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Presented at the Mark III Pow-Wow
Hillsborough, CA, May 9, 1987

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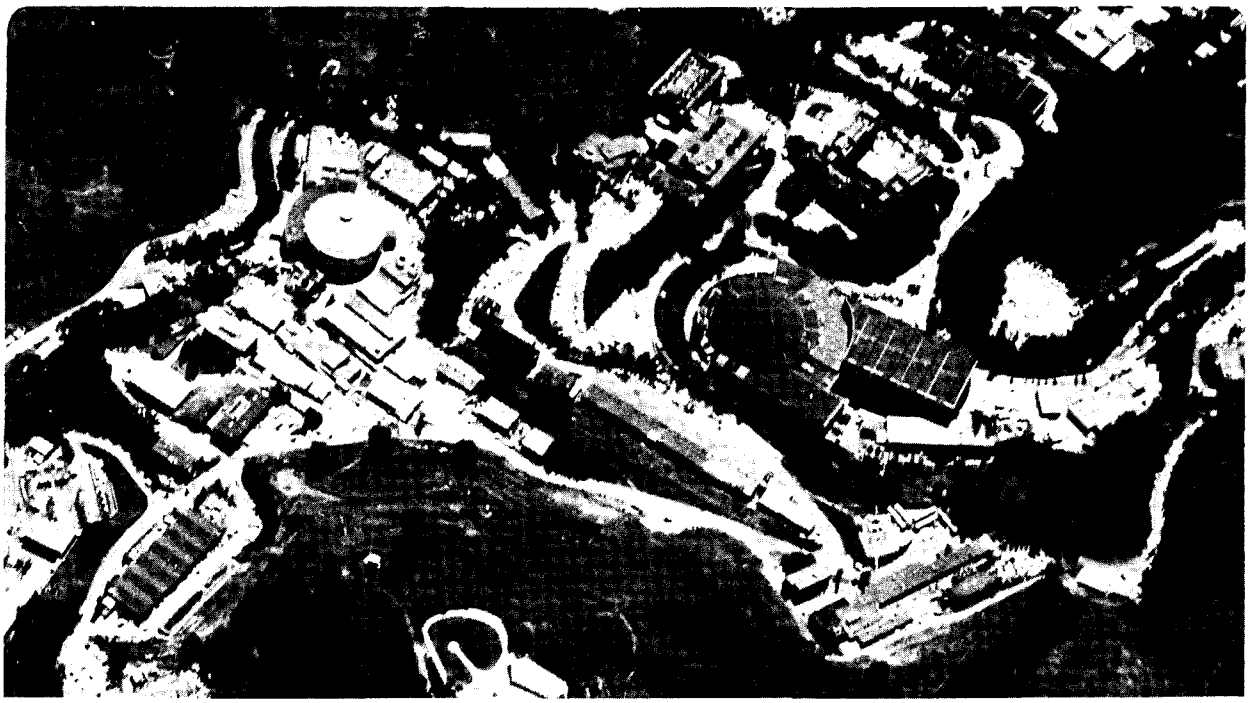

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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July 30, 1987 LBL-23549

Charmonium Spectroscopy: 1987* †

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Abstract

The state of charmonium spectroscopy is reviewed.

*Talk given at the Mark III Pow–Wow, May 9, 1987 Hillsborough, CA.

†This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U. S. Department of Energy under Contract DE-AC03-76SF00098.

The charmonium system has been studied in enormous detail both theoretically and experimentally. Excellent reviews from SLAC Summer Schools exist from as early as 1976[1] and as late as 1986.[2] All analyses proceed from a spin–dependent, non–relativistic Schrödinger equation:

$$\Big[-\frac{1}{2m_{red}}\frac{d^2}{dr^2} + \frac{\ell(\ell+1)}{2m_{red}r^2} + V_0(r) + V_{spin-spin}(r)\vec{S}_1\cdot\vec{S}_2 + V_{LS}(r)\vec{L}\cdot\vec{S} + V_{tensor}(r)S_{12}\Big]\,u_\ell(r) = Eu_\ell(r) \quad (1)$$

