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Leptonic Widths of ψ and Υ Resonances[†]

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Abstract

The determination of leptonic widths of heavy narrow vector resonances crucially depends on the incorporation of radiative corrections to the process $e^+e^- \to V \to hadrons$. A consistent definition of radiative corrections for this process and the leptonic branching ratio $B_{\mu\mu}$ results in a substantial change in the total widths of ψ and Υ vector mesons. A precision scan by the Crystal Ball group over the $\Upsilon(1S)$ resonance is utilized to study in detail the different theoretical prescriptions for radiative corrections.

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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 $W \lesssim 10\,\mathrm{GeV}$ the interaction proceeds primarily through the electromagnetic force and we may neglect the weak interaction. Neutral vector meson states V with the quantum numbers of the photon, $J^{PC} = 1^{--}$, are produced directly in e^+e^- interaction with a strength proportional to their leptonic partial width Γ_{ee}:

$$\sigma_o(W) = \frac{3\pi}{W^2}\,\frac{\Gamma_{ee}\Gamma_{had}}{(W - M_V)^2 + \Gamma_{tot}^2/4} \qquad (1)$$

where it is assumed that the vector meson is detected via its hadronic decays with width Γ_{had}; Γ_{tot} is the total decay width. The integral over the cross section equ. 1 directly measures a product of widths: $A_o \equiv \int \sigma_o dW = (6\pi^2/M^2) \times \Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$. The hadronic branching ratio $\Gamma_{had}/\Gamma_{tot} = B_{had}$ can be expressed in terms of the leptonic branching ratio $B_{had} = 1 - nB_{\mu\mu}$ assuming the resonance to decay into nothing but hadrons and leptons. Lepton universality requires all leptonic channels to proceed with the same strength.[1] A measurement of the integral over the resonance cross section thus yields a direct determination of $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ and, combined with the leptonic branching ratio, yields the leptonic width Γ_{ee} and the total width $\Gamma_{tot} = \Gamma_{ee} / B_{\mu\mu}$.

Figure 1 shows the visible hadronic cross section measured by the Crystal Ball collaboration [1] in the region of the $\Upsilon(1S)$ resonance. A total of 45 measurements were taken in four different scans over the resonance resulting in an integrated luminosity of $4.1\,\mathrm{pb}^{-1}$. It is apparent from Fig. 1 that the cross section shape is neither symmetric nor distributed like a Breit-Wigner (equ. 1).

Radiative Corrections

The emission of real and virtual photons in the process $e^+e^- \to V \to hadrons$ modifies the lowest order cross section. These radiative corrections can be classified into initial state hard- and soft-photon bremsstrahlung, initial state vertex corrections, and vacuum polarization of the intermediate virtual photon. They have originally been calculated [2] by Yennie *et al.* and by Bonneau & Martin. Several other theoretical analyses have appeared since [3,4,5,6] which in particular

[1] For charmonium ψ states the energetically allowed leptonic decays are into electron and muon pairs ($n_\psi = 2$), whereas for bottonium Υ states the decay into tau pairs is also possible ($n_\Upsilon = 3$). Threshold effects due to lepton mass reduce the branching ratio by at most 1% in the case of $\Upsilon \to \tau\tau$.

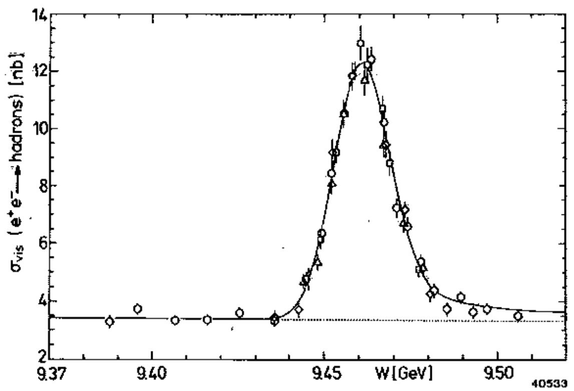

Figure 1: Visible hadronic cross section at the $\Upsilon(1S)$ resonance, obtained with the Crystal Ball detector at DORIS II (preliminary result). The solid line is a fit to the data.

