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Radiative decays, photoproduction and total cross section of the ψ particles

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Abstract. It is pointed out that the coupling characterizing the $\psi-\gamma$ vertex must change substantially between the limits, ψ on mass-shell which occurs in $\psi \rightarrow e^+e^-$ and photon on mass-shell which is relevant in radiative decays like $\psi \rightarrow \pi\pi\gamma$, $\psi \rightarrow \eta\gamma$ and photoproduction of ψ. This has the consequence that the value of ψN total cross section must be larger than what is inferred from the use of naive vector dominance in photoproduction.

Keywords. ψ - γ vertex; radiative decays; photoproduction; total cross section.

1. Introduction

The narrow resonance ψ (3.1) originally seen in e^+e^- collisions (Augustin *et al.* 1974) and in hadron collisions (Aubert *et al.* 1974) has now been seen in photoproduction experiments (Camerini *et al.* 1975, Knapp *et al.* 1975, Theodosiou *et al.* 1975). In the last process the differential cross section of the inclusive reaction

$$\gamma + Be \rightarrow \psi + \text{anything}$$

is measured and is very similar to the process in which ψ is replaced by the ρ meson. This implies that ψ is photoproduced diffractionally like other vector mesons such as ρ, a fact which may have a natural explanation under the hypothesis of vector dominance. According to this hypothesis, the diffractive nature of the ψ-photoproduction would be visualised as the conversion of the incident photon into a virtual ψ which subsequently is converted into a physical ψ on the mass-shell by elastic scattering with the target nucleus. Thus if the ψ-γ-coupling is known the ψ-photoproduction becomes a source of information on ψN scattering. Assuming that the $\psi\gamma$-coupling has the same value as determined from the observed width of $\psi \rightarrow e^+e^-$, it is estimated (Knapp *et al.* 1975) that the total cross section $\sigma_T(\psi N)$ is about 1 mb. This value is an order of magnitude smaller than $\sigma_T(\rho N) \simeq 30$ mb, which has been estimated in a similar manner and is typical of hadron total cross sections.

In the following we wish to point out that the $\psi\,\gamma$ vertex must vary substantially as the ψ goes from on-shell to off-shell, resulting in a ψN cross section which is larger than the value of 1 mb estimated from the naive vector dominance hypothesis. Our view is supported by the absence of a dominant radiative decay mode of ψ.

The higher resonance ψ' (3.7) seen (Abrams *et al.* 1974) in e^+e^- collisions has a larger total width than ψ. It is known (Abrams *et al.* 1975) to decay into $\psi(3.1)+\pi^++\pi^-$ with a branching ratio 31 $\pm 4\%$ which shows that the effective $\psi'\psi\pi\pi$ coupling must have a typical strong interaction value. The radiative decay $\psi'\to\pi\pi\gamma$ can be regarded in the sense of dispersion theory to be dominated by $\psi'\to\pi\pi\psi$ followed by the conversion of $\psi\to\gamma$. Similar considerations apply for $\to\pi\pi\gamma$ and $\psi\to\eta\gamma$. If one assumes that the ψ-γ vertex has the same value as found in $\psi\to e^+e^-$ one expects substantial radiative decay rates for ψ, barring fortuitous cancellations. Since the total width of $\psi(3.1)$ (Boyarski *et al.* 1975) is only around 70 keV, one expects that the radiative decay rates should be very much smaller than naively calculated ones. In other words the effective coupling of ψ-γ must vary substantially as ψ goes off-shell, contrary to vector meson dominance hypothesis. This has the important consequence that the elastic cross section of ψN seen in photoproduction has actually a value larger than one naively calculated. The next section presents the calculations relating all these processes, and in the last section our conclusion are stated.

