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SOME PROBLEMS OF MESON SPECTROSCOPY. POSSIBLE SOLUTIONS AT DAΦNE.

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ABSTRACT

The e^+e^- collider with luminosity of the order of 10^{32} - 10^{33} $cm^{-2}s^{-1}$ in the energy range $\sqrt{s}$ = 1-2 GeV is a very good facility to study hadron physics. We discuss here some problems of meson spectroscopy, namely the problem of radial and orbital vector meson exitations and their electromagnetic widths, the two particle decays of vector mesons and the level structure of P-wave meson multiplets. In the first two cases one can study the vector mesons produced in s-channel. In the last case the study of radiative decays of $\rho(1700)$ meson into P-wave states gives a possibility to discriminate between different candidates for P-wave multiplet members.

The study of light mesons gives information about QCD interactions at large distances in nonperturbative region. Unfortunately, this information comes in indirect form and has to be compared with different model predictions. Nevertheless the study of light meson level structure and their decays is very important for understanding of underlying quark-gluon dynamics.

1. VECTOR MESON EXCITATIONS.

At e^+e^- collider one can study the production of 1^{--} resonance with $I = 0$ and 1. In the energy interval up to 2 GeV there exist the ground state $\rho(770)$ $I = 1$ meson and the two excited states with the same quantum numbers: $\rho(1450)$ and $\rho(1700)$ mesons. In the constituent quark model $\rho(1450)$ can be described as the first radial excitation 2^3S_1 of the ground $^3S_1$ level and $\rho(1700)$ as an orbital $^3D_1$ excitation. In the sector of I = 0 mesons which do not decay predominantly into $K\overline{K}$ pairs there is the $\omega(783)$ ground state and the two excitations: $\omega(1390)$ and $\omega(1600)$. However, in the sector of I = 0 mesons which decay mainly into $K\overline{K}$ pair there is a ground state $\phi(1020)$ and only one excitation $\phi(1680)$. On the other hand three $^3D_3$ states for I = 1 and I = 0 mesons are known. They are $\rho_3(1690)$, $\omega_3(1670)$ and $\phi_3(1850)$ mesons. Note, that $^3D_1$ ρ and ω states have masses very close to ones of $^3D_3$ states. It seems naturally to expect the $^3D_1$ ϕ state in the region of $\phi_3(1850)$ meson. If it appears that all $^3D_1$ states including ϕ are approximately degenerated with $^3D_3$ states, that will be a strong argument for small splitting picture in high wave multiplets. We shall discuss this possibility in more details later.

The other problem of radial and orbital excitations which can be solved at e^+e^- collider is the problem of electronic widths of 1^{--} mesons. The measured electronic widths of ground states are $\Gamma[\rho(770) \to e^+e^-] = 6.77 \pm 0.32$ KeV, $\Gamma[\omega(783) \to e^+e^-] = 0.60 \pm 0.02$ KeV and $\Gamma[\phi(1020) \to e^+e^-] = 1.37 \pm 0.05$ KeV [1]. These data are in a good agreement with the ratios 9:1:2 which come from a $q\bar{q}$ structure of 1^{--} mesons with ideal mixing. The electronic widths of radial and orbital excitations should be in any case less than the widths of ground states. Moreover, this statement should be valid even out of the frame of $q\bar{q}$ model because any possible admixtures like glueballs, hybrids, 4q systems can only decrease the electronic widths of excited states. Now the electronic widths of excited 1^{--} mesons are known with a very poor accuracy. But even more important is that while for ρ and ϕ excited states the measured electronic widths are less than ground state electronic widths ($\Gamma[\rho(1450) \to e^+e^-] > 2.5$ KeV, $\Gamma[\rho(1700) \to e^+e^-] = 0.6 \div 3$ KeV and $\Gamma[\phi(1680) \to e^+e^-] = 0.5 \div 0.7$ KeV), for ω excitations the electronic width are much larger: $\Gamma[\omega(1390) \to e^+e^-]\, B[\omega(1390) \to \rho\,\pi] = 137 \pm 40$ KeV and $\Gamma[\omega(1600) \to e^+e^-]\, B[\omega(1600) \to \rho\,\pi] = 96 \pm 35$ KeV. Here $B(\omega \to \rho\,\pi)$ are the branching ratios of ω decays into $\rho\,\pi$ channel. The exact measurment of all electronic widths of excited vector mesons is very desirable, especially for ω states.

