A Light σ in $\omega \rightarrow \pi^+\pi^-\gamma$ Decay?

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Abstract

Trends in studies of the σ meson are briefly discussed, particularly those involving the radiative decay channel $\varphi \rightarrow \pi^+\pi^-\gamma$. The properties of this decay channel are compared with those of the decay $\omega \rightarrow \pi^+\pi^-\gamma$. Arguments are presented highlighting the prospect of finding a σ signature in ω decay. From these points, an experiment is proposed in which the existence of the σ resonance may be confirmed.

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One of the most controversial issues of meson spectroscopy today is the existence and properties of the σ meson. There continues to be a lack of experimental data on the subject, in spite of substantial progress in recent years by the CMD-2 and SND collaborations [1][2] in regards to the radiative decay $\varphi \rightarrow \pi\,\pi\,\gamma$. The E791 Collaboration has also made great strides in studying the decays $D_s^+ \rightarrow \pi^+\pi^-\pi^+$ [3] and $D^+ \rightarrow \pi^+\pi^-\pi^+$ [4], but these results will not be discussed in depth here.

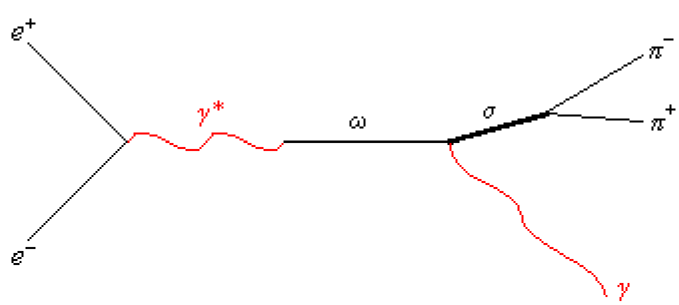
The decay $\varphi \rightarrow \pi^+\pi^-\gamma$, first observed by the CMD-2 Collaboration [1], is of particular interest. In the analysis of φ decays, $\varphi \rightarrow \pi^+\pi^-\gamma$ events were extracted from a background dominated by the decay $e^+e^- \rightarrow \varphi \rightarrow \pi^+\pi^-\pi^0$, the radiative decay $e^+e^- \rightarrow \mu^+\mu^-\gamma$, and the collinear events $e^+e^- \rightarrow \mu^+\mu^-$ and $\pi^+\pi^-$. Various cuts were applied to take into account the removal of cosmic ray background, Bhabha events, $K_S \rightarrow \pi^+\pi^-$ background, and spurious background from photons emitted by initial electrons [1]. On a volume of about 1.97×10^7 events, the results indicated a branching ratio of $B(\varphi \rightarrow \pi^+\pi^-\gamma) = (0.41 \pm 0.12 \pm 0.04) \times 10^{-4}$, as well as many properties of $f_0\,(980)$, but did not show any convincing signs of the presence of the σ meson. The SND Collaboration [2], in the PHI96 and PHI98 experiments, repeated this result by studying the decay $\varphi \rightarrow \pi^0\pi^0\gamma$. Not only did the σ meson take a back seat to $f_0\,(980)$, but it is practically non-existent in the data. This fact does establish one positive note in that the strangeness-saturated channel $\varphi \rightarrow \pi^+\pi^-\gamma$ does not readily produce the σ meson. This is somewhat helpful to know, as it confirms the theoretical supposition that σ is dominantly non-strange. In fact, the strangeness-poor channel $D^+ \rightarrow \pi^+\pi^-\pi^+$ showed a much more active role for the σ meson [4]. However, this channel is capable of producing many different resonances that may compete with σ, such as ρ and non-resonant $\pi^+\pi^-\pi^+$ [5].

Unfortunately, the decay channels mentioned here all have very small branching ratios and a number of competing intermediate resonances. These are also limited by very small signal statistics; for example, the PHI96 and PHI98 experiments altogether yielded a total of 419 ± 31 $\varphi \rightarrow \pi^0\pi^0\gamma$ events over the total volume [2]. Small branching ratios also result in a small cross-section. The Breit-Wigner cross-section can be related to the branching ratios for the entrance and exit channels, if the resonance is isolated and sufficiently narrow, by the relation;

$$1) \qquad \sigma_{BW}(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \left(\frac{\pi}{k^2}\right) \left(\frac{B_{in} B_{out} \Gamma_{tot}^2}{(E-E_R)^2 + \frac{\Gamma_{tot}^2}{4}} \right)$$

where J is the total spin of the resonance produced by particles of spins S_1 and S_2, k is the center-of-mass momentum, E_R is the resonance mass with E being the energy in the center-of-mass, B_{in} and B_{out} are the branching ratios of the entrance and exit channels respectively, and Γ_{tot} is the total width of the resonance. As the branching ratios for the channels $e^+e^- \to \varphi$ and $\varphi \to \pi^+\pi^-\gamma$ are in fact quite small, the resulting inherent lack of statistics continues to plague the studies involving the light scalars, and especially the σ meson.