Here u is the radial wave function so

$$\begin{aligned}\psi &= \frac{u_\ell(r)}{r}Y_{\ell m}\times\text{spin wavefunction}\\ &\equiv R_\ell(r)Y_{\ell m}\times\text{spin wavefunction}\end{aligned} \quad (2)$$

The reduced mass is $m_{red} = \frac{1}{2}m_c$, $\vec{S}_1$ and $\vec{S}_2$ represent the quark spins, $\vec{L}$ the orbital angular momentum and S_{12} the tensor–force operator

$$\begin{aligned}S_{12} &= 3\vec{\sigma}_1\cdot\hat{r}\vec{\sigma}_2\cdot\hat{r} - \vec{\sigma}_1\cdot\vec{\sigma}_2 = 4(3\vec{S}_1\cdot\hat{r}\vec{S}_2\cdot\hat{r} - \vec{S}_1\cdot\vec{S}_2)\\ &= 2[3(\vec{S}\cdot\hat{r})^2 - \vec{S}^2]\end{aligned} \quad (3)$$

where $\vec{S} = \frac{1}{2}(\vec{\sigma}_1 + \vec{\sigma}_2)$.

Let us at first ignore the spin–dependent forces. Qualitatively, the potential lies between Coulombic and harmonic oscillator since the lowest p–wave states (center–of–gravity 3525 MeV) lie between the mid–point of 1^3S_1 and 2^3S_1 (3391 MeV) and the second s–wave state (3685 MeV). A variety of functional forms have been obtained that yield the proper spectrum for the observed states.

More detailed testing of the model is possible by examining electromagnetic transitions and hadronic decays, the latter using the perturbative QCD ansatz. The standard results are, specifically for the $c\bar{c}$ system[1]

$$\Gamma(^3S\to ggg) = \frac{40}{81\pi}(\pi^2-9)\frac{\alpha_s^3}{M^2}\,|R_0(0)|^2 \quad (4a)$$

$$\Gamma(^1S\to gg) = \frac{8}{3}\frac{\alpha_s^2}{M^2}\,|R_0(0)|^2 \quad (4b)$$

$$\Gamma(^3P_2\to gg) = \frac{128}{5}\frac{\alpha_s^2}{M^4}\,|R_1'(0)|^2 \quad (4c)$$

$$\Gamma(^3P_0\to gg) = \frac{96\alpha_s^2}{M^4}\,|R_1'(0)|^2 \quad (4d)$$

$$\Gamma(^3S_1\to e^+e^-) = \frac{4\alpha^2}{M^2}\left(\frac{2}{3}\right)^2|R_0(0)|^2 \quad (5)$$

$$\Gamma(^1S_0 \to \gamma\gamma) = \frac{12\alpha^2}{M^2}\left(\frac{2}{3}\right)^4 |R_0(0)|^2 \tag{6a}$$

$$\Gamma(^3P_0 \to \gamma\gamma) = \frac{256}{3}\frac{\alpha^2}{M^4}|R_1'(0)|^2 \tag{6b}$$

$$\Gamma(^3P_2 \to \gamma\gamma) = \frac{1024}{45}\frac{\alpha^2}{M^4}|R_1'(0)|^2 \tag{6c}$$

$$\Gamma(2^3S_1 \to {}^3P_J\gamma) = \frac{4\alpha}{27}\left(\frac{2}{3}\right)^2 (2J+1)k^3 |< 2p|r|2s >|^2 \tag{7a}$$

$$\Gamma(^3P_J \to 1^3S_1\gamma) = \frac{4\alpha}{27}\left(\frac{2}{3}\right)^2 3k^3 |< 1s|r|2p >|^2 \tag{7b}$$