2. TWO-PARTICLE DECAYS.

The other important problem which can be solved at e^+e^- collider is the problem of mixing among 1^{--} excited states. One of the possible mechanisms of mixing between different $q\bar{q}$ mesons is the non-perturbative instanton-induced interaction [2]. This interaction is forbidden in 1^{--} channel and by this reason all 1^{--} mesons should be ideally mixed.

Let us consider the ratio:

$$R_\rho^{(1)} = \frac{\Gamma_{\rho' \to K\overline{K}}}{\Gamma_{\rho' \to \pi\pi}}, \qquad (1)$$

where ρ' is either $\rho(1450)$ or $\rho(1700)$ meson.

The SU(3) prediction for this ratio is equal to:

$$\overline{R}_\rho^{(1)} = \frac{1}{2}\left(\frac{p_K}{p_\pi}\right)^3, \qquad (2)$$

where p_K is the momentum of kaon in ρ' rest frame and p_π is the momentum of pion in the same frame. For $\rho(1450)$ $R_\rho^{(1)} = 0.21$ and for $\rho(1700)$ $R_\rho^{(1)} = 0.28$. The SU(3) violation diminishes the value of $R_\rho^{(1)}$, so the experimental values of $R_\rho^{(1)}$ larger than $R_\rho^{(1)}$ will contradict the $q\bar{q}$ content of ρ mesons.

The two other ratios that can be predicted in the frame of quark model are:

$$R_\rho^{(2)} = \frac{\Gamma_{\rho' \to \eta\rho}}{\Gamma_{\rho' \to \pi\omega}}, \qquad (3)$$

and

$$R_\rho^{(3)} = \frac{\Gamma_{\rho' \to K\overline{K}^* + \overline{K}K^*}}{\Gamma_{\rho' \to \pi\omega}}. \qquad (4)$$

The predicted values are equal to $R_\rho^{(2)} = 0.07$ or $R_\rho^{(2)} = 0.17$ and $R_\rho^{(3)} = 0.07$ or $R_\rho^{(3)} = 0.38$ for $\rho(1450)$ or $\rho(1700)$ mesons.

For ω mesons we can write the two ratios:

$$R_\omega^{(1)} = \frac{\Gamma_{\omega' \to \eta\omega}}{\Gamma_{\omega' \to \pi\rho}}, \qquad (5)$$

$$R_\omega^{(2)} = \frac{\Gamma_{\omega' \to K\overline{K}^* + \overline{K}K^*}}{\Gamma_{\omega' \to \pi\rho}}, \qquad (6)$$

with quark model predictions:

$$\overline{R}_\omega^{(1)} = \tfrac{1}{9}\left(\frac{p_\eta}{p_\pi}\right)^3, \qquad (7)$$

$$\overline{R}_\omega^{(2)} = \tfrac{1}{3}\left(\frac{p_K}{p_\pi}\right)^3. \qquad (8)$$

If ω' s were an SU(3) singlet (glueball), than instead of (7) and (8) we had:

$$\widetilde{R}_\omega^{(1)} = \tfrac{1}{3}\left(\frac{p_\eta}{p_\pi}\right)^3, \qquad (9)$$

$$\widetilde{R}_\omega^{(2)} = \tfrac{4}{3}\left(\frac{p_K}{p_\pi}\right)^3. \qquad (10)$$

Unfortunately the numerical values of R_ω's are rather small: $R_\omega^{(1)} = 0.1$ for $\omega(1390)$ and $R_\omega^{(1)} = 0.11$ for $\omega(1600)$, while $R_\omega^{(2)} = 6\ 10^{-4}$ and 0.09 respectvely.

