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The Spin-Parity Determination of the Boson Resonance X in the Process $J/\psi \to V_1 + X, X \to \gamma + V_2$

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The angular distribution for the process of $J/\psi \to V_1 + X$, $X \to \gamma + V_2$, $V_2 \to 2P$ or $3P$ (where V_1 and V_2 stand for the vector mesons, P is a pseudoscalar meson) are presented. They can be used to determine the spin of the boson resonance X and its parity in some special cases.

In the last ten years, a search for and determination of new hadronic states, including glueballs, hybrids and four quark states, has become one of the important research directions in theoretical and experimental particle physics.

According to the perturbative QCD calculation, the J/ψ radiative decay

$$e^+ + e^- \to J/\psi \to \gamma + X \tag{1}$$

is a very ideal process to search for the glueball (gg) while the J/ψ hadronic decay process

$$e^+ + e^- \to J/\psi \to M + X \tag{2}$$

(here M represents a meson) is favorable to the production hybrids. Therefore, the study of processes (1) and (2) are very important.

Experimentally, some possible new hadronic states, such as the ι/η (1440), $\theta/f_2(1720)/f_0(1710)$

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and $\xi(2230)$ [1], have been discovered from process (1). Their production and decay properties show that they (especially, the $\iota(1440)$ and $\theta(1720)$) do not like general $q\bar{q}$ mesons, perhaps they are the glueball candidates [2]. Of cause, other possibilities for these new hadrons cannot be ruled out [3].

To further study the characteristics of these new hadrons, in [4] we discussed the double radiative decay process of the J/ψ,

$$
\begin{aligned}
&e^+ + e^- \to J/\psi \to \gamma + X \\
&\qquad\qquad\qquad\qquad\quad \llcorner\!\!\longrightarrow \gamma + V \\
&\qquad\qquad\qquad\qquad\qquad\qquad \llcorner\!\!\longrightarrow 2P\,(\text{or } 3P)
\end{aligned}
\tag{3}
$$

(where P and V represent the pseudoscalar and vector mesons, respectively), and presented the corresponding angular distribution formulas and the expressions of moments. The results show that by using these angular distribution formulas we can distinguish effectively the spin 0 boson resonance X from or 2. However, due to the parity P of the boson resonance X do not appear in these angular distribution formulas, we cannot expect to determine the parity of the boson resonance in terms of process (3).

In this paper we discuss the J/ψ hadronic decay process

$$
\begin{aligned}
&e^+ + e^- \to J/\psi \to V_1 + X \\
&\qquad\qquad\qquad\qquad\quad \llcorner\!\!\longrightarrow \gamma + V_2 \\
&\qquad\qquad\qquad\qquad\qquad\qquad \llcorner\!\!\longrightarrow 2P\,(\text{or } 3P)
\end{aligned}
\tag{4}
$$

(here V_1 and V_2 stand for the vector mesons), present the corresponding angular distribution formulas, and show how to distinguish the spins of the boson resonance X and determine the parity P by using these formulas.

In what follows we will continue to adopt the notations used in [4], except those indicated specially. Similar to [4], we obtain the following angular distribution for process (4):

$$
\begin{aligned}
W_{J^P}(\theta_V, \theta, \phi, \theta_1, \phi_1) \sim &\sum_{\lambda_X, \lambda'_V, \lambda_V, \lambda'_V} I_{\lambda_J, \lambda'_J}(\theta_V) A_{\lambda_1, \lambda_X} \\
&A^*_{\lambda'_1, \lambda'_X} B^J_{\lambda_\gamma, \lambda_V} B^{J*}_{\lambda_\gamma, \lambda'_V} D^{J*}_{-\lambda_X, \lambda_\gamma - \lambda_V}(\phi, \theta, -\phi) \\
&D^J_{-\lambda'_X, \lambda_\gamma - \lambda'_V}(\phi, \theta, -\phi) D^{1*}_{\lambda_V, 0}(\phi_1, \theta_1, 0) D^1_{\lambda'_V, 0}(\phi_1, \theta_1, 0),
\end{aligned}
\tag{5}
$$