take into account the narrowness of heavy quark vector resonances and which are exclusively used by experimenters to extract $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$. All four analyses can be stated as a convolution of the lowest order cross section $\sigma_o(W)$ with a photon (bremsstrahl) spectrum $B(x, W)$, where $x = k/E$ is the energy fraction carried away by photons:[2]

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

For the sake of simplicity we ignore the hard bremsstrahlung part which would add a factor $(1 - x + x^2/2)$ to the integrand. Due to the narrow width of the ψ and Υ resonances this part introduces a negligible contribution of at most 0.1%. The bremsstrahl spectra obtained by Greco [3], Jackson & Scharre [4], Tsai [5] and Kuraev & Fadin [6] are

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

Ignored are higher order corrections as *e.g.* calculated in ref. [5,6]. In the above formula $\delta_e = 3t/4 + (2\alpha/\pi) \times (\pi^2/6 - 1/4)$ arises from the vertex corrections and

[2] Note that the identification of x with 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. [6]).

$t = (2\alpha/\pi) \times (\ln(s/m_e^2) - 1)$ is the effective radiator thickness (Tsai's radiator $T = (t/\Pi) \times \ln(1/1-\Pi)$ contains the conversion into lepton pairs). $\Pi = \sum_{i=e,\mu,\tau,q} \Pi_i$ is the total vacuum polarization (V.P.) contribution from electron, muon, tau and all quark pairs (see Tsai for a detailed calculation of the individual contributions). For example the electron loop contribution is given by $\Pi_e = (\alpha/3\pi) \times (\ln(s/m_e^2) - 5/3)$. At center-of-mass energies $W = 10$ GeV we obtain: $t = 8.7\%$, $T = 8.9\%$, $\delta_e = 7.2\%$, $2\Pi_e = 2.8\%$ and $2\Pi = 6.8\%$.

It is apparent from the different bremsstrahl spectra in equ. 3 that the radiatively corrected cross section will differ for the different prescriptions and consequently Γ_{ee} will differ. An inspection of the bremsstrahl spectra equ. 3 reveals the major difference: Jackson & Scharre and Greco include the vacuum polarization Π in their formulæ, whereas Kuraev & Fadin and Tsai do not include this term. In addition Jackson & Scharre separate the vertex correction δ_e from the exponentiated soft bremsstrahlung x^t, an approach criticised by Kuraev & Fadin. Their criticism is corroborated by a recent calculation by Behrends *et al.* [7] of complete $\mathcal{O}(\alpha^2)$ initial state radiative corrections. The result shows very good agreement with first order radiative corrections after exponentiation of the infrared parts from soft photon *and* vertex corrections.

Concerning the (non)-presence of the vacuum polarisation term the question arises which procedure is correct. The answer depends on what needs to be determined: if we want to determine $\Gamma_{tot} = \Gamma_{ee} \,/\, B_{\mu\mu}$ we should use consistent definitions for numerator and denominator. As $B_{\mu\mu}$ is determined directly by counting muons it *does* include the vacuum polarization.[3] Therefore, the Γ_{ee} definition *should also* include the vacuum polarization term. This is achieved by *not* having Π appear in the bremsstrahl spectrum. 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}^o). The necessary distinction between Γ_{ee} and Γ_{ee}^o has been known theoretically, but was not taken into account by the experimenters.

Crystal Ball $\Upsilon(1S)$ Scan

In order to investigate the different bremsstrahl spectra the Crystal Ball collaboration has analyzed [1] the scan shown in Fig. 1. The visible hadronic cross section σ^{vis} is fit to the cross section $\tilde{\sigma}$ (equ. 2) convoluted with a gaussian energy distribution for the storage ring beams $G(W) = (1/\sqrt{2\pi}\Delta) \times \exp(-(W - M)^2/2\Delta^2)$.

[3] Due to the Kinoshita, Lee and Nauenberg theorem [8] radiative corrections to the final state $\mu^+\mu^-$ are negligible; see Tsai [5] for a discussion on this subject.

