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Production, Spectroscopy and Decays of Heavy Quark Bound States[1]

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Abstract

New developments on the physics of heavy quark bound states will be summarized and put in a perspective to previous results. The topics to be discussed are:

- a substantial change in total width for ψ and Υ vector mesons due to a consistent definition of radiative corrections for the process $e^+e^- \to 1^{--}$;
- the spectroscopy of heavy quark bound states including the possible existence of two new $^1P_1$ states;
- the precision measurements of hadronic and electromagnetic transitions from the $\Upsilon(3S)$ state and comparison with QCD inspired models;
- exclusive and inclusive radiative decays of the $\Upsilon(1S)$ state and a comparison with ψ radiative decays; and finally
- a search for the elusive Axion and Higgs bosons.

[1] Invited talk presented at the 6^{th} International Conference on Physics in Collision; Chicago, U.S.A., September 3-5 1986.

Production of ψ and Υ States

When positrons and electrons collide, they may scatter elastically or annihilate into a virtual photon of mass $\sqrt{s} = W = 2E$, where E is the beam energy. At total center-of-mass energies $W \lesssim 10$ GeV the interaction proceeds primarily through the electromagnetic force and we may neglect the weak interaction. Neutral vector meson states V, having the same quantum numbers as the photon, $J^{PC} = 1^{--}$, are therefore produced directly in e^+e^- interaction with a strength proportional to their leptonic partial width:

$$\tilde{\sigma}(W) = \frac{3\pi}{W^2} \frac{\Gamma_{ee}\Gamma_{had}}{(W - M_V)^2 + \Gamma_{tot}^2/4} \tag{1}$$

where it is assumed that the vector meson is detected in its hadronic decay, Γ_{had}, and Γ_{tot} is its total decay width. The integral over this cross section directly measures a product of widths: $\int \tilde{\sigma} dW \equiv A_\circ = (6\pi^2/M^2) \times \Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$. The hadronic branching ratio $B_{had} = \Gamma_{had}/\Gamma_{tot}$ can be expressed in terms of the leptonic branching ratio $B_{had} = 1 - nB_{\mu\mu}$ assuming lepton universality, *i.e.* the vector meson couples to electrons, muons and taus with the same strength. For the charmonium ψ states the only energetically allowed leptonic decays are into electron and muon pairs (n = 2), whereas n = 3 for the bottonium Υ states as the decay into tau pairs is also possible. A measurement of the integral over the resonance cross section thus yields a direct determination of Γ_{ee} and, combined with the leptonic branching ratio, yields the total width $\Gamma_{tot} = \Gamma_{ee} / B_{\mu\mu}$.

In the process $e^+e^- \to V \to$ hadrons the emission of additional photons, both virtual and real, results in modifications to the lowest order cross section. These radiative corrections can be categorized into initial state hard- and soft-photon bremsstrahlung, initial state vertex corrections, and vacuum polarization for the intermediate virtual photon. They have originally been calculated [1] by Yennie *et al.* and by Bonneau & Martin. Several other theoretical analyses have appeared since [2,3,4,5] which in particular take into account the narrowness of heavy quark vector resonances and which are exclusively used by experimenters to extract $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$. In general, all four prescriptions can be stated as a convolution of the lowest order cross section $\tilde{\sigma}(W)$ with a bremsstrahlung spectrum $B(x, W)$, where $x = k/E$ is the fraction of the energy carried away by photons:

$$\sigma(W) = \int dx\, \tilde{\sigma}\,(W\,(1 - x))\; B(x, W). \tag{2}$$

Note that the identification of x with the photon energy is valid only for $x \ll 1$. For hard photon bremsstrahlung, $x \sim 1$, it may be violated in higher orders (see ref. [5]). The bremsstrahl spectra obtained by Greco [2], Jackson & Scharre [3], Tsai [4] and Kuraev & Fadin [5] are

$$\begin{aligned} B_{Greco} &= tx^{t-1}\,(1 + \delta_e + 2\Pi) \\ B_{Jackson} &= tx^{t-1} \;+\; (\delta_e + 2\Pi)\;\delta(x) \\ B_{Tsai} &= tx^{t-1}\,(1 - \Pi)^{-\delta_e/\Pi} \\ B_{Kuraev} &= tx^{t-1}\,(1 + \delta_e). \end{aligned} \tag{3}$$

where for the sake of simplicity the hard bremsstrahlung part has been ignored; note that this part introduces a negligible contribution for narrow resonances. Also ignored are higher order corrections which are calculated in ref. [4,5]. In the above formula $t = \frac{2\alpha}{\pi}(\ln \frac{s}{m_e^2} - 1)$ is the effective radiator thickness, $\Pi = \frac{\alpha}{\pi}(\frac{1}{3}\ln \frac{s}{m_e^2} - \frac{5}{9})$ arises from the vacuum polarization (V.P.) and $\delta_e = \frac{3}{4}t + \frac{2\alpha}{\pi}(\frac{\pi^2}{6} - \frac{1}{4})$ arises from vertex modifications.

It is apparent from the different bremsstrahl spectra equ. (3) that the radiatively corrected cross section will differ for the different prescriptions and consequently Γ_{ee} will differ. This difference has recently been realized by Baru *et al.* [6]. They have analyzed their $\Upsilon(1S)$ resonance scan (figure 1) with the theoretical spectrum by Kuraev & Fadin which is based on renormalization-group methods. Baru *et al.* noted that the Jackson & Scharre formalism yields a 9% lower leptonic

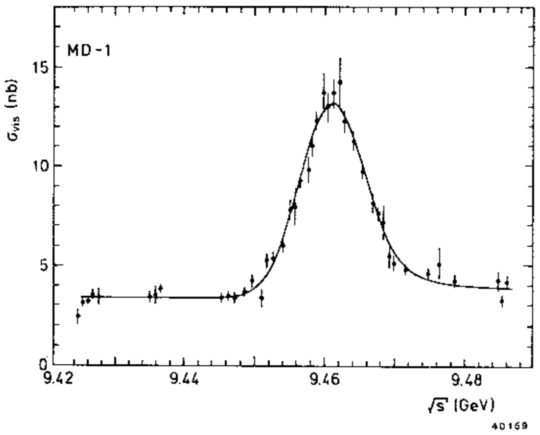

Figure 1: Observed hadronic cross section at the $\Upsilon(1S)$ from Baru *et al.* [6], obtained with the MD-1 detector at Novosibirsk.

width than that extracted with the Kuraev & Fadin method. An inspection of the bremsstrahl spectra stated above reveales the major difference: Jackson & Scharre (and Greco) include the vacuum polarization Π in their formulæ, whereas Kuraev & Fadin do not include this term. The question as to what procedure is correct depends on what needs to be determined: if we want to determine $\Gamma_{tot} = \Gamma_{ee} / B_{\mu\mu}$ we should *not* include the vacuum polarization in the definition of the bremsstrahl spectrum such that it will be part of the experimental Γ_{ee} definition. This procedure is then consistent with an experimental $B_{\mu\mu} = \Gamma_{ee} / \Gamma_{tot}$ measurement which, by definition, includes the vacuum polarization. On the other hand, if we want to compare experimental and theoretical Γ_{ee} values no V.P. contribution should be present (to be denoted by Γ°_{ee}). As the V.P. contribution is a small quantity ($\Pi \simeq 0.014$ at $\sqrt{s} \simeq 10\,\text{GeV}$ for electrons only in the loop) this contribution can

be factored: $\Gamma^{\circ}_{ee} = \Gamma_{ee} \times (1 - \Pi)^2$.