where we have chosen the helicity frame in which the J/ψ is at rest and the moving direction of V_1 is taken as the z axis. θ_V is the angle between incident positron momentum $\boldsymbol{P}_+$ and the moving direction of V_1. λ_1, λ_γ, λ_X, λ_V and λ_J are the helicities of the vector meson V_1, photon γ, boson X, vector meson V_2 and the J/ψ, respectively. They obey the helicity conservation relation:

$$
\lambda_J = \lambda_1 - \lambda_X. \tag{6}
$$

Due to the parity conservation the helicity amplitudes A_{λ_1, λ_X} and $B^J_{\lambda_\gamma, \lambda_V}$ satisfy the following symmetry relations:

$$
A_{\lambda_1, \lambda_X} = P(-1)^J A_{-\lambda_1, -\lambda_X}, \quad B^J_{\lambda_\gamma, \lambda_V} = P(-1)^J B^J_{-\lambda_\gamma, -\lambda_V}, \tag{7}
$$

where J and P are the spin and parity of the boson resonance X, respectively. If $J = 0$, there are two independent helicity amplitudes $A_{1,0}$ and $A_{0,0}$ for the process of $J/\psi \to V + X$ and there is only one independent helicity amplitude $B^0_{1,1}$ for the radiative decay process of X, $X \to \gamma + V$. From Eq. (5) we have the normalized angular distribution for $J = 0$:

$$\overline{W}_0^{\,P}(\theta_V,\theta,\phi,\theta_1,\phi_1) = \frac{9}{128\pi^2}\frac{1}{2+z_1^2}\{1+\cos^2\theta_V + z_1^2\sin^2\theta_V\}\sin^2\theta_1, \tag{8}$$

where we have defined

$$z_1 e^{i\phi_z} = \frac{A_{0,0}}{A_{1,0}}. \tag{9}$$

The characteristic of angular distribution (8) is that it depends only on θ_V and θ_1 and is independent of θ, ϕ and ϕ_1. From Eq. (8) we obtain the following normalized projective angular distributions:

$$\overline{W}_0^{\,P}(\theta_V) = \frac{3}{4(2+z_1^2)}\{1+\cos^2\theta_V + z_1^2\sin^2\theta_V\}; \tag{10}$$

$$\overline{W}_0^{\,P}(\theta_1) = \frac{3}{4}\sin^2\theta_1. \tag{11}$$

When $J = 1$, there are four independent helicity amplitudes: $A_{1,0}$, $A_{1,1}$, $A_{0,0}$, and $A_{0,1}$ for the process of $J/\psi \to V + X$ and there are two independent helicity amplitudes $B_{1,0}$ and $B_{1,1}$ for the process of $X \to \gamma + V$. Define

$$z_2 e^{i\phi_z} = \frac{A_{0,1}}{A_{1,0}}, \tag{12}$$

we obtain the normalized angular distribution for process (4):

$$\overline{W}_1^{\,P}(\theta_V,\theta,\phi,\theta_1,\phi_1) = \frac{1}{N_1}\{(1+\cos^2\theta_V)\,\mathrm{I} + \sin^2\theta_V\,\mathrm{II} + \sin 2\theta_V\,\mathrm{III}\}, \tag{13}$$

where

$$\begin{aligned}
\mathrm{I} = {} & 2\cos^2\theta\sin^2\theta_1 + 2\xi^2\sin^2\theta\cos^2\theta_1 \\
& - \xi\sin 2\theta\sin 2\theta_1\cos(\phi+\phi_1)\cos\phi_\xi \\
& + z_2^2\sin^2\theta\sin^2\theta_1 + z_2^2\xi^2(1+\cos^2\theta)\cos^2\theta_1 \\
& + \frac{1}{2}z_2^2\xi\sin 2\theta\sin 2\theta_1\cos(\phi+\phi_1)\cos\phi_\xi; \\
\mathrm{II} = {} & 2x^2\sin^2\theta\sin^2\theta_1 + 2x^2\xi^2(1+\cos^2\theta)\cos^2\theta_1 \\
& + 2z_1^2(\cos^2\theta\sin^2\theta_1 + \xi^2\sin^2\theta\cos^2\theta_1) \\
& + (x^2 - z_1^2)\xi\sin 2\theta\sin 2\theta_1\cos(\phi+\phi_1)\cos\phi_\xi \\
& + \mathrm{P}z_2^2\sin^2\theta(\sin^2\theta_1 - \xi^2\cos^2\theta_1)\cos 2\phi \\
& + \mathrm{P}z_2^2\xi\sin\theta\sin 2\theta_1[\sin 2\phi\sin(\phi+\phi_1) \\
& \qquad + \cos 2\phi\cos(\phi+\phi_1)\cos\theta]\cos\phi_\xi;
\end{aligned}$$

