Production of $\Upsilon(9.5)$ in e^+e^- Annihilation and Photoproduction*

Gordon J. Aubrecht, II and Walter W. Wada

Department of Physics
The Ohio State University
Columbus, Ohio 43210

Abstract

Assuming that the new resonance $\Upsilon(9.5)$ is a vector meson, its leptonic and hadronic decay widths are calculated in analogy to those of $\psi(3.1)$. Then, using the Breit-Wigner formula, the production cross section in e^+e^- annihilation is predicted. The tensor dominance of the Pomeron, together with the vector dominance model, is invoked to estimate the photoproduction cross section.

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A resonance in dimuon mass at 9.54 ± 0.04 GeV, designated by $\Upsilon(9.5)$, has recently been observed in energetic proton-nucleus collisions,[1] with width 1.16 ± 0.09 GeV if the enchantment above background is fitted by a single Gaussian. An alternative fit with two Gaussians was also given with masses 9.44 ± 0.03 GeV and 10.17 ± 0.05 GeV.[1] The purpose of this paper is to present the results of several calculations that may have relevance to the possible observation of the above state(s) in energetic e^+e^- annihilation and in photoproduction.

We begin with the assumption that the state(s) is (are) a bound state of a quark-antiquark pair in quantum state $^3S_1$ (1^{--}) of yet another flavor that decays into dimuon via electromagnetic interaction. Including the color degree of freedom, the width of the decay into a lepton pair is given by[2]

$$\Gamma(\Upsilon \to \ell\bar{\ell}) \equiv \Gamma_\ell = 16\pi \frac{\alpha^2 e_Q^2}{m_\Upsilon^2} |\psi(0)|^2, \tag{1}$$

where e_Q is the quark charge in units of e, m_Υ the mass of the vector meson $\Upsilon(9.5)$, and $\psi(0)$ the bound state wave function at the origin. According to QCD, the binding of the quark-antiquark pair arises from the exchange of gluons that couple only to the color and not to the flavor of the quarks. Then, the potential responsible for the binding may be assumed to be the same as that which binds the low-mass quarks (p, n, λ, and c) and the antiquarks into the well-known vector meson states ρ^o, ω, ϕ, and $\psi(3.1)$ in quantum state 1^3S_1 (1^{--}). The wave function $\psi(0)$ should then depend only on the mass of the vector mesons. Indeed, it was shown by Jackson[3] that for these low-mass vector meson states there exists a remarkable regularity between $|\psi(0)|^2$ and the mass m of the vector mesons given by

$$|\psi(0)|^2 \propto m^{1.89\pm 0.15}. \tag{2}$$

In the absence of vector mesons between the state at 9.5 GeV and those below 4.5 GeV which can be interpreted as either ground state 1^3S_1 or excited states of the ordinary quark pairs, we propose that $\Upsilon(9.5)$ is a ground state of the new quark-antiquark pair. We may then regard (2) as applicable to $\Upsilon(9.5)$:

$$|\psi(0)|^2 \approx 0.324 \ \mathrm{GeV}^3. \tag{3}$$

From (1) we then get

$$\Gamma_\ell \approx 9.61\, e_Q^2 \ \mathrm{KeV}. \tag{4}$$

From the Breit-Wigner formula

$$\sigma(e^+e^- \to \mathrm{hadrons}) = \frac{\pi(2J+1)}{s} \frac{\Gamma_\ell \Gamma_h}{(m_\Upsilon - \sqrt{s})^2 + \Gamma^2/4}, \tag{5}$$

where $\Gamma_h = \Gamma(\Upsilon \to \mathrm{hadrons})$ and $\Gamma = \Gamma_\ell + \Gamma_h$, at the peak of the resonance ($J = 1$), we have

$$\sigma(e^+e^- \to \mathrm{hadrons})_{\mathrm{peak}} = \frac{12\pi}{m_\Upsilon^2} \frac{\Gamma_\ell}{\Gamma} \frac{\Gamma_h}{\Gamma}. \tag{6}$$