V	Experiment	Ref.	Model	Δ MeV	$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ quoted, keV	$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ corr., keV
J/ψ	ADONE	[7]	Greco	1.3	4.0±0.8	4.1±0.8
	ADONE[1]	[7]	Greco	1.3	4.0±0.9	4.0±0.9
	Mark I	[8]	Tsai	1.8	4.1±0.4	4.2±0.4
	MEA	[9]	Greco	1.3	4.6±0.5	4.7±0.5
	DASP	[10]	J - S	1.0	3.7±0.5	4.0±0.5
	DASP[1]	[10]	J - S	1.0	4.4±0.3	4.7±0.3
	average				4.2±0.2	4.4±0.2
ψ'	Mark I	[11]	Tsai	1.8	2.0±0.3	2.1±0.3
	DASP	[10]	J - S	1.4	2.0±0.3	2.2±0.3
	average				2.0±0.2	2.2±0.2
$\Upsilon(1S)$	PLUTO	[12]	Greco	8.0	1.24±0.13	1.29±0.14
	DESY-H	[13]	J - S	8.0	1.00±0.23	1.10±0.25
	DASP	[14]	J - S	8.0	1.12±0.08	1.24±0.09
	LENA	[15]	J - S	8.0	1.00±0.11	1.10±0.12
	CUSB	[16]	J - S	4.0	1.05±0.10	1.16±0.11
	CLEO[2]	[17]	J - S	4.0	1.17±0.09	1.37±0.10
	average				1.11±0.04	1.23±0.05
$\Upsilon(2S)$	DESY-H	[13]	J - S	8.0	0.37±0.16	0.41±0.18
	DASP	[14]	J - S	8.0	0.55±0.13	0.61±0.14
	LENA	[18]	J - S	8.0	0.53±0.09	0.61±0.14
	CUSB	[16]	J - S	4.0	0.53±0.06	0.59±0.06
	CLEO[2]	[17]	J - S	4.0	0.49±0.05	0.58±0.06
	average				0.51±0.03	0.58±0.04
$\Upsilon(3S)$	CUSB	[16]	J - S	4.0	0.35±0.04	0.39±0.04
	CLEO[2]	[17]	J - S	4.0	0.38±0.04	0.45±0.06
	average				0.36±0.03	0.41±0.03

Table 1: Reduced widths of the narrow vector resonances J/ψ and Υ. [1]These measurements have been obtained in $e^+e^- \to e^+e^-$ and yield $\Gamma^2_{ee}/\Gamma_{tot}$; for comparison they have been multiplied with B_{had}/B_{ee} to obtain $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$. [2]The CLEO group uses the Jackson-Scharre prescription with full vacuum polarization including all fermion loops. The CUSB [16] values are preliminary.

For a consistent experimental average on Γ_{ee} it is easy to put the vacuum polarization back into the $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ determinations obtained for example by using the Jackson & Scharre prescription. The best way of recalculating $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ for different experiments consists in calculating the peak values of the cross section after the convolution with the beam resolution function has been taken into account. We obtain:

$$\begin{array}{llcl} \text{Greco} & \sigma(M) & = & A_0\,(1+\delta_e+2\Pi)\,(2\Delta/M)^t\,F(0,t) \\ \text{Jackson} & \sigma(M) & = & A_0\,(2\Delta/M)^t\,F(0,t)+ \\ & & & +A_0\,(\delta_e+2\Pi)/\sqrt{2\pi}\Delta\;-2tA_0/M \\ \text{Tsai} & \sigma(M) & = & A_0\,(1+\delta_e)\,(2\Delta/M)^t\,F(0,t) \\ \text{Kuraev} & \sigma(M) & = & A_0\,(1+\delta_e)\,(2\Delta/M)^t\,F(0,t) \end{array} \quad (4)$$

where Δ is the r.m.s of the CMS resolution function, F(0, t) can be calculated in terms of the Γ function (see for example Jackson & Scharre [3]) and $A_0 \propto \Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ is the integral over the resonance for the lowest order cross section. As an example we obtain for a resolution of Δ = 8 MeV (DORIS storage ring) $\sigma_{Jackson}/\sigma_{Kuraev}$ = 1.094 for M = M_Υ. With this number we have to multiply $\Upsilon(1S)$ experimental $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ values which were obtained by experiments using the Jackson & Scharre prescription. This has been done in table 1. Note that a proper inclusion of higher order effects as calculated by Tsai and Kuraev & Fadin changes the above correction factors by at most 0.5% and have therefore been ignored. It is obvious from table 1 that a consistent definition of radiative corrections increases the average $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ values by about 10%.

Leptonic Branching Ratios

In order to determine Γ_{ee} and Γ_{tot} we need average values for the vector meson branching ratio into two leptons, $B_{\mu\mu}$. We will assume lepton universality to average branching ratios into electron pairs and muon pairs. The experimental results are shown in table 2. The $B_{\mu\mu}$ branching ratios for the charmonium vector states have been taken from the Review of Particle properties. For the bottonium resonances we have included the new $B_{\mu\mu}$ determinations by ARGUS [23] for the $\Upsilon(1S)$ and by CUSB [26] for the $\Upsilon(3S)$, both of which were presented at the Berkeley 1986 HEP conference. With the new world average value for $B_{\mu\mu}(\Upsilon(1S))$ we have also recalculated the ARGUS determination [25] of $B_{\mu\mu}(\Upsilon(2S))$. Overall averages have been obtained by adding statistical and systematic errors in quadrature and then forming weighted averages.

Γ_{ee} Determination

With the average values for the leptonic branching ratios we can calculate the leptonic width Γ_{ee} (including vacuum polarization) and the total width Γ_{tot}:

$$\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_{tot}} \times \frac{1}{1 - nB_{\mu\mu}} \quad ; \quad \Gamma_{tot} = \frac{\Gamma_{ee}}{B_{\mu\mu}}. \quad (5)$$

The results are presented in table 3. It turns out that the redefined Γ_{ee} values are on the average 10% larger than those stated in the 1986 Review of Particle properties [19]. The derived values for Γ_{tot} are also shown in table 3. It is the total widths stated in column three of table 3 that should be used to convert theoretical widths into branching ratios.

V	Experiment	Ref.	$B_{\mu\mu}$ (%)
J/ψ	PDG[1]	[19]	6.9±0.6
ψ'	PDG[1]	[19]	0.9±0.15
$\Upsilon(1S)$	PLUTO	[12]	2.2±2.0
	PLUTO[2]	[20]	5.1±3.0
	DESY-H	[13]	$1.4^{+3.4}_{-1.4}$
	DASP	[14]	3.2±1.3±0.3
	LENA	[15]	3.8±1.5±0.2
	CUSB	[16]	2.7±0.3±0.3
	CLEO	[21]	2.7±0.3±0.3
	CLEO[3]	[22]	2.84±0.18±0.20
	ARGUS[3]	[23]	2.39±0.18
	average		2.58±0.13
$\Upsilon(2S)$	LENA	[18]	< 3.8
	CUSB	[16]	1.9±0.3±0.5
	CLEO	[24]	1.8±0.8±0.5
	ARGUS	[25]	0.9±0.8
	average		1.60±0.42
$\Upsilon(3S)$	CLEO	[21]	3.3±1.3±0.7
	CUSB	[26]	1.53±0.29±0.21
	average		1.63±0.35

Table 2: Vector meson branching ratio $B(V \to \mu\mu)$. [1]The Particle Data Group value is the combined $B_{\mu\mu}$ and B_{ee} branching ratio. [2]This BR is for the e^+e^- final state. [3]Here both final states, e^+e^- and $\mu^+\mu^-$, have been combined. The ARGUS [23] and CUSB [26] branching ratios are preliminary.

Vector Meson	Γ_{ee} keV	Γ_{tot} keV	Γ_{tot}(PDG) keV
J/ψ	5.1±0.3	74±8	63±9
ψ'	2.3±0.2	256±48	215±40
$\Upsilon(1S)$	1.34±0.06	51±3	43±3
$\Upsilon(2S)$	0.61±0.04	38±10	30±7
$\Upsilon(3S)$	0.43±0.03	27±7	(12^{+10}_{-4})

Table 3: Leptonic and total widths of heavy vector mesons as calculated from redefined $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ values and using new world average values of $B_{\mu\mu}$. Also shown are for comparison the Γ_{tot} values as they are stated in the 1986 Review of Particle Properties [19].