2. Vector meson dominance and radiative decays

Our discussions are easily done within the framework of a phenomenological Lagrangian which we write as

$$\mathcal{L}_{\text{int}} = f'\,\psi'_{\mu\nu}\psi^{\mu\nu}\,\pi.\pi + f\psi_{\mu\nu}\psi^{\mu\nu}\,\pi.\pi + \ldots + g\,\epsilon^{\mu\nu\lambda\sigma}\,\psi'_{\mu\nu}\psi_{\lambda\sigma}\eta + \ldots$$

$$+\frac{em^2}{2\gamma}\,\psi_\mu A^\mu + \frac{e\,(m')^2}{2\gamma'}\,\psi'_\mu A^\mu. \tag{2.1}$$

$$\psi_{\mu\nu} = \partial_\mu\psi_\nu - \partial_\nu\psi_\mu$$

$$\psi'_{\mu\nu} = \partial_\mu\psi'_\nu - \partial_\nu\psi'_\mu$$

where $f, f', g, \gamma, \gamma'$ are coupling constants, e is the electric charge, m and m' are the masses of ψ and ψ', ψ_μ, ψ'_μ, η, π and A_μ are respectively the fields of ψ (3.1), ψ' (3.7), η (549), pion and the photon. There is an apparent violation of gauge invariance which disappears if as in eq. (2.1) the source of ψ_μ and ψ'_μ are conserved.

A. $\underline{\psi\to e^+e^-}$. We have from eq. (2.1)

$$\Gamma(\psi\to e^+e^-) = \frac{a^2}{12}\left(\frac{4\pi}{\gamma^2}\right) m \tag{2.2}$$

We take $m = 3{\cdot}095$ GeV and the above partial rate to be 4.8 keV (Boyarski *et al.* 1975). This gives

$$\frac{\gamma^2}{4\pi} = 2{\cdot}86$$

B. $\underline{\psi'\to\psi\pi\pi}$. Although there are five possible couplings for this decay, it is easy to check that only the amplitude of the form in eq. (2.1) makes the dominant contribution. We therefore have

$$\Gamma(\psi'\to\psi\pi\pi) = \frac{(f')^2}{4\pi}\,\frac{m'}{3\pi^2}\,R \tag{2.3}$$

where R is the phase space integral $= 0{\cdot}273\ (\text{GeV})^4$ for $m' = 3{\cdot}684$ GeV.

C. $\psi' \to \pi\pi\gamma$. We picture this process as $\psi' \to \pi\pi\psi$ followed by $\psi \to \gamma$ transition. Eq. (2.1) then gives the effective coupling as

$$\mathcal{L}_{\text{effective}} = \frac{ef'}{2\gamma}\,[\psi'_{\mu\nu}F^{\mu\nu}\pi\,.\,\pi] \tag{2.4}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and is manifestly gauge invariant. The decay rate according to eq. (2.4) is

$$\Gamma(\psi' \to \pi\pi\gamma) = \frac{1}{4\pi}\left(\frac{ef'}{2\gamma}\right)^2 \cdot \frac{2m'}{3\pi^2}\,2\cdot 89\,(\text{Gev})^4$$

D. $\psi \to \pi\pi\gamma$. We proceed as in *C* to get

$$\Gamma(\psi \to \pi\pi\gamma) = \frac{1}{4\pi}\left(\frac{ef}{2\gamma}\right)^2 \cdot \frac{2m}{3\pi^2}\,1\cdot 26\,(\text{GeV})^4 \tag{2.5}$$

Using *A*, *B* and *C* we find *assuming that the* ψ-γ *vertex is a constant* and off-shell effects at the $\psi'\psi\pi\pi$ vertex can be ignored,

$$\Gamma(\psi' \to \pi\pi\gamma)/\Gamma(\psi' \to \psi\pi\pi) = 1\cdot 4 \times 10^{-2}$$

or

$$\frac{\Gamma(\psi' \to \pi\pi\gamma)}{\Gamma(\psi' \to \text{all})} \simeq 0\cdot 7\%.$$ We have taken

$$\Gamma(\psi' \to \psi\pi^0\pi^0) = \tfrac{1}{2}\,\Gamma(\psi' \to \psi\pi^+\pi^-).$$