$$
\begin{aligned}
\text{III} = & x\sin 2\theta(\sin^2\theta_1 - \xi^2\cos^2\theta_1)\cos\phi\cos\phi_\xi \\
& - x\xi\sin^2\theta\sin 2\theta_1\cos\phi\cos(\phi+\phi_1)\cos(\phi_x - \phi_\xi) \\
& - \frac{1}{2}x\xi\cos\theta[(1-\cos\theta)\cos(2\phi+\phi_1) - (1+\cos\theta)\cos\phi_1]\sin 2\theta_1\cos(\phi_x+\phi_\xi) \\
& - z_1z_2(\sin^2\theta_1 - \xi^2\cos^2\theta_1)\sin 2\theta\cos\phi\cos(\phi_z - \phi'_z) \\
& + \frac{1}{2}z_1z_2\xi\sin^2\theta\sin 2\theta_1(\cos\phi_1 + \cos(2\phi+\phi_1))\cos(\phi_z - \phi'_z + \phi_\xi) \\
& + \frac{1}{2}z_1z_2\xi\cos\theta\sin 2\theta_1[(1-\cos\theta)\cos(2\phi+\phi_1) \\
& \quad - (1+\cos\theta)\cos\phi_1]\cos(\phi_z - \phi'_z - \phi_\xi),
\end{aligned}
$$

and the normalization constant

$$N_1 = \frac{512\pi^2}{27}(1+\xi^2)(1+x^2+\frac{1}{2}z_1^2+z_2^2). \tag{14}$$

Therefor, we obtain the normalized projective angular distributions for $J = 1$:

$$\overline{W}_{1^P}(\theta_V) = \frac{3}{8}\frac{1+2x^2+z_1^2+z_2^2}{1+x^2+\frac{1}{2}z_1^2+z_2^2}[1+\frac{1-2x^2-z_1^2+z_2^2}{1+2x^2+z_1^2+z_2^2}\cos^2\theta_V]; \tag{15}$$

$$\overline{W}_{1^P}(\theta_1) = \frac{3}{4}\frac{1}{1+\xi^2}[1-(1-2\xi^2)\cos^2\theta_1]; \tag{16}$$

$$\overline{W}_{1^P}(\phi) = \frac{1}{2\pi}(1+\beta_1\cos 2\phi), \beta_1 = \frac{P(2-\xi^2)z_2^2}{4(1+\xi^2)(1+x^2+\frac{1}{2}z_1^2+z_2^2)}. \tag{17}$$

When $J = 2$, there are five independent helicity amplitudes: $A_{1,0}$, $A_{1,1}$, $A_{1,2}$, $A_{0,0}$ and $A_{0,1}$ for the process of $J/\psi \to V + X$ and there are three independent helicity amplitudes $B_{1,1}$, $B_{1,0}$ and $B_{1,-1}$ for the process of $X \to \gamma + V$. Due to limited space, we do not give the normalized angular distribution here, and write out only the following normalized projective angular distributions:

$$\overline{W}_{2^P}(\theta_V) = \frac{3}{8}\frac{1+2x^2+y^2+z_1^2+z_2^2}{1+x^2+y^2+\frac{1}{2}z_1^2+z_2^2}[1+\frac{1-2x^2+y^2-z_1^2+z_2^2}{1+2x^2+y^2+z_1^2+z_2^2}]; \tag{18}$$

$$\overline{W}_{2^P}(\theta_1) = \frac{3}{4}\frac{1+\eta^2}{1+\zeta^2+\eta^2}[1-\frac{1-2\zeta^2+\eta^2}{1+\eta^2}\cos^2\theta_1]; \tag{19}$$

$$\overline{W}_{2^P}(\phi) = \frac{1}{2\pi}[1+\beta_2\cos 2\phi],$$

$$\beta_2 = -\frac{P(6+\zeta^2-4\eta^2)}{12(1+\zeta^2+\eta^2)(1+x^2+y^2+\frac{1}{2}z_1^2+z_2^2)}. \tag{20}$$