In the case of ϕ mesons we have only one ratio:

$$R_\phi = \frac{\Gamma_{\phi' \to \eta\phi}}{\Gamma_{\phi' \to K\overline{K}^* + \overline{K}K^*}}, \qquad (11)$$

with two predictions

$$\overline{R}_\phi = \tfrac{1}{3}\left(\frac{p_\eta}{p_K}\right)^3 \qquad (12)$$

for $s\bar{s}$ ϕ state and

$$\tilde{R}_\phi = 1/4 \left(\frac{p_\eta}{p_K}\right)^3 \tag{13}$$

for SU(3) singlet state.

The values of R_ϕ are equal to 0.08 for $\phi(1680)$ and to 0.16 for possible $^3D_1$ state with mass about 1850 MeV.

3. SPLITTINGS IN P-WAVE MULTIPLETS.

Now we discuss the problem of splittings in P-wave multiplets.

In non-relativistic approach the energy levels of P-wave multiplet are splitted as follows:

$$\begin{aligned} M_2 &= M + 1/4 S + 1/5 T + L \\ M_1 &= M + 1/4 S + T - L \\ M_0 &= M + 1/4 S - 2T - 2L \\ M'_1 &= M - 3/4 S \end{aligned} \tag{14}$$

here M_J are the masses of ^3P_J states and M'_1 is the mass of a singlet $^1P_1$ state. M is the contribution of spin independent terms, S is the contribution of quark spin-spin interactions, L is the spin-orbit term and T is the contribution of tensor forces. Eq's (14) can be inverted:

$$\begin{aligned} S &= M_g - M'_1 \\ L &= 1/12(5M_2 - 3M_1 - 2M_0) \\ T &= 5/36(3M_1 - M_2 - 2M_0) \end{aligned} \tag{15}$$

where M_g is the mass of ^3P_J multiplet center of gravity:

$$M_g = M + 1/4 S = 1/9(5M_2 + 3M_1 + M_0) \tag{16}$$

Now consider the P-wave I = 1 multiplet. There are at least two possibilities to fill this multiplet: to consider $a_0(980)$ meson as $^3P_0$ state (A) and to consider as the same state $a_0(1320)$ meson (B). In the A case $a_0(1320)$ meson should be regarded as the radial excitation of $a_0(980)$; in the case B we need to have a non-$q\bar{q}$ explanation for $a_0(980)$. One possibility is to treat this meson as $K\bar{K}$ molecule [3,4]. The rest three members of P-wave multiplet are fixed. They are $a_2(1320)$, $a_1(1260)$ mesons and a singlet state $b_1(1235)$.

In the case A for S, L and T values we have approximately equal numbers: S = 92 MeV, L = 72 MeV and T = 69 MeV. In the case B we have large S = 130 MeV and small L and T terms of opposite signs: L = 15 MeV, T = - 25 MeV. The large value of S cannot be obtained in potential models with one-gluon exchange potential and in this case the non-perturbative forces should be essential even at small distances between quarks.

For I = 0 mesons which do not decay mainly into kaons there are two possibilities A and B again. Here we have $f_2(1270)$ as $^3P_2$ state, $f_1(1285)$ as $^3P_1$ state, $h_1(1170)$ as $^1P_1$ state and two candidates: $f_0(975)$ and $f_0(1400)$ for $^3P_0$ state. In the case A which corresponds to the choice of $f_0(975)$ as $^3P_0$ state we have the large values of S, L and T: S = 72 MeV, L = 45 MeV and T = 88 MeV. In the case B when $f_0(1400)$ is the $^3P_0$ state S is large (119 MeV), but L and T are small and negative: L = - 25 MeV and T = - 30 MeV. The negative sign of L may be due to great experimental uncertainity in the value of $f_0(1400)$ mass.

For the I = 1/2 multiplet of strange mesons the situation is different. As far as the $^3P_1$ and the $^1P_1$ states of this multiplet have no definite charge parity they can mix. In the simplest solution when low lying 1^+ $K_1(1270)$ meson is the $^1P_1$ state and the next 1^+ $K_1(1400)$ meson is the $^3P_1$ state we come to the solution of type B (S = 150 MeV, L = 7.5 MeV and T = - 12 MeV). The other members of this multiplet are fixed: $K_2(1430)$ is the $^3P_2$ state and $K_0(1430)$ is the $^3P_0$ state.

