Study of the electromagnetic transitions $J/\psi \rightarrow Pl^+l^−$ and probe dark photon

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We study the electromagnetic Dalitz decay modes of $J/\psi \rightarrow Pl^+l^−$ ($P = π^0, \eta$ or $\eta'$). In these decays, the lepton pairs are formed by internal conversion of an intermediate virtual photon with invariant mass $m_{l^+l^−}$. Study of the effective-mass spectrum of the $l^+l^−$ will shed light on the dynamic transition form factor $F_{J/\psi P}(q^2)$ ($q^2 = m_{l^+l^−}^2$), which characterizes the electromagnetic structure arising at the vertex of the transition $J/\psi$ to pseudoscalars. We also discuss the direct productions of a GeV scale vector $U$ boson in these processes $J/\psi \rightarrow PU (U \rightarrow l^+l^−)$. It is responsible for mediating a new $U(1)_d$ interaction, as recently exploited in the context of weakly interacting massive particle dark matter. In this paper, we firstly use the usual pole approximation for the form factor to estimate the decay rate of $J/\psi \rightarrow Pl^+l^−$ in the standard model. Then the reach of searching for the dark photon is estimated. We suggest that these Dalitz decays can be used to search for the light $U$ boson in the BESIII experiment with a huge $J/\psi$ data set.

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INTRODUCTION

Study of the electromagnetic (EM) decays of the hadronic states is of interest for understanding the structure of hadronic matter and for revealing the fundamental mechanisms for the interactions of photons and hadrons [1,2]. The EM Dalitz decays $V \rightarrow Pl^+l^−$ of light unflavored vector mesons ($\rho$, $\omega$ or $\phi$) are specially interesting for probing the electromagnetic structure arising at the vertex of the transition $V$ to the pseudoscalar. In table I we summarize the experimental results for the EM Dalitz decays of the light vector mesons. The ratios of the Dalitz decays to the corresponding radiative decays of vector mesons are suppressed by two orders of magnitude, especially, for $V \rightarrow Pe^+e^−$ modes. Assuming point-like particles, the decay rate of this process vs. $m_{l^+l^−}$ can be exactly described by QED [3] in the standard model (SM). However, the rate is strongly modified by the dynamic transition form factor $F_{VP}(q^2)$ ($q^2 = m_{l^+l^−}^2$), which can be estimated based on models of QCD [1,2,3].

TABLE I: The experimental results on the light vector Dalitz decays $V \rightarrow Pl^+l^−$ ($V = \rho, \omega$ or $\phi$), and ratios of the Dalitz decays to radiative decays of the vector mesons. These data are from PDG2010 [12].

| Decay mode | Experimental results | $Γ(V \rightarrow Pl^+l^−)$ |
|------------|---------------------|---------------------------|
| $\rho^0 \rightarrow π^0e^+e^−$ | $< 1.2 \times 10^{−5}$ (90% C.L.) | $< 2.0 \times 10^{−2}$ |
| $ω \rightarrow π^0e^+e^−$ | $(7.7 ± 0.6) \times 10^{−4}$ | $(0.93 ± 0.08) \times 10^{−4}$ |
| $ω \rightarrow π^+μ^−μ^+$ | $(1.3 ± 0.4) \times 10^{−4}$ | $(0.16 ± 0.05) \times 10^{−4}$ |
| $ω \rightarrow γe^+e^−$ | $< 1.1 \times 10^{−7}$ (90% C.L.) | $< 2.4 \times 10^{−7}$ |
| $φ \rightarrow π^+e^−e^−$ | $(1.15 ± 0.10) \times 10^{−4}$ | $(0.88 ± 0.08) \times 10^{−4}$ |
| $φ \rightarrow γμ^+μ^−$ | $< 9.4 \times 10^{−7}$ (90% C.L.) | $< 0.07 \times 10^{−6}$ |

