Vector meson rescattering effect in understanding the threshold enhancement observed in $J/\psi \to \gamma p\bar{p}$ *

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Abstract We propose one possible mechanism, i.e., the vector meson (VV) rescattering effects, to interpret the near threshold narrow enhancement observed in $J/\psi \to \gamma p\bar{p}$. The estimate indicates that these effects can give sizeable contributions to this channel, and a destructive interference between different rescattering amplitudes is required to reproduce the line shape of the data.

Key words threshold enhancement, rescattering effect, final state interaction

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1 Introduction

In 2003, BESII collaboration observed a very narrow near-threshold enhancement in the $p\bar{p}$ invariant mass distribution in $J/\psi \to \gamma p\bar{p}$ [1]. By fitting this enhancement with a Breit-Wigner function

$$BW(M) \propto \frac{q^{(2l+1)}k^3}{(M^2-M_0^2)^2+M_0^2\Gamma^2}, \tag{1}$$

the S-wave gives the best result, which means the quantum number of the $p\bar{p}$ enhancement, if originated from a resonance, should be $J^{PC}=0^{-+}$. The invariant mass is about 1859 MeV, which is slightly lower than $2m_p$, and the width $\Gamma<30$ MeV at 90% C.L.

This result has stimulated many studies on understanding its underlying structure. For instance, since it is observed in J/ψ radiative decays, which are gluon rich processes, it is proposed to be a glueball candidate [2–4]. However, the glueball solution will encounter some difficulties. For example, the pseudoscalar glueball can couple to a pair of vector mesons, and the decay should be flavor-independent. Since the experiments have accumulated a sizeable data sample of $J/\psi \to \gamma VV$, the absence of such a narrow resonance in VV final state will strongly disfavor such a picture. This enhancement is also interpreted as a bound state of proton-antiproton, or baryonium [5–8], for which the exotic structure and relevant dynamics should be carefully studied. There are also much less exotic interpretations proposed in the literature. In Refs. [9–15], the enhancement is attributed to the $p\bar{p}$ final-state interaction effect. This mechanism fit the data very well in the near threshold region. But it encounters a difficulty in understanding the absences of a similar enhancement in $\psi' \to \gamma p\bar{p}$ or $\Upsilon \to \gamma p\bar{p}$ etc. In this sense, further studies of the final state interactions are still needed.

2 VV-rescattering mechanism

In this proceeding, we report another possible mechanism for understanding the $p\bar{p}$ near-threshold enhancement. Our VV-rescattering mechanism is based on the following points: Firstly, in $J/\psi \to \gamma VV$, the VV invariant mass distribution is dominated by 0^- components [16], this is consistent with that the quantum number of the $p\bar{p}$-system may be $J^{PC}=0^{-+}$, and most of these channels have relatively larger branching ratios. We list some of them in Table 1, of which the branching ratios are at the order of 10^{-3}. Secondly, these vector mesons generally have strong couplings with the nucleons or hyperons.

Therefore, considering these reasons, the VV-

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rescattering effect may play an important role in $J/\psi \to \gamma p\bar{p}$.

We illustrate the model in Fig. 1, the VV-rescattering mechanism is represented by these triangle diagrams. Apart from VV-rescattering, there may be some other processes that can contribute to this channel, such as VP-rescattering effect (Fig. 1(d)). But this process happens via exchanging at least three gluons. Therefore, we suppose that it would be suppressed compared with the VV-rescattering. The $p\bar{p}$-system can also directly couple to η or η' (Fig. 1(e)). But notice that these exchanged particles are far off-shell, and the ηNN coupling is relatively weaker. As a result, their contributions would become insignificant.

Table 1. Branching ratios of $J/\psi \to \gamma VV$ via pseudoscalar components.