The situation with multiplet of I = 0 mesons which decay mainly into kaons is more complicated. Here are some possibilities to fill the multiplet. In any case the two states are fixed: $f_2(1525)$ meson is the $^3P_2$ state and $h_1(1380)$ meson is the $^1P_1$ state. If to choose $f_0(1240)$ meson as $^3P_0$ state and $f_1(1420)$ meson as $^3P_1$ state than we come to the type A solution (S = 78 MeV, L = 73 MeV, T = 35 MeV). Another choice of $^3P_0$ and $^3P_1$ candidates, namely $f_0(1525)$ and $f_1(1510)$ gives us the type B solution (S = 140 MeV, L = 4 MeV, T = - 6 MeV).

High luminosity e^+e^- collider with invariant energy up to 1.7 GeV can resolve this ambiguity experimentally.

4. RADIATIVE VECTOR MESON DECAYS.

The P-wave states can be produced at e^+e^- collider in radiative decays of 1^{--} mesons. Consider the decays of $\rho(1700)$ meson into triplet P-wave states. They are caused by the electric dipole transition and the ratio:

$$R = \frac{\Gamma_{\rho(1700)\ \to f_0\gamma}}{\Gamma_{\rho(1700)\ \to f_2\gamma}} \qquad (17)$$

does not depend on the transition matrix element. Here f_2 meson is the $f_2(1270)$ meson. In the case A the f_0 state is $f_0(975)$ meson and

$$R_{f_0(975)} = \frac{\Gamma_{\rho(1700) \to f_0(975)\,\gamma}}{\Gamma_{\rho(1700) \to f_2(1270)\,\gamma}} = {}^1\!/_5\left(\frac{\omega_0}{\omega_2}\right)^3 = .7 \quad , \qquad (18)$$

where ω_0 and ω_2 are the photon energies.

In this case the ratio of radiative decay into $f_0(1400)$ meson is equal to:

$$R_{f_0(1400)} = \frac{\Gamma_{\rho(1700) \to f_0(1400)\,\gamma}}{\Gamma_{\rho(1700) \to f_2(1270)\,\gamma}} = {}^C\!/_5\left(\frac{\omega_0}{\omega_2}\right)^3 = 0.08C \quad , \qquad (19)$$

where C is the suppression factor for $^3D_1 \to 2^3P_0$ transition with respect to $^3D_1 \to 1^3P_0$ transition. It may be expected to be less than 1/10 so in the case A $R_{f0(975)}$ should be at least two order of magnitude higher than $R_{f0(1400)}$.

In the opposite case B if $f_0(1400)$ meson is regarded as 1^3P_0 state, $R_{f_0(1400)} = 0.4$ while $R_{f_0(975)}$ is supressed. In this case $f_0(975)$ is non-$q\bar{q}$ state and the radiative transition into this state is very small.

Similar ratios can be written for radiative transitions of $\rho(1700)$ resonance into isovector mesons:

$$R_{a_0(980)} = \frac{\Gamma_{\rho(1700) \to a_0(980)\,\gamma}}{\Gamma_{\rho(1700) \to a_2(1320)\,\gamma}} \tag{20}$$

and

$$R_{a_0(1320)} = \frac{\Gamma_{\rho(1700) \to a_0(1320)\,\gamma}}{\Gamma_{\rho(1700) \to a_2(1320)\,\gamma}} \,. \tag{21}$$

The two possibilities A and B in the case of $I = 1$ mesons lead to the same predictions as for $I = 0$ mesons.

To clarify the situation with $s\bar{s}$ states it is necessary to study the radiative decays of *$\phi(1680)$* meson into scalar, axial and tensor states, namely to measure the ratios:

$$R_{f_0} = \frac{\Gamma_{\phi(1680) \to f_0\,\gamma}}{\Gamma_{\phi(1680) \to f_2(1525)\,\gamma}} \,, \tag{22}$$

where f_0 is either $f_0(1240)$ or $f_0(1525)$ meson and

$$R_{f_1} = \frac{\Gamma_{\phi(1680) \to f_1\,\gamma}}{\Gamma_{\phi(1680) \to f_2(1525)\,\gamma}} \,, \tag{23}$$

where f_1 is either $f_1(1420)$ or $f_1(1510)$ meson.

