Covariant Tensor Formalism for Partial Wave Analyses of ψ Decays into $\gamma B\bar{B}$ *

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Abstract Recently BESⅡ collaboration observed an enhancement near the $p\bar{p}$ invariant mass spectrum. Using the covariant tensor formalism, here we provide theoretical formulae for the partial wave analysis (PWA) of the ψ radiative decay channels $\psi\to\gamma p\bar{p}$, $\gamma\Lambda\bar{\Lambda}$, $\gamma\Sigma\bar{\Sigma}$, $\gamma\Xi\bar{\Xi}$. By performing the Monte Carlo simulation, we give the angular distributions for the photon and proton in the process of $J/\psi\to\gamma p\bar{p}$, which may serve as a useful reference for the future PWA on these channels.

Key words PWA, J/ψ, $\gamma B\bar{B}$

1 Introduction

J/ψ and ψ′ radiative decay to $B\bar{B}$ (baryon and antibaryon pair) is a good channel to study the possible bound or resonant states of the $B\bar{B}$ system[1—4]. Abundant J/ψ and ψ′ events have been collected at the Beijing Electron Positron Collider (BEPC). More data will be collected at the upgraded BEPC and CLEO-C. Based on the analysis of the 58 million J/ψ events accumulated by the BESⅡ detector at the BEPC, recently BESⅡ reported[5] that they have observed a strong, narrow enhancement near the threshold in the invariant mass spectrum of $p\bar{p}$ (proton - antiproton) pairs from $J/\psi\to\gamma p\bar{p}$ radiative decays. The structure has the properties consistent with either an $S(0^{-+})$- or $P(0^{++})$-wave Breit-Wigner resonance function. In the S-wave case, the peak mass is blow $2M_p$ around $M=1859$MeV with a total width $\Gamma<30$MeV. In order to get more useful information about properties of the resonances such as their J^{PC} quantum numbers, mass, width, production and decay rates, etc., partial wave analyses (PWA) are necessary. PWA is an effective method for analysing the experimental data of hadron spectrum. There are two types of PWA: one is based on the covariant tensor (also named Rarita-Schwinger) formalism[6] and the other is based on the helicity formalism[7]. In the work[8], it showed the connection between the covariant tensor formalism and the covariant helicity one. In the article[9], the author provided PWA formulae in a covariant tensor formalism for ψ decays to mesons, which have been used for a number of channels already published by BES[10—15] and are going to be used for more channels. A similar approach has been used in analyzing other reactions[16—18]. Another work[19] provided explicit formulae for the angular distribution of photon of the ψ radiative decays in the covariant tensor formalism, and also discussed helicity formalism of the angular distribution of the ψ radiative decays to two pseudoscalar mesons, and

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its relation to the covariant tensor formalism. Now we extend the covariant tensor formalism to the $\psi \to \gamma B\bar{B}$ with B represents baryons p, Λ, Σ, Ξ etc., and derive the decay amplitudes for various intermediate resonant states in the framework of the relativistic covariant tensor formalism.

In this paper we study the phenomenological spin parity determination of resonances. The plan of this article is as follows: in Section 2, we present the necessary tools for the calculation of the tensor amplitudes, within a covariant tensor formalism. This will allow us to derive covariant amplitudes for all possible processes. In Section 3, we present covariant tensor formalism for ψ radiative decays to baryon antibaryon pairs. Since covariance is a general requirement of any decay amplitude, all possible amplitudes are written in terms of covariant tensor form. All amplitudes include a complex coupling constant and Blatt-Weisskopf centrifugal barriers where necessary. In Section 3, we provide the angular distribution of the photon and proton. The conclusions are given in Section 5.

2 Prescriptions for the construction of covariant tensor amplitudes

In this section we present the necessary tools for the construction of covariant tensor amplitudes. The partial wave amplitudes $U_i^{\mu\nu\alpha}$ in the covariant Rarita-Schwinger tensor formalism can be constructed by using pure orbital angular momentum covariant tensors $\tilde{t}^{(L_{\rm bc})}_{\mu_1\cdots\mu_{L_{\rm bc}}}$ and covariant spin wave functions $\phi_{\mu_1\cdots\mu_{\rm s}}$ together with metric tensor $g^{\mu\nu}$, totally antisymmetric Levi-Civita tensor $\varepsilon_{\mu\nu\lambda\sigma}$ and momenta of parent particles. For a process a → bc, if there exists a relative orbital angular momentum $\boldsymbol{L}_{\rm bc}$ between the particle a and b, then the pure orbital angular momentum $\boldsymbol{L}_{\rm bc}$ state can be represented by covariant tensor wave functions $\tilde{t}^{(L_{\rm bc})}_{\mu_1\cdots\mu_{L_{\rm bc}}}$ [7] which is built out of relative momentum. Thus here we give only covariant tensors that correspond to the pure S-, P-, D-, and F-wave orbital angular momenta:

$$\tilde{t}^{(0)} = 1, \tag{1}$$

$$\tilde{t}^{(1)}_\mu = \tilde{g}_{\mu\nu}(p_{\rm a})r^\nu B_1(Q_{\rm abc}) \equiv \tilde{r}_\mu B_1(Q_{\rm abc}), \tag{2}$$

$$\tilde{t}^{(2)}_{\mu\nu} = [\tilde{r}_\mu\tilde{r}_\nu - \frac{1}{3}(\tilde{r}\cdot\tilde{r})\tilde{g}_{\mu\nu}(p_{\rm a})]B_2(Q_{\rm abc}), \tag{3}$$

$$\begin{aligned}\tilde{t}^{(3)}_{\mu\nu\lambda} = {} & [\tilde{r}_\mu\tilde{r}_\nu\tilde{r}_\lambda - \frac{1}{5}(\tilde{r}\cdot\tilde{r})(\tilde{g}_{\mu\nu}(p_{\rm a})\tilde{r}_\lambda + \\ & \tilde{g}_{\nu\lambda}(p_{\rm a})\tilde{r}_\mu + \tilde{g}_{\lambda\mu}(p_{\rm a})\tilde{r}_\nu)]B_3(Q_{\rm abc}), \\ & \dots\end{aligned} \tag{4}$$

where $r = p_{\rm b} - p_{\rm c}$ is the relative four-momentum of the two decay products in the parent particle rest frame; $(\tilde{r}\cdot\tilde{r}) = -\boldsymbol{r}^2$. and

$$\tilde{g}_{\mu\nu}(p_{\rm a}) = g_{\mu\nu} - \frac{p_{{\rm a}\mu}p_{{\rm a}\nu}}{p_{\rm a}^2}; \tag{5}$$

$B_{L_{\rm bc}}(Q_{\rm abc})$ is a Blatt-Weisskopf barrier factor[7, 20], here $Q_{\rm abc}$ is the magnitude of $\boldsymbol{p}_{\rm b}$ or $\boldsymbol{p}_{\rm c}$ in the rest system of a,

$$Q^2_{\rm abc} = \frac{(s_{\rm a} + s_{\rm b} - s_{\rm c})^2}{4s_{\rm a}} - s_{\rm b} \tag{6}$$

with $s_{\rm a} = E_{\rm a}^2 - \boldsymbol{p}_{\rm a}^2$.

The spin-1 and spin-2 particles wave functions $\phi_\mu(p_{\rm a}, m)$ and $\phi_{\mu\nu}(p_{\rm a}, m)$ satisfy the following conditions

$$\begin{aligned}& p^\mu_{\rm a}\phi_\mu(p_{\rm a}, m) = 0, \qquad \phi_\mu(p_{\rm a}, m)\phi^{*\mu}(p_{\rm a}, m) = -\delta_{mm'} \\ & \sum_m \phi_\mu(p_{\rm a}, m)\phi^*_\nu(p_{\rm a}, m) = -g_{\mu\nu} + \frac{p_{{\rm a}\mu}p_{{\rm a}\nu}}{p^2_{\rm a}} \equiv -\tilde{g}_{\mu\nu}(p_{\rm a}),\end{aligned} \tag{7}$$

and

$$\begin{aligned}& p^\mu_{\rm a}\phi_{\mu\nu}(p_{\rm a}, m) = 0, \qquad \phi_{\mu\nu} = \phi_{\nu\mu}, \\ & g^{\mu\nu}\phi_{\mu\nu} = 0, \qquad \phi_{\mu\nu}(m)\phi^{*\mu\nu}(m') = \delta_{mm'} \\ & P^{(2)}_{\mu\nu\mu'\nu'}(p_{\rm a}) = \sum_m \phi_{\mu\nu}(p_{\rm a}, m)\phi^*_{\mu'\nu'}(p_{\rm a}, m) = \\ & \frac{1}{2}(\tilde{g}_{\mu\mu'}\tilde{g}_{\nu\nu'} + \tilde{g}_{\mu\nu'}\tilde{g}_{\nu\mu'}) - \frac{1}{3}\tilde{g}_{\mu\nu}\tilde{g}_{\mu'\nu'}.\end{aligned} \tag{8}$$