In order to compare the experimental leptonic width Γ_{ee} with theoretical predictions we have to remove the vacuum polarization contribution: $\Gamma^{\circ}_{ee} = \Gamma^{exp}_{ee} \times (1-\Pi)^2$, where $(1-\Pi)^2 = (0.958, 0.932)$ for charmonium and bottonium, respectively. These values include contributions from $e^{\pm}$ pairs, $\mu^{\pm}$ pairs, $\tau^{\pm}$ pairs and quark pairs in the vacuum polarization loop. They have, for example, been calculated by Tsai [4]. We obtain the Γ°_{ee} values stated in column one and three of table 4 for the vector states J/ψ and $\Upsilon(1S)$, respectively. For radially excited

Authors	Ref.	J/ψ keV	ψ'/ψ	Υ keV	Υ'/Υ	Υ''/Υ
Experiment		4.9 ±.3	0.45 ±0.05	1.25 ±0.06	0.46 ±0.04	0.32 ±0.03
Bander *et al.*	[27]	9.0	0.51	1.63	0.41	0.28
Buchmüller *et al.*	[28]	3.7 ±3.1	0.46	1.07 ±.24	0.44	0.32
Eichten *et al.*	[29]	4.8	0.44	1.25	0.36	0.25
Falkensteiner *et al.*	[30]	13.3	0.35	1.1	0.44	0.31
Gupta *et al.*	[31]	5.1	0.50	1.29	0.48	0.36
Heikkilä *et al.*	[32]		0.35		0.38	0.29
Jacobs *et al.*	[33]	5.4	0.47	0.95	0.41	0.33
Sum Rules	[34]	4.3		1.2		

Table 4: Predictions for Γ°_{ee}. The experimental values have been obtained by multiplying the experimental Γ_{ee} width with $(1-\Pi)^2 = (0.958, 0.932)$ for the ψ and Υ states, respectively, which removes the vacuum polarization from the experimental Γ_{ee} definition.

vector mesons the leptonic widths are normalized to those of the ground state mesons. In addition, we compare in this table the experimental Γ°_{ee} values with theoretical predictions. In the non-relativistic approximation this decay width is given by the van Royen-Weisskopf formula [35]:

$$\Gamma^{\circ}_{ee} = 4e_Q^2\alpha^2\frac{|R_V(0)|^2}{M_V^2} \times (1 - 16\alpha_s/3\pi) \qquad (6)$$

where first order radiative QCD corrections [36] have been included. The agreement with experimental data is rather good for ratios of leptonic widths where radiative corrections cancel. Relativistic effects, however, in general depend on the principal quantum number and will therefore not cancel completely.

Buchmüller & Tye have estimated the contribution from higher order radiative and relativistic corrections and found them to be of roughly equal magnitude and to be large, resulting in the errors given in the table. The two lowest order calculations by Bander *et al.* [27] and Falckensteiner *et al.* [30] clearly demonstrate the need for inclusion of first order radiative QCD corrections. This can be seen by comparing their predictions for J/ψ and $\Upsilon(1S)$ with calculations including first order corrections by Eichten *et al.* [29], Buchmüller & Tye [28] and Gupta *et al.* [31]. Jacobs *et al.* [33], who have studied both the Schrödinger and spin-less Salpeter equations have shown that relativistic effects increase Γ_{ee} by about 20% (10%)

for charmonium (bottonium). It is thus only after the inclusion of both effects that theory meets experimental data: relativistic corrections increase the leptonic width, whereas QCD radiative corrections decrease it. Coupled channel mixing, however, does not significantly alter Γ_{ee} for the low lying states, see Heikkilä *et al.* [32]. It should be noted that QCD sum-rules also predict leptonic widths rather accurately.

SPECTROSCOPY OF HEAVY QUARK BOUND STATES

Transitions between heavy quark bound states have proven to be an ideal testing ground for QCD. The remarkable success of potential models in heavy quarkonium implies that a static local potential provides a good approximation to the interaction between quarks. The scalar confinement model of the spin dependent forces will be shown to be in excellent agreement with experimental data on the splittings of the $^3P'_J$ states, also called χ'_b states. The possible discovery of the missing $^1P_1$ states in charmonium as well as bottonium will provide additional information on the spin forces. Finally, hadronic transitions between heavy quarkonia states test the conjecture of a multipole expansion of the gluon gauge field.

Search for the $^1P_1$ States

The $^1P_1$ state with $J^{PC} = 1^{+-}$ is expected to be very close in mass to the center-of-gravity of the ^3P_J states. The hyperfine force responsible for this spin-spin splitting is proportional to the second derivative of the vector-like one-gluon potential: $V_{\vec{S}\cdot\vec{S}} \propto \nabla^2 V_v \propto \nabla^2(1/r) \propto \delta(r)$. The expectation value of the delta function between P-state wave functions will strictly be zero for hydrogen wave functions, but due to the non-negligible size of the $q\bar{q}$ system $\langle\delta(r)\rangle$ will be smeared over the compton wavelength of the heavy quark. This yields values for the mass splittings $M(^3P_{cog}) - M(^1P_1)$ of about 1 MeV for charmonium and 0.5 MeV for bottonium.

In charmonium the $^1P_1$ state is the only $c\bar{c}$ state predicted for which no evidence existed. The Crystal Ball collaboration at SPEAR had searched for this state [37] in the I-spin violating decay $\psi' \to \pi\, ^1P_1$ and obtained a 95% confidence level upper limit for the branching ratio $B(\psi' \to \pi\, ^1P_1) < 0.55\%$, a value not inconsistent with theoretical expectations [38]. The R704 experiment [39] at the CERN ISR has studied the direct formation of charmonium states in $p\bar{p}$ annihilations. With excellent energy resolution they were able to determine masses and widths of the χ_1 and χ_2 states; for a summary of our experimental knowledge on the $c\bar{c}$ χ states see *e.g.* ref. [40]. In addition, R704 has observed [39] five events in a scan over the center-of-gravity mass range of the χ_b states. When interpreted as a resonance its mass would be $M = 3525.4 \pm 0.9$ MeV. This value is within 0.1 MeV of the center-of-gravity of the χ_b masses [40]: $M(\chi_b) = 3525.5 \pm 0.3$ MeV. Given a statistical significance of only 2.3 standard deviations we can only conclude that this signal is consistent with a $^1P_1$ observation.

The Υ system offers a direct way to search for the $b\bar{b}$ $^1P_1$ state: Kuang &

Yan [41] have suggested the spin-flip $\pi\pi$ transition $\Upsilon(3S) \to \pi\pi\ ^1P_1$ and the subsequent decay $^1P_1 \to \gamma\eta_b$. CLEO [42] has recently investigated the transition $\Upsilon(3S) \to \pi^+\pi^- X$ both in the inclusive decay mode where X decays hadronically, and in the exclusive decay mode where $X = \Upsilon(1S \text{ or } 2S)$ decays into two leptons. Their (preliminary) inclusive $\pi^+\pi^-$ missing mass spectrum, figure 2b, exhibits a

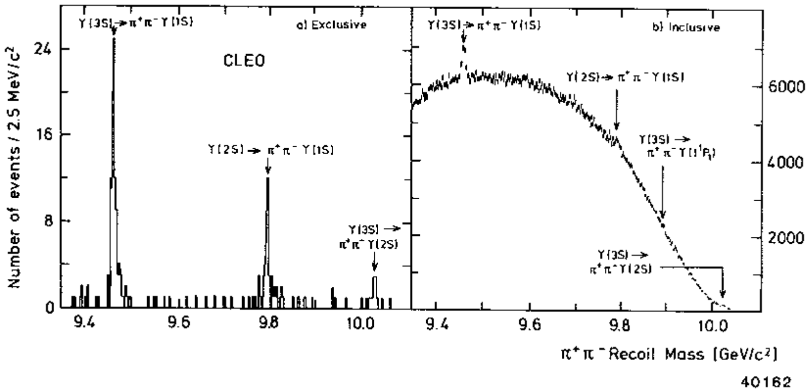

Figure 2: CLEO $\pi^+\pi^-$ recoil-mass spectra for a) exclusive and b) inclusive events from $\Upsilon(3S) \to \pi^+\pi^- X$. These results are preliminary.

2.5σ peak at a mass of 9894.8 ± 1.5 MeV. Again this signal is close to the world average value for the center-of-gravity of the χ_b mass [43] of 9900.5 ± 0.6 MeV. Assuming that this signal is evidence for the transition $\Upsilon(3S) \to \pi^+\pi^-\ ^1P_1$ the branching fraction has been determined to $(0.37 \pm 0.15)\%$.

