Table I.

In the *exclusive analysis* no constraint on $E(\gamma)$ was imposed. Instead, for the decays $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to X$, $\eta_c$ candidates were reconstructed in 15 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 $\eta_c$ decays were identified from the reconstructed charged particles, and $\pi^0$'s and $\eta$'s. For $\eta$ 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 $K_S^0$ decaying into a $\pi^+\pi^-$ pair, it was required that the invariant mass of the pair be within 10 MeV of the nominal mass $M(K_S^0) = 497.6$ 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 $\eta_c$ decay channel. A four-momentum constrained (4C) kinematic fit was done for the events, and only events with $\chi^2 < 15$ were accepted. The mass of the $\eta_c$ candidates was required to be within 30 MeV of the nominal mass of $M(\eta_c) = 2980$ MeV [1]. If multiple $\eta_c$ candidates were found in an event, only the one with the smallest $\chi^2$ was retained.

The $\pi^0$ 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 parametrize the background. The fitted number of counts from individual decays range from 1 to 30. The fit to the summed distribution 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

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.

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

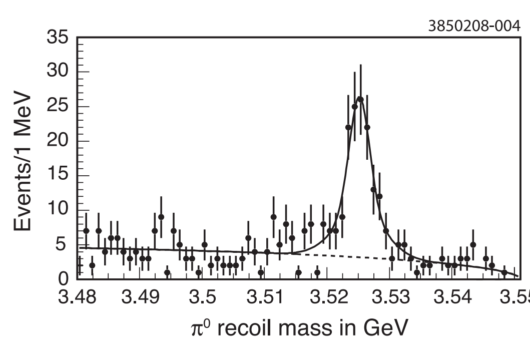


FIG. 2. Summed distribution of recoil masses against $\pi^0$ in the exclusive analysis with 15 decays channels of $\eta_c$. See text for details.

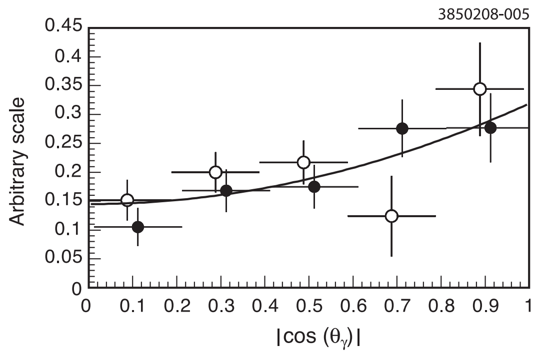


FIG. 3. Angular distributions of the photons from $h_c \to \gamma\eta_c$. Circles and solid points denote results from inclusive and exclusive analyses, respectively. The curve shows $N(1 + \alpha\cos^2\theta)$ distribution, corresponding to $\alpha = 1.20$, as explained in the text.

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

Here $(X, h_c)$ means $h_c \to \gamma\eta_c$, $\eta_c \to X$, and $(X$, direct) means $\psi(2S) \to \gamma\eta_c$, $\eta_c \to X$.

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 $\eta_c$ from $h_c$ and $\eta_c$ from direct decay of $\psi(2S)$. We do so by placing a window of $\pm 7$ MeV around $M(h_c)$ in $\pi^0$ 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], convolved with the experimental resolution function as determined by the MC simulation for that channel. 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 $\pi^0$ 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)

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

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 $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.15 \pm 0.48(\mathrm{stat.})) \times 10^{-4}$.

