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ELECTROMAGNETIC DECAYS OF $X^0(960)$ AND $E(1420)$ MESONS

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The electromagnetic decays of the X^0 (960) and E (1420) mesons are studied. Decays with Dalitz pair production are analysed in detail.

1. *Introduction*

There are two main candidates, the X^0 (960) and the E(1420) mesons, at present, for the ninth pseudoscalar meson [1, 2]. The spin-parity of the X^0(960) meson has not been yet firmly established, and of the two possible hypotheses $J^P(X^0) = 0^-$ and 2^-, the latter is even more preferable than the former [2]. On the other hand, the alternative hypothesis for the E(1420) meson spin-parity is $J^P(E) = 1^+$. In the paper [3] an estimation for the $E \to 2\gamma$ decay probability has been obtained assuming $E-\eta$ mixing. The importance of the experimental study of this process is emphasized as the detection of the $E \to 2\gamma$ decay would unambiguously solve the problem of the E(1420) meson spin-parity in favour of the 0^- hypothesis and completely exclude the other possible 1^+ hypothesis.

The interst in the experimental investigation of the $X^0 \to 2\gamma$ [4, 5] has recently increased. The experimental study of the E(1420) radiative decay may appear to be very interesting, since, according to the available estimations [3], the branching ratios for these decays are not small.

In this paper we shall mainly consider the rare radiative decays of the X^0 and E mesons with Dalitz pair production. In cases when it makes sense, the possibility of determining the spin-parity of the X^0 and E mesons by their radiative decay will be emphasized.

2. *The radiative decays of the X^0(960) meson*

1. The $X^0 \to \varrho e^+ e^-$ decay

For the $J^P(X^0) = 0^-$ hypothesis, the formula for the width of the $X^0 \to \varrho\gamma$ decay is well known:

$$\Gamma(X^0 \to \varrho\gamma) = |g_{x\varrho\gamma}|^2 \frac{(M_x^2 - M_\varrho^2)^3}{32\pi M_x^3}, \tag{1}$$

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where $g_{X\varrho\gamma}$ is determined by the matrix element of the $X^0 \to \varrho\gamma$ decay:

$$M_{0^-}(X^0 \to \varrho\gamma) = \frac{g_{X\varrho\gamma}}{4}\,\varphi(Q)\tilde{\mathscr{F}}_{\mu\nu}(\Delta)\varrho_{\mu\nu}(q). \tag{2}$$

Assuming that the form factor $g_{X\varrho\gamma}(\Delta^2)$, where $\Delta^2 = (p_{e^+}+p_{e^-})^2$, is a constant [6, 7] at small energy separation ($\sim$ 200 MeV), it will be easy to calculate the conversion coefficient $K = \Gamma(X^0 \to \varrho e^+e^-)/\Gamma(X^0 \to \varrho\gamma)$ and the Dalitz plot distribution for the $X^0 \to \varrho e^+e^-$ decay with an accuracy to $\Delta^2/M_X^2 < 1/25$, $(4m_e^2 \leqslant \Delta^2 \leqslant (M_X - M_\varrho)^2)$:

$$K = \frac{\Gamma(X^0 \to \varrho e^+e^-)}{\Gamma(X^0 \to \varrho\gamma)} = \frac{\alpha}{3\pi}\left(2\ln\frac{Mx - M_\varrho}{m_e} - 3,4\right) \approx \frac{1}{150}. \tag{3}$$

$$dW = \frac{\alpha M_X}{(2\pi)^2}\,|\,g_{X\varrho\gamma}(\Delta^2)|^2\left\{(\Delta^2+2m_e^2)\,[(E_1+E_2)^2-\Delta^2]+\right.$$

$$\left.+\Delta^2\left(\frac{\Delta^2}{2}-2E_1E_2\right)\right\}\frac{dE_1dE_2}{\Delta^4}. \tag{4}$$

Here $E_1(E_2)$ is the electron (positron) energy in the X^0 meson rest frame and $\Delta^2 = 2M_X(E_1 + +E_2) + M_\varrho^2 - M_X^2$.

As the energy separation is small, the hypothesis 0^- cannot be distinguished from 2^- for the $X^0(960)$ spin-parity by means of the magnitude of the conversion coefficient K and the Dalitz plot for the $X^0 \to \varrho e^+e^-$ decay [8]. One can show that the conversion coefficient and the Dalitz plot distribution for the $X^0 \to \varrho\, e^+e^-$ in the case of $J^P(X^0) = 2^-$ coincide within an accuracy up to the terms $\Delta^2/M_X^2 < 1/25$ with the formulae (3) and (4) obtained on the assumption that the X^0 meson is pseudoscalar.

However, the study of the correlation between the relative momentum of pions from the ϱ^0 meson decay and the momenta of e^+e^- pair in the ϱ^0 meson rest frame allows one to distinguish between hypotheses 0^- and 2^- for X^0 (960).