where $M = M_\psi = 3096$ MeV etc. and k is the photon energy in the decay rest frame. The pertinent decay rates gleaned from the Review of Particle Properties[3] and other sources are given in Tables I, II, and III. The hadronic decay widths are deduced by combining a number of measurements. For the $\psi(3096)$ the branching ratio to e^+e^- and $\mu^+\mu^-$ together is 14% while there is a 17% branching ratio for $\psi \to \gamma* \to$ hadrons. In addition, there is a 6% rate to γ+hadrons.[4] Altogether $\Gamma(\psi \to \text{hadrons}) = 63\text{ keV}\cdot(1-0.14-0.17-0.06) = 40$ keV. For the ψ' we must subtract 50% for $\psi' \to \psi\pi\pi$, 3% for $\psi' \to \psi\eta$, 9.35% for $\psi' \to \chi_0\gamma$, 8.65% for $\psi' \to \chi_1\gamma$, 7.83% for $\psi' \to \chi_2\gamma$, 2.9% for $\psi' \to \gamma^* \to$hadrons, 1.7% for $\psi' \to e^+e^-, \mu^+\mu^-$, 0.3% for $\psi' \to \eta_c\gamma$, 0.2 - 1.3% for $\psi' \to \eta_0'\gamma$, and about 2% for $\psi' \to \gamma$+hadrons. With $\Gamma(\psi') = 215$ keV we find $\Gamma(\psi' \to$hadrons$) \approx 29$ keV. We expect

$$\frac{\Gamma(\psi \to had)}{\Gamma(\psi \to e^+e^-)} = \frac{\Gamma(\psi' \to had)}{\Gamma(\psi' \to e^+e^-)} \tag{8}$$

and find the left hand side is 8.4 while the right hand side is 14, in qualitative agreement only.

For the $2^3S_1 \to^3 P_J\gamma$ transitions we expect $J=2 : J=1 : J=0 = 1 : 1.4 : 1.7$ and find $1 : 1.1 : 1.2$ from the numbers in the Review of Particle Properties 1986 Edition.

For the $^3P_J \to 1^3S_1+\gamma$ transitions we have the theoretical predictions $J=2 : J=1 : J=0 = 1 : 0.75 : 0.35$. Taking[3,6] $\Gamma(^3P_0 \to 1^3S_1\gamma) \approx 120$ keV, we predict $\Gamma(^3P_2 \to 1^3S_1\gamma) \approx 340$ keV and $\Gamma(^3P_1 \to 1^3S_1\gamma) \approx 260$ keV. The former is in agreement with the poorly known value (see Table III). The latter does not contradict the limit set by experiment.

While it is possible to adopt an explicit model and calculate theoretical predictions from Eqs. (4)-(7) we content ourselves with a few comparisons chosen so that the wave functions cancel in the predictions. Thus for example

$$\frac{\Gamma(\chi_0)}{\Gamma(\chi_2)} = \frac{\Gamma(^3P_0 \to gg)}{\Gamma(^3P_2 \to gg)} = \frac{15}{4} = 3.75 \tag{9}$$

while experimentally

$$\frac{\Gamma(\chi_0)}{\Gamma(\chi_2)} = \frac{13-21}{1.6-4} = 3.25-13 \tag{10}$$

so that the test is not very exacting. From Eqs. (5) and (6a)

$$\frac{\Gamma(^3S_1 \to e^+e^-)}{\Gamma(^1S_0 \to \gamma\gamma)} = \frac{3}{4} \tag{11}$$

while experimentally

$$\frac{\Gamma(^3S_1 \to e^+e^-)}{\Gamma(^1S_0 \to \gamma\gamma)} = \frac{4.75 \text{ keV}}{4.3^{+3.4}_{-3.7} \pm 2.4 \text{ keV}} \tag{12}$$

using the $\gamma\gamma$ width obtained in the ISR experiment R704 which studied $p\bar{p}$ annihilation using a hydrogen gas jet target.[8]

The prediction

$$\frac{\Gamma(^3P_2 \to \gamma\gamma)}{\Gamma(^3P_2 \to gg)} = \frac{\Gamma(^1S_0 \to \gamma\gamma)}{\Gamma(^1S_0 \to gg)} \tag{13}$$

can be tested crudely with the data:

$$\frac{2.9^{+1.3}_{-1.0} \pm 2.4 \text{ keV}}{2.6^{+1.4}_{-1.0} \text{ MeV}} = \frac{4.3^{+3.4}_{-3.7} \pm 2.4 \text{ keV}}{11.5 \pm 4.3 \text{ MeV}} \tag{14}$$

Again, there is qualitative agreement.