Accounting for the hadronic continuum contribution C, we obtain

$$\sigma^{vis}(W) = C/W^2 + \int dW'\, G(W'-W) \int dx\, \sigma_o^{vis}(W'(1-x))\; B(x,W')\ . \quad (4)$$

As the total width of the resonance $\Gamma_{tot} \simeq 50\,\mathrm{keV}$ is much smaller than the CMS-energy resolution $\Delta \simeq 8\,\mathrm{MeV}$, we can approximate the cross section by $\sigma_o(W) = A_o\,\delta(W-M)$ and obtain:

$$\sigma^{vis}(W) = C/W^2 + A_o^{vis} \times \int dx\, G(W(1-x))\; B(x,M) \quad (5)$$

$$= C/W^2 + 6\pi^2\, \epsilon_{had}\, \Gamma_{ee}/M^2 \times \int dx\, G(W(1-x))\; B(x,M)\ , \quad (6)$$

where in the last equation A_o^{vis} was substituted using $A_o = (A_o^{vis}/\epsilon_{had}) \times (1-3\,B_{\mu\mu})$ (note that with our definition of ϵ_{had} the total hadronic and the visible hadronic cross sections are related by $\sigma^{had} = \sigma^{tot}(1-3\,B_{\mu\mu}) = \sigma^{vis}(1-3\,B_{\mu\mu})/\epsilon_{had}$). The integral in equ. 5 $\int dx\, G(W(1-x))\; B(x,M)$ can be expressed [4] with the gamma function and with Weber's parabolic cylinder function. The final state hadronic detection efficiency $\epsilon_{had} \equiv \epsilon_{3g}(1-(R+3)B_{\mu\mu}) + \epsilon_{q\bar{q}} R B_{\mu\mu} + \epsilon_{\tau\tau} B_{\mu\mu}$ is determined with Monte Carlo data sets for the corresponding decay modes of the $\Upsilon(1S)$ resonance into three gluons (3g), into 2 jets via $q\bar{q}$ and into tau-pairs. With a continuum hadronic R value (from Niczyporuk *et al.* [10]) $R = 3.37 \pm 0.24$, a leptonic branching ratio [11] $B_{\mu\mu} = (2.58 \pm 0.13)\%$ and the individual efficiencies $\epsilon_{3g} = (91.0 \pm 0.1)\%$, $\epsilon_{q\bar{q}} = (78.9 \pm 0.4)\%$, $\epsilon_{\tau\tau} = (15.8 \pm 0.5)\%$, we obtain $\epsilon_{had} = (83.1 \pm 0.4)\%$.

The solid line in Fig. 1 shows as an example the result of a fit with the second order bremsstrahl spectrum calculated by Kuraev & Fadin. The confidence level of this fit is 16%. Figure 2 displays in a graphical form the fit results for the three free parameters Γ_{ee}, C and Δ as a function of the bremsstrahl spectrum. Firstly we note that all three spectra yield consistent values for the continuum contribution C and the energy resolution Δ. But the leptonic widths differ substantially. With the KF and Tsai spectra we obtain very similar Γ_{ee} values, but using the JS-spectrum results in a 10% lower Γ_{ee} (point with solid error bar). Omitting from B_{JS} the vaccum polarization contibution results in the data point with the dashed error bar. The remaining difference of 5% is due to the incorrect separation of soft photon exponentiation and vertex corrections (see the section on *Radiative Corrections*). Using Kuraev & Fadin's photon spectrum in second order, we obtain the following preliminary result:

$$\Gamma_{ee}(\Upsilon(1S)) = (1.33 \pm 0.03 \pm 0.06)\,\mathrm{keV}\ , \quad (7)$$

where the first error is statistical. The second systematic error arises mostly from the luminosity determination and the uncertainty in the hadronic selection

