

# Evidence for $h_c$ Production from $\psi'$ at CLEO

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**Abstract.** Using the  $\sim 6 \text{ pb}^{-1}$  of  $e^+e^-$  annihilation data taken at  $\psi'(3686)$  with CLEO III and CLEO-c detectors with estimated  $\sim 3.0 \times 10^6$   $\psi'$  events, we have searched for the  $h_c(1^1P_1)$  state of charmonium in the reaction  $\psi'(3686) \rightarrow \pi^0 h_c \rightarrow (\gamma\gamma)(\gamma\eta_c)$ . The preliminary results are reported.

## 1. Introduction

Charmonium spectroscopy has played a crucial role in the understanding of the quark-gluon structure of hadrons and the underlying theory of Quantum Chromodynamics (QCD). This is primarily due to the fact that the charmonium system is expected to be far less sensitive to the problems associated with relativistic effects and the large value of the strong coupling constant,  $\alpha_s$ , than the light quark ( $u, d, s$ ) systems. Formation cross-sections for charmonium states, their masses and widths are also favorable for precision measurements. The existing experimental data have defined the spin-independent one-gluon exchange part of the  $q\bar{q}$  interaction quite well, however, the spin dependence of the  $q\bar{q}$  potential is not very well understood. In particular, the  $\vec{s}_1 \cdot \vec{s}_2$  spin-spin, or hyperfine interaction is not well understood, because there is little experimental data to provide the required constraints for theory. The primary experimental data required for understanding the  $q\bar{q}$  hyperfine interaction is hyperfine, or spin-singlet/spin-triplet splitting:  $\Delta M_{hf}(nL) \equiv \langle M(n^3L_J) \rangle - M(n^1L_{J=L})$ .

For nearly 20 years, the only hyperfine splitting known was that for the  $1S$  states of charmonium,  $\Delta M_{hf}(1S) = M(J/\psi) - M(\eta_c) = 116 \pm 2 \text{ MeV}$ . Very recently, Belle, CLEO and BaBar succeeded in identifying  $\eta'_c(2S)$ , with the rather surprising result that  $\Delta M_{hf}(2S) = M(\psi') - M(\eta'_c) = 48 \pm 4 \text{ MeV}$ . Potential model and quenched lattice calculations predicted a larger  $\Delta M_{hf}(2S)$  [1].

It is of great importance to find out how the hyperfine interaction manifests itself in  $P$  states, i.e., to find  $\Delta M_{hf}(1P) \equiv M(\langle^3P_J \rangle) - M(1P_1)$ . With scalar confinement,  $\Delta M_{hf}(1P) = 0$  is expected. It is necessary to determine if this is true. The c.o.g. of  $^3P$  states,  $M(\langle^3P_J \rangle)$ , is well measured,  $M(\langle^3P_J \rangle) = 3525.3 \pm 0.1 \text{ MeV}$ . What is needed is to identify  $h_c$  and make a precision measurement of its mass.

## 2. Prior Experimental Searches for $h_c$

The Crystal Ball experiment at SLAC made a search for  $h_c$  in 1982 [2]. The search was unsuccessful and they reported 95% confidence limits of  $B(\psi' \rightarrow \pi^0 h_c, h_c \rightarrow \gamma\eta_c) < 0.32\%$  in the range  $M_{h_c} = 3440 - 3543 \text{ MeV}$ . The next search for  $h_c$  was made by the Fermilab experiment E760 [3] in the reaction  $p\bar{p} \rightarrow h_c \rightarrow \pi^0 J/\psi$ . It was claimed that a statistically

significant enhancement was observed and that the data indicated  $M(h_c) = 3526.2 \pm 0.15 \pm 0.2$  MeV. However, such an enhancement has not been confirmed by the successor Fermilab E835 experiment, with significantly higher statistics [4,5]. The E835 experiment also searched for  $h_c$  in the reaction  $p\bar{p} \rightarrow h_c \rightarrow \gamma\eta_c$ . Preliminary evidence at the  $\sim 3\sigma$  significance level has been recently reported with  $M(h_c) = 3525.8 \pm 0.2 \pm 0.2$  MeV [5]. No positive evidence has been reported yet by Belle and BaBar Collaborations.