Experimentally, $|F_{VP}(q^2)|^2$ is directly accessible by comparing the measured invariant mass spectrum of the lepton pairs from the Dalitz decays with the point-like QED prediction. A comprehensive review of the topic is contained in reference [2]. Recently, high quality data from NA60 experiment measured the $q^2$-dependent form factor of the Dalitz decay $ω \rightarrow π^0μ^+μ^−$ [11]. Using the usual pole approximation $F(q^2) = 1/(1 − q^2/m_ω^2)$ for the form factor, the $Λ−2$ has been found to be $2.24 ± 0.06$ GeV$^{−2}$, which strongly deviates from the expectation of vector meson dominance (VMD) [3,4]. The form factor showed a relative increase close to the kinematic cut-off by a factor of $∼ 10$ [11]. For the decay of $ϕ → γe^+e^−$, the SND experiment has looked for the $m_{e^+e^-}$ invariant mass distribution with 213 events [12], and measured the form factor slope $Λ−2$ to be $3.8 ± 1.8$ GeV$^{−2}$. Most recently, KLOE-2 has selected 7000 $ϕ → γe^+e^−$ events with $η → π^0π^−π^0$ using a sample of 739 pb$^{−1}$ on the $ϕ$ peak [13]. A preliminary fit to the $m_{e^+e^-}$ indicates the possibility to reach a 5% error on the form factor slope [13].

These theoretical and experimental investigations of the EM Dalitz decays of light vector mesons motivate us to study the rare charmonium decays $J/\psi \rightarrow Pl^+l^−$ ($P = π^0, \eta$ or $\eta'$). The measurements of the $q^2$-dependent form factors will provide useful information on the interaction of the charmonium states with electromagnetic field. In particular, with more phase space, the transition between $J/\psi$ and the pseudoscalar can be explored over a large region of momentum transfer, which will be used to test QCD prediction cleanly. The decay rates of the $J/ψ → γ\pi^0$, $γ\eta$ and $γ\eta'$ are $(3.49^{+0.33}_{−0.30}) \times 10^{−5}$, $(1.104 ± 0.034) \times 10^{−3}$ and $(5.28 ± 0.15) \times 10^{−3}$ [10], respectively. From a direct estimation according to the ratios of $ω$ and $ϕ$ Dalitz decays to the corresponding radiative decays, the expected Dalitz decay rates could reach $∼ 10^{−7}$ for $J/ψ → π^0e^+e^−$ and $∼ 10^{−5}$ for $J/ψ → γe^+e^−$ and $η' e^+e^−$, respectively.
It is also interesting to search for dark photon, the light U boson, in $J/\psi \rightarrow PU$ and $U \rightarrow l^+l^-$, in which the virtual photon is replaced by the light on-shell dark photon $U$. The light U boson may couple to the SM charged particles with a much suppressed coupling which has been considered in various contexts [14–19]. We consider the new Abelian gauge group $U(1)_d$ which has a gauge-invariant kinetic mixing with the SM hypercharge $U(1)_Y$ [20–22]. After electroweak symmetry breaking, we have the Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \epsilon \gamma^{\mu} F_{\mu
u} F_{\mu
u}^d + m_d^2 A_d^{\mu} A_d^\mu,$$  \hspace{0.5cm} (1)

where $\mathcal{L}_{SM}$ is the SM Lagrangian, $F_{\mu
u}$ and $F_{\mu
u}^d$, are the field strength for the SM gauge boson $B$ and $U$ boson, respectively, $A_d^{\mu}$ is the gauge field of a massive dark $U(1)_d$ gauge group [21]. The second term in Eq. (1) is kinetic mixing operator, and $\epsilon \sim 10^{-8} - 10^{-2}$ is generated at any scale by loops of heavy fields charged under both $U(1)_d$. In a supersymmetry theory, the kinetic mixing operator induces a mixing between the $D$-terms associated with $U(1)_d$ and $U(1)_Y$. The hypercharge $D$-term gets a vacuum expectation value from the electroweak symmetry breaking and induces a weak-scale effective Fayet-Iliopoulos term for $U(1)_Y$. Consequently, the $U(1)_d$ symmetry breaking scale is suppressed by loop factors or by $\sqrt{\epsilon}$, leading to MeV to GeV-scale $U$ boson mass [21, 22]. The parameters of concern in this paper are $\epsilon$ and $m_U$.