For the case that $\Upsilon(9.5)$ is a <u>single</u> resonance with $\Gamma \approx 1.16$ GeV, (6) is a relation relevant to experimental observation since e^+e^- beam energy resolution is expected to be narrower than the resonance width.[4,5] Taking $\Gamma_h/\Gamma \approx 1$, we then obtain from (4) and (6)

$$\sigma(e^+e^- \to \text{hadrons})_{\text{peak}} \approx 1.35\, e_Q^2\ \text{nb}. \quad (\text{single resonance}) \tag{7}$$

Since one unit of R at $\sqrt{s}$ = 9.5 GeV corresponds to 0.97 nb, at the energy of the resonance R increases by only about 0.15 for $|e_Q| = 1/3$ but by about 0.62 for $|e_Q| = 2/3$ above the present value R ≈ 5.5.

Next, we take up the case of the alternative fit with two Gaussians,[1] and assume that they are two narrow resonances separated by ~ 0.7 GeV. We take these resonances similar to $\psi(3.1)$ in $1\,^3S_1$ and $\psi(3.7)$ in $2\,^3S_1$. The narrowness of the hadronic decay width may then be ascribed to violation of the OZI rule. Within QCD, the hadronic decay may then be viewed as arising from emission of three gluons in a color-SU(3) singlet state. Thus, we have[6]

$$\Gamma_h = \frac{160}{81}(\pi^2 - 9)\frac{\alpha_s^3}{m_\Upsilon^2}|\psi(0)|^2, \tag{8}$$

where the gluon coupling constant α_s is to be identified with the running coupling constant in the asymptotically free field theory:[6]

$$\bar{\alpha}(s) = \frac{\alpha_s}{1 + \frac{23}{12\pi}\alpha_s \ln(s/m^2)},$$

where the factor 23 in the denominator arises from 33 minus twice the number of flavors. Taking α_s = 0.19[3,6] at m = 3.1 GeV, we get $\bar{\alpha}(s = 9.5^2) = 0.15$. Assuming that the lower of the two narrow resonances [which we continue to denote $\Upsilon(9.5)$] is in quantum state $1\,^3S_1$, we use (3) in (8) and obtain

$$\Gamma_h = 22.5 \text{ KeV}. \tag{9}$$

This value is to be compared with $\Gamma_h\big(\psi(3.1)\big) = 65$ keV. Since the ratio $|\psi(0)|^2/m^2$ is approximately constant for 1^3S_1 states [see (2)], the reduction in the value of Γ_h from that of $\Gamma_h\big(\psi(3.1)\big)$ is due primarily to the reduction in the values of α_s in going from $\psi(3.1)$ to $\Upsilon(9.5)$. In the ratio obtained from (1) and (8), the factor $|\psi(0)|^2/m^2$ drops out:

$$\frac{\Gamma_\ell}{\Gamma_h} = \frac{81\pi}{10(\pi^2-9)}\,\frac{\alpha^2 e_Q^2}{\alpha_s^3} = 0.43\, e_Q^2. \tag{10}$$

From the Breit-Wigner formula (6) we then get

$$\underset{(\text{narrow resonance})}{\sigma(e^+e^-\to \text{hadrons})_{\text{peak}}} = \frac{12\pi}{m_\Upsilon^2}\,\frac{\Gamma_\ell/\Gamma_h}{(1+\Gamma_\ell/\Gamma_h)^2}$$

$$= \begin{cases} 7.1\,\mu b \text{ for } |e_Q| = 1/3, \\ 38.0\,\mu b \text{ for } |e_Q| = 2/3. \end{cases}$$

