Two-particle decays of ψ resonances and electromagnetic effects

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A formula is obtained for the cross section of the processes $e^+e^- \to l^+l^-$ in the resonance region; this formula is valid in all orders in the electromagnetic interaction. Its application to ψ resonances makes it possible to determine the resonance parameters.

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In this article we continue[6] the analysis of the electromagnetic effects in the production of the recently discovered heavy narrow $\psi(J)$ resonances,[1–3] and examine the cross sections of the two-particle processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ in the resonance region. In this case, unlike the total annihilation cross section,[6]

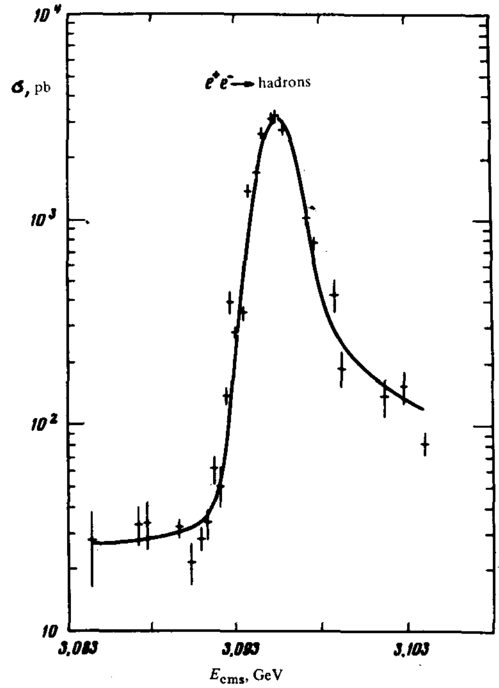

FIG. 1.

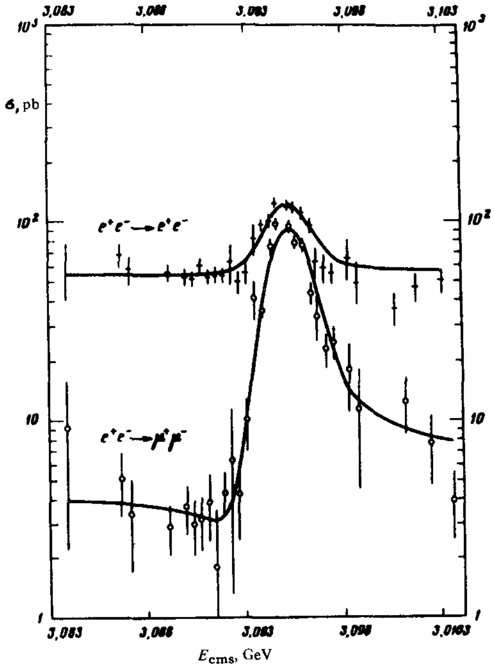

FIG. 2.

there is interference with background processes.

In the production of ψ resonances, owing to the small width and large mass M, the electromagnetic corrections are characterized by three different effective constants: $a\ln(M/m_e)\ln(M/d)$, $a\ln(M/m_e)$, and a, where m_e is the electron mass, d is the width of the resonance or the energy resolution of the beam, and a is the fine-structure constant. The first constant is close to 0.5 and it is necessary to sum over it. It suffices to take terms of order $a\ln(M/m_e) \sim 0.1$ into account in the lowest order, while the corrections of order a can be disregarded.

The cross section of the two-particle process $e^+e^- \to l^+l^-$ near resonance consists of a resonant term, an interference term, and a background term. The background process is the well known[7,8] Bhabha scattering.

In experiments,[2,8] one includes among the two-particle processes those events in which the momenta of the final leptons lie in the region (in the c.m.s.)

$$E' > E/2; \quad |\cos\theta| < 0{,}6; \quad \Delta\theta,\ \Delta\phi < 10^\circ, \tag{1}$$

where E (E') is the total energy of the initial (final) leptons, θ is the scattering angle, and $\Delta\theta$ and $\Delta\phi$ are the noncollinearity angles of the final leptons.