$\pi\pi$ transitions are described in QCD as a two step process. First the excited quarkonium state radiates in lowest order two gluons. Since the available energies are small and the relevant α_s is large, perturbation methods are not applicable. However, Gottfried and Yan [44] have pointed out that a multipole expansion of the gluonic field converges rapidly since the dimensions of the radiating heavy quark system are small compared to the wavelength of the emitted gluons. In a second step the gluons fragment into light hadrons; here the properties of the $\pi\pi$ system are determined by using partial conservation of axial-vector current and current algebra [41,44]. Absolute branching ratio predictions depend on the dynamics of the light hadron system. For transitions between $^3S_1$ states the transition strength in charmonium is used to predict those in bottonium. But for the transition to the $^1P_1$ no analogous process exists in charmonium. Therefore Kuang & Yan [41] convert the gluons with probability 1 into $\pi\pi$, a method which also gives good agreement with their predictions for $\pi\pi$ transitions between $^3S_1$ states. They calculate a branching ratio of $B(\Upsilon(3S) \to \pi^+\pi^-\ ^1P_1) \simeq 0.4\%$, in good

agreement with the experimental datum. However, Voloshin [45] relates $\langle\pi\pi|gg|0\rangle$ to matrix elements of the QCD energy momentum tensor. For transitions between $^3S_1$ states he obtains predictions similar to Kuang & Yan, but his calculated transition strength to the $^1P_1$ is smaller by a factor of 150. Assuming that the signal observed by CLEO is really due to the $^1P_1$ transition is seems that the prescription by Kuang & Yan is the correct one. Voloshin also calculates the I-spin forbidden π° transition and finds it to be a factor of 10 larger than his $\pi\pi$ transition strength. Data from CUSB will eventually tell us more about this transition. Taking the CLEO measurement at face value CUSB should have about 15 events in their present data sample for the full cascade decay $\Upsilon(3S) \to \pi\pi\ ^1P_1$, $^1P_1 \to \gamma\eta_b$. The discovery of those events would be the ultimate proof for the $^1P_1$ state.

Hadronic Transitions $\Upsilon(3S) \to \pi\pi X$

The decays $\Upsilon(2S) \to \pi^0\pi^0\Upsilon(1S)$ and $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(2S)$ have been studied with high statistics by all four groups at Cornell and DESY [46,47,48,49]. The experimental results for the branching ratios, collected in table 5, are in very good agreement with theoretical predictions [41]. The ratio of the branching ratios for the neutral pion decay mode to the charged mode indictates consistency with isospin conservation for this decay. The measured angular distributions were found to be consistent with those expected for a spin zero di-pion system emitted in an S-wave. Partial conservation of the axial-vector current together with the observed isotropic angular distributions predicts [44] the invariant $\pi\pi$ mass spectrum to be peaked at high values, which indeed is being observed.

Previous studies [51,52] of the transition $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ suggested that the $\pi\pi$ invariant mass spectrum was approximately uniform, quite in contrast to the strong peaking observed for $\Upsilon(2S) \to \pi\pi\,\Upsilon(1S)$. With recently collected 165K $\Upsilon(3S)$ events CLEO has again investigated [42] the hadronic cascade transitions both in the exclusive decay mode (figure 2a), where the daughter Υ resonance decays to either a pair of electrons or muons, and in the inclusive hadronic decay mode of the daughter (figure 2b). Figure 3 shows the $\pi^+\pi^-$ invariant mass distribution for the transitions to the $\Upsilon(1S)$ and $\Upsilon(2S)$. The $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ spectrum is indeed rather flat, definitely not peaked at high masses and with a significant number of events immediately above threshold. A fit to the spectrum with *e.g.* the formula of Kuang & Yan [41] does not yield an acceptable description of the data (solid curve in fig. 3a). Led by CLEO's previous result, Peskin [53] had suggested the presence of a scalar and tensor glueball at masses of about 600 MeV and with widths of comparable size. With such an assumption Peskin obtained a good description of the data. However, Voloshin [54] noticed that the di-pion spectrum would also be flat if there exists a four-quark iso-vector resonance with mass close to the $\Upsilon(3S)$. It seems that the question regarding the origin of the flatness of the spectrum is still open.

The di-pion mass spectrum for the transition $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ (fig. 3b) has unfortunately insufficient statistics to distinguish between a peaked spectrum

Experiment	Ref.	Method	BR(%)
		$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	
ARGUS	[46]	inclusive	(17.9 ± 2.3)
Crystal Ball	[47]	exclusive	$(0.49 \pm 0.11)/B_{\mu\mu}(1S)$
CLEO	[48]	inclusive	(19.1 ± 1.3)
CUSB	[49]	exclusive	$(0.54 \pm 0.04)/B_{\mu\mu}(1S)$
LENA	[50]	exclusive	$(0.61 \pm 0.26)/B_{\mu\mu}(1S)$
average			(19.3 ± 1.0)
		$\Upsilon(2S) \to \pi^\circ\pi^\circ\Upsilon(1S)$	
Crystal Ball	[47]	exclusive	$(0.25 \pm 0.03)/B_{\mu\mu}(1S)$
CUSB	[49]	exclusive	$(0.29 \pm 0.05)/B_{\mu\mu}(1S)$
average			(9.8 ± 1.4)
		$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	
CUSB	[52]	exclusive	$(0.13 \pm 0.03)/B_{\mu\mu}(1S)$
CLEO	[51]	exclusive	$(0.15 \pm 0.04)/B_{\mu\mu}(1S)$
CLEO	[51]	inclusive	(5.4 ± 1.4)
CLEO	[42]	exclusive	$(0.09 \pm 0.01)/B_{\mu\mu}(1S)$
CLEO	[42]	inclusive	(3.7 ± 0.5)
average			(3.8 ± 0.3)
		$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$	
CUSB	[52]	exclusive	$(0.06 \pm 0.03)/B_{\mu\mu}(2S)$
CLEO	[42]	exclusive	$(0.06 \pm 0.02)/B_{\mu\mu}(2S)$
CLEO	[42]	inclusive	(2.0 ± 0.6)
average			(2.2 ± 0.6)

Table 5: Experimental results for two-pion transitions in the Υ system. The leptonic branching ratios from table 2 have been used. The CLEO [42] results are preliminary.

(solid curve, as found in $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$) or a flat spectrum (dashed curve, as found in $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$). Therefore no additional information can be obtained from this decay regarding the two theoretical assumptions discussed above. Hopefully this situation will be clarified with forthcoming results from additional data accumulated by CLEO and CUSB.

Electromagnetic Transitions $\Upsilon(3S) \to \gamma\ \chi_b'$

At last year's Physics in Collision Conference at Autun high precision measurements were presented [43,55] on the transitions $\Upsilon(2S) \to \gamma\chi_b$. It was shown that the masses of the χ_b states, their spin ordering, and the transition strengths are in agreement with theoretical expectations. An analysis of the spin-splittings of the χ_b states revealed clear evidence that the long range force in QCD transforms as a scalar under Lorentz transformations. It was therefore of considerable interest to study the corresponding transitions $\Upsilon(3S) \to \gamma\chi_b'$ in order to verify this transformation behaviour of the long range force. Although information regarding these transitions was available [56] it was felt that higher quality data was desirable. The

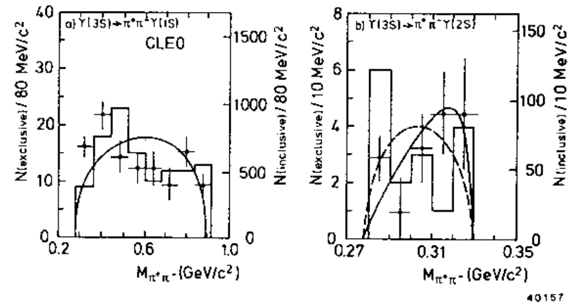

Figure 3: CLEO $\pi^+\pi^-$ (preliminary) invariant mass distributions for a) $\Upsilon(3S) \to \pi^+\pi^-\ \Upsilon(1S)$ and b) $\Upsilon(3S) \to \pi^+\pi^-\ \Upsilon(2S)$. The curves are explained in the text.

CUSB-II detector with a newly installed BGO inner calorimeter had, by the time of the Berkeley Conference, accumulated about 180K $\Upsilon(3S)$ events. Preliminary results on these transitions were presented [57] at the Berkeley HEP Conference.