To estimate the branching ratio of isovector radiative decay $\rho(1700) \to f_2(1270)\,\gamma$ we may use the experimental width of $\omega \to \pi\,\gamma$ decay which is equal to 720 ± 40 KeV:

$$\Gamma_{\rho(1700) \to f_2(1270)\,\gamma} = 5k\,\Gamma_{\omega \to \pi\,\gamma}\left(\frac{\omega_2}{\omega_0}\right)^3 , \tag{24}$$

where ω_2 is the photon energy in $\rho(1700) \to f_2(1270)\,\gamma$ decay and ω_0 is the photon energy in $\omega \to \pi\,\gamma$ decay. Here k is the ratio of the squared matrix element of $1^3D_1 \to 1^3P_2$ transition with respect to squared matrix element of $1^3S_1 \to 1^1S_0$ transition. The value of k is model dependent. We may estimate the value of k for $1^3P_2 \to 1^1S_0$ and $1^1P_1 \to 1^1S_0$ transitions from experimental data on $a_2(1320) \to \pi\,\gamma$ and $b_1(1235) \to \pi\,\gamma$ decays. In both these cases k is approximately equal to 0.7. In our case k should be smaller and we put it equal to 0.1. Than we obtain $\Gamma_{\rho(1700) \to f_2(1270)\,\gamma} = 350$ KeV. The total width of $\rho(1700)$ meson is equal to 235 MeV and we come to the branching ratio $B_{\rho(1700) \to f_2(1270)\,\gamma} = 1.5\ 10^{-3}$ and $B_{\rho(1700) \to a_2(1320)\,\gamma} = 1.5\ 10^{-4}$. With this value of k and at the lumonisity of e^+e^- collider equal to $10^{31}\ cm^{-2}s^{-1}$ we shall have about 25000 events per year of $\rho(1700) \to f_2(1270)\,\gamma$ decays and about 2500 events of $\rho(1700) \to a_2(1320)\,\gamma$ decays.

Because of small branching ratios of radiative decays it is necessary to detect not only the photon from radiative transition but also the final state of P-wave meson decay. The most reliable way to determine the mass and quantum numbers of decaying P-wave state is to detect the two-particle decay mode.

Let us discuss briefly possible two-particle decay modes. For $I = 0$ non-$s\bar{s}$ 2^{++} and 0^{++} mesons the largest two-particle mode is the $\pi^+\pi^-$ mode. The branching ratio of decay into $\pi^0\pi^0$ mode is equal to $1/2$ of $\pi^+\pi^-$ branching ratio and for $f_2(1270)$ and $f_0(1400)$ mesons is about 30%. In the case of $I = 1$ mesons the $K\overline{K}$ and $\pi^0\eta$ modes are rather large but $\pi^0\eta$ channel is specific for a_2 and a_0 decays. For $a_2(1320)$ meson $B_{a_2(1320)\to\pi^0\eta}$ is equal to 14.5%. The $I = 0$ 2^{++} and 0^{++} $s\bar{s}$ mesons have $\eta\eta$ decay mode. For $f_2(1525)$ $B_{f_2(1525)\to\eta\eta} = 28\%$.

So we see that for all 2^{++} and 0^{++} mesons under consideration there are significant branching ratios for decays into neutral particles ($\pi^0\pi^0$, $\pi^0\eta$, $\eta\eta$). Using a photon detector with high resolution one can detect both the photon emitted in radiative decay and the photons from π^0 and η decays. A TPC liquid Xenon calorimeter or a detector of Crystall Barrel type seem to be appropriate detectors for the solution of P-wave multiplet 0^{++} component problem.

We did not discuss here the problem of backgrounds which is very essential for this type of experiment. Another problem which should be solved is the problem of the more accurate theoretical estimation of the constants C and k. The constant k is very essential because the number of events at given luminosity is proportional to k. The exact value of C is not so essential because even at $C = 1$ the predicted large difference in radiative decay widths into $f_0(975)$ and $f_0(1400)$ mesons allows to discriminate between the perturbative and non-perturbative type solutions.

To conclude with we would like to stress that e^+e^- collider with high luminosity together with high resolution neutral particle calorimeter may solve not only the problem of P-wave multiplets.

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