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Electromagnetic production and decay of $\psi(3105)^\dagger$

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The electromagnetic production and decay of the $\psi(3105)$ meson is shown to be consistent with the vector-meson–dominance model and the assignment of ψ to an SU(4) $J^P = 1^-$ multiplet.

The recent discovery[1-3] of two new particles which appear as very narrow resonances in the e^+e^- cross section is likely to inspire extensive theoretical activity concerning their dynamical roles, their placement in classification schemes, and their reluctance to decay strongly into hadrons. Given the last, however, namely accepting their narrow total width, we would like here to point out that the charged lepton-antilepton production and decay of the better-known $\psi(3105)$ meson is consistent with (1) the simple vector-meson-dominance model[4] (VDM) and (2) the assignment of ψ to a $J^P=1^-$ member of the SU(4) multiplet[5] which includes the ρ, ϕ, ω as its other neutral members. In SU(4) quark (c, u, d, s) language, that is, the ψ will be taken to be a $\bar{c}c$ bound state. Assumptions (1) and (2) enable us to calculate the partial widths of ψ for decay into charged lepton-antilepton pairs and the cross sections $\sigma_{e^+e^-\to e^+e^-}$ and $\sigma_{e^+e^-\to\mu^+\mu^-}$, which we shall compare with the data. In addition, partial rates for decay *via this mechanism* into any charged pair can also be calculated and we shall comment on some of these in the summary.

PARTIAL WIDTH OF $\psi(3105)$ FOR DECAY INTO e^+e^- AND $\mu^+\mu^-$ PAIRS

In the VDM the partial width for the electromagnetic decay of a 1^- meson V of mass m_V into e^+e^- or $\mu^+\mu^-$, with lepton masses neglected and a universal coupling assumed, is given by

$$\Gamma_{V\to l\bar{l}} = \tfrac{4}{3}\pi\alpha^2 F_V^2 m_V^{-3} , \tag{1}$$

where

$$\epsilon_\mu F_V = \langle V | J_\mu^{\text{e.m.}} | 0 \rangle . \tag{2}$$

In an SU(4) quark model the ratios of F_V^2/m_V^p for ρ, φ, ω, ψ are 9:2:1:8, where the power p depends on one's model for symmetry breaking. A common choice, with some theoretical justification, is $p=2$, which yields

$$R_{\rho\phi} = \frac{\Gamma_{\rho\to e^+e^-}}{\Gamma_{\phi\to e^+e^-}} = 6.0 \quad (p=2) , \tag{3}$$

compared to $R_{\rho\phi}=4.1$ (experiment). A better fit is given by $p=3$ which yields

$$R_{\rho\phi}=4.5 \quad (p=3) .$$

Guided by this p range inferred from the known partial widths, we predict

$$\frac{\Gamma_{\psi\to e^+e^-}}{\Gamma_{\phi\to e^+e^-}} = \begin{cases} 1.3 & (p=2) \\ 4.0 & (p=3) \end{cases} \tag{4}$$

where $\Gamma_{\phi\to e^+e^-}=1.4$ keV (experiment).

Crude estimates of, or constraints on, the partial width $\Gamma_{\psi\to e^+e^-}$ and the total width Γ_ψ have already been made[6] on the basis of the reported ψ data by folding the beam width $\Delta W=1.9$ MeV with a Breit-Wigner resonance shape in the 1^- channel, which yields a total cross section at resonance of

$$(\sigma^T)_{\max} \cong \frac{12\pi}{m_\psi^2}\frac{\Gamma_{\psi\to e^+e^-}}{\Gamma_\psi+\Delta W} \tag{5}$$

or

$$(\sigma_f)_{\max} \cong \frac{12\pi}{m_\psi^2}\frac{\Gamma_{\psi\to e^+e^-}\Gamma_{\psi\to f}}{\Gamma_\psi(\Gamma_\psi+\Delta W)} \tag{6}$$

for partial cross section at resonance to a final state f. Assuming e-μ universality, the branching ratio is then

$$B = \frac{\Gamma_{\psi\to\mu^+\mu^-}}{\Gamma_\psi} = \frac{\Gamma_{\psi\to e^+e^-}}{\Gamma_\psi} = \frac{\sigma_{\mu^+\mu^-}}{\sigma_T} \equiv \frac{\sigma_{\mu^+\mu^-}}{x\sigma_h} = 0.06/x , \tag{7}$$