In order to assure the proper observation of the σ signature, if it exists in any strength, the following conditions are necessary when selecting a potential decay channel to observe, according to the relations of equation 1); a) the branching ratios for the entry and exit channels for the decaying resonance should be as large as possible, b) the decaying resonance should be as light as possible in order to limit the number of intermediate resonances to as few as possible above the target resonance, and c) the decaying resonance must be as strangeness-poor as possible. With these conditions in mind, one may search for a decay resonance that adequately fits the characteristics that will enhance σ production through $V \to S\gamma$. As the σ meson is expected in the range of about 400 to 700 MeV in most light σ models, the decay of a particle in the range 700 to 900 MeV is ideal for excluding any interference from $f_0(980)$. As the φ meson is ideally $s\bar{s}$, the ω meson fits the conditions above beautifully. The target production and decay should proceed via the following Feynman diagram;

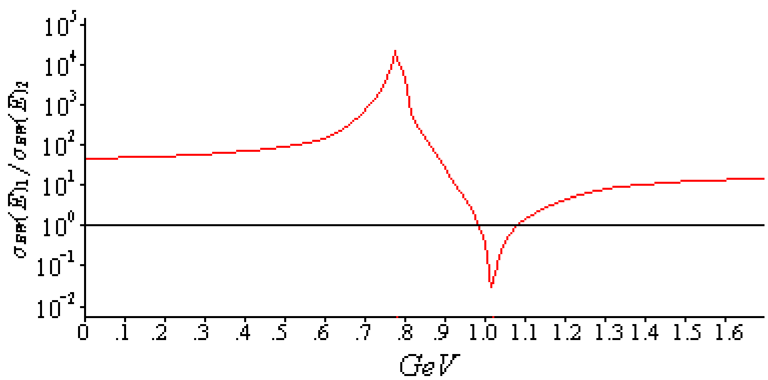


The non-resonant $\omega \to \pi^+\pi^-\gamma$ process will likely be the dominant contributor, forming the background to the target process.

The effectiveness of the channel $e^+e^- \rightarrow \omega \rightarrow \pi^+\pi^-\gamma$ compared to the more orthodox channel $e^+e^- \rightarrow \varphi \rightarrow \pi^+\pi^-\gamma$ can be characterized by the ratio $\sigma_{BW}(e^+e^- \rightarrow \omega \rightarrow \pi^+\pi^-\gamma)$ / $\sigma_{BW}(e^+e^- \rightarrow \varphi \rightarrow \pi^+\pi^-\gamma)$, which, following the form of equation 1), is equal to;

$$2)\qquad \frac{\sigma_{BW}(E)_1}{\sigma_{BW}(E)_2} = \frac{(B_{in}B_{out}\Gamma^2_{tot})_1\left((E-E_R)^2+\frac{\Gamma^2_{tot}}{4}\right)_1}{(B_{in}B_{out}\Gamma^2_{tot})_2\left((E-E_R)^2+\frac{\Gamma^2_{tot}}{4}\right)_2}$$

where the cross-section $\sigma_{BW}(E)_1$ represents $\sigma_{BW}(e^+e^- \rightarrow \omega \rightarrow \pi^+\pi^-\gamma)$, and the cross section $\sigma_{BW}(E)_2$ represents $\sigma_{BW}(e^+e^- \rightarrow \varphi \rightarrow \pi^+\pi^-\gamma)$. The solution for the ratio is energy dependent. Using the appropriate values established in [5] for the branching ratios and widths yield the following graph of the ratio function;



which shows that the ratio remains well above one for most possible center-of-mass energies. Of particular interest is the enhancement near the ω mass and the drop-off near the φ mass, due to the two different resonance energies used in equation 2). On average, the ratio is generally at or below 21:1, indicating that the effectiveness of the channel $e^+e^- \rightarrow \varphi \rightarrow \pi^+\pi^-\gamma$ is dwarfed by that of the channel $e^+e^- \rightarrow \omega \rightarrow \pi^+\pi^-\gamma$. This fact may warrant a serious investigation into the possibility of using a collider facility, such as SLAC at Stanford or DAΦNE at Frascati, as an ω factory.

Electron-positron annihilation at about 782 MeV should produce a significant number of $\omega \rightarrow \pi^+\pi^-\gamma$ events, highlighting the role of any possible σ meson. Nearly 90 times the signal statistics can be expected over the total volume as compared with the results of PHI96 and PHI98 [2]. Contributions from photo-produced pions can be eliminated by requiring the center-of-mass of the two-pion system to exceed 391 MeV. In order to rule out contributions from the C-parity violating process $\omega \rightarrow \rho\gamma$, if necessary, additional cuts may be applied requiring photon energy to exceed 40 MeV. Overall, the invariant-mass search range for the two-pion system may be limited to that between 391 MeV and 742 MeV. Other cuts may be used to isolate $e^+e^- \rightarrow \omega \rightarrow \pi^+\pi^-\gamma$ events from other background such as $e^+e^- \rightarrow \omega \rightarrow \pi^+\pi^-\pi^0$ and $e^+e^- \rightarrow \omega \rightarrow \mu^+\mu^-\gamma$. If such experiments are carried out, there is a strong possibility of determining the characteristics of the σ meson.

Update

The finding of a signature for the $\rho \to \sigma\gamma \to \pi\pi\gamma$ decay mode in [6] and [7] may serve to renew interest in these kinds of experiments, as well as to motivate others to explore the $V \to S\gamma$ family more vigorously at the low-energy end below 1 GeV, as demonstrated by the content of [8]. A more in-depth understanding of the role of $S \to \gamma\gamma$ is also coming to fruition, regarding how these decay channels can be used to determine the internal structure of the lightest neutral scalar mesons, with data beginning to reach more useful thresholds.

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