It is fair to say that at present there is no convincing experimental evidence for  $h_c$  observation.

### 3. CLEO Searches and Results

The above considerations have motivated us to search for  $h_c$  in the  $\sim 6pb^{-1}$  data taken at CLEO with estimated  $\sim 3.0 \times 10^6$   $\psi'$  events, in the reaction

$$\psi' \rightarrow \pi^0 h_c, h_c \rightarrow \gamma\eta_c.$$

We search for this channel: (a) without using  $\eta_c$  decays (INCLUSIVE approach, see Section 3.1), and (b) using six dominant  $\eta_c$  decay modes (EXCLUSIVE approach, see Section 3.2). In both methods we search for  $h_c$  in the mass recoiling against  $\pi^0$  from decay  $\psi' \rightarrow \pi^0 h_c$ . This method benefits from the excellent resolution of the CLEO calorimeter.

#### 3.1. Inclusive Analyses

Two independent analyses have been performed, and results from the two are consistent. I will describe one of them in detail, and will later mention the differences between the two analyses. We use the following selection criteria:  $N_{shower} \geq 3$ ,  $N_{track} \geq 2$ . The selection of the showers and charged particles are done using the standard CLEO quality cuts.

We reconstruct  $\pi^0$ 's by requiring that the two photon invariant mass be in the range  $M_{\gamma\gamma} = 135 \pm 15$  MeV, and that the two photons have been successfully fitted to  $\pi^0$ . We require that there be only one  $\pi^0$  in the event with a recoil mass in the expected  $h_c$  mass range of  $3526 \pm 30$  MeV.

The  $\psi' \rightarrow \pi^+\pi^- J/\psi$  and  $\psi' \rightarrow \pi^0\pi^0 J/\psi$  events are removed by cutting on the recoil mass of  $\pi^+\pi^-$  and  $\pi^0\pi^0$ , respectively.

We define hard  $\gamma$ 's, the possible candidates from  $h_c \rightarrow \gamma\eta_c$  decays, by  $E_\gamma > 400$  MeV. We reject such  $\gamma$ 's which make a  $\pi^0$  or  $\eta$  with any other  $\gamma$ 's. We then require that the energy of hard  $\gamma$  should be in the range  $E_\gamma = 503 \pm 40$  MeV.

The background in data has been fitted in three ways: (a) ARGUS shape,  $y = x \times \sqrt{1 - (x/a)^2} \times \exp(b \times [1 - (x/a)^2])$ , (b) second-order polynomial shape, (c) background shape from Monte Carlo. The significance levels are obtained as  $\sigma \equiv \sqrt{-2 \ln(L_0/L_{max})}$ , where  $L_{max}$  and  $L_0$  are the likelihoods of the fits with and without the  $h_c$  resonance.