In the BESIII experiment, more than 1 billion $J/\psi (\psi')$ sample will be collected next year, the first look of these decay modes will be accessible [23]. It will shed light on probing new physics beyond the standard model, such as possible $U$ boson with mass less than 300 MeV range [24–28], which may contribute to the process by replacing virtual photon. By looking at the spectrum of the dilepton, with huge data set in the BESIII experiment, one may see possible new physics contribution which will modify the shape of the di-lepton spectrum and total decay rate of the Dalitz decay process.

In this paper, the full angular distribution and $q^2$-dependent rate are derived in the SM framework in Section 4. Using the pole approximation, the decay rates for the EM Dalitz decays of $J/\psi$ are estimated for the first time. An interesting consequence is that the dark photon can be probed in the low energy BESIII experiment. In Section 5, we estimate the reach of the $U$ boson search in the $J/\psi \rightarrow PU$ and $U \rightarrow l^+l^-$ decay.

$q^2$-DEPENDENT DECAY RATE OF $J/\psi \rightarrow Pt^+l^-$

The amplitude of the Dalitz decay $\psi \rightarrow Pt^+l^-$ (hereafter, $\psi$ denotes $J/\psi$) has the Lorentz-invariant form:

$$T = 4\pi \alpha f_{\psi P} e^{\mu\nu\rho\sigma} p_{\mu} q_{\nu} \epsilon_{\rho\sigma} \frac{1}{q^2} u_1 \gamma_{\nu} v_2,$$ \hspace{0.5cm} (2)

where $f_{\psi P}$ is the form factor of the $\psi \rightarrow P$ transition; $q_\nu$ is the 4-momentum of the virtual photon or the total 4-momentum of $l^+l^-$ ($l = e, \mu$) system; $q^2 = m_{P_{l^+l^-}}^2$ is the effective mass squared of the lepton pair; $p_{\mu}$ is the 4-momentum of the pseudoscalar meson; $\epsilon_{\rho\sigma}$ is the polarization 4-vector of the $\psi$; $e^{\mu\nu\rho\sigma}$ is the totally antisymmetric unity tensor. It is straightforward to obtain the shape of the di-lepton spectrum and total decay rate of the Dalitz decay process.

$$|T|^2 = 16\pi^2 \alpha^2 \frac{|f_{\psi P}(q^2)|^2}{q^4} \left[ (8(p \cdot q)^2 m_{\psi}^2 - 8p^2 q^2 m_l^2 - 2p^2 q^4 - 8(k_1 \cdot p)(k_2 \cdot p)q^2 + 4(p \cdot q)^2 q^2) \right],$$ \hspace{0.5cm} (3)

where $m_l$ is the lepton mass; $q = k_1 + k_2$, and $p$, $k_1$ and $k_2$ are 4-momenta of particles $P$, $l^+$ and $l^-$, respectively.

The angular distribution of the differential decay width can be obtained as

$$\frac{d\Gamma(\psi \rightarrow Pt^+l^-)}{dq^2} = 1 \frac{\alpha^2}{3 256 \pi m_{\psi}^3} \left| f_{\psi P}(q^2) \right|^2 \left( 1 - \frac{4m_{\psi}^2}{q^2} \right)^{1/2} \left[ (m_{\psi}^2 - m_P^2 + q^2)^2 - 4m_{\psi}^2 q^2 \right]^{3/2} \times$$

$$\int d\Omega_3 d\Omega_1^* \left[ \left( 1 + \frac{4m_{\psi}^2}{q^2} \right) + \left( 1 - \frac{4m_{\psi}^2}{q^2} \right) \cos^2 \theta_1^* \right],$$ \hspace{0.5cm} (4)