Note that for a given decay process $a \to bc$, the total angular momentum should be conserved, which means

$$\boldsymbol{J}_{\rm a} = \boldsymbol{S}_{\rm bc} + \boldsymbol{L}_{\rm bc}, \tag{9}$$

where

$$\boldsymbol{S}_{\rm bc} = \boldsymbol{S}_{\rm b} + \boldsymbol{S}_{\rm c}. \tag{10}$$

In addition parity should also be conserved, which means

$$\eta_{\rm a} = \eta_{\rm b}\eta_{\rm c}(-1)^{L_{\rm bc}}, \tag{11}$$

where η_a, η_b, and η_c are the intrinsic parities of particles a, b, and c, respectively. From this relation, one knows whether L_{bc} should be even or odd. Then from Eq. (9) one can find out how many different $L_{bc}-S_{bc}$ combinations determine the number of independent couplings. Also note that in the construction of the covariant tensor amplitude, for $S_{bc}-L_{bc}-J_a$ coupling, if $S_{bc}+L_{bc}+J_a$ is an odd number, then $\varepsilon_{\mu\nu\lambda\sigma}p_a^{\sigma}$ with p_a the momentum of the parent particle is needed; otherwise it is not needed.

3 Covariant tensor formalism for ψ decay into γBB̄

The general form of the decay $\psi\rightarrow\gamma X\rightarrow\gamma p\bar{p}$ amplitude can be written as follows by using the polarization four-vectors of the initial and final states,

$$A^{(s)}=\psi_\mu(m_J)e_\nu^*(m_\gamma)\psi_{\alpha_s}(p_b,S_b;p_c,S_c)A^{\mu\nu\alpha_s}=\psi_\mu(m_J)e_\nu^*(m_\gamma)\psi_{\alpha_s}(p_b,S_b;p_c,S_c)\sum_i\Lambda_iU_i^{\mu\nu\alpha_s}. \quad (12)$$

where $\psi_\mu(m_J)$ is the polarization four-vector of the ψ with spin projection of m_J; $e_\nu(m_\gamma)$ is the polarization four-vector of the photon with spin projections of m_γ; $U_i^{\mu\nu\alpha_s}$ is the i-th partial wave amplitude with coupling strength determined by a complex parameter Λ_i. The spin-1 polarization vector $\psi_\mu(m_J)$ for ψ with four-momentum p_μ satisfies

$$\sum_{m_J=1}^{3}\psi_\mu(m_J)\psi_\nu^*(m_J)=-g_{\mu\nu}+\frac{p_\mu p_\nu}{p^2}\equiv-\tilde{g}_{\mu\nu}(p), \quad (13)$$

with $p^\mu\psi_\mu=0$. Here the Minkowsky metric tensor has the form

$$g_{\mu\nu}=\mathrm{diag}(1,-1,-1,-1).$$

For ψ production from e^+e^- annihilation, the electrons are highly relativistic, with the result that $J_z=\pm1$ for the ψ spin projection taking the beam direction as the z-axis. This limits m_J to 1 and 2, i.e. components along x and y. Then one has the following relation

$$\sum_{m_J=1}^{2}\psi_\mu(m_J)\psi_{\mu'}^*(m_J)=\delta_{\mu\mu'}(\delta_{\mu1}+\delta_{\mu2}). \quad (14)$$

For the photon polarization four-vector, there is the usual Lorentz orthogonality conditions. Namely, the polarization four-vector $e_\nu(m_\gamma)$ of the photon with momenta q satisfies

$$q^\nu e_\nu(m_\gamma)=0, \quad (15)$$

which states that spin-1 wave function is orthogonal to its own momentum. The above relation is the same as for a massive vector meson. However, for the photon, there is an additional gauge invariance condition. Here we assume the Coulomb gauge in the ψ rest system, i.e., $p^\nu e_\nu=0$. Then we have[21]

$$\sum_{m_\gamma}e_\mu^*(m_\gamma)e_\nu(m_\gamma)=-g_{\mu\nu}+\frac{q_\mu K_\nu+K_\mu q_\nu}{q\cdot K}-\frac{K\cdot K}{(q\cdot K)^2}q_\mu q_\nu\equiv-g_{\mu\nu}^{(\perp\perp)} \quad (16)$$

with $K=p-q$ and $K^\nu e_\nu=0$. For $X\rightarrow p\bar{p}$, the total spin of $p\bar{p}$ system can be either 0 or 1. These two states can be represented by ψ and ψ_α[22]. where

$$\psi=\bar{u}(p_b,S_b)\gamma_5v(p_c,S_c),\quad \text{if}\quad s=0, \quad (17)$$

$$\psi_\alpha=\bar{u}(p_b,S_b)(\gamma_\alpha-\frac{r_\alpha}{m_X+2m})v(p_c,S_c),\quad \text{if}\quad s=1. \quad (18)$$