For the alternative $J^P(X^0) = 0^-$ the dependence of the distribution of the decay pions on the angle of emission is sharply expressed

$$W(\theta, \varphi, \gamma) = \left[\frac{\Delta^2}{2} - 2\,\vec{p}_+\sin^2\theta\sin^2\varphi\right]\sin^2\gamma, \tag{5}$$

where θ is the angle between the directions of the positron momentum $\vec{p}_+$ and the X^0 meson momentum $\vec{k}$ in ϱ^0 rest frame, γ is the angle between the directions of the X^0 and the π^+ in the same frame, and φ is the angle between the planes formed by the vectors $(\vec{k}\vec{p})$ and $(\vec{k}\vec{q})$.

A good agreement of the experimental data on the $X^0 \to \varrho\gamma$ decay with the $J^P(X^0) = 2^-$ hypothesis is achieved with the help of a simple matrix element [1,2]

$$M_{2^-}(X^0 \to \varrho\gamma) = g_1 T_{\mu\nu}(Q)\,\tilde{\mathscr{F}}_{\mu\lambda}(\Delta)\,\varrho_{\lambda\nu}(q). \tag{6}$$

The distribution $W(\theta, \varphi, \gamma)$ calculated using this matrix element, has the form

$$W(\theta\varphi\gamma) = \tfrac{1}{2}(\Delta^2 - 2\vec{p}^2 \sin^2\theta) + \tfrac{1}{6}\frac{2M_\varrho^2 - M_X^2}{M_X^2}\sin^2\gamma\left[\frac{\Delta^2}{2} - 2\vec{p}^2\sin^2\theta\sin^2\varphi\right] -$$

$$-\Delta^2\frac{M_X^2 + M_\varrho^2}{2M_X^2}\cos\gamma\left[\left(\frac{M_X^2 - M_\varrho^2}{2M_\varrho^2} - \frac{|\vec{p}|}{M_\varrho}\right)\cos\gamma + \frac{2p_0 - \Delta_0}{|\vec{\Delta}|}\frac{|\vec{p}|}{M_\varrho}\cos\psi\right],$$

$$\cos\psi = \cos\theta\cos\gamma + \sin\theta\sin\gamma\cos\varphi,$$

and depends weakly on the angles φ and γ. Thus, the stude of the $X^0 \to \varrho e^+e^-$ decay in case of sufficient statistics allows one to distinguish between the hypotheses 0^- and 2^- for the spin-parity of $X^0(960)$ meson.

3. The $X^0 \to \gamma e^+e^-$, $X^0 \to e^+e^-$ and $X^0 \to \pi^+\pi^-\pi^0$ decays

The $X^0 \to \gamma\gamma$ decay has been experimentally studied in the reactions $\pi^-p \to nX^0 \to 2\gamma n$ [4] and $\pi^+d \to p(p) + 2\gamma$ [5]. The averaged branching ratio for this decay is $\Gamma(X^0 \to 2\gamma) = 9{,}9^{+4{,}4}_{-3{,}9}\%$. The conversion coefficient $K_2 = \Gamma(X^0 \to e^+e^-\gamma)/\Gamma(X^0 \to \gamma\gamma)$ estimated by the Dalitz formula [6] on the assumption that X^0 meson is pseudoscalar, is equal to about 1/50. In this case, however, because the energy separation is great, the form factor $g_{X\varrho\gamma}(\Delta^2)$ must be taken into account. We have estimated the conversion coefficient in the vector dominance model. For the vertices $g_{X\varrho\gamma}$, $g_{X\omega\gamma}$, $g_{X\psi\gamma}$ we have used the relations of SU (3) and $SU_w(6)$ symmetries. The ratio $\Gamma(X^0 \to \gamma e^+e^-)/\Gamma(X^0 \to \varrho\gamma)$ has appeared to be equal to $1{,}6 \times 10^{-3}$ while the relative decay probability $\Gamma(X^0 \to \gamma e^+e^-)/\Gamma(X^0 \to \text{all}) \approx 0.5 \times 10^{-3}$.

For the two possible hypotheses $J^P(X^0) = 0^-$ and 2^-, the $X^0 \to e^+e^-$ decay is suppressed by a factor of $\left(\frac{m_e}{m_X}\right)^2 \approx 10^{-6}$ since $CP(X^0) = -1$ [9].

If $J^P(X^0) = 2^-$, then the strong decay $X^0 \to \eta\, 2\pi$ is suppressed because of the centrifugal barrier, and the relative contribution of the radiative decay modes must be great [2]. This qualitative remark is in agreement with the experimental values: $\Gamma(X^0 \to \varrho\gamma)/\Gamma(X^0 \to \text{all}) \sim 30\%$, $\Gamma(X^0 \to \gamma\gamma)/\Gamma(X^0 \to \text{all}) \sim 10\%$. In this case the probability of the electromagnetic decay $X^0 \to \pi^+\pi^-\pi^0$ may also appear not to be small (about some per cent). The experimental observation and the study of the Dalitz plot of the electromagnetic decay $X^0 \to \pi^+\pi^-\pi^0$ would help to clarify the question concerning the X^0 meson spin as had been achieved earlier, when some arguments in favour of the pseudoscalar η-meson were obtained with the aid of the decay $\eta \to \pi^+\pi^-\pi^0$.