where x is related to the fraction of σ_T coming from (missing) neutral channels, and σ_h is the reported[2] cross section for "hadronic" events.[7] Estimates of $\sigma_{\mu^+\mu^-}$ may be inferred from the data by (i) assuming a 1^- angular distribution, (ii) making the corresponding correction for the missing solid angle, and (iii) correcting for the asymmetric radiative tail beam shape. Since σ_h requires the same radiative correction (iii), this factor cancels in the branching-ratio calculation. The data for σ_h are reported to have already been corrected for missing solid angle. Assuming $\Delta W \gg \Gamma$, we then have

$$\Gamma_{\psi\to e^+e^-} \cong 3.9x \text{ keV} , \tag{8}$$

$$\Gamma_\psi \cong 65x^2 \text{ keV} . \tag{9}$$

Thus,

$$\frac{\Gamma_{\psi\to e^+e^-}}{\Gamma_{\varphi\to e^+e^-}} = 2.8x \text{ keV} \tag{10}$$

and our theoretical estimate (4) is consistent with a reasonable value of x (between 1 and 2).

DIFFERENTIAL CROSS SECTIONS FOR $e^+e^- \to e^+e^-$ AND $e^+e^- \to \mu^+\mu^-$ NEAR RESONANCE

Concurrent with our VDM calculation of the partial widths, we can calculate the above cross sections using the diagrams of Fig. 1. The results are

$$\left(\frac{d\sigma}{d\Omega}\right)_{e^+e^-\to e^+e^-} = \frac{\alpha^2}{16E^2}\left[(1+\cos^2\theta)|A|^2 - \frac{2\cos^4\frac{1}{2}\theta}{\sin^2\frac{1}{2}\theta}(AD^* + DA^*) + \frac{2(1+\cos^4\frac{1}{2}\theta)}{\sin^4\frac{1}{2}\theta}|D|^2\right], \tag{11}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{e^+e^-\to \mu^+\mu^-} = \frac{\alpha^2}{16E^2}\left(1+\cos^2\theta + \frac{m_\mu^{\,2}}{E^2}\sin^2\theta\right)|A|^2, \tag{12}$$

where

$$A = 1 + \frac{3B}{\alpha}\frac{m_\psi^{\,2}}{4E^2}\frac{m_\psi\Gamma}{4E^2 - m_\psi^{\,2} + i m_\psi \Gamma}, \tag{13}$$

$$D = 1 - \frac{3B}{\alpha}\frac{m_\psi^{\,2}}{4E^2}\frac{m_\psi\Gamma}{\sin^2\frac{1}{2}\theta(-4E^2\sin^2\frac{1}{2}\theta - m_\psi^{\,2} + i m_\psi\Gamma)}. \tag{14}$$

In Fig. 2 we plot the e^+e^- elastic cross section, Eq. (11), integrated over the 50°–130° angular acceptance and scaled down by 43% to match the low end of the reported data where the cross section should accurately be described by pure Bhabha scattering. A total width of $\Gamma = 200$ keV and a branching ratio $B = 0.039$ are the inputs, suggested by one of our better fits to the data when the theoretical cross section is folded with beam shape (see below).

In Fig. 3, we present the $e^+e^- \to \mu^+\mu^-$ theoretical cross section integrated over the 50°–130° angular acceptance and again scaled down by 43%, for $\Gamma = 200$ keV and $B = 0.039$. The dip structure, analogous to that observed in $e^+e^- \to \phi \to \mu^+\mu^-$, is much sharper here because cf the narrow total width of the ψ.

In Fig. 4, we fold the theoretical cross section, integrated and scaled as above, with the e^+e^- ring beam shape implied by Fig. 1 of Ref. 2, for

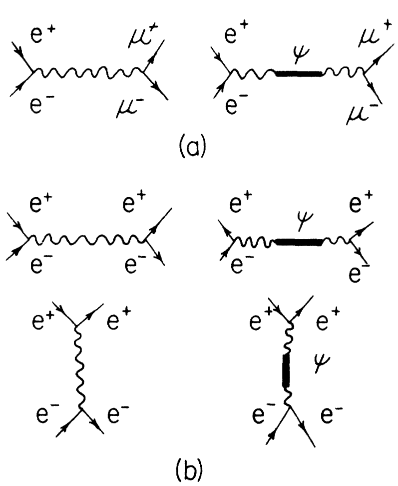

FIG. 1. (a) Diagrams for VDM of $e^+e^- \to \mu^+\mu^-$. (b) Diagrams for VDM of e^+e^- elastic.