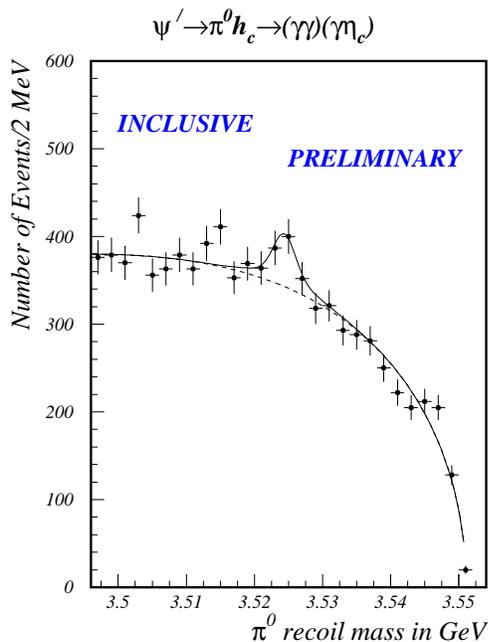
The analysis on the Monte Carlo samples has been performed. The event selection criteria applied to the Monte Carlo samples were identical to those applied to the data. 10,000 signal Monte Carlo events for the channel  $\psi' \rightarrow \pi^0 h_c \rightarrow (\gamma\gamma)(\gamma\eta_c)$  were simulated. The recoil mass distribution against  $\pi^0$  in signal Monte Carlo, for input  $\Gamma(h_c) = 0$  MeV is well fitted with a double Gaussian with parameters  $\sigma_1 = 1.3$  MeV,  $\sigma_2 = 3.7$  MeV, and the fraction of second Gaussian was 0.43. These parameters, which represent the  $\pi^0$  recoil mass resolution at  $h_c$ , are used to fit the signal in the data. The selection efficiency was about 16%. We also analyzed a sample of  $\sim 12 \times 10^6$  generic  $\psi'$  Monte Carlo events (events containing all measured  $\psi'$  decays except those via  $h_c$ ) in four separate samples, each with approximately the same size ( $\sim 3 \times 10^6$ ) as the data. The signal Monte Carlo events were added in to the generic Monte Carlo. The study of these Monte Carlo events yielded good agreement between input and output values for both,  $M(h_c)$  and  $B(\psi' \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma\eta_c)$ , and showed that the analysis is sensitive to  $h_c$  production.

Figure 1 shows recoil mass distribution against  $\pi^0$  in data. The results of the fit are:  $M(h_c) = 3524.4 \pm 0.7$  MeV,  $N(h_c) = 156 \pm 48$ ,  $\text{significance}(h_c) = 3.3 \sigma$ .

An independent alternative analysis has been done. The main difference is that in this analysis instead of constraining the energy of the hard photon, the constraint is put in terms of recoil against  $\pi^0\gamma$  ( $\eta_c$  mass). The results are consistent with those shown above. Thus our preliminary CLEO results from two inclusive analyses are:

- $M(h_c)=3524.8\pm 0.7(\text{stat})\pm \sim 1(\text{syst})$  MeV,
- $B(\psi' \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c) = (2-6) \times 10^{-4}$ ,
- The significance of  $h_c$  detection  $> 3 \sigma$ .

Estimates of systematic errors in  $M(h_c)$  have been made by studying the following:  $\pi^0$  energy scale, background shapes, Monte Carlo input/output differences, non-resonant background, assumed  $h_c$  width, binning effects, cut variations, and finally, the difference in  $M(h_c)$  in the two inclusive analyses.



**Figure 1.** Distribution of the recoiling mass against  $\pi^0$  in data (inclusive analysis). The curves are the results of the fit. The shape of the signal is assumed as Double Gaussian, and the shape of the background is assumed as ARGUS shape (see text).