Channel	BR ($\times 10^{-3}$)
$\gamma\eta(1405/1475) \to \gamma\rho^0\rho^0$	1.7 ± 0.4
$\gamma\eta(1760) \to \gamma\omega\omega$	1.98 ± 0.33
$\gamma 0^- \to \gamma K^* \bar{K}^*$	2.3 ± 0.9

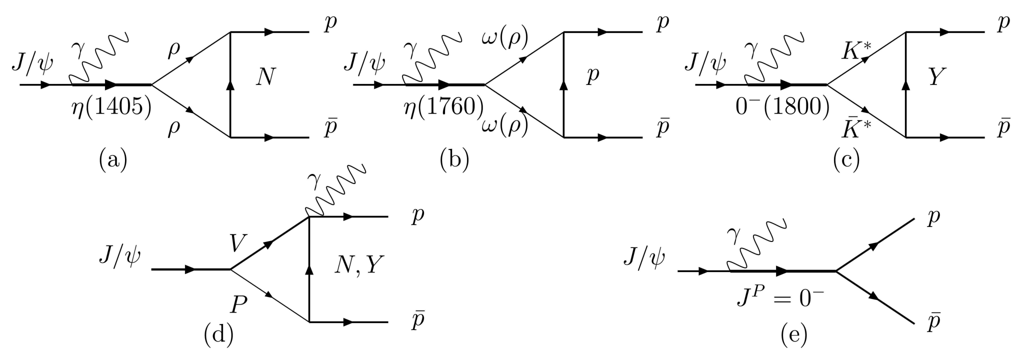

Fig. 1. Diagrams for $J/\psi \to \gamma p\bar{p}$. Diagrams (a)-(c) are via VV rescattering, where N and Y represent the exchanged nucleon or hyperon, respectively. Diagram (d) is via VP rescattering, where V and P represent vector and pseudoscalar meson, respectively. Diagram (e) is $p\bar{p}$ production via direct couplings to pseudoscalar resonances, such as η or η'.

The momenta of the intermediate meson rescatterings in Fig. 1(a)-(c) are denoted as $J/\psi(P) \to \gamma(k)\eta(k_1) \to \gamma V(q_1)\bar{V}(q_2) \to \gamma p(p_1)\bar{p}(p_2)$. With an effective Lagrangian method, the rescattering amplitude reads

$$\mathcal{M}_\eta = e\frac{g_{\gamma\psi\eta}}{m_\psi}\frac{\epsilon_{\alpha\beta\gamma\delta}k^\alpha\epsilon^{*\beta}P^\gamma\epsilon_\psi^\delta}{s-m_\eta^2+\mathrm{i}m_\eta\Gamma_\eta}\int\frac{\mathrm{d}^4q}{(2\pi)^4}\times \frac{A(\eta\to VV\to p\bar{p})}{(q_1^2-m_V^2)(q_2^2-m_V^2)}\mathcal{F}(q^2), \quad (2)$$

where

$$A(\eta\to VV\to p\bar{p})\equiv \frac{g_{VV\eta}}{m_V}\epsilon_{\alpha\beta\gamma\delta}q_1^\alpha q_2^\gamma\times g_{VBB}^2\bar{u}(p_1)\left(\gamma^\beta+\frac{\mathrm{i}\kappa}{2m_N}\sigma^{\beta\mu}q_{1\mu}\right)\times \frac{\not{q}+m_B}{q^2-m_B^2}\left(\gamma^\delta+\frac{\mathrm{i}\kappa}{2m_N}\sigma^{\delta\nu}q_{2\nu}\right)v(p_2). \quad (3)$$

As the exchanged particles may be off-shell, and the interacting fields are not point particles, We phenomenally introduce a form factor $\mathcal{F}(q^2)$ which is commonly used in the rescattering processes as follows

$$\mathcal{F}(q^2)=\left(\frac{\Lambda^2-m_B^2}{\Lambda^2-q^2}\right)^n, \quad (4)$$

where $n=2$ is adopted in this work. The form factor is also used to kill the ultra-violet divergence that appears in the loop integrals. We should mention that this kind of form factor is model-dependent, and the reasonable cut-off energy is usually taken as hundreds of MeV higher than the mass of the exchanged particles. The total scattering amplitude is

$$\mathcal{M}=\mathcal{M}_\eta^{\mathrm{dir}}+\mathcal{M}_{\eta(1405)}^{\rho\rho,\mathrm{res}}+\mathrm{e}^{\mathrm{i}\theta}\mathcal{M}_{\eta(1760)}^{\omega\omega,\mathrm{res}}+\mathrm{e}^{\mathrm{i}\phi}\mathcal{M}_{\eta(1760)}^{\rho\rho,\mathrm{res}}, \quad (5)$$

where the relatively phases between different rescattering amplitudes are introduced as free parameters, and will be determined by fitting