Two qualifications are in order regarding the above calculation (1). We have ignored the contribution from ψ' pole in $\psi' \to \pi\pi\psi'$, followed by the conversion of ψ' into a photon. (There is no *a priori* reason for this amplitude to cancel the contribution from ψ pole that we have calculated. Specific models of ψ and ψ' like the bound charmed-quark pair model would suggest that they add rather than cancel) (2) We have ignored the constraints imposed by partial conservation of the axial vector current (PCAC) on the $\psi'\psi\pi\pi$ vertex. Subject to these caveats our calculations suggest that $\Gamma(\psi' \to \pi\pi\gamma)$ is between 1 to 3 keV if we take $\Gamma(\psi' \to \text{all}) = 225 \pm 56$ keV (Boyarski *et al.* 1975).

We can also estimate $\Gamma(\psi \to \pi\pi\gamma)$ if we make the reasonable assumption $f \simeq f'$ and proceed exactly as in the above calculation for $\psi' \to \pi\pi\gamma$. We get

$$\Gamma(\psi \to \pi\pi\gamma)/\Gamma(\psi' \to \psi\pi\pi) \simeq 0\cdot 51 \times 10^{-2}$$

or

$$\Gamma(\psi \to \pi\pi\gamma) \sim 1\text{ keV}.$$

E. $\psi' \to \eta + \gamma$ Because of the pseudoscalar nature of η, the matrix element has the form

$$M(\psi' \to \eta + \gamma) = g_\gamma \epsilon^{\mu\nu\lambda\sigma}\,\epsilon'_\mu \epsilon_\nu p_\lambda q_\sigma$$

where ϵ'_μ, p_λ are the polarization and momentum of ψ' and ϵ_ν and q_σ are those of the photon. PCAC for the η field and gauge invariance constraints are automatically and trivially satisfied in this case. Using the phenomenological $\psi'\psi\eta$ vertex given in eq. (2.1) and the dominance of ψ-pole as in $\psi' \to \pi\pi\gamma$ we can calculate the ratio $\Gamma(\psi' \to \eta + \gamma)/\Gamma(\psi' \to \psi + \eta)$ to get

$$\Gamma(\psi' \to \eta + \gamma)/\Gamma(\psi' \to \psi + \eta) = 0{\cdot}49$$

F. $\underline{\psi \to \eta + \gamma.}$ We can calculate

$$\Gamma(\psi \to \eta + \gamma)/\Gamma(\psi' \to \psi + \eta)$$

assuming the equality of the couplings $g_{\psi'\psi\eta} \simeq g_{\psi\psi\eta}$. The result is

$$\Gamma(\psi \to \eta + \gamma)/\Gamma(\psi' \to \psi + \eta) \simeq 0{\cdot}28.$$

If we take $\Gamma(\psi' \to \psi + \eta) \simeq 9$ keV as suggested by the values $\Gamma(\psi' \to \text{all}) = 225 \pm 56$ keV and $\Gamma(\psi' \to \psi + \eta)/\Gamma(\psi' \to \text{all}) = 4 \pm 2\%$ Boyarski *et al.* 1975] then our naive predictions are

$$\Gamma(\psi' \to \eta + \gamma) \simeq 4{\cdot}4 \text{ keV}$$

$$\Gamma(\psi \to \eta + \gamma) \simeq 2{\cdot}5 \text{ keV}$$

3. Comparison with experiment and conclusions

The only radiative decay mode that has been measured so far is (Wolf 1975)

$$\Gamma(\psi \to \eta + \gamma)/\Gamma(\psi \to e^+e^-) = 0{\cdot}07^{+0{\cdot}2}_{-0{\cdot}04}$$

Using the values $\Gamma(\psi' \to \psi + \eta) \simeq 9$ keV and $\Gamma(\psi \to e^+e^-) = 4{\cdot}8$ keV we can write

$$\frac{\Gamma(\psi \to \eta + \gamma)}{\Gamma(\psi' \to \psi + \eta)} \approx 0{\cdot}035.$$

In other words, our naive estimate using *constant* ψ - γ vertex, seems to be approximately an order of magnitude too high.