One can see that both ψ and ψ_α have no dependence on the direction of the momentum $\hat{\boldsymbol{p}}$, hence correspond to pure spin states with the total spin of 0 and 1, respectively. Where p_b, p_c, and S_b, S_c are momenta and spin of the proton antiproton pairs, respectively. m_X and m are the masses of X and $p,\bar{p}$, respectively; $u(p_b,S_b)$ and $v(p_c,S_c)$ are the standard Dirac spinor. If we sum over the polarization, we have the two projection operators:

$$\begin{aligned}\textstyle\sum_{S_b}u_\alpha(p_b,S_b)\bar{u}_\beta(p_b,S_b)&=\left(\frac{\not{p}_b+m}{2m}\right)_{\alpha\beta},\\ \textstyle\sum_{S_c}v_\alpha(p_c,S_c)\bar{v}_\beta(p_c,S_c)&=\left(\frac{\not{p}_c-m}{2m}\right)_{\alpha\beta}.\end{aligned} \quad (19)$$

To compute the differential cross section, we need an expression for $|A|^2$. Note that the square modulus of the decay amplitude, which gives the decay probability of a certain configuration should be independent of any particular frame, that is, a Lorentz scalar. Thus by using Eqs. (14) and (16), the differential cross section for the radiative decay to an

3-body final state is:

$$\frac{d\sigma^{(s)}}{d\Phi_3} = \frac{1}{2}\sum_{S_b,S_c}\sum_{m_J=1}^{2}\sum_{m_\gamma=1}^{2}\Big|\psi_\mu(m_J)e^*_\nu(m_\gamma)\times \psi_{\alpha_s}(p_b,S_b;p_c,S_c)A^{\mu\nu\alpha_s}\Big|^2 = -\frac{1}{2}\sum_{S_b,S_c}\sum_{\mu=1}^{2}A^{\mu\nu\alpha_s}g^{(\perp\perp)}_{\nu\nu'}A^{*\mu\nu'\alpha'_s}\psi^*_{\alpha_s}\psi_{\alpha'_s} = -\frac{1}{2}\sum_{i,j}\Lambda_i\Lambda^*_j\sum_{\mu=1}^{2}U_i^{\mu\nu\alpha_s}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'\alpha'_s}\times \sum_{S_b,S_c}\psi^*_{\alpha_s}\psi_{\alpha'_s}\equiv\sum_{i,j}P_{ij}\cdot F^{(s)}_{ij} \tag{20}$$

where

$$P_{ij}=P^*_{ji}=\Lambda_i\Lambda^*_j,$$
$$F^{(s)}_{ij}=F^{*(s)}_{ji}=-\frac{1}{2}\sum_{\mu=1}^{2}U_i^{\mu\nu\alpha_s}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'\alpha'_s}\sum_{S_b,S_c}\psi^*_{\alpha_s}\psi_{\alpha'_s}. \tag{21}$$

$d\Phi_3$ is the standard Lorentz invariant 3-body phase space given by

$$d\Phi_3(p;q,p_b,p_c) = \delta^4(p-q-p_b-p_c)\times \frac{d^3\boldsymbol{q}}{(2\pi)^3 2E_\gamma}\frac{m^2 d^3\boldsymbol{p}_b d^3\boldsymbol{p}_c}{(2\pi)^3E_b(2\pi)^3E_c}. \tag{22}$$

$$F^{(0)}_{ij} = F^{*(0)}_{ji} = -\frac{1}{2}\sum_{\mu=1}^{2}U_i^{\mu\nu}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'}\sum_{S_b,S_c}\psi^*\psi = \frac{1}{2}\sum_{\mu=1}^{2}U_i^{\mu\nu}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'}\mathrm{Tr}\Big(\frac{\not p_b+m}{2m}\gamma_5\frac{\not p_c-m}{2m}\gamma_5\Big) = -\frac{m_X^2}{4m^2}\sum_{\mu=1}^{2}U_i^{\mu\nu}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'}. \tag{23}$$