CUSB has analyzed both, the inclusive transition $\Upsilon(3S) \to \gamma\chi_b'$ and the fully exclusive transition $\Upsilon(3S) \to \gamma\chi_b'$, $\chi_b' \to \gamma\Upsilon$, $\Upsilon \to e^+e^-$ and $\mu^+\mu^-$, where Υ is either the $\Upsilon(1S)$ or the $\Upsilon(2S)$. Figure 4 shows their spectra for a) the inclusive analysis

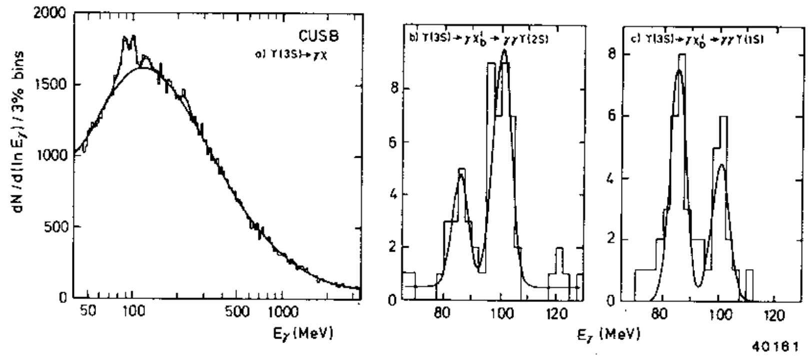

Figure 4: CUSB preliminary photon energy spectrum for $\Upsilon(3S) \to \gamma\chi_b'$ a) inclusive and b,c) exclusive analysis. The curves are described in the text.

and b,c) the exclusive events via the $\Upsilon(1S)$ and $\Upsilon(2S)$, respectively. The curve on the inclusive spectrum is from a fit to the data. Four significant structures stand out: the three transitions to the χ_b' around 100 MeV and the merged daughter transitions from the χ_b' to the $\Upsilon(2S)$ at an energy of about 230 MeV. The expected transition down to the $\Upsilon(1S)$ at about 800 MeV is barely significant.

The analysis of the fully exclusive events, shown in figures 4b,c, exhibit two prominent peaks around 85 MeV and 100 MeV in the plot of the lowest energetic photon. The high energy photon is then around 230 MeV or 760 MeV, depending on whether the transition proceeds via the $\Upsilon(2S)$ or $\Upsilon(1S)$, respectively. The transition via the lowest lying state χ_0' is not expected to be seen with the same strength like the two other decays as this state has a rather large total width and thus a small electromagnetic branching ratio. This is in agreement with what is observed for the corresponding transitions from the ψ' and the $\Upsilon(2S)$.

The experimental results on photon energies and branching ratios from inclusive and exclusive decays are summarized in table 6. Where appropriate, both

Decay	χ_0'	χ_1'	χ_2'
E_γ(inclusive)	124.2±2.3	99.3±0.8	86.5±0.7
E_γ(exclusive)		100.1±0.5	85.4±0.6
E_γ(average)	124.2±2.3	99.9±0.4	85.9±0.5
$M_{\chi_b'}$(average)	10230.5±2.4	10255.1±0.6	10269.2±0.7
$B(\Upsilon(3S)\to\gamma\chi_b')$	5.3±2.3	11.7±3.0	12.8±3.3
$B(\Upsilon(3S)\to\gamma\chi_b'\to\gamma\gamma\Upsilon(1S))$	< 0.2	1.0±0.3	1.9±0.4
$B(\Upsilon(3S)\to\gamma\chi_b'\to\gamma\gamma\Upsilon(2S))$	< 0.6	3.6±1.1	1.8±0.7
$B(\chi_b'\to\gamma\Upsilon(1S))$	< 4	9±4	15±5
$B(\chi_b'\to\gamma\Upsilon(2S))$	< 12	31±12	14±7

Table 6: Experimental results for the radiative transitions from the $\Upsilon(3S)$ resonance (CUSB, prelim.). Photon energies are in units of MeV, branching ratios are in %.

photon energy determinations are averaged and masses for the χ_b' states are calculated. With these values the spin weighted average, the center-of-gravity (COG), yields: $M_{COG}(\chi_b') = 10260.2 \pm 0.5$ MeV. Dividing the exclusive by the inclusive branching ratio yields values for the secondary branching ratios $B(\chi_b'\to\gamma\Upsilon(1S))$ and $B(\chi_b'\to\gamma\Upsilon(2S))$. Both values are also given in the last two rows of table 6.

Comparison with Theory

Following the notation of ref. [43] the averaged spin-dependent part of the potential can be written as a sum of three terms, the spin-orbit, the tensor, and the spin-spin interaction potentials:

$$\langle V_{spin}(r)\rangle = a\,\langle \vec{L}\cdot\vec{S}\rangle + b\,\langle T_{12}\rangle + c\,\langle \vec{S}_1\cdot\vec{S}_2\rangle, \qquad (7)$$

where the parameters a, b, c depend on the short range (vector) potential V_v and on the long range (scalar) potential V_s. The last term, the hyperfine part, is constant for the P-states under consideration. It is also customary to define a ratio $r = (M_2 - M_1)/(M_1 - M_0)$ where M_J are the masses for the states with total spin J. In terms of a and b this ratio is given by $r = (2a - 0.6\,b)/(a + 1.5\,b)$. With the χ_b' masses from table 6 we obtain the following values for the parameters a

and b:

$$a = \frac{1}{2m_b^2}\langle\frac{3V_v'-V_s'}{r}\rangle = 10.0 \pm 0.5 \text{ MeV}$$
$$b = \frac{-1}{3m_b^2}\langle V_v'' - \frac{V_v'}{r}\rangle = 9.8 \pm 1.4 \text{ MeV}. \qquad (8)$$

These values are very similar to those obtained for the world-average ground state χ_b masses [43], see table 7. If we were to set the long-range potential to zero we

P-States	a (MeV)	b (MeV)	r
χ_b ($b\bar{b}$)	14.1 ± 0.4	12.0 ± 0.9	0.65 ± 0.05
χ_b' ($b\bar{b}$)	10.0 ± 0.5	9.8 ± 1.4	0.57 ± 0.07
χ_c ($c\bar{c}$)	34.9 ± 0.3	40.1 ± 0.8	0.48 ± 0.01

Table 7: Expectation values of the spin-orbit (a) and tensor (b) potentials as determined from the experimental χ_b' and χ_b masses. Included are also the corresponding values for the charmonium system [19]. The ratio r is defined in the text.

would retain the spin dependence as in pure QED. With the standard Coulomb force this yields the relation $a = 1.5\,b$ and $r = 0.8$ (pure QED). The experimental values in table 7 indicate that the heavy $b\bar{b}$ system is close to this value. For the $c\bar{c}$ system the relation $a < b$ reveales the importance of the long-range component of the force. In particular, it is important to note that $r < 0.8$ for all three χ-states. Adding a pure vector confining term to the coulomb vector-potential would yield r values larger than 0.8 [64], whereas a scalar confining term yields $r < 0.8$. Therefore we have ample proof that the long-range confining potential transforms as a Lorentz scalar.

With the spin-potential expectation values determined above we can calculate how spin-orbit and tensor forces affect the unperturbed center-of-gravity of the P-states. The mass shift due to these forces is sketched in figure 5. It is obvious that the mass splittings in both systems are of the same magnitude, with the χ_b' splittings about 30% smaller.

Hadronic Widths of the χ_b'

From a physics point of view it is very interesting to obtain estimates on the hadronic widths of the χ_b' states. The measured radiative branching ratios can be converted into hadronic widths according to $\Gamma_{had}(\chi_b') = \Gamma_{E1}(1/B_{E1} - 1)$ if we use some estimate for the χ_b' E1 width. It turns out that in potential models the prediction for this radiative width is rather stable, especially for the $b\bar{b}$ system. This is demonstrated nicely by McClary & Byers [59]. Averaging theoretical predictions [29,31,58,59,60,61] for the E1 transitions from the χ_b' states to the $\Upsilon(1S)$ and the $\Upsilon(2S)$ yields the results stated in the first two rows of table 8. The errors indicate the spread between different predictions. Combining these E1 width estimates with the experimental E1 branching ratios yields values for the hadronic widths of the three χ_b' states, indicated in the third row of table 8. Also included in this table (in the fourth row) are the results obtained for the χ_b ground states [43]. It

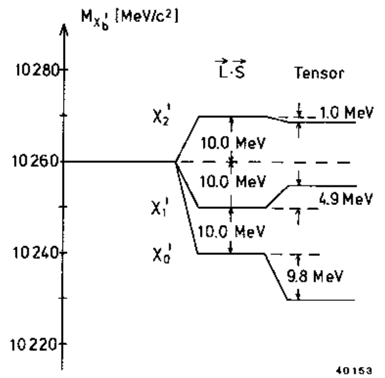

Figure 5: Indicated are the splittings of the χ_b and χ_b' states from the center-of-gravity.

appears that the hadronic widths decrease in size by about a factor of two for the radial excitation. This decrease is about the same size as the observed decrease of the leptonic widths of radial excitations of the Υ states. The latter widths are proportional to the wave function at the origin, whereas the hadronic P-state widths are proportional to the derivative of the wave function at the origin. Both observations of decreasing widths for radial excitations are consistent with the potential being convex near the origin ($d^2V/dr^2 < 0$).