The splittings among the ^3P states are due to the spin–orbit and tensor forces. Using the standard matrix elements for S_{12} we find

$$\begin{aligned} m(^3P_2) - m(^3P_1) &= 45 \text{ MeV} = [< V_{LS} > -(2/5) < V_{tensor} >] \\ &\quad - [- < V_{LS} > +2 < V_{tensor} >] \end{aligned} \tag{15a}$$

$$\begin{aligned} m(^3P_1) - m(^3P_0) &= 96 \text{ MeV} = [- < V_{LS} > +2 < V_{tensor} >] \\ &\quad - [-2 < V_{LS} > -4 < V_{tensor} >] \end{aligned} \tag{15b}$$

whence $< V_{LS} >= 35$ MeV, $< V_{tensor} >= 10$ MeV. It is possible to relate V_{LS} and V_{tensor} to V_0 if one assumes that all the forces arise as exchanges of vectors (gluons?) or scalars. The theoretical predictions using a pure vector exchange are not in agreement with the above figures. A mixture of scalar and vector of course is capable of fitting the two numbers.

In addition to the S and P states, there is the $\psi(3770)$, which is primarily $^3D_1$. Because it has the same J^{PC} as a $^3S_1$ state, mixing is possible. Indeed, the tensor force contributes a $\Delta L = 2$ operator to the Hamiltonian so mixing is expected. Without mixing the coupling

of the $^3D_1$ state to γ^* would be proportional to the second derivative of R at the origin and thus quite small:[10]

$$\Gamma(^3D_1 \to e^+e^-) = \frac{4\alpha^2}{M^2}\left(\frac{2}{3}\right)^2 \frac{50}{M^4}\,|R_2''(0)|^2 \tag{16}$$

The behavior of R_2 can be found in Ref. 11. Using a linear plus Coulomb potential they write a Schrödinger equation

$$\left(\frac{d^2}{d\rho^2} - \frac{\ell(\ell+1)}{\rho^2} - \rho + \frac{\lambda}{\rho} + \zeta\right) u_\ell = 0 \tag{17}$$

where ρ is a scaled radial variable

$$r = a(m_c a)^{-1/3}\rho$$

ζ is a scaled energy variable

$$E = m_c(m_c a)^{-4/3}\zeta \tag{18}$$

and

$$\lambda = \kappa(m_c a)^{2/3}. \tag{19}$$

Here the potential is

$$V = -\frac{\kappa}{r} + \frac{r}{a^2}. \tag{20}$$

Typical values are $m_c = 1.37$ GeV, $a = 2.2$ GeV^{-1}, $\kappa = (4/3)(0.19) = 0.25$ so $\lambda = 0.52$. From Table III of Ref. 11, we find for small ρ

$$u_2 \simeq 0.23\rho^3 \tag{21}$$

so

$$R_2 \simeq 0.23\left(\frac{m_c}{a^2}\right)^{7/6} r^2 \tag{22}$$

and

$$R_2''(0) \simeq 0.10\ \text{GeV}^{7/2}. \tag{23}$$

This would give

$$\begin{aligned}\Gamma(^3D_1 \to e^+e^-) &= \frac{800\alpha^2}{9M^6}\,|R_2''(0)|^2 \\ &= 16\ \text{eV}.\end{aligned} \tag{24}$$

The measured partial width of the $\psi(3770)$ is[12]

$$\Gamma(\psi(3770) \to e^+e^-) = 276 \pm 50\ \text{eV} \tag{25}$$

so the $\psi(3770)$ is not purely $^3D_1$.

Let us suppose that

$$|\psi(3770)>=\cos\theta|^3D_1>+\sin\theta|^3S_1> \tag{26}$$

Then[10]

$$\Gamma(\psi(3770)\to e^+e^-)=\frac{4\alpha^2}{M^2}\left(\frac{2}{3}\right)\left[\cos\theta R_0(0)-\sin\theta\frac{5\sqrt{2}}{M^2}R_2''(0)\right]^2 \tag{27}$$

where corrections like $\frac{1}{M^2}R_0''(0)$ have been dropped. If we suppose that the $^3S_1$ component is essentially the near–lying $\psi(3685)$ whose width into e^+e^- is 2.1 keV we have

$$\begin{aligned}\Gamma(\psi(3770)\to e^+e^-) &= \left|\cos\theta\sqrt{\Gamma(^3D_1)}-\sin\theta\sqrt{\Gamma(^3S_1)}\right|^2\\ 276\text{ keV} &= |4\cos\theta-46\sin\theta|^2\text{ keV}\\ \theta &= -16^0\text{ or }+26^0.\end{aligned} \tag{28}$$