The spin sums can be performed using the completeness relations from Eq. (19):

$$F^{(1)}_{ij} = F^{*(1)}_{ji} = -\frac{1}{2}\sum_{\mu=1}^{2}U_i^{\mu\nu\alpha}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'\alpha'}\sum_{S_b,S_c}\psi^*_\alpha\psi_{\alpha'} = -\frac{1}{2}\sum_{\mu=1}^{2}U_i^{\mu\nu\alpha}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'\alpha'}\times \Big[\mathrm{Tr}\Big(\frac{\not p_b+m}{2m}\gamma_\alpha\frac{\not p_c-m}{2m}\gamma_{\alpha'}\Big) - \frac{r_\alpha}{m_X+2m}\mathrm{Tr}\Big(\frac{\not p_b+m}{2m}\frac{\not p_c-m}{2m}\gamma_{\alpha'}\Big) - \frac{r_{\alpha'}}{m_X+2m}\mathrm{Tr}\Big(\frac{\not p_b+m}{2m}\gamma_\alpha\frac{\not p_c-m}{2m}\Big) + \frac{r_\alpha r_{\alpha'}}{(m_X+2m)^2}\mathrm{Tr}\Big(\frac{\not p_b+m}{2m}\frac{\not p_c-m}{2m}\Big)\Big] = -\frac{1}{4m^2}\sum_{\mu=1}^{2}U_i^{\mu\nu\alpha}g^{(\perp\perp)}_{\nu\nu'}U_j^{*\mu\nu'\alpha'}\times \Big[p_{b\alpha}p_{b\alpha'}+p_{c\alpha}p_{c\alpha'}+p_{b\alpha}p_{c\alpha'}+p_{b\alpha'}p_{c\alpha}-m_X^2 g_{\alpha\alpha'}\Big]. \tag{24}$$

where we have used traces of γ matrics,

$$\mathrm{tr}(1)=4,\quad \mathrm{tr}(\gamma^5)=0,\quad \mathrm{tr}(\gamma^\mu\gamma^\nu)=4g^{\mu\nu}$$
$$\mathrm{tr}(\text{ any odd}\,\sharp\,\gamma's)=0,\quad \mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^5)=0. \tag{25}$$

Amplitudes for the radiative decay $\psi\to\gamma p\bar{p}$

We consider the decay of a ψ state into two steps: $\psi\to\gamma X$ with $X\to p\bar{p}$. The possible J^{PC} for X are 0^{++}, 0^{-+}, 1^{++}, 2^{++}, 2^{-+}, etc. For $\psi\to\gamma X$, we choose two independent momenta p for ψ and q for the photon to be contracted with spin wave functions. We denote the four-momentum of X by K. The tensor describing the first and second steps will be denoted by $\tilde{T}^{(L)}_{\mu_1\cdots\mu_L}$ and $\tilde{t}^{(l)}_{\mu_1\cdots\mu_l}$, respectively.

For $\psi\to\gamma 0^{++}\to\gamma p\bar{p}$, there is one independent covariant tensor amplitude:

$$U^{\mu\nu\alpha}=g^{\mu\nu}\tilde{t}^{(1)\alpha}. \tag{26}$$

For $\psi\to\gamma 0^{-+}\to\gamma p\bar{p}$, there is one independent covariant tensor amplitude:

$$U^{\mu\nu}=\varepsilon^{\mu\nu\lambda\sigma}p_\lambda q_\sigma B_1(Q_{\psi\gamma X}). \tag{27}$$

For $\psi\to\gamma 1^{++}\to\gamma p\bar{p}$, there are two independent covariant tensor amplitudes:

$$U_1^{\mu\nu\alpha} = \varepsilon^{\mu\nu\lambda\sigma}p_\lambda\varepsilon_\sigma^{\alpha\beta\rho}K_\rho\tilde{t}^{(1)}_\beta, \tag{28}$$
$$U_2^{\mu\nu\alpha} = \varepsilon^{\nu\lambda\sigma\gamma}p_\lambda q^\mu q_\gamma\varepsilon_\sigma^{\alpha\beta\rho}K_\rho\tilde{t}^{(1)}_\beta B_2(Q_{\psi\gamma X}). \tag{29}$$

For $\psi\to\gamma 1^{-+}$, the exotic 1^{-+} meson cannot decay into $p\bar{p}$.