Also given in table 8 are lowest order QCD predictions by Jacobs *et al.* [33] for the spin 0 and spin 2 χ_0' and χ_2' states, which were originally calculated by Barbieri *et al.* in lowest order [62] and including radiative corrections [63]. The annihilation rate of the spin 1 P-state was also calculated by Barbieri *et al.* Although this state can decay into three gluons, the leading contribution results from a $q\bar{q}g$ decay. The value for the χ_1' width cited in table 8 has been estimated with the help of values [33] on the derivative of the P-wave function at the origin and a value of $\alpha_s = 0.17$. The overall agreement between data and theory is striking given that we use theoretical input for the P-wave function and the radiative E1 width. We conclude that radiative QCD corrections probabely do not change the lowest order widths by more than 50%. The agreement is certainly much better than for the corresponding $c\bar{c}$ χ_c states. The failure of the QCD calculation in the charmonium system is assumed to be due to relativistic wave-function effects. These effects should be much smaller in the heavier $b\bar{b}$ system as the b quarks are more non-relativistic. Second order QCD predicts for the ratio

$$\frac{\Gamma(0^{++} \to hadrons)}{\Gamma(2^{++} \to hadrons)} = \frac{15}{4}\,(1 + 9.5\frac{\alpha_s}{\pi}) \qquad (9)$$

which, evaluated with the above given value of α_s, yields $\Gamma_{0^{++}}/\Gamma_{2^{++}} = 5.7$ to be compared to the lowest order prediction of $15/4 = 3.7$. The current experimental

limits on this ratio are > 1.6 for the χ_b and > 1.1 for the χ_b' (at 90% CL). This is obviously insufficient to test even the lowest order QCD calculation. It is therefore still of great importance to measure more accurately the hadronic width of the χ_0 and χ_0' widths.

Decay Width	χ_0' keV	χ_1' keV	χ_2' keV
$\Gamma(\chi_b' \to \gamma\Upsilon(1S))_{th}$	8±2	10±2	13±2
$\Gamma(\chi_b' \to \gamma\Upsilon(2S))_{th}$	11±2	14±2	16±2
$\Gamma_{had}(\chi_b')_{exp}$	> 127	40±17	79±27
$\Gamma_{had}(\chi_b)_{exp}$	> 340	81±25	147±47
$\Gamma_{had}(\chi_b')_{th}$	410±80	≃ 30	110±20
$\Gamma_{had}(\chi_b)_{th}$	410±80	≃ 30	110±20

Table 8: Theoretical values for $\Gamma(\chi_b' \to \gamma\Upsilon(1S))$ and $\Gamma(\chi_b' \to \gamma\Upsilon(2S))$ used in calculating $\Gamma_{had}(\chi_b')$. For comparison, the last three rows show the corresponding values for the χ_b states and theoretical predictions [33] for $\Gamma_{had}(\chi_b, \chi_b')$.

Radiative Decays of the ψ and Υ States

Search for the η_b and η_b' States

After the possible identification of the $^1P_1$ state the only missing states in bottonium remain the $b\bar{b}$ $^1S_0$, also called η_b and η_b'. These states may be found via the M1 transitions $\Upsilon \to \gamma\, \eta_b$ with a predicted rate [29]

$$\Gamma\,(\Upsilon(1S) \to \gamma + \eta_b) = \frac{16}{3}\left(\frac{e_b}{2m_b}\right)^2 \alpha_{em}\, k^3\, |M_{if}|^2, \qquad (10)$$

which is proportional to the third power of the radiated photon energy k. M_{if} is the overlap integral of the $\Upsilon(1S)$ and η_b wave functions which is expected to be very close to 1 for allowed transitions between hyperfine partners with the same radial quantum numbers. Theoretical estimates for the mass splitting yield values between 40 MeV [28] and 100 MeV [59]. Correspondingly, the branching ratios turn out to bracket values from about 10^{-4} to 10^{-3}.

The Crystal Ball [65] and CUSB [55] experiments have searched for this state in $\Upsilon(1S)$ radiative decays; the Crystal Ball has also searched for the decay $\Upsilon(2S) \to \gamma\eta_b'$ and for the hindered M1 transition $\Upsilon(2S) \to \gamma\eta_b$. No signals have been found. As an example, figure 6a shows the inclusive photon energy spectrum obtained by the Crystal Ball. The 90% CL upper limit for the Crystal Ball branching ratio $B(\Upsilon(1S) \to \gamma\eta_b)$ is shown in figure 6b as the solid curve; the dashed curve is the result from CUSB and the dotted curve is the theoretical prediction. Current experimental sensitivity is thus not sufficient to test for mass-splittings between $\Upsilon(1S)$ and η_b in the interesting mass range from 40 MeV to about 100 MeV.

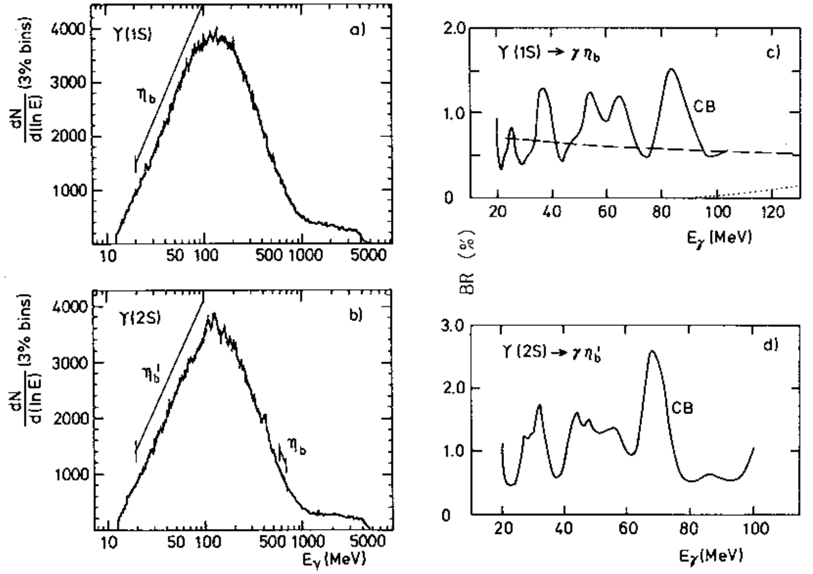

Figure 6: a) Crystal Ball inclusive photon spectrum used for the search for the η_b. b)90% CL upper limits $B(\Upsilon(1S) \to \gamma\eta_b)$ from Crystal Ball (solid curve, prelim.) and from CUSB (dashed curve, prelim.); the dotted curve represents the theoretical expectation.

J/ψ and $\Upsilon(1S)$ Inclusive Radiative Decays

The main energetically allowed decay modes of heavy vector mesons require the quark and anti-quark to annihilate. The decay mode with the largest rate is described in lowest order QCD by a three gluon intermediate state where it is assumed that the gluons fragment into light hadrons with probability one. The partial rate is calculated to

$$\Gamma(V \to ggg) = \frac{40}{81\pi}\,(\pi^2 - 9)\,\alpha_s^3\,\frac{|R_V(0)|^2}{M_V^2}, \tag{11}$$

where $\alpha_s(q^2)$ is the strong coupling constant to be evaluated at the scale $q = 0.44\,M_V$ [66], M_V is the mass of the vector resonance, and $R_V(0)$ is the radial wave function at the origin. The radiative decay of vector mesons is obtained by substituting one gluon with a photon. The ratio of partial widths, including first order QCD corrections, is given by Brodsky *et al.* [66]:

$$\frac{\Gamma(V \to \gamma gg)}{\Gamma(V \to ggg)} = \frac{36}{5}\,\frac{\alpha_{em}}{\alpha_s}\,e_Q^2\,\left(1 + (2.2 \pm 0.6)\,\frac{\alpha_s}{\pi}\right), \tag{12}$$

where α_{em} is Sommerfeld's fine structure constant and e_Q the heavy quark charge in units of the elementary charge.

Experimental results on direct photon production from the J/ψ were obtained by the Lead-Glass-Wall [67] and Mark II [68] collaborations at SPEAR. Both experiments observe a branching ratio of about 4% for photon energies above 930 MeV, consistent with an expected 5% in this range. The photon energy spectrum from Mark II seems to be softer than predicted in leading order calculations [69], but non-perturbative effects are expected to modify the high end of this spectrum [70].