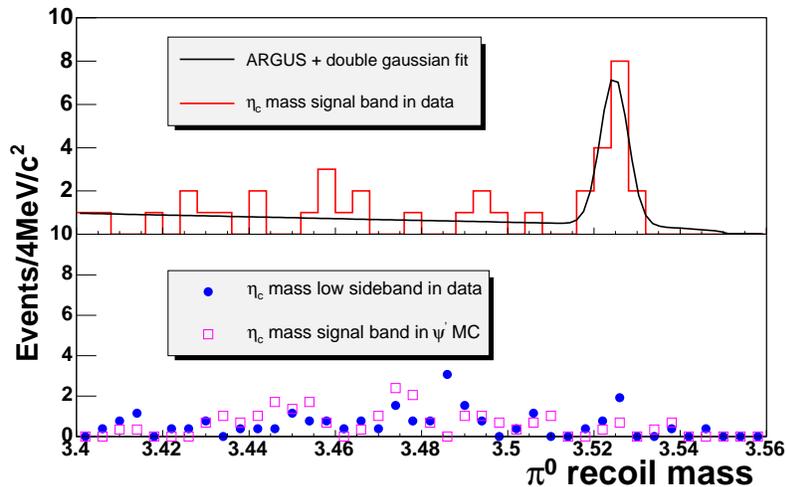
### 3.2. Exclusive Analysis

Six  $\eta_c$  decay modes which have reasonably high PDG04 branching ratios have been studied:  $K_s K^\pm \pi^\mp$ ,  $K^+ K^- \pi^0$ ,  $K^+ K^- \pi^+ \pi^-$ ,  $2\pi^+ 2\pi^-$ ,  $\pi^+ \pi^- \eta$  ( $\eta \rightarrow \gamma\gamma$ ), and  $\pi^+ \pi^- \eta$  ( $\eta \rightarrow \pi^+ \pi^- \pi^0$ ).

Standard CLEO selections are used for showers, tracks, and particle identification. The total energy-momentum conservation of the event has been required, and the invariant mass of the  $\eta_c$  decay candidates are required to be close to the nominal  $\eta_c$  mass (within 50 MeV). Figure 2(upper plot) shows the  $\pi^0$  recoil mass distribution for the sum of the six exclusive channels. The fit results are:

- $M(h_c)=3524.4\pm 0.9(\text{stat})$  MeV,
- $N(h_c)=15.0\pm 4.2$ ,
- The significance of  $h_c$  detection  $\sim 5 \sigma$ .

Note that the significance is calculated using likelihood differences. The background estimation by using  $\eta_c$  sidebands(closed circles in Figure 2, lower plot), or by using generic Monte Carlo events(open squares in Figure 2, lower plot), yield consistent results. No estimate of the systematic uncertainty in  $M(h_c)$  has been made so far.



**Figure 2.** Distribution of the recoiling mass against  $\pi^0$  (exclusive analysis).

#### 4. Summary

We have analyzed  $\sim 3.0 \times 10^6$   $\psi'$  from CLEO III and CLEO-c to search for  $h_c(^1P_1)$  production in the reaction  $\psi' \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$  by two methods 1. INCLUSIVE – which does not use  $\eta_c$  decay modes, 2. EXCLUSIVE – which uses six hadronic decay modes of  $\eta_c$ . In the recoil mass spectrum of  $\pi^0$ , we see an enhancement in both analyses.

- In the inclusive analysis we obtain

$$M(h_c) = 3524.8 \pm 0.7(\text{stat}) \pm \sim 1(\text{syst}) \text{ MeV},$$

$$B(\psi' \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c) = (2-6) \times 10^{-4},$$

significance of  $h_c$  detection  $> 3 \sigma$ .

$$\text{Thus, } \Delta M_{hf} \equiv \langle M(\chi_J) \rangle - M(^1P_1) = 0.5 \pm 0.7(\text{stat}) \pm \sim 1(\text{syst}) \text{ MeV}.$$

- In the exclusive analysis we obtain

$$M(h_c) = 3524.4 \pm 0.9(\text{stat}) \text{ MeV},$$

significance of  $h_c$  detection  $\sim 5 \sigma$ .

- The inclusive and exclusive results for  $M(h_c)$  are in excellent agreement.

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#### References

- [1] Z. Metreveli, Presented at Heavy Quarks and Leptons Workshop 2004, San Juan, Puerto Rico, 1-5 Jun 2004. hep-ex/0408001.
- [2] F. C. Porter, et. al., 17<sup>th</sup> Rencontre de Moriond Workshop on New Flavors, Les Arcs, France, (1982) p. 27. E. D. Bloom and C. W. Peck, Ann. Rev. Nucl. Part. Sci. **33** (1983) 143.
- [3] E760 Collaboration, T. A. Armstrong, et. al., Phys. Rev. Lett. **69** (1992) 2337.
- [4] D. Joffe., Ph. D. dissertation, Northwestern University, 2004.
- [5] C. Patrignani, Presented at BEACH2004, Chicago, June 27–July 3, 2004, and at QWGIII workshop, Beijing, Oct. 12–15, 2004.