where $m_{\psi}$ and $m_P$ are the masses of the initial charmonium state and pseudoscalar meson; $d\Omega_3 = d\phi_3 d(cos \phi_3)$ is the solid angle of $P$ in the rest frame of $\psi$ and $d\Omega_1^* = d\phi_1^* d(cos \theta_1^*)$ is the solid angle of one of the lepton pair in the rest frame of $l^+l^-$ system (the $z$ direction is defined as the momentum direction of $l^+l^-$ in the $\psi$ system); $\theta_1^*$ is the helicity angle of $l^+l^-$ system, which is defined as the angle between momentum direction of one of the lepton pair and direction of the $P$ meson in the rest frame of $l^+l^-$ system. By integrating the solid angles in Eq. (4) one can obtain the $q^2$-dependent differential decay width:

$$\frac{d\Gamma(\psi \rightarrow Pt^+l^-)}{dq^2} = 1 \frac{\alpha^2}{24 \pi m_{\psi}^3} \left| f_{\psi P}(q^2) \right|^2 \left( 1 - \frac{4m_{\psi}^2}{q^2} \right)^{1/2} \left( 1 + \frac{2m_{\psi}^2}{q^2} \right) \left[ (m_{\psi}^2 - m_P^2 + q^2)^2 - 4m_{\psi}^2 q^2 \right]^{3/2}. $$ \hspace{0.5cm} (5)
For the corresponding radiative decay of $\psi \to P\gamma$, the decay width can be obtained as:

$$\Gamma(\psi \to P\gamma) = \frac{1}{3} \frac{\alpha(m_\psi^2 - m_p^2)^3}{8m_\psi^3} |f_{\psi P}(0)|^2. \quad (6)$$

From Eqs. (5) and (6) the $q^2$-dependent differential decay width in the $\psi \to Pl^+l^-$ decay normalized to the width of the corresponding radiative $\psi \to P\gamma$ is derived:

$$\frac{d\Gamma(\psi \to Pl^+l^-)}{dq^2\Gamma(\psi \to P\gamma)} = \frac{\alpha}{3\pi} \left| f_{\psi P}(q^2) \right|^2 \frac{1 + \frac{q^2}{m_\psi^2}}{q^2} \left( 1 - \frac{4m_\psi^2}{q^2} \right)^{1/2} \left( 1 + \frac{q^2}{m_\psi^2 - m_p^2} \right)^2 - \frac{4m_\psi^2q^2}{(m_\psi^2 - m_p^2)^2} \right]^{3/2} \quad (7)$$

where the normalized form factor for the $\psi \to P$ transition is defined as $F_{\psi P}(q^2) = f_{\psi P}(q^2)/f_{\psi P}(0)$, and the normalization is $f_{\psi P}(0) = 1$. The form factor defines the electromagnetic properties of the region in which $\psi$ is converted into pseudoscalar. By comparing the measured spectrum of the lepton pairs in the Dalitz decay with QED calculations for point-like particles, it is possible to determine experimentally the transition form factor in the time-like region of the momentum transfer $q^2$. Namely, the form factor can modify the lepton spectrum as compared with that obtained for point-like particles.

For the decays accompanied by the production of the electron-positron pair, we should note that the radiative corrections proportional to $\alpha m_\psi^2(q^2/m_\psi^2)$ will be important. We will not discuss the high order QED corrections in this analysis since the data sample in the BESIII experiment is still small, and BESIII is expected to see the first signal for the effect at leading order. In addition to that, the external conversion of the $\gamma$ from the radiative decay of $\psi \to P\gamma$ will make the analysis more complicated, however, at the BESIII the external conversion rate could be up to 2%, and the invariant mass of the $e^+e^-$ will form a narrow peak at 20-40 MeV, which will not really affect the slope shape of the dilepton. For the decays accompanied by the production of the muon pairs the radiative corrections and external radiation effects are negligibly small.