The direct photon spectrum has also been measured at the $\Upsilon(1S)$ by the collaborations CUSB [71] and recently by CLEO [72]. Both groups obtain spectra that fit nicely the leading order perturbative calculation by Brodsky *et al.* [69]. From the dependance on α_s the scale parameter of QCD, $\Lambda_{\overline{MS}}$ can be derived; both groups find values consistent with $\Lambda_{\overline{MS}} \simeq 220 \pm 100\,\text{MeV}$. In addition, CLEO has shown that their spectrum is also well represented by the calculations by Photiadis [73] and by Field [74], calculations which predict a softening of the spectrum at the highest photon energies. To distinguish between the different theoretical analyses data are needed with substantially better photon energy resolution.

ψ and Υ Exclusive Radiative Decays

It should be possible to describe radiative decays to exclusive final states by the dual mechanism of γgg emission described above, where now the two gluons are required to materialize into specific resonances. Given the rather large γgg width, the production rate of mesons in radiative vector meson decays should be sizable. A further step in this direction has been performed by Billoire *et al.* and Körner *et al.* [75]. They carried out a spin-parity analysis of the produced two gluon system. The interesting feature is a strong presence of $J^{PC} = 0^{++}, 0^{-+}$ and 2^{++} contributions. Predictions on the production of spin-one states depend crucially on the effective mass of the intermediate gluons as the formation of a vector particle by two massless gluons is forbidden by Yang's theorem [76].

One of the consequences of colored gluons interacting with each other is the possible existence of bound states of gluons, often referred to as gluonic mesons, gluonia or glueballs. Observation of such particles would provide a striking and very direct verification for the non-Abelian nature of QCD. The lightest gluonic mesons are expected to have masses ranging from 0.5 GeV – 2.5 GeV and to have spin-parities 0^{++}, 0^{-+} and 2^{++}. Radiative decays of the vector meson J/ψ have been studied in detail over the last six years and have yielded a wealth of information on the nature of gluonium candidates like the $\iota(1440)$ (now called the $\eta(1440)$) and the $\theta(1720)$ (now the $f_2(1720)$), and on other 'conventional' mesons like the $E(1420)$ (now the $f_1(1420)$) and the tensor mesons $f_2(1270)$ and $f_2'(1525)$. In particular, the production rate of θ and ι is observed to be large in radiative J/ψ decays, whereas their rate in hadronic decays is suppressed compared to other 2^{++} mesons. The θ and ι still remain our prime glueball candidates. For more details see the recent reviews [40,77] on radiative J/ψ decays.

$\Upsilon(1S)$ Exclusive Radiative Decays

Radiative branching ratios on the J/ψ to exclusive final states are typically 0.1% and may be as large as 0.6%. The radiative production rate on the $\Upsilon(1S)$, however, is expected to be much smaller. Using the γgg decay width with a gluon distribution function [69] F(x) and ignoring phase space effects yields the prediction (see *e.g.* ref. [75])

$$\Gamma(\Upsilon(1S) \to \gamma(gg \to m)) \;\propto\; e_b^2\,\alpha_s^2\,\frac{|R_\Upsilon(0)|^2}{M_\Upsilon^2}\int_{\Delta x} F(x)dx \qquad (13)$$

where $x = 2E_\gamma/\sqrt{s} = 1 - m_m^2/M_\Upsilon^2$ and Δx is the photon energy bite corresponding to the total width of the produced meson m; *i.e.* we assume that gluons with an invariant mass of $m_m \pm \Gamma_{tot}$ produce the meson. Eliminating $|R_V(0)|^2/M_V^2$ with the leptonic width (equation 6) and normalizing to the J/ψ width yields

$$\frac{B(\Upsilon(1S)\to\gamma m)}{B(J/\psi\to\gamma m)} = \left(\frac{\alpha_s(\Upsilon)}{\alpha_s(\psi)}\right)^2\left(\frac{M_\psi}{M_\Upsilon}\right)^2\frac{B(\Upsilon(1S)\to\mu\mu)}{B(J/\psi\to\mu\mu)} \simeq \frac{1}{40}\,. \qquad (14)$$

Therefore the expected radiative branching ratios from the $\Upsilon(1S)$ should be typically 10^{-5} to 10^{-4}.

CLEO [78] and Crystal Ball [79] have searched for $\Upsilon(1S)$ radiative decays in channels which have been seen on the J/ψ. The experimental results are summarized in table 9 and compared with predictions obtained by dividing the corresponding J/ψ branching ratios by 40. None of the predictions can be excluded by the upper limits. With more than twice the current data samples of about 300K $\Upsilon(1S)$ decays it might be possible to probe the most promising channel, $\Upsilon(1S) \to \gamma f_2(1270)$. But it should be remembered that it was only with mega-samples of J/ψ decays that the first exciting radiative decay channels emerged. Unfortunately such large data samples will take many years to accumulate.

Decay Mode	Experiment	$B_{exp} \times 10^5$	$B_{th} \times 10^5$
$\Upsilon(1S) \to \gamma\eta$	CB	< 30	~ 2
$\Upsilon(1S) \to \gamma\eta'$	CB	< 100	~ 10
$\Upsilon(1S) \to \gamma f_2(1270)$	CB	< 40	~ 3
$\Upsilon(1S) \to \gamma f_2(1270)$	CLEO	< 5	~ 3
$\Upsilon(1S) \to \gamma f_2'(1525)$	CLEO	< 10	~ 2
$\Upsilon(1S) \to \gamma f_2(1720), f_2 \to K^+K^-$	CLEO	< 3	~ 0.5
$\Upsilon(1S) \to \gamma\xi(2200), \xi \to K^+K^-$	CLEO	< 3	~ 0.1

Table 9: Experimental results (90% CL) and theoretical predictions for exclusive radiative decays of the $\Upsilon(1S)$. The Crystal Ball data are preliminary.

Search for the Axion

The axion [80] is a Goldstone boson which appears after the breaking of a U(1) symmetry imposed on the strong interaction Lagrangian to circumvent large P and CP violations. The standard axion with mass $m_a \simeq \mathcal{O}(100\,\text{keV})$ and long lifetime $\tau_a \simeq \mathcal{O}(10^{-2\pm2}\text{sec})$ was ruled out by a combination of radiative decay searches on the J/ψ [81] and the $\Upsilon(1S)$ [82], where it was assumed that the axion does not decay within the active detector volume. Hence the signature for this decay was only one photon of beam energy.

However, the observation of narrow positron lines observed in heavy ion collision [83] have revived the interest in a 1.7 MeV axion. Such a 'heavy' axion would decay into e^+e^- with a lifetime of about 4×10^{-12}sec which renders the above searches rather insensitive. Therefore the groups, ARGUS, CLEO, and CUSB have searched [84] for events of the type '1 photon plus an e^+e^- pair very close together'. The 90% upper limit results on the branching ratio $\Upsilon(1S) \to \gamma\,$axion are presented in figure 7. The measured branching ratios have been corrected for that part of the

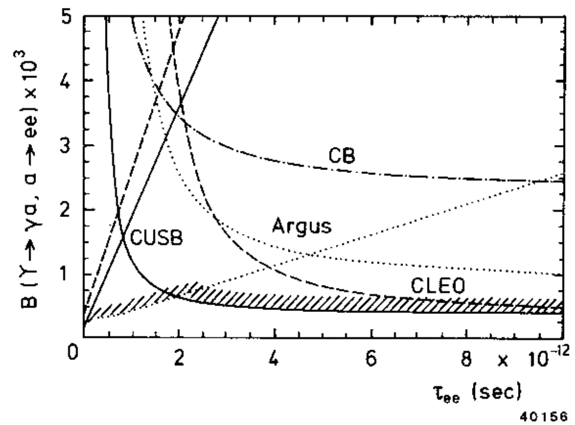

Figure 7: 90% upper limit curves for the branching ratio $\Upsilon(1S) \to \gamma\,$axion vs. the axion lifetime. The ARGUS and Crystal Ball data are preliminary.

decay distribution outside the detector. This yields falling branching ratios with τ_{ee} for the search $\Upsilon(1S) \to \gamma\,$invisible ($B = B_{meas}\exp(r/\gamma\beta c\tau)$, r=detector radius) and rising BR's for $\Upsilon(1S) \to \gamma\,(\text{axion} \to e^+e^-)$ ($B = B_{meas}(1 - \exp(-r/\gamma\beta c\tau))^{-1}$). As the prediction for a 1.7 MeV axion is a stunning $B(\Upsilon(1S) \to \gamma\,\text{axion}) \simeq 5\%$, and the combined upper limit from plot 7 is $< 6 \times 10^{-4}$ for all lifetimes, such an axion hypothesis is definitely ruled out.