For the decay mode $\psi' \to \eta + \gamma$, the experimental upper limit is (Wolf 1975)

$$\frac{\Gamma(\psi' \to \eta + \gamma)}{\Gamma(\psi' \to e^+ e^-)} < 0{\cdot}4.$$

If we take $\Gamma(\psi' \to e^+e^-) \simeq 2{\cdot}2$ keV (Boyarski *et al.* 1975), we get

$$\frac{\Gamma(\psi' \to \eta + \gamma)}{\Gamma(\psi' \to \psi + \eta)} < 0{\cdot}09,$$

to be compared with the value 0·49 obtained in Sec. 2E.

The decay rate $\psi \to \pi\pi\gamma$ has not yet been measured. Disregarding for the moment our calculation in Section 2D we can estimate this decay rate alternatively as follows. The width $\Gamma(\psi \to \pi\pi\omega)$ has been measured (Boyarski *et al.* 1975) and is approximately 1 keV. Since off-shell effects aren ot expected to be large for the ω - γ vertex we can expect that $\Gamma(\psi \to \pi\pi\gamma)$ will be at least of the order of $e^2/4\pi$ $\Gamma(\psi \to \pi\pi\omega$

$\approx 0{\cdot}01$ keV. On the other hand " asymptotic freedom " arguments (Applequist and Politzer 1975) would suggest

$$\Gamma(\psi \to \text{hadrons} + \gamma)/\Gamma(\psi \to \text{hadrons})$$
$$= \Gamma(\psi \to 2\text{ gluons} + \gamma)/\Gamma(\psi \to 3\text{ gluons}) \approx 0{\cdot}12 \quad \text{if one uses}$$

$\alpha_s = \frac{g_s^2}{4\pi} \approx 0{\cdot}19$ for the quark-gluon coupling obtained from

$$\Gamma(\psi \to e^+e^-)/\Gamma(\psi \to \text{hadrons}).$$

This gives $\Gamma(\psi \to \gamma + \text{hadrons}) \approx 6$ keV. It is reasonable to expect that single exclusive channel like $\psi \to \pi\pi\gamma$ will have a width of at most a fraction of a keV. This is to be compared with our value of 1 keV for $\Gamma(\psi \to \pi\pi\gamma)$ in the last section.

In summary the assumption that the ψ - γ vertex has the same value independent of whether ψ is on mass shell or photon is on mass shell *systematically* overestimates the radiative decay rates by an order of magnitude.

The ψN total cross section is extracted from the photoproduction data using naive vector meson dominance model as follows. The experimental differential photoproduction cross section (ignoring the change in the coupling at the ψ - γ vertex) is related to the elastic ψN differential cross section by

$$\left(\frac{d\sigma}{dt}\right)^{\gamma N \to \psi N} = \left(\frac{d\sigma}{dt}\right)^{\psi N \to \psi N} \left(\frac{e}{2\gamma}\right)^2$$

Since experimentally the cross section is known to be diffractive in nature we can assume the forward scattering amplitude to be purely absorptive and relate it to the total cross section

$$\left(\frac{d\sigma}{dt}\right)_{t=0}^{\psi N \to \psi N} = [\sigma_T^{\psi N}]^2 \Big/ 16\pi.$$

Analysis of the experimental data (Barger 1975) gives $\sigma_T^{\psi N} \simeq 1$ mb. We have seen in our discussion of the radiative decays that the naive vector meson dominance overestimates the rates by an order of magnitude. Since photoproduction is like an inverse radiative decay process, the naive vector meson dominance model therefore underestimates the differential cross section for elastic ψN scattering. If the change in the ψ - γ vertex as ψ goes off-shell is the same as in radiative decays then the ψN total cross section is more like 3 or 4 mb instead of 1 mb.

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