To estimate the order of magnitude, one may use the Vector Dominance Model (VDM), in which the hadronic EM current is proportional to vector meson fields $\vec{u}_{\mu} \vec{d}_{\mu}$. Hence the VDM predicts a growth of the transition form factors with increasing dilepton mass. The form factor may be parameterized in the simple pole approximation as

$$F_{\psi P}(q^2) = \frac{1}{1 - \frac{q^2}{\Lambda^2}}, \quad (8)$$

where the pole mass $\Lambda$ should be the mass of the vector resonance near the energy scale of the decaying particle according to the VDM model. In $\psi$ decay the pole mass could be the mass of $\psi'$. By assuming the pole approximation and taking $\Lambda = m_{\psi'}$, in Fig. 1 we show the differential decay rates for $\psi \to \pi^0 l^+l^-$, $\eta l^+l^-$ and $\eta' l^+l^-$, respectively. The decay rates for $\psi \to \pi^0 l^+l^-$, $\eta l^+l^-$ and $\eta' l^+l^-$ are estimated and presented in Table II. To study the dependence of the decay rates on the value of the pole mass, we varied the pole mass in the range $\Lambda^2 > q_{max}^2 = (m_\psi - m_p)^2$ in the Dalitz decay process of $J/\psi$. The reason can be well understood. The dominant contribution to the decay rate comes from the region of small value of $q^2$. For the pole mass with large value, $q^2/\Lambda^2$ is small, therefore this term cannot give large effect. This is different from the case for the light vector meson Dalitz decays.

Because the decay rates are not sensitive to the pole mass in the form factor, the predicted decay rates in Table II are more reliable. Comparing these predictions with experimental measurement should make sense. In the BESIII experiment, more than 1 billion $J/\psi(\psi')$ sample will be collected in year 2012, the first look of these decay modes will be accessible.

TABLE II: The estimated decay rates for $\psi \to \pi^0 l^+l^-$, $\eta l^+l^-$ and $\eta' l^+l^-$ based on Eq. (7) by assuming pole approximation and $\Lambda = m_{\psi'}$. The error on the decay rate is from the measured error of $\psi \to P\gamma$ which is used as normalization.

| Decay mode | $e^+e^-$ | $\mu^+\mu^-$ |
|------------|----------|-------------|
| $\psi \to \pi^0 l^+l^-$ | $(3.89^{+3.39}_{-3.13}) \times 10^{-7}$ | $(1.01^{+1.29}_{-1.09}) \times 10^{-7}$ |
| $\psi \to \eta l^+l^-$ | $(1.21 \pm 0.04) \times 10^{-7}$ | $(0.30 \pm 0.01) \times 10^{-7}$ |
| $\psi \to \eta' l^+l^-$ | $(5.66 \pm 0.16) \times 10^{-7}$ | $(1.31 \pm 0.04) \times 10^{-7}$ |
FIG. 1: The differential decay rates for $\psi \to \pi^0 l^+ l^-$, where the solid curve is for $\psi \to \pi^0 e^+ e^-$, the dashed curve for $\psi \to \eta l^+ l^-$ and the dotted for $\psi \to \eta' l^+ l^-$. (a) is for the case that the lepton pair is $e^+ e^-$, while (b) for the case $\mu^+ \mu^-$. In (a), only part of the phase space for $m_{e^++e^-}$ is shown for demonstration purpose since most of the phase space is accumulated near small $m_{e^++e^-}$ region.

FIG. 2: The differential decay rate for $\psi \to \eta l^+ l^-$, where the solid curve is for the pole mass taken as $\Lambda = 3.0$ GeV and the dotted for $\Lambda = 4.0$ GeV.

FIG. 3: The decay rate for $\psi \to \eta \mu^+ \mu^-$ with the variation of the pole mass $\Lambda$.

U boson as well.

The on-shell U boson will decay to a pair of leptons in $J/\psi \to PU$, leading to a signal of $Pl^+ l^-$. The SM background $J/\psi \to P\gamma^* \to Pl^+ l^-$, although large for this process, is not a severe problem as the kinematics of the signal are quite distinct. The invariant mass of the lepton pair is just within a single bin due to the tiny width of the vector U boson and can be distinguished from the SM background. It will be interesting to look for a low mass, up to GeV scale, U boson in these modes.