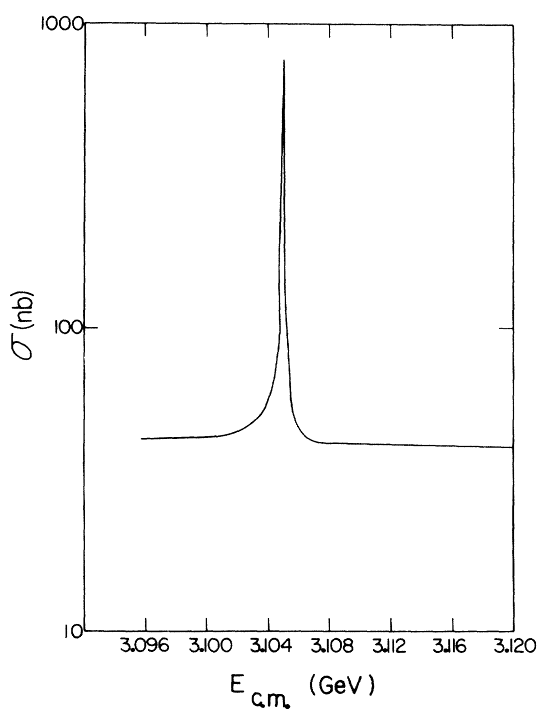

FIG. 2. VDM for e^+e^- elastic cross section integrated from 50°–130° and rescaled by 43%. Total width of 200 keV and branching ratio of 0.039.

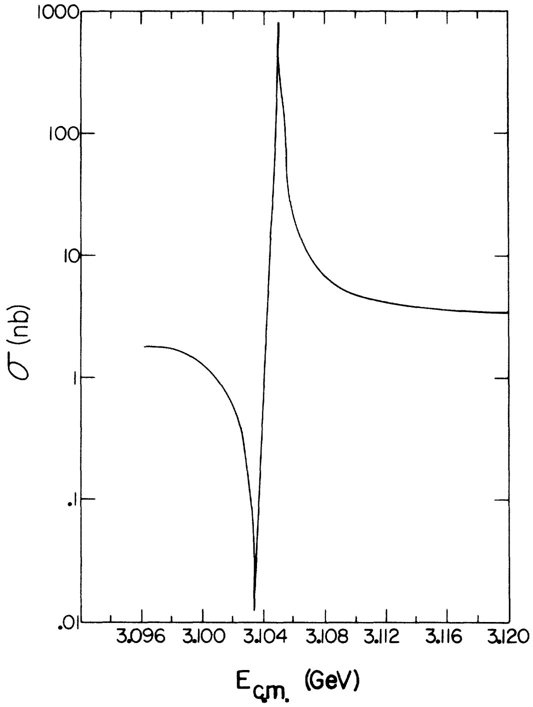

FIG. 3. VDM for $e^+e^- \to \mu^+\mu^-$ cross section integrated from 50°–130° and rescaled by 43%. Total width of 200 keV and branching ratio of 0.039.

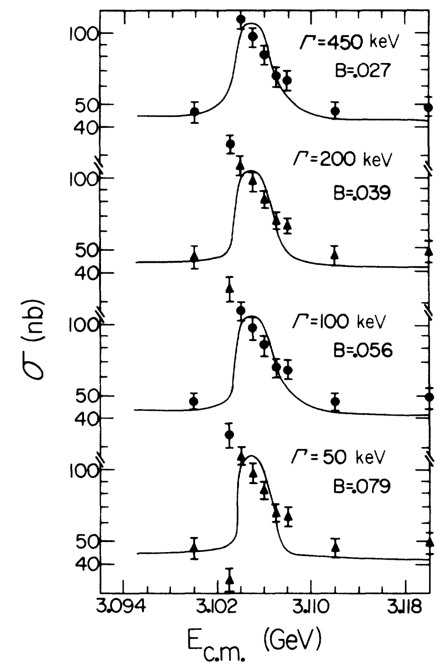

FIG. 4. Curves: VDM for e^+e^- elastic cross section integrated from 50°–130°, rescaled by 43% and folded with the beam shape implied by Fig. 1 of Ref. 2. Data: e^+e^- elastic from SLAC, Ref. 2.

total widths of 50, 100, 200, and 450 keV and branching ratios (adjusted to give best fits) of 0.079, 0.056, 0.039, and 0.027, respectively.