Within the context of a model for the spin dependent forces, θ can be calculated treating configuration mixing as a consequence of the tensor force.[13] Using perturbation theory

$$|\psi(3770)>\cong|^3D_1>+\frac{|^3S_1><^3S_1|S_{12}V_{tensor}|^3D_1>}{E_{^3D_1}-E_{^3S_1}} \tag{29}$$

and

$$<J=1\ L=0\ S=1\ M_J|S_{12}|J=1\ L=2\ S=1\ M_J>=2\sqrt{2} \tag{30}$$

we see that

$$\sin\theta\approx 2\sqrt{2}\frac{<^3S_1|V_{tensor}|^3D_1>}{E_{^3D_1}-E_{^3S_1}}. \tag{31}$$

Now if the spin–dependent forces arise from vector and scalar exchanges, V_{tensor} is due entirely to the vector exchange. If the spin–independent potential due to the vector exchange is $v(r)$ then

$$V_{tensor}(r)=\frac{1}{12m_c^2}\left(\frac{1}{r}\frac{dv}{dr}-\frac{d^2v}{dr^2}\right). \tag{32}$$

This is, in fact, positive for reasonable potentials since if $v = Ar^\nu$, $V_{tensor} = A\nu(2-\nu)/(12m_c^2)$ and typical potentials of this form have $0<\nu<1$. Unfortunately, this doesn't tell us much since the 2^3S_1 radial wave function has a node and there will be some cancellation in the overlap. Indeed, mixing with the 1^3S_1 may be as important.[13]

In addition to its interesting dynamical issues, the $\psi(3770)$ is important for its role in the determination of the branching ratios of the D mesons. The Mark II branching ratios were obtained by reconstructing exclusive decays and dividing by the number of produced D's. The numbers of D's produced was inferred from the cross section ascribed to the $\psi(3770)$ resonance, assuming the $\psi(3770)$ decays exclusively to $D\bar{D}$. The Mark III measurements

compared events with one reconstructed D to events with two reconstructed D's. This yields the branching ratios directly. From the branching ratios and the numbers of observed D's, the total number of D's produced could be inferred. The Mark III found branching ratios about twice as big as those measured by Mark II and accordingly found about one–half as big as D meson production cross section. Although the discrepancy may be slightly less than originally believed, the discrepancy remains and warrants additional study.

The discrepancy would disappear if it were shown that the $\psi(3770)$ has important decays other than to $D\bar{D}$. This would invalidate the Mark II assumption. Alas, it is quite improbable that this is the case.[15] There are three decays to consider:

$$\psi(3770) \rightarrow \psi(3096)\pi\pi \qquad (a)$$

$$\psi(3770) \rightarrow \psi(3096)\eta \qquad (b)$$

$$\psi(3770) \rightarrow \eta(2980)\omega(783). \qquad (c)$$

The last can be disregarded because of the preposterously small phase space: 2980 + 783=3763, leaving only 7 MeV of kinetic energy. The $\psi' \rightarrow \psi\eta$ decay has much more phase space, is also a p–wave decay and has a partial width of 5.8 keV while the full width of the $\psi(3770)$ is about 25 MeV.

The $\psi(3770) \rightarrow \psi(3096)\eta$ partial width can be estimated by correcting for phase space:

$$\frac{\Gamma(\psi(3770) \rightarrow \psi(3096)\eta)}{\Gamma(\psi(3685) \rightarrow \psi(3096)\eta)} \approx \left(\frac{353 \text{ MeV}}{196 \text{ MeV}}\right)^3 \simeq 6$$