From Eq. (1), the number of background events in the window of $\delta q^2$ (resolution of the $q^2$) around $q^2 = m_{Pl}^2$ is about

$$N_B = N_\psi \int_{q^2_{\text{min},i}}^{q^2_{\text{max},i}} \frac{d\Gamma(\psi \to Pl^+ l^-)}{dq^2 \Gamma(\psi \to P\gamma)} dq^2 \times BR(\psi \to P\gamma)$$

$$= N_\psi |F_{\psi P}(q^2)|^2 \times [\text{QED}(q^2)] \delta q^2 \times BR(\psi \to P\gamma),$$

(9)

where $q^2_{\text{max},i}$ ($q^2_{\text{min},i}$) is the upper (lower) value of the $i$-th $q^2$ bin; $N_\psi$ is the total number of $\psi$ decay events; and $BR(\psi \to P\gamma)$ is the branching fraction from PDG [10]. The size of the bin is the window size $\delta q^2$ which is obtained from the resolution functions of the $m_{Pl}$ in Eqs. (4) and (5) in Ref. [21] based on the BESII Monte Carlo simulations. By replacing the photon by $U$ boson in $\psi \to P\gamma$, the signal rate can be estimated to be $BR(\psi \to PU) \approx \epsilon^2 BR(\psi \to P\gamma)$, where $\epsilon$ was defined in Eq. (1). Thus, the expected number of signal events is about

$$N_S = N_\psi \times \epsilon^2 BR(\psi \to P\gamma) BR(U \to l^+ l^-),$$

(10)

where we assume $BR(U \to l^+ l^-) = 1$ in this study. Combining Eqs. (9) and (10), We estimate the expected nu-
merical results based on the significance

\[
\frac{S}{\sqrt{B}} = \frac{N_S}{\sqrt{N_B}} = \sqrt{\frac{\epsilon^2 \sqrt{BR(\psi \rightarrow P\gamma)BR(U \rightarrow l^+l^-)}}{\sqrt{F_{e\gamma}(\gamma^2)\times \text{QED}(\gamma^2)}}} \quad \text{(11)}
\]

Therefore, with 1 billion \( \psi \) events, the reach for U-boson searching can be \( \epsilon \sim 10^{-2} - 10^{-3} \) in the \( \psi \rightarrow PU \) decays. In Figs. 4 and 5, we show the reach of the parameter \( \epsilon \) by defining \( S/\sqrt{B} = 5 \) for different mass of \( U \) boson.

![FIG. 4: Illustrative plot of the reach of vector boson at BES-III in the channel of \( \psi \rightarrow PU \) (solid curve for \( P = \pi^\pm \); dot-dashed curve for \( P = \eta \) and dashed curve for \( P = \eta' \), respectively), where \( U \) decay into \( e^+e^- \).](image)

![FIG. 5: The same as Fig. 4 with \( U \) decay into \( \mu^+\mu^- \).](image)

**SUMMARY**

In summary, the EM Dalitz decays of \( \psi \rightarrow Pl^+l^- \) are studied in this paper. We demonstrate the differential decay rate as both \( q^2 \)-dependent rate and angular dependent rate explicitly. By assuming simple pole approximation the decay rates for \( \psi \rightarrow Pl^+l^- \) are estimated for the first time. The estimated Dalitz decay rates could reach \( \sim 10^{-7} \) for \( \psi \rightarrow \pi^0l^+l^- \) and \( \sim 10^{-5} \) for \( \psi \rightarrow \eta l^+l^- \) and \( \eta' l^+l^- \), respectively. They will be accessible in the BESIII experiment with data sample of 1 billion \( \psi \) decay events. Especially, the \( q^2 \)-dependent differential decay rate can be measured by looking at the invariant mass of the lepton pairs.

In the BESIII experiment, these measurements will be important for us to understand the interaction of vector charmonium states with photon, as well as to probe new physics beyond the standard model. We have investigated the signatures of a hidden \( U(1)_d \) sector at the BESIII experiment in \( \psi \rightarrow PU \) decays, and find that the BESIII should have an intrinsic sensitivity to the kinetic mixing parameter \( \epsilon \) in the range of \( 10^{-2} - 10^{-4} \), which depends on the mass values of the \( U \) boson.

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