In Fig. 5 are plots of the $e^+e^- \to \mu^+\mu^-$ cross section, scaled, integrated, and folded with beam shape as above, for various total widths and the branching ratios which best fit the elastic data.

All fits are quite good. [The combination $\Gamma = 100$ keV and $B = 0.056$ yields a partial width which agrees with the higher prediction of Eq. (4).] The salient feature is the pronounced dip at $E_{c.m.} \approx 3.1025$ where the $e^+e^- \to \mu^+\mu^-$ cross section (folded) falls sharply compared to the background.

SUMMARY AND CONCLUSIONS

The reported data on $\psi(3105)$ are consistent with a VDM for production and decay of a 1^- meson carrying $\bar{c}c$ SU(4) quantum numbers.

The VDM mechanism also allows prediction of the exclusive cross section for $\pi^+\pi^-$, K^+K^-, $\bar{p}p$, etc., but these will be reduced by hadronic electromagnetic form factors in the timelike region. We have calculated the $\pi^+\pi^-$ cross section; the combination of spin factors and a form-factor[8] correction $[|F_\pi(m_\psi^2)|^2 \leq 0.2]$ reduce this cross section to < 7% of the $\mu^+\mu^-$ cross section.

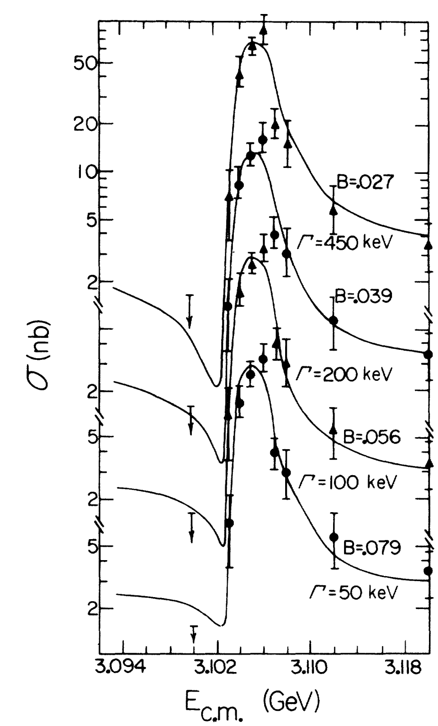

FIG. 5. Curves: VDM for $e^+e^- \to \mu^+\mu^-$ cross section integrated from 50°–130°, rescaled by 43% and folded with the beam shape implied by Fig. 1 of Ref. 2. Data: $e^+e^- \to \mu^+\mu^-$ from SLAC, Ref. 2.

The fraction of the purely hadronic inclusive cross section *due to this mechanism* can also be calculated by the VDM; essentially, the $e^+e^- \to$ hadrons cross section in the resonant region receives an enhancement shape factor equal to that in $e^+e^- \to \mu^+\mu^-$ cross section which yields, when folded, a cross section of 20–25 times the nonresonant background at maximum, implying that ~20% of the hadronic peak in Ref. 2 can be accounted for by purely electromagnetic decay via the VDM mechanism.

Note added in proof. After submission of this manuscript we learned of the related work of D. R. Yennie [Phys. Rev. Lett. 34, 239 (1975)], who points out that the vector-meson widths are SU(4) symmetric (our $p=3$). Further, we would like to note that Yennie's more detailed calculation of beam shape does not differ significantly from the shape we used (Fig. 1, Ref. 2).

ACKNOWLEDGMENTS

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[4]For a recent review, see R. P. Feynman, *Photon-Hadron Interactions* (Benjamin, New York, 1972).

[5]For a recent review, see Mary K. Gaillard, Benjamin W. Lee, and Jonathan L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[6]Benjamin W. Lee, NAL Mini Conference, 1974 (unpublished).

[7]"Hadronic" events contain more than two charged particles or two charged tracks noncoplanar by >20°.

[8]Carlo Bernardini, in *Proceedings of the 1971 International Symposium on Electron and Photon Interactions at High Energy*, edited by N. B. Mistry (Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y., 1972).