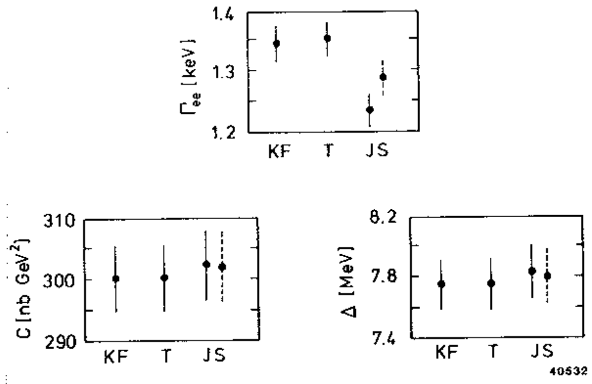

Figure 2: Comparison of the three fit parameters determined with the different bremsstrahl spectra by: KF = Kuraev & Fadin, T = Tsai, JS = Jackson & Scharre. (Crystal Ball, preliminary).

efficiency. Our result is the most precise single measurement. It agrees nicely with the renormalized and averaged results from other groups, see table 2.

From the parameter C we have also determined R, the ratio of non-resonant hadronic cross section to the Born μ-pair cross section, at a CMS energy of $W = 9.46\,\mathrm{GeV}$. We obtain [1] $R = 3.51 \pm 0.07 \pm 0.13$. This result with its rather small systematic error agrees well with already published results and with the expectation: $R = 3\sum Q_i^2(1+\alpha_s/\pi) \simeq 3.6$.

Renormalization of Published Results

In order to compare our result with published data the latter have to be renormalized to the correct photon spectrum. The easiest way consists in calculating the peak values of the total cross section for each bremsstrahl spectrum: $\sigma(M) = \Gamma_{ee} \times f(B,M,\Delta)$. This method is explained in more detail in ref. [11,12]. As an example we obtain for a resolution of $\Delta = 8$ MeV (DORIS II storage ring) a correction factor of $f^{JS}/f^{KF} = 1.094$ for $M = M_\Upsilon$. Table 1 summarizes the average $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ data [11] before and after correction. We note an increase in $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ between 5% for the J/ψ and 14% for the $\Upsilon(2S)$ and $\Upsilon(3S)$. Inclusion of higher order effects in α as calculated by Tsai and Kuraev & Fadin change the results by at most 0.5% and have therefore been ignored.

Table 1: Average values of the reduced widths for the narrow vector resonances. The experimental data on ψ [9] and on Υ [10] have been corrected and averaged in ref. [11]. The latest world average values for the vector meson branching ratios $B(V \to \mu\mu)$ in the fourth column are taken from ref. [13] for charmonium and from ref. [11] for bottonium states.

Vector Meson	$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ uncorr., (keV)	$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ corr., (keV)	$B_{\mu\mu}$ (%)
J/ψ	4.2 ± 0.2	4.4 ± 0.2	6.9 ± 0.6
ψ'	2.0 ± 0.2	2.2 ± 0.2	0.9 ± 0.15
$\Upsilon(1S)$	1.11 ± 0.04	1.23 ± 0.05	2.58 ± 0.13
$\Upsilon(2S)$	0.51 ± 0.03	0.58 ± 0.04	1.60 ± 0.42
$\Upsilon(3S)$	0.36 ± 0.03	0.41 ± 0.03	1.63 ± 0.35

In order to determine Γ_{ee} and Γ_{tot} we need average values for the vector meson branching ratio into two leptons, $B_{\mu\mu}$. The experimental results are also shown in table 1. The $B_{\mu\mu}$ branching ratios for the charmonium vector states have been taken from the Review of Particle properties [13]; for the bottonium resonances they are from ref. [11]. 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}:

$$\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_{tot}} \times \frac{1}{1 - nB_{\mu\mu}} \quad ; \quad \Gamma_{tot} = \frac{\Gamma_{ee}}{B_{\mu\mu}}. \tag{8}$$

The results are presented in table 2. Averaging the Γ_{ee} result from table 2 with the Crystal Ball result equ. 6 we obtain the following new and slightly more precise world average value $\Gamma_{ee}(\Upsilon(1S)) = (1.34 \pm 0.05)$ keV. Concerning the total widths it turns out that the derived values for Γ_{tot} are about 20% *larger* than those stated in the 1986 Review of Particle properties [13]. It is the total widths stated in column four of table 2 that should be used to convert theoretical widths into branching ratios.

