Use of radiation effects to determine widths of resonances

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We discuss the use of resonance radiation "tails" that appear in processes in which electron-positron pairs take part and are due to the shift to the resonance as a result of emission of a photon by the electron or positron for the purpose of determining the widths of the resonances observed at the end of 1974 in the Stanford and Brookhaven experiments.

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Colliding electron-positron beam experiments at Stanford[1] have established quite recently the existence of a narrow resonance, named by the authors the ψ particle, in the reactions

$$e^+e^- \to \psi \to \text{hadrons};\quad e^+e^-;\quad \mu^+\mu^- + \pi^+\pi^- + K^+K^-. \tag{1}$$

The mass of the ψ particle is $m_\psi = 3105 \pm 3$ MeV, and the total width is $\Gamma_\psi \leqslant 1.9$ MeV, with the value 1.9 MeV the total width (at half-height) of the energy distribution of the electrons and positron in SPEAR. The same resonance was observed simultaneously in an experiment with the Brookhaven proton beam[2] in the reaction

$$p + \text{Be} \to e^+ + e^- + X, \tag{2}$$

where they measured the invariant mass of the electron-positron pair $(p_+ + p_-)^2 = m^2_{e^+e^-}$. It was found that $m_\psi = 3100$ MeV, $\Gamma_\psi \leqslant 20$ MeV (20 MeV is the apparatus width). It is noted in both papers that the data do not contradict the assumption that the resonance width Γ_ψ is much smaller than the experimental resolution. There is also a preliminary report[3] of another resonance of the same type, with $m_{\psi'} = 3700 \pm 20$ MeV and $\Gamma_{\psi'} \leqslant 4$ MeV.

It is known that when narrow resonances are produced in colliding electron-positron beams (1) they have a broad radiative tail, due to the fact that at $2\epsilon - m_\psi > 0$ (ϵ is the energy of the initial electron (positron)) the photon emission by the initial particles causes them to return to the region of the resonance energy.[1)] [4] If the cross section of resonance production is represented in the standard Breit-Wigner form

$$\sigma^{Res} = 4\pi(2J+1)\frac{\Gamma_{\psi\to f}\Gamma_{\psi\to e^+e^-}}{(s - m_\psi^2)^2 + m_\psi^2\Gamma_\psi^2} = \frac{\pi(2J+1)}{m_\psi^2}\,\frac{\Gamma_{\psi\to f}\Gamma_{\psi\to e^+e^-}}{(2\epsilon - m_\psi)^2 + \Gamma_\psi^2/4}, \tag{3}$$

where J is the spin of the particle and $\Gamma_{\psi\to f}$ is the partial width of the decay into the state f, then the cross section of the process with photon emission takes the form[4] (see also[5])

$$\sigma^{Rad} = \frac{(2J+1)}{m_\psi^2}\,\frac{\Gamma_{\psi\to f}\Gamma_{\psi\to e^+e^-}}{(2\epsilon - m_\psi)^2 + \Gamma_\psi^2/4} \times \alpha L\left[\frac{2\tau(0)}{\Gamma_\psi}\operatorname{Arc\,tg}\frac{2\omega\Gamma_\psi}{\tau(\omega)\tau(0) + \Gamma_\psi^2} + \ln\frac{\tau^2(0) + \Gamma_\psi^2}{\tau^2(\omega) + \Gamma_\psi^2}\right], \tag{4}$$

where $\alpha = 1/137$, $L = 2\ln(m_\psi/m_e) - 1$, $\tau(\omega) = 2(2\epsilon - m_\psi - \omega)$, and ω is the maximum allowed energy of the emitted photon,[2)] determined for the total cross section by the kinematic limit. We have left out of expression (4) those radiative effects which are not connected with the return to resonance. The logarithmic term in (4) is significant only near the resonance, and on the right side far from resonance the principal role is played by the first term in the square brackets; at $2\epsilon - m_\psi \gg \Gamma_\psi$ we have $\tan^{-1} 2\omega\Gamma_\omega/[\tau(\omega)\tau(0) + \Gamma_\psi^2] \to \pi$. In this region, the resonance peak is essentially asymmetrical, since its left slope decreases like $(2\epsilon - m_\psi)^{-2}$ (3), and the right slope, according to (4), decreases like $(2\epsilon - m_\psi)^{-1}$. According to experiment,[1] $\Gamma_{\psi\to \mathrm{hadr}} \approx \Gamma_\psi$, and it is then obvious that by comparing the right slope of the resonance peak observed in the reaction $e^+e^- \to \psi \to$ hadrons with Eq. (4) we can obtain the experimental value of the partial width[3)] $\Gamma_{\psi\to e^+e^-}$. We note also that by comparing the slopes on the left and on the right of the resonance point we can determine the total width of the resonance from one excitation curve (see below).