For $\psi\to\gamma 2^{++}\to p\bar{p}$, there are three independent covariant tensor amplitudes:

$$U_1^{\mu\nu\alpha} = P^{(2)\mu\nu\alpha\beta}(K)\tilde{t}^{(1)}_\beta, \tag{30}$$
$$U_2^{\mu\nu\alpha} = g^{\mu\nu}P^{(2)\alpha\beta\lambda\sigma}p_\beta p_\lambda\tilde{t}^{(1)}_\sigma B_2(Q_{\psi\gamma X}), \tag{31}$$
$$U_3^{\mu\nu\alpha} = P^{(2)\nu\alpha\beta\lambda}q^\mu p_\beta\tilde{t}^{(1)}_\lambda B_2(Q_{\psi\gamma X}). \tag{32}$$

For 2^{++} decaying to $p\bar{p}$, the orbital angular momentum between the proton and antiproton l could be 1 and 3; but we ignore $l=3$ contribution because of the strong centrifugal barrier.

For $\psi \to \gamma 2^{-+} \to p\bar{p}$, the possible partial wave amplitudes are the following:

$$U_1^{\mu\nu} = \varepsilon^{\mu\nu\lambda\sigma} p_\lambda q^\gamma \tilde{t}^{(2)}_{\gamma\sigma} B_1(Q_{\psi\gamma\mathrm{X}}), \tag{33}$$

$$U_2^{\mu\nu} = \varepsilon^{\mu\nu\lambda\sigma} p_\lambda q_\sigma p_\gamma p_\delta \tilde{t}^{(2)\gamma\delta} B_3(Q_{\psi\gamma\mathrm{X}}), \tag{34}$$

$$U_3^{\mu\nu} = \varepsilon^{\nu\gamma\lambda\sigma} p_\lambda q_\sigma q^\mu p^\delta \tilde{t}^{(2)}_{\gamma\delta} B_3(Q_{\psi\gamma\mathrm{X}}). \tag{35}$$

It is worth mentioning here that the above partial wave amplitudes for the process $J/\psi \to \gamma p\bar{p}$ are applicable to the processes $J/\psi \to \gamma\Lambda\bar{\Lambda}$, $\gamma\Sigma\bar{\Sigma}$, and $\gamma\Xi\bar{\Xi}$ as well.

4 Monte Carlo simulation for $J/\psi \to \gamma p\bar{p}$

We perform Monte Carlo simulation for the decay process $J/\psi \to \gamma X \to \gamma p\bar{p}$, with the J^{PC} of X to be 0^{++}, 0^{-+}, 1^{++}, 2^{++}, 2^{-+}. The predicted angular distributions for various J^{PC} intermediate resonances could serve as a useful reference for people performing partial wave analysis of $\psi \to \gamma B\bar{B}$ channels.

BESⅡ reported the observation of a narrow enhancement near $2m_p$ in the invariant mass spectrum of $p\bar{p}$ pairs from radiative $J/\psi \to \gamma p\bar{p}$ decays. The peak has properties consistent with either a $J^{PC} = 0^{-+}$ or 0^{++}. We simulate these two processes with the Breit-Wigner mass and width of X from BES[5]. The angular distributions of the photon and proton are shown in Fig. 1, while the invariant mass of $p\bar{p}$ and momentum distribution of the proton are shown in Fig. 2. The two fits of 0^{-+} and 0^{++} are indeed hardly distinguishable from these distributions. However, if the narrow structure is really due to a narrow 0^{-+} or 0^{++} resonance, it can be distinguished by its other decay modes. While a 0^{-+} resonance can decay into $\eta\pi\pi$, $K\bar{K}\pi$, a 0^{++} resonance cannot. On the other hand, while a 0^{++} resonance can decay into two pseudoscalar mesons, such as $\pi\pi$, $K\bar{K}$, a 0^{-+} resonance cannot. Both 0^{-+} and 0^{++} resonances can decay into 4π and $\pi\pi K\bar{K}$ channels. Previous data on these channels[10—15] have not seen such narrow structure around $2m_p$. This gives support to the explanation of $p\bar{p}$ 0^{-+} final state interaction[23, 24] for the observed narrow peak structure in $p\bar{p}$ channel only.