We note the difference between (7) and the above values by a factor $\sim 10^4$, depending upon whether $\Upsilon(9.5)$ is a broad or narrow resonance [similar to $\psi(3.1)$]. However, in searches using e^+e^- annihilation, if the resonance is narrower than the e^+e^- beam energy resolution, it is the total area under the resonance that is relevant to experimental observation. Assuming that the resonance is narrower than the beam energy resolution, we have,[4,5] together with (1) and (10)

$$\int \sigma(e^+e^- \to \text{hadrons})\, d\sqrt{s} = \frac{6\pi^2}{m_\Upsilon^2} \frac{\Gamma_\ell}{1+\Gamma_\ell/\Gamma_h}$$

$$= \begin{cases} 0.26 \text{ nb}\cdot\text{GeV for } |e_Q| = 1/3, \\ 0.92 \text{ nb}\cdot\text{GeV for } |e_Q| = 2/3. \end{cases} \tag{11}$$

These values are to be compared, in units of nb • GeV, with 10.4 for $\psi(3.1)$, 3.7 for $\psi(3.7)$, 0.35 for $\psi(3.95)$, 2.5 for $\psi(4.1)$, 0.25 for $\psi(4.4)$,[4] and 0.60 for the newly discovered resonance $\psi(3.772 \pm 0.006)$.[7] A similar, but riskier analysis follows for $\Upsilon(10.2)$.[8]

We now turn briefly to the estimation of the photoproduction cross section for $\Upsilon(9.5)$. The $\Upsilon(9.5)$-photon coupling constant is determined from $\Gamma_\ell = \frac{1}{3} m_\Upsilon \alpha^2 \big/ (g_\Upsilon^2 (g^2/4\pi)$ [9] in the vector dominance model. From (4), we then get $g_\Upsilon^2/4\pi \approx 17.5\, e_Q^{-2}$. Next, we assume that the energetic scattering of $\Upsilon(9.5)$ off nucleons is dominated by the diffractive component (Pomeron exchange). The hypothesis of tensor dominance of the Pomeron[10] and the exchange degeneracy between leading even- and odd-signature trajectories then lead to[11]

$$\frac{\sigma(\Upsilon N)}{\sigma(VN)} \approx \frac{m_V^2}{m_\Upsilon^2}, \quad V = \rho, \omega, \phi, \text{ and } \psi.$$

If we take $V = \rho$, ω, or ϕ, we obtain $\sigma\big(\Upsilon(9.5)N\big) \approx 0.15$ mb; if, however, we use $V = \psi(3.1)$ with $\sigma\big(\psi(3.1)N\big) \approx 3.5$ mb,[12] $\sigma\big(\Upsilon(9.5)N\big) \simeq 0.37$ mb [note that the prediction of $\sigma\big(\psi(3.1)N\big)$ from $V = \rho$, ω, or ϕ is[11] $\sigma\big(\psi(3.1)N\big) \approx 1.6$ mb]. The well-known formula for photoproduction in asymptotic limit is[13]

$$\left.\frac{d\sigma(\gamma N \to \Upsilon N)}{dt}\right|_{t=0} = \frac{e^2}{16\pi\, g_\Upsilon^2} \sigma^2(\Upsilon N) \tag{12}$$

$$\approx 2.9\, e_Q^2 \text{ nb/GeV}^2,$$

where we have used $\sigma\left(\Upsilon(9.5)N\right) \approx 0.37$ mb and $g_{\Upsilon}^{2}/4\pi \approx 17.5\ e_{Q}^{-2}$. This may be compared with the observed value 55 ± 24 nb/GeV^{2} for the $\psi(3.1)$ photoproduction;[14] the suppression in the value above is due primarily to the massiveness of $\Upsilon(9.5)$. The $\Upsilon(9.5)N$ elastic scattering slope parameter $b\left(\Upsilon(9.5)N\right)$ may be determined from the empirical rule $b \propto \sqrt{\sigma}$, where σ is the total cross section.[15] Thus, $b\left(\Upsilon(9.5)N\right)/b\left(\psi(3.1)N\right) \approx \left(\sigma\left(\Upsilon(9.5)N\right)/\sigma\left(\psi(3.1)N\right)\right)^{\frac{1}{2}} \approx m_{\psi(3.1)}/m_{\Upsilon}$. Taking $b\left(\psi(3.1)N\right) \approx 4$ GeV^{-2},[16] we obtain $b\left(\Upsilon(9.5)N\right) \approx 1.3$ GeV^{-2}. The integrated cross section, obtained by dividing (12) by $b\left(\Upsilon(9.5)N\right)$, is