This gives $\Gamma(\psi(3770) \rightarrow \psi(3096)\eta) \approx 35$ keV, an insignificant contribution. Finally we turn to $\psi(3770) \rightarrow \psi(3096)\pi\pi$. The $\psi(3685) \rightarrow \psi(3096)\pi\pi$ spectrum has the form[16]

$$\begin{aligned}
\frac{d\Gamma}{dm_{\pi\pi}^2} &\propto (m_{\pi\pi}^2)^2[m_{\psi'}^2 - (m_\psi + m_{\pi\pi})^2] \\
&\approx (m_{\pi\pi})^4[m_{\psi'} - (m_\psi + m_{\pi\pi})] \\
\Gamma &\propto \int_{2m_\pi}^{m'_\psi - m_\psi} dm_{\pi\pi} m_{\pi\pi}^5 [m_{\psi'} - m_\psi - m_{\pi\pi}] \\
&\propto (m_{\psi'} - m_\psi)^7
\end{aligned}$$

Thus, very crudely, we estimate

$$\frac{\Gamma(\psi(3770) \rightarrow \psi(3096)\pi\pi)}{\Gamma(\psi(3686) \rightarrow \psi(3096)\pi\pi)} \approx \left(\frac{3770 - 3096}{3685 - 3096}\right)^7 \sim 2.6$$

and thus

$$\Gamma(\psi(3770) \rightarrow \psi(3096)\pi\pi) \approx 275 \text{ keV}.$$

Even this is far too small to have an impact on the branching ratio for $\psi(3770) \to D\bar{D}$ in view of the 25 MeV total width.

There are other D states that may be of interest. The ${}^1D_2$ $J^{PC} = 2^{-+}$ and ${}^3D_2$ $J^{PC} = 2^{--}$ states cannot decay strongly into $D\bar{D}$. Since these states should have masses near 3.8 Gev, they will be below the threshold for $D\bar{D}^*$, and thus will be narrow.[17] The ${}^3D_2$ can decay radiatively by an E1 transition to ${}^3P_2(\chi_2)$ or ${}^3P_1(\chi_1)$. The decay ${}^3D_2 \to \psi\pi\pi$ with $\pi\pi$ in 0^{++} requires that the ψ and the $\pi\pi$ system be in a relative d–wave. The ${}^1D_2$ can decay by an E1 radiative transition to ${}^1P_1$. Of these, the best bet is resonant production of the ${}^3D_2$ signalled by the decay sequence ${}^3D_2 \to {}^3P\gamma$, ${}^3P \to \psi\gamma, \psi \to e^+e^-, \mu^+\mu^-$.

The study of charmonium in resonant $p\bar{p}$ annihilation carried out by R704 at the ISR was very successful. In addition to measurements of the χ states and the $\eta_c(2980)$, they appear to have established the existence of the ${}^1P_1$.[8] The sequence observed is $p\bar{p} \to {}^1P_1 \to \psi X, \psi \to e^+e^-$. Although only five events were seen, the background is small and the mass found agreed perfectly with the center–of–gravity of the ${}^3P$ states, 3525 MeV.

Nearly twelve years after the discovery of the ψ, its associated spectroscopy is still of great interest. It provides a laboratory for the study of hadron dynamics in as controlled an environment as we are ever likely to have.

This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE–AC03–76SF00098.

Table I

Hadronic widths of charmonium states. The P state widths include the radiative decays. The S wave state widths do not.

State		Γ(hadronic)	Ref.
1^3S_1	$\psi(3096)$	40 keV	(3)
2^3S_1	$\psi(3685)$	29 kev	(3)
1^1S_0	$\eta_c(2980)$	11.5± 4.3 MeV	(3)
2^1S_0	$\eta_c(3590)$	<8 MeV	(3)
$^3P_0$	$\chi_0(3415)$	13-21 MeV	(6)
$^3P_1$	$\chi_1(3510)$	< 1.3 MeV	(5)
$^3P_2$	$\chi_2(3555)$	$2.6^{+1.4}_{-1.0}$ MeV	(5)

Table II

Fully electromagnetic decays of charmonium states.

State & Decay		Γ	Ref.
1^3S_1	$\psi(3096) \to e^+e^-$	4.75 ± 0.51 keV	(3)
2^3S_1	$\psi(3685) \to e^+e^-$	2.05 ± 0.21 keV	(3)
$^3D_1$	$\psi(3770) \to e^+e^-$	0.257 ± 0.046 keV	(3)
1^1S_0	$\eta_c(2980) \to \gamma\gamma$	$8.0 \pm 5.0 \pm 2.0$ keV	(7)
		$4.3 \pm^{3.4}_{3.7} \pm 2.4$ keV	(8)
$^3P_2$	$\chi_2(3555) \to \gamma\gamma$	$2.9^{+1.3}_{-1.0} \pm 1.7$ keV	(8)
		2.8 ± 2.0 keV	(9)

Table III

Radiative transitions in the charmonium system.