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 $\alpha_{\mathrm{incl}} = 0.87 \pm 0.65(\chi^2/\mathrm{d.o.f.} = 3.9/3)$ and $\alpha_{\mathrm{excl}} = 1.89 \pm 0.94(\chi^2/\mathrm{d.o.f.} = 1.8/3)$. 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 the inclusive and exclusive analyses is $\alpha_{\mathrm{average}} = 1.20 \pm 0.53$, and the curve in Fig. 3 illustrates it. This is consistent with $\alpha = 1$ 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 parametrization, $\Gamma(h_c) = 0.5$–$1.5$ MeV, $\pi^0$ line width (varied by $\pm 10\%$

TABLE II. Summary of estimated systematic errors and their sum in quadrature.

| | $M(h_c)$ (MeV) | | $\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$ | |
|---|---|---|---|---|
| Systematic uncertainty in | Inclusive | Exclusive | Inclusive | Exclusive |
| $N(\psi(2S))$ | ··· | ··· | 0.08 | ··· |
| $\mathcal{B}(\psi(2S) \to \gamma\eta_c)$ | ··· | ··· | ··· | 0.66 |
| Background shape | 0.10 | 0.01 | 0.26 | 0.15 |
| $\pi^0$ energy calibration | 0.08 | 0.08 | ··· | ··· |
| $\pi^0$ signal width | 0.03 | 0.01 | 0.14 | ··· |
| $h_c$ width | 0.03 | 0.02 | 0.27 | <0.01 |
| Efficiency | ··· | ··· | 0.20 | 0.22 |
| Binning, fitting range | 0.03 | 0.03 | 0.08 | 0.27 |
| $M(h_c)$ fit bias | 0.05 | 0.11 | ··· | ··· |
| $\eta_c$ decays | ··· | ··· | 0.18 | <0.01 |
| $\eta_c$ width | ··· | ··· | 0.16 | <0.01 |
| $\eta_c$ line shape | ··· | ··· | ··· | 0.09 |
| $\psi(2S)$ mass | 0.03 | 0.03 | ··· | ··· |
| Sum in quadrature | ±0.15 | ±0.14 | ±0.52 | ±0.77 |

from its MC determined value of $\sigma = 2.4$ MeV, or full width equal to 5.6 MeV), and bin size (varied between 0.5 and 2 MeV). The CLEO energy calibration for photons is based on the known mass of $\pi^0$, the line shape characterizing the calorimeter response, and at low energy on the photon energies in the radiative decays $\psi(2S) \to \chi_{cJ}(J = 1, 2)$, all of which are known with high precision. The uncertainty in this calibration varies from 0.2% to 1% for $E_\gamma = 30$–200 MeV. The *measured* energies of the daughter photons from our recoil $\pi^0$'s were varied by these amounts, and the resulting variation in the *fitted* mass of the $\pi^0$'s was considered as the estimate of the systematic uncertainty due to this source. The difference between the MC generator level $h_c$ mass and the reconstructed mass is called "$M(h_c)$ fit bias" in Table II. The larger error from this source in the exclusive analysis arises due to the kinematic fit which introduces an additional uncertainty in $\pi^0$ energy because of the more poorly determined hadronic system mass. In the branching ratio for $\psi(2S) \to \gamma\eta_c$ [10] the dominant systematic uncertainty is due to the line shape of the $\eta_c$. 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 magnetic dipole (M1) transition in direct $\psi(2S) \to \gamma\eta_c$ transition in a way that does not cancel in Eq. (2). It was determined that the results were stable well within statistical errors.

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 $M(h_c) = 3525.35 \pm 0.27(\text{stat.})$. The average of this result for the (inclusive − exclusive) events and the result in Table II for the exclusive events gives our final result as

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

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

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

The nearly 1 order of magnitude larger statistics available in our 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 CLEO-c results with the previous CLEO-c results in Ref. [2]. The resulting average results are

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

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

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 $h_c \to \gamma\eta_c$, as well as 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, $\mathcal{B}(\psi(2S) \to \pi^0 J/\psi) = (1.26 \pm 0.13) \times 10^{-3}$. A recent theoretical prediction [11] gives the range $\mathcal{B}(\psi(2S) \to \pi^0 h_c) = (0.4\text{–}1.3) \times 10^{-3}$.

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

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

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

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

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, $95.9 \pm 0.4$ 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.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the A. P. Sloan Foundation, the National Science Foundation, the U.S. Department of Energy, the Natural Sciences and Engineering Research Council of Canada, and the U.K. Science and Technology Facilities Council.

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