$$\sigma(\gamma N \rightarrow \Upsilon N) \approx 2.2\, e_Q^2\ nb. \tag{13}$$

The values implied by (13) are to be compared with $\sigma\left(\gamma N \rightarrow \psi(3.1)N\right) \approx 14 \pm 6$ nb. If $\Upsilon(9.5)$ is to be observed by its dimuon decay, (13) should further be multiplied by the branching ratio $\Gamma_{\ell}/\Gamma = \Gamma_{\ell}/\Gamma_{h}\Big/(1 + \Gamma_{\ell}/\Gamma_{h})$ obtainable from (10). Even if one makes allowances for the approximate nature of the steps taken leading to (13), the values implied are extremely small.

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References

1. S. W. Herb et al., Phys. Rev. Lett 39, 252 (1977).

2. For the case of pure QED, see, for example, J. M. Jauch and F. Rohrlich, The Theory of Photons and Electrons, p.282 (Addison and Wesley, Cambridge, MA 1955).

3. J. D. Jackson, Proc. of the 1976 SLAC Summer Institute on Particle Physics, SLAC-198, p.147.

4. B. Richter, SLAC-PUB-1737, April 1976.

5. H. L. Lynch, Proc. International Conf. on the Production of Particles with New Quantum Numbers, Univ. of Wisconsin, Madison, WI (1976).

6. T. Appelquist and H. D. Politzer, Phys. Rev. Lett. 34, 43 (1975); Phys. Rev. D 12, 1404 (1975).

7. P. A. Rapidis et al., SLAC-PUB-1959, June 1977.

8. Let us return to our earlier assumption that $\Upsilon(10.2)$ is the first radial excitation in quantum state 2^3S_1, similar to $\psi(3.7)$ in relation to $\psi(3.1)$. It then seems plausible to assume that the mass dependence of $|\psi(0)|$ for the 2^3S_1 states is of the same functional form as that for 1^3S_1 states given in (2). Then $|(\psi(0, \Upsilon(10.2))|$ is expected to scale to $|(\psi(0,\psi(3.7))|$ approximately as $|\psi((0, \Upsilon(10.2))|^2 / |\psi(0,\psi(3.7))|^2 \approx \left(m_{\Upsilon(10.2)}/m_{\psi(3.7)}\right)^{1.89}$. We obtain $\Gamma_\ell = 4.0\ e_Q^2$ keV, Γ_h = 8.1 keV, and $\int\sigma\left(e^+e^- \to \Upsilon(10.2)\right) d\sqrt{s} \approx 0.24$ nb • GeV for $|e_Q| = 1/3$ and 0.53 nb • GeV for $|e_Q| = 2/3$.

9. R. P. Feynman, Photon-Hadron Interactions (Benjamin, Reading, MA, 1972).

10. R. Carlitz, M. B. Green, and A. Zee, Phys. Rev. Lett. 26, 1515 (1971); Phys. Rev. D 4, 3439 (1971).

11. C. E. Carlson and P. G. O. Freund, Phys. Lett. 39B, 349 (1972); Phys. Rev. D 11, 2453 (1975).

12. R. L. Anderson et al., Phys. Rev. Lett. 38, 263 (1977).

13. J. F. Martin et al., Phys. Rev. Lett. 34, 288 (1975).

14. W. Y. Lee, in W. T. Kirk, ed., Proc. of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, p.213, Stanford Univ., Stanford, CA (1975).

15. C. J. Joachain and C. Quigg, Rev. Mod. Phys. 46, 279 (1974); C. Quigg and J. L. Rosner, Phys. Rev. D 14, 160 (1976).

16. B. Knapp et al., Phys. Rev. Lett. 34, 1040 (1975).