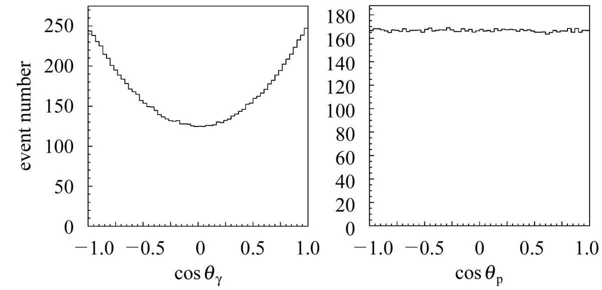

Fig. 1. Angular distributions of the photon and proton in the process $J/\psi \to \gamma 0^{\pm+} \to \gamma p\bar{p}$.

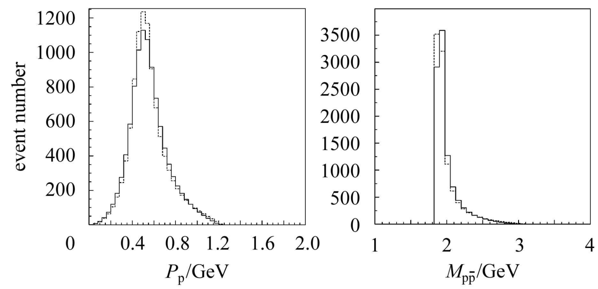

Fig. 2. Momentum distributions of proton and invariant mass of $p\bar{p}$ in the process $J/\psi \to \gamma 0^{\pm+} \to \gamma p\bar{p}$. The dashed curve is the case of 0^{++}; the solid curve is the case of 0^{-+}.

The processes with other J^{PC} intermediate X resonances are simulated by assuming the mass of X at 2.15GeV with a width of 0.15GeV. The angular distribution of photon and proton are shown in Figs.3—5. The θ_γ and θ_p are given in J/ψ rest frame and X rest frame, respectively. The θ_γ angular distributions coincide with general analytic formulae given in the previous work[19] as it should be. One can see that various partial wave amplitudes give different angular distributions. By fitting the theoretical differential cross section given by Eq.(20) with parameters Λ_i to the data, one can get the magnitudes of each partial wave contribution.

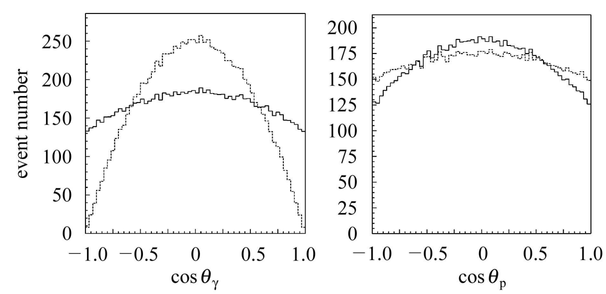

Fig. 3. Angular distributions of the photon and proton for independent amplitudes of the process $J/\psi \to \gamma 1^{++} \to \gamma p\bar{p}$. The solid curve and dashed curve correspond to Eqs. (28) and (29), respectively.

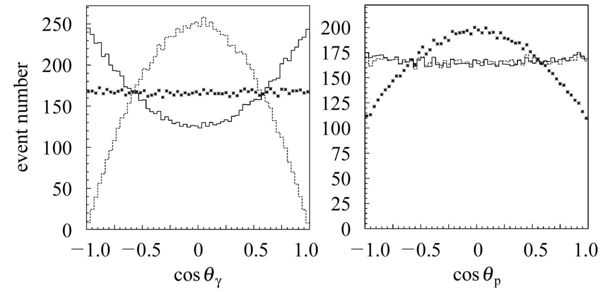

Fig. 4. Angular distributions of the photon and proton given by independent amplitudes Eq. (30) (stars), Eq. (31) (solid lines), and Eq. (32) (dashed lines) of the process $J/\psi \to \gamma 2^{++} \to \gamma p\bar{p}$.

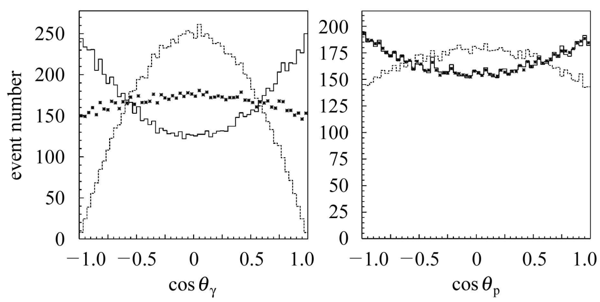

Fig. 5. Angular distributions of the photon and proton given by independent amplitudes Eq. (33) (stars), Eq. (34) (solid lines), and Eq. (35) (dashed lines) of the process $J/\psi \to \gamma 2^{-+} \to \gamma p\bar{p}$.