Transition	Photon momentum	BR	Γ	Ref. for BR
$2^3S_1 \rightarrow {}^3P_0\gamma$	261 MeV	9.35%	20 keV	(3)
$2^3S_1 \rightarrow {}^3P_1\gamma$	172 MeV	8.65%	19 keV	(3)
$2^3S_1 \rightarrow {}^3P_2\gamma$	128 MeV	7.83%	17 keV	(3)
$2^3S_1 \rightarrow 1^1S_0\gamma$	638 MeV	(0.28±0.06)%	0.6 keV	(3)
$2^3S_1 \rightarrow 2^1S_0\gamma$	90 MeV	(0.2 - 1.3)%	0.4 - 2.8 keV	(3)
${}^3P_0 \rightarrow 1^3S_1\gamma$	303 MeV	(0.70± 0.23)%	91 - 147 keV	(3)
		(0.60± 0.18)%	78 - 126 keV	(6)
${}^3P_1 \rightarrow 1^3S_1\gamma$	389 MeV	25.8±2.5%	<335 keV	(3)
		28.4± 2.1%	<369 keV	(6)
${}^3P_2 \rightarrow 1^3S_1\gamma$	429 MeV	14.8±1.7%	237 - 600 keV	(3)
		12.4± 1.5%	198 - 496 keV	(6)

References

1. J. D. Jackson in "Weak Interactions and the Production of New Particles", Proc. SLAC Summer Inst. on Particle Physics, Aug. 2–13, 1976, ed. M. Zipf. SLAC Report No. 198, Stanford 1976 pp. 147–202. See also J. D. Jackson in Proc. 1977 European Conf. on Particle Physics, Budapest, eds. L. Jenik, I. Montvay, Budapest, Central Inst. of Physics.

2. F. J. Gilman in "Probing the Standard Model", Proc. SLAC Summer Inst. on Particle Physics, July 28–Aug.8, 1986, ed. E.C. Brennan. See also: W. Kwong. J.L. Rosner, and C. Quigg, "Heavy Quark Systems" EFI–86–60, Fermilab–Pub–87/15-T, to be published in Ann. Rev. Nucl. Part. Sci.; S. Cooper in Proc. XXIII Int. Conf. on High Energy Physics, July 16–23, 1986, Berkeley. World Scientific, 1987, p.67.

3. Particle Data Group, Phys. Lett. 170B, 1(1987).

4. Estimate by M. S. Chanowitz, private communication.

5. R704 Collaboration, C. Baglin et al., Phys. Lett. 172B, 455 (1986).

6. Crystal Ball Collaboration, Phys. Rev. D34, 711 (1986).

7. Mark II collaboration, G. Gidal et al. Proc. XXIII Int. Conf. on High Energy Physics *op cit.* p. 1220.

8. R704 Collaboration, C. Baglin et al., Phys. Lett. 187B 191 (1987).

9. R. A. Lee, Thesis (Crystal Ball). SLAC Rep. 282. May 1985.

10. R. N. Cahn and J. D. Jackson, 1977 unpublished and J. D. Jackson, Budapest meeting, Ref. 1. See also F. Palumbo and V. Zakharov preprint LNF-77/17–P unpublished.

11. E. Eichten et al., Phys. Rev. D17, 3090 (1978).

12. R. H. Schindler et al., Phys. Rev. D21, 2716 (1980).

13. See, for example, G. R. Goldstein and J. Maharana, Zeit. Phys. C12, 23(1982).

14. Mark III Collaboration, R. M. Baltrusaitis et al. Phys. Rev. Lett. 56, 2140 (1986).

15. See K. Lane, HUTP 86/A045 unpublished.

16. L. S. Brown and R. N. Cahn, Phys. Rev. Lett. 35, 1, 1975.

17. W. Kwang, J. L. Rosner, and C. Quigg, *op. cit.*

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