4. The radiative decays of E (1420) meson

1. The decays $E \to 2\gamma$, $E \to \varrho\gamma$

As to the existing alternative spin value for $E(1420)$, it is very important to study the radiative decays $E \to 2\gamma$, $E \to \varrho\gamma$, *etc.*

The probability of the decay $E \to 2\gamma$, estimated on the assumption about the E-η mixing with mixing angle equal to $-6.5°$ [3], is great: $\Gamma(E \to 2\gamma) \sim$ (300–1000) keV and $\Gamma(E \to \varrho\gamma) \sim 10$ MeV. These circumstances are in favour of the experimental search for

E-meson radiative decays. The detection of the decay $E \to 2\gamma$ would definitively prove that E(1420) is pseudoscalar and would completely exclude the other possible value $J^P(E) = 1^+$.

The detection of the decay $E \to \varrho\gamma$ and the investigation of its distribution with respect to the angle θ between the relative momentum of the pions and the γ quantum momentum in ϱ meson rest frame is of interest. If $J^P(E) = 0^-$, then $W(\theta) \sim \sin^2\theta$. The deviation from the distribution $\sin^2\theta$ is incompatible with the pseudoscalarity of E(1420) meson. For the hypothesis $J^P(E) = 1^+$, the amplitude of the transition M_1 leads to the distribution $W(\theta) \sim 1+\cos^2\theta$ while the simple relativistic matrix element $T = gb_\mu(\varrho)\tilde{\mathscr{F}}_{\mu\nu}\varrho_\nu(q)$ (b_μ and ϱ_ν are the polarization of E and ϱ mesons, respectively) gives

$$W(\theta) \sim 1+\cos^2\theta - \frac{(M_E^2 - M_\varrho^2)}{M_E^2}\sin^2\theta \sim \cos^2\theta.$$

2. The decays $E \to \varrho e^+e^-$, $E \to \gamma\, e^+e^-$ and $E \to e^+e^-$

If E(1420) is pseudoscalar, then the conversion coefficient $K = \Gamma(E \to \varrho\, e^+e^-)/\Gamma(E \to \varrho\gamma)$ estimated by a formula analogous to (3), is equal to 1/115. Any deviation of the distribution $W(\theta\varphi\gamma)$ for the decay $E \to \varrho e^+e^-$ from the distribution given by the formula (5) shows an evidence for $J^P(E) = 1^+$.

For the decay $E \to \gamma e^+e^-$, the Dalitz formula [6] leads to $K_3 = \Gamma(E \to \gamma e^+e^-)/\Gamma(E \to \gamma\gamma) = 1/45$ while the vector dominance model gives $K_4 = \Gamma(E \to \gamma e^+e^-)/\Gamma(E \to \varrho\gamma) = 3{,}5 \times 10^{-4}$.

For the alternative $J^P(E) = 0^-$ the decay $E \to e^+e^-$ is suppressed by a factor $(m_e/M_E)^2 \sim 10^{-7}$ due to helicity conservation. The detection of the decay $E \to e^+e^-$, therefore, would show evidence for $J^P(E) = 1^+$.

3. M° (953) meson

An evidence [10] for the existence of a new M^0 (953) resonance decaying into $\eta\pi^-\pi^+$ and $\pi^+\pi^-\gamma$ has been recently obtained in the reaction $K^-p \to K^-pM^\circ$. The difference between M^0(953) and X^0(960) is that the $\pi^+\pi^-$ effective mass distribution in the decay $M^0 \to \pi^+\pi^-\gamma$ is isotropic. The possible existence of the M^0(953) requires a more careful analysis of the final $\pi\pi\gamma$ state [1].

The suggested explanation of this fact [11] accepts that $T^G J^P(M) = 0^+1^+$ and the decay $M^0 \to \varrho\gamma$ is suppressed in the vector dominance model. This explanation is incorrect since in this case the vector dominance model does not limit the number of the spin amplitudes.

Now, the most essential are the questions about the isospin and the C-parity of the new resonance. Since the decay $M \to \eta\pi^+\pi^-$ was observed, than $G(M) = 1$ with a high probability. As the pion effective mass distribution is isotropic, then it will be more natural to make the assumption that $C(M) = -1$ and $T(M) = 1$. In this case the detection of the decay $M^0 \to 2\pi^0\gamma$ and the search for M(953) in the reaction $K^-\varrho \to K^0pM^-$ are important.

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