Comparison with Theory

In order to compare the experimental leptonic width Γ_{ee} with theoretical predictions we have to remove the vacuum polarization contribution: $\Gamma^{o}_{ee} = \Gamma^{exp}_{ee} \times (1 - \Pi)^2$, where $(1 - \Pi)^2 = (0.958, 0.932)$ for charmonium and bottonium, respectively. These values were calculated by Tsai [5] and include contributions from $e^{\pm}$ pairs, $\mu^{\pm}$ pairs, $\tau^{\pm}$ pairs and quark pairs in the vacuum polarization loop. We obtain

Table 2: Leptonic and total widths of heavy vector mesons calculated from redefined $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ values and using new world average values of $B_{\mu\mu}$. Γ_{ee} values include the vacuum polarization, whereas Γ^{o}_{ee} are the widths in lowest order in α. Also shown for comparison are the Γ_{tot} values as they are stated in the 1986 Review of Particle Properties [13].

Vector Meson	Γ_{ee} (keV)	Γ^{o}_{ee} (keV)	Γ_{tot} (keV)	Γ_{tot}(PDG) (keV)
J/ψ	5.1 ± 0.3	4.9 ± 0.3	74 ± 8	63 ± 9
ψ'	2.3 ± 0.2	2.2 ± 0.2	256 ± 48	215 ± 40
$\Upsilon(1S)$	1.34 ± 0.06	1.25 ± 0.06	52 ± 3	43 ± 3
$\Upsilon(2S)$	0.61 ± 0.04	0.57 ± 0.04	38 ± 10	30 ± 7
$\Upsilon(3S)$	0.43 ± 0.03	0.40 ± 0.03	27 ± 7	(12^{+10}_{-4})

the Γ^{o}_{ee} values stated in table 2 for all ψ and Υ resonances and in column one and three of table 3 for J/ψ and $\Upsilon(1S)$, respectively. For radially excited vector

Table 3: Predictions for Γ^{o}_{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.

Γ^{o}_{ee}	Ref.	J/ψ (keV)	ψ'/ψ	Υ (keV)	Υ'/Υ	Υ''/Υ
Experiment		4.9 ±0.3	0.45 ±0.05	1.25 ±0.06	0.46 ±0.04	0.32 ±0.03
Bander *et al.*	[14]	9.0	0.51	1.63	0.41	0.28
Buchmüller *et al.*	[15]	3.7 ±3.1	0.46	1.07 $\pm.24$	0.44	0.32
Heikkilä *et al.*	[19]		0.35		0.38	0.29
Jacobs *et al.*	[20]	5.4	0.47	0.95	0.41	0.33
Sum Rules	[21]	4.3		1.2		

mesons the leptonic widths are normalized to those of the ground state mesons. In the non-relativistic approximation this decay width can be determined with the van Royen-Weisskopf formula [22]: $\Gamma^{o}_{ee} = (4e_Q^2\alpha^2|R_V(0)|^2/M_V^2) \times (1 - 16\alpha_s/3\pi)$ where first order radiative QCD corrections [23] have been included. To demonstrate the need for the inclusion of first order radiative QCD corrections we list in table 3 the results of a calculation in lowest order (Bander *et al.* [14]): clearly the predictions are too high.

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. By studying both the Schrödinger and the spin-less Salpeter equations Jacobs *et al.* [20], 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.* [19]. It should be noted that QCD sum-rules [21] also predict leptonic widths rather accurately.

I am indepted to my colleagues in the Crystal Ball collaboration for many interesting and fruitful discussions on the material presented here. Special thanks go to M. Reidenbach and Z. Jakubowski who analyzed the CB scan data. I would also like to acknowledge financial support from the Heisenberg Foundation as well as the hospitality received at DESY. Finally, I would like to thank the organizers of the Rencontres de Moriond for the very pleasant ambience maintained throughout this excellent conference.

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