Search for the Higgs

A radiative $\Upsilon(1S)$ decay mode of very high interest leads to the production of the Higgs boson. This elusive particle is predicted in the Standard Model after spontaneous breakdown of the SU(2) symmetry group. In the standard 1-Higgs model the theoretically lower limit [85] on the Higgs mass is about 7.3 GeV. Therefore we can search for this particle in the mass region from 7 GeV up to the mass of the $\Upsilon(1S)$. The rate for this decay was calculated by Wilczek [86]:

$$\frac{\Gamma(\Upsilon(1S) \to \gamma + H)}{\Gamma(\Upsilon(1S) \to \mu^+\mu^-)} = \frac{G_F m_b^2}{\sqrt{2}\pi\alpha_{em}} \left(1 - \frac{M_H^2}{M_\Upsilon^2}\right) , \tag{15}$$

where M_H is the mass of the Higgs, m_b the bottom quark mass, and G_F Fermi's weak coupling constant. Radiative QCD corrections and mixing effects with the *P*-wave bottonium states reduce this width further by a factor of about two [87]. The predicted branching ratio for a Higgs with a mass of *e.g.* $M_H = 8$ GeV is $B(\Upsilon(1S) \to \gamma H) \simeq 2 \times 10^{-5}$. It has to be noted though, that in models with more than one doublet of Higgs fields this branching ratio could be enhanced or suppressed substantially.

All four groups at the storage rings CESR and DORIS have searched for monoenergetic photons in the decay $\Upsilon(1S) \to \gamma X$, where X is assumed to decay hadronically. Analyses from the two magnetic detectors, ARGUS [88] and CLEO [89], have yielded upper limits on the branching ratio $B(\Upsilon(1S) \to \gamma X) \lesssim 10^{-3}$ for Higgs masses in the range from 3.7 GeV (ARGUS) to 9.3 GeV (CLEO). CUSB [55] and Crystal Ball [90], the two non-magnetic calorimetric detectors, have also searched for this decay. They obtain (preliminary) upper limits depicted in figure 8. It should be mentioned that only the Crystal Ball analysis takes into

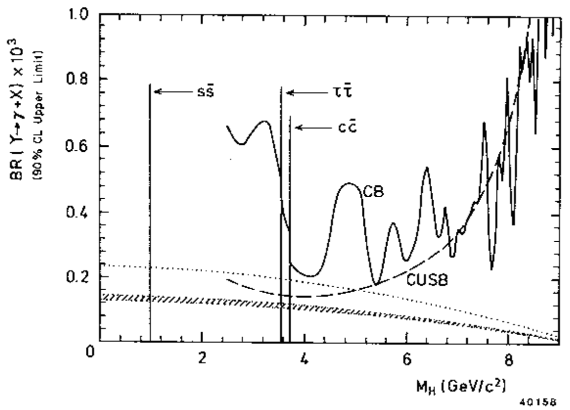

Figure 8: Preliminary upper limits for branching ratio $\Upsilon(1S) \to \gamma X$ from Crystal Ball (solid line) and CUSB (dashed line). Theoretical predictions for the decay into a Higgs (dotted line) are explained in the text.

account the variation of the efficiency with different decay channels for the Higgs particle. This introduces discontinuities in the upper limit determination. All four experiments rule out the existence of a resonance at 8.3 GeV [93] which was seen in 1983 by the Crystal Ball experiment with a branching ratio of about 0.5%. One

model which could explain the disappearance of this resonance ς was that of Tye and Rosenfeld [94]. Here the ς is viewed as a squarkonium ground state, populated by radiative decays of an excited state located close to the $\Upsilon(1S)$ resonance. To study this scenario the Crystal Ball experiment collected two data sets at center-of-mass energies $M(\Upsilon(1S)) \pm 12$ MeV. No indication of a ς resonance showed up, ruling out this last hypothesis. It seems that the original ς observation was due to a statistical fluctuation.

Included in figure 8 are also the lowest order prediction by Wilczek (dotted line) and the one by Vysotsky (band between dotted lines) which includes higher order radiative QCD corrections. The figure shows clearly that the experimental results are not yet sensitive enough to rule out a Higgs boson in mass below the $\Upsilon(1S)$. In order to reach the Linde-Weinberg limit at 7.3 GeV a detector with 1/2 the Crystal Ball resolution and twice its efficiency would still need about 7.5M events, a goal not within reach in the near future.

There is, of course, the possibility that more than one doublet of Higgs fields exists, resulting in more Higgs bosons. One possible scenario is to have one Higgs doublet couple to down-type quarks and leptons, the other one to up-type quarks and leptons. This could result in an enhancement of the Higgs coupling to τ leptons over *c* quarks. At the same time the production rate could be enhanced in $\Upsilon(1S)$ decays. ARGUS [91] and Crystal Ball [92] (prelim.) have searched for the decay $\Upsilon(1S) \to \gamma H$, $H \to \tau\tau$. In addition, the Crystal Ball searched for the corresponding decay from the $\Upsilon(2S)$. Neither experiment has found significant structures in the photon spectrum. The resulting 90% CL uppper limit on the product branching ratio $B(\Upsilon(1S) \to \gamma H) \times B(H \to \tau\tau)$ is for both experiments around 10^{-3} for Higgs masses below 8.5 GeV and rising for higher masses. Again, the present sensitivity is an order of magnitude too small to check the predictions of the Standard Model, but the results may be used to put constraints on models with more complicated Higgs fields.

SUMMARY

New developments on the physics of heavy quark bound states are summarized. It is shown that a proper and consistent definition of radiative corrections for the process $e^+e^- \to$ Vector-meson yield total widths for these resonances that are about 20% larger than those stated in the latest Summary Tables of Particle Properties. Spectroscopic studies of heavy quark bound states have revealed the possible existence of two new states: the $^1P_1$ states in charmonium and bottonium. In addition, precision measurements of hadronic and electromagnetic transitions from the $\Upsilon(3S)$ allow for a detailed comparison with QCD inspired models. In particular is it shown that the spin-splittings of all $c\bar{c}$ and $b\bar{b}$ χ states require the long range force in QCD to transform as a scalar under Lorentz transformations. Figure 9 shows our current knowledge of the spin-splittings in charmonium as well as bottonium below the open flavor threshold. Indicated are the actions of the three spin-forces on the different states.

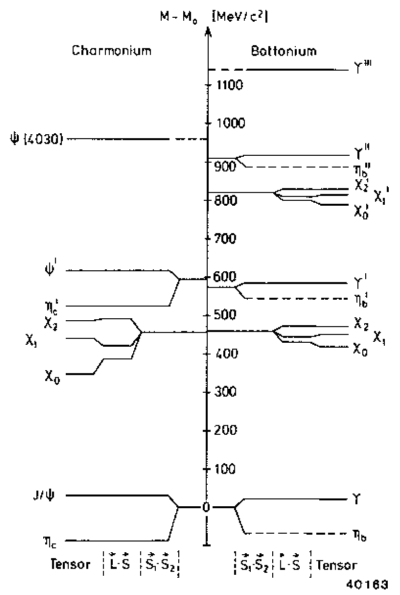

Figure 9: Spin splittings in charmonium and bottonium. The center-of-gravity of the lowest lying S-States are chosen as zero-points for both spectra: $M_o(\psi) = 3068$ MeV and $M_o(\Upsilon) = 9438$ MeV. Missing states are indicated as dashes lines.

In charmonium, exclusive radiative decays of the J/ψ have become a prime channel for a state-of-the-art study of low lying mesons and gluonium states. The current data samples for the bottonium $\Upsilon(1S)$ state have not yet allowed the determination of any exclusive decay modes. A factor of ten in data-sample times efficiency would allow the discovery of such decays and consequently help clarify the situation of low mass states. Finally, the Axion and Higgs Bosons have been searched for in radiative $\Upsilon(1S)$ decays. Whereas the standard Axion is definitely ruled out, the experimental sensitivity for a Higgs boson is still too low by at least a factor of 20.

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