From Eqs. (11) and (16) we can see that if $\xi \neq 0$, the dependence on θ_1 for $\overline{W}_{1^P}(\theta_1)$ and $\overline{W}_{0^P}(\theta_1)$ are different. If $\xi = 0$ and $z_2 = 0$, we have $\xi(\phi) \sim 1 + \beta_1 \cos 2\phi$ ($\beta_1 = 0$), and $\overline{W}_{0^P}(\phi)$ is independent of ϕ. When $\xi = z_2 = 0$ and $x \neq 0$, different dependence on θ_V for $\overline{W}_{0^P}(\theta_V)$ and $\overline{W}_{1^P}(\theta_V)$ are given in Eqs. (10) and (15). Finally, if $\xi = z_2 = x = 0$, we have $\overline{W}_{0^P}(\theta) \sim \cos^2\theta$, whereas $\overline{W}_{1^P}(\theta)$ is independent of θ, in fact. Therefore, from the different angle dependence of the normalized projective angular distributions we can distinguish spin 0 boson resonance X from 1. Moreover, from Eq. (17) we can see that the parity P of the boson resonance X with $J = 1$ can be determined from the positive or negative value of β_1 according to the measurement of $\overline{W}_{1^P}(\phi)$, provided ξ ; 2 and z_2 ; 0. For $J^P = 0^-$, Eq.(7) leads to $A_{0,0} = 0$, i.e., $z_1 = 0$. Therefore, if the measurement of $\overline{W}_{0^P}(\theta_V)$ gives $z_1 = 0$, we can determine that the parity P of the boson resonance with spin $J = 0$ must be positive.

Similarly, the boson resonances with spins $J = 0$ and 2 can be distinguished and through the measurement of $\overline{W}_{2^P}(\phi)$ given in Eq. (20) we can determine the parity P of the $J = 2$ boson resonance $J = 2$ from β_2 being positive or negative under the conditions $6 + \xi^2 - 4\eta^2 = 0$ and $z_2 = 0$.

In the range of 1.35-1.5 GeV, which is called "E energy range", a few resonances with spin 0 and 1 have been discovered in experiments. In addition to two 0^{-+} states and one 1^{++} state which are included in the peak of the original glueball candidate $\iota(1440)$ [5], the E/$f_1(1420)$ with $J^{PC} = 1^{++}$, the ($\eta\pi\pi$) resonance X(1400) with $J^{PC} = 0^{-+}$ [6], a candidate of hybrids or four quark states: C(1480) with $J^{PC} = 1^{--}$ [7] and the exotic candidate M(1405) with $J^{PC} = 1^{-+}$ and so on, have been reported. Therefore, in this energy range it is important to distinguish the resonance with spin 0 from that with spin 2 and to determine their parities. It is still unclear if the spin of the $\theta(1720)$ is 0 or 2 [9]. Near the energy range of 2.2 GeV, in addition to the $\xi(2230)$ with spin $J = 2$ or 4, three g_T states with $J^{PC} = 2^{++}$ (the possibility that one of them is a hybrid cannot been ruled out) and the ($\eta\eta$) resonance G(2180) with $J^{PC} = 2^{++}$, a ($\phi\phi$) resonance with $J^{PC} = 0^{-+}$ was discovered by Mark III [11] and DM2 [12]. Hence, it is also significant to distinguish the resonances with spin $J = 0$ and 2, and to determine their parities in this energy range. Besides, a research of different radiative decay channels ($\gamma\rho$, $\gamma\omega$, $\gamma\phi$) of these new hadrons is also useful for understanding the characteristics of the new hadrons [13]. Therefore, the discussion in this paper presents a possible way to further understand the properties of the new hadrons.

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