5 Conclusion

In this paper we provided a theoretical formalism and a Monte Carlo study of the partial wave analysis for the radiative decay $J/\psi \to \gamma p\bar{p}$, which are also applicable to the processes $J/\psi \to \gamma\Lambda\bar{\Lambda}$, $\gamma\Sigma\bar{\Sigma}$ and $\gamma\Xi\bar{\Xi}$. We have constructed all possible covariant tensor amplitudes for intermediate resonant states of $J \leqslant 2$. For intermediate resonant states of $J \geqslant 3$, the production vertices need $L \geqslant 2$ and are expected to be suppressed[9]. The formulae here can be directly used to perform partial wave analysis of forthcoming high statistics data from CLEO-c and BESIII on these channels to extract useful information on the baryon-antibaryon interactions.

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References

1 Edwards C. PhD Thesis, Cal. Tech. Preprint CALT-68-1165

2 Coffman D, DeJongh F, Dubois G et al. Phys. Rev., 1990, **D41**: 1410

3 Augustin J E et al. Orsay Preprint LAL/85-27

4 BES Collaboration. Nucl. Phys., 2000, **A675**: 337—340

5 BES Collaboration. Phys. Rev. Lett., 2003, **91**: 022001

6 Rarita W, Schwinger J. Phys. Rev., 1941, **60**: 61

7 Chung S U. Phys. Rev., 1993, **D48**: 1225; Chung S U. Phys. Rev., 1998, **D57**: 431

8 Filippini V, Fontana A, Rotondi A. Phys. Rev., 1995, **D51**: 2247

9 ZOU B S, Bugg D V. Eur. Phys. J., 2003, **A16**: 537

10 BES Collaboration. Phys. Lett., 1998, **B440**: 217

11 BES Collaboration. Phys. Lett., 1999, **B446**: 356

12 BES Collaboration. Phys. Lett., 2000, **B472**: 200

13 BES Collaboration. Phys. Lett., 2000, **B472**: 208

14 BES Collaboration. Phys. Lett., 2000, **B476**: 25

15 BES Collaboration. Phys. Rev., 2003, **D68**: 052003

16 Anisovich V V, Bugg D V, Sarantsev A V. Nucl. Phys., 1992, **A537**: 501; Anisovich V V, Kobrinsky M N, Melikhov D I et al. Nucl. Phys., 1992, **A544**: 747

17 Anisovich A V et al. Phys. Lett., 1999, **B452**: 173; Phys. Lett., 1999, **B452**: 180; Phys. Lett., 1999, **B452**: 187; Phys. Lett., 1999, **B468**: 304; Phys. Lett., 1999, **B468**: 309; Phys. Lett., 2001, **B500**: 222; Phys. Lett., 2001, **B507**: 23

18 Anisovich A V, Sadovnikova V A. Euro. Phys. J., 1998, **A2**: 199; Anisovich A V et al. J. Phys., 2002, **G28**: 15

19 Sayipjamal Dulat, ZOU Bing-Song, WU Ji-Min. HEP&NP, 2004, **28**: 350—358 (in Chinese)
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20 Greiner W et al. Quantum Chromodynamics. Springer. 2002. 242; Behtends E, Fronsdal C. Phys. Rev., 1957, **106**: 345

21 von Hippel F, Quigg C. Phys. Rev., 1972, **D5**: 624

22 ZOU B S, Hussain F. Phys. Rev., 2003, **C67**: 015204

23 ZOU B S, Chiang H C. Phys. Rev., 2004, **D69**: 034004

24 Kerbikov B, Stavinsky A, Fedotov V. Phys. Rev., 2004, **C69**: 055205

基于协变张量方法的ψ衰变到$\gamma B\bar{B}$的分波分析*

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摘要　最近BESⅡ合作组在$p\bar{p}$不变质量谱阈值附近观测到一个增强. 利用协变张量方法, 给出了ψ辐射衰变道$\psi\to\gamma p\bar{p}$, $\gamma\Lambda\bar{\Lambda}$, $\gamma\Sigma\bar{\Sigma}$, $\gamma\Xi\bar{\Xi}$分波分析的理论公式. 通过蒙特卡罗模拟, 还给出了$J/\psi\to\gamma p\bar{p}$中光子和质子的角分布, 它们可以作为将来对这些道分波分析的有用参考.

关键词　分波振幅　J/ψ　$\gamma B\bar{B}$

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