We wish to call attention to the possibility of determining the total resonance width Γ_ψ from radiative effects also for a reaction of type (2). This is particularly timely, because here the observed cross section has no absolute normalization and its hadronic part cannot be calculated theoretically. The standard condition for being able to determine experimentally the width Γ_ψ is $\Gamma_\psi/2 \gg \delta_{\mathrm{exp}}$, where δ_{exp} is the effective spread with respect to energy (the invariant mass). In this case the radiative effects afford essentially new possibilities. The point is that whereas in the case of the process (1) the photon emission has caused a "return" to the resonance, in the case of process (2) emission of a photon by the electron or positron leads to "advancement" to resonance. In fact, in that case we have at the resonant point $m_\psi^2 = (p_+ + p_- + k)^2$, whereas $m_{e^+e^-}^2 = (p_+ + p_-)^2 < m_\psi^2$. In other words, on the plane of N (the number of events) the $m_{e^+e^-}^2$ peak in the reaction (2) *is asymmetrical with a slowly decreasing left slope*. It is easy to verify that in this case we can use for the radiative tail the formula (4), in which we must make the substitution $2\epsilon - m_\psi \to m_\psi - \sqrt{m_{e^+e^-}^2}$. At the points $2\epsilon_1 - m_\psi = m_\psi - 2\epsilon_2 > 0$ which are symmetrical with respect to the maximum of the resonance (where $2\epsilon = \sqrt{m_{e^+e^-}^2}$), we have

$$\sigma^{Rad}(\epsilon_2) = \frac{4\alpha L |m_\psi - 2\epsilon_1|}{\Gamma_\psi} \sigma^{Res}(\epsilon_1), \tag{5}$$

from which we can determine the total width of the resonance for both reaction (2) and reaction (1) (it is then necessary to put $\epsilon_1 \rightleftarrows \epsilon_2$), if the conditions that enable us to establish the asymmetry of the peak slopes are satisfied. Let us examine these conditions. Let R be the ratio of the cross section at the resonance point $(2\epsilon = m\psi)$ to the cross section σ^b far from resonance, i.e.,

$$\frac{\sigma^{Res}}{\sigma^b} = \frac{R\Gamma^2}{4\left[\delta^2 + \dfrac{\Gamma^2}{4}\right]},$$

where $\delta^2 = (2\epsilon - m_\psi)^2$. We are then interested in the energy region where the inequalitites $\sigma^{\mathrm{Rad}} > \sigma^{\mathrm{Res}}$ and $\sigma^{\mathrm{Res}} > \sigma^b$ are satisfied. Taking (5) into account, we have the following inequalities for the energy interval δ:

$$R\Gamma^2 > 4\delta^2 > \frac{\Gamma^2}{(2\alpha L)^2}, \tag{6}$$

In addition, it is necessary that the energy spread δ_{exp} not smear out the effect considered above, i.e., it is necessary to have $\delta \gg \delta_{\mathrm{exp}}$. Then we get for δ_{exp} from (6) the condition $\sqrt{R}(\Gamma_+/2) \gg \delta_{\mathrm{exp}}$, which is obviously much weaker than $\Gamma_\psi/2 \gg \delta_{\mathrm{exp}}$.

The foregoing inequalities are well satisfied in the Stanford experiment,[1] so that it is possible to obtain from the published data the approximate values $\Gamma_{\psi\to e^+e^-} = 5$ keV (this estimate was obtained by many workers) and $\Gamma_{\psi'} = 140$ keV. The resonance curve observed in the Brookhaven experiment[2] is indeed asymmetrical with a slowly decreasing left slope, but its use yields only rough estimates. These estimates will become much more accurate if the experimental resolution is improved by several times.

1)For the considered processes we can confine ourselves to the region where $|2\epsilon - m_\psi| \ll m_\psi$.

2)If we measure the differential (with respect to frequency) photon cross section $d\sigma/d\omega$ at a fixed energy of the electrons and positrons, then we obtain a resonance curve with maximum at the point $\omega = 2\epsilon - m_\psi$.

3)According to the information available to us, this method of determining $\Gamma_{\psi\to e^+e^-}$ was discuss by Vaĭnshtein, Ioffe, Lipatov, Sushkov, and Khoze.

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