The conditions (1) denote that the fraction of the energy going to the nonregistered photons may amount to $M/2$, and these photons can of course not be regarded as soft. It is easy to show, however, that the resonant contribution is determined by the soft photons (it is precisely to them that the principal effective constant pertains), and can be calculated in all orders with the aid of the general method of S-matrix electrodynamics.[4-6]

The result takes the form

$$\frac{d\sigma^{res}(E,\cos\theta)}{d\cos\theta} = A\,\mathrm{Im}(-z)^{-1+a}\left(1+\frac{3}{4}a\right), \tag{2}$$

where $z = 2(E-M)/M + i\Gamma/M$, Γ is the total width of the resonance,

$$a = \frac{2\alpha}{\pi}\left(2\ln\frac{M}{m_e} - 1\right), \tag{3}$$

$$A = \frac{12\pi}{M^3}\,\frac{\Gamma_e}{\Gamma}\,\frac{d\Gamma_{l\gamma}}{d\cos\theta} \tag{4}$$

Γ_e is the width of the $\psi \to e^+e^-$ decay without radiative corrections, $d\Gamma_{l\gamma}/d\cos\theta$ is the width of the decay $\psi \to l^+l^-$ and an arbitrary number of γ quanta, when the lepton momenta lie in the region (1) at fixed θ.

Formula (2) is valid accurate to factors $[1+O(\alpha)] \times (1+O)[(E-M)/M]$, i.e., it is accurate to 1% at $(E-M) \sim 40$ MeV.

It is important to note that formula (2) differs from the total cross section for the production of ψ only by the factor $(1/\Gamma)(d\Gamma_{l\gamma}/d\cos\theta)$. It can be shown that for any other final state X the electromagnetic effects do not violate the relation

$$d\sigma_x^{res} = \frac{d\Gamma_x}{\Gamma}\,\sigma_{tot}^{res}, \tag{5}$$

where $d\sigma_x^{res}(d\Gamma_x)$ is the resonant cross section (the width of the decay) in the given state X. The universality of the radiative corrections is caused by the fact that the radiative change of the shape of the resonance curve is due to the radiation prior to the collision, and is consequently determined only by the initial state.

In the calculation of the interference term, it suffices to take into account in the background processes only the emission of the soft photons

$$\frac{d\sigma^{\text{interf}}(E,\theta)}{d\cos\theta} = 2\,\text{Re}\,B(-z)^{-1+a}. \qquad (6)$$

We then have for elastic e^+e^- scattering

$$B = -\frac{3}{2}\frac{a\Gamma_e}{M^3}\left[(1+\cos^2\theta) - \left(\frac{1+\cos\theta}{1-\cos\theta}\right)^2\right]. \qquad (7)$$

In the case of $e^+e^- \to \mu^+\mu^-$ scattering, there is no second term in the square bracket in (7), and the interference at all angles is destructive up to resonance and constructive beyond resonance. In the elastic channel at small angles, the situation is reversed.

To fit the experimental curves, it is necessary to integrate the obtained expressions with the beam energy distribution function, which we assume to be Gaussian with a variance d.

Comparison of the formulas with the SPEAR data[9] yielded the following ratios, which are independent of d within the limits of errors: $\Gamma_e\tilde{\Gamma}_{e\gamma}/\Gamma = 0.13 \pm 0.01$ keV; $\Gamma_e\tilde{\Gamma}_{\mu\gamma} = 0.16 \pm 0.02$ keV; $\Gamma_e\Gamma_h/\Gamma = 5.6 \pm 0.6$ keV, where $\Gamma_{l\gamma}$ is the width of the decay $\psi(3095) \to l^+l^-$ + photons for lepton momenta in the region (1). The corresponding curves for $d = 1$ MeV are shown in the figures.

With accuracy 10%, we can assume that $\tilde{\Gamma}_{l\gamma} = 0.50\Gamma_l$. We then obtain $\Gamma_h/\Gamma_e = 22.4 \pm 4.5$, $\Gamma_\mu/\Gamma_e = 1.2 \pm 0.2$, and $\Gamma_e = 5.6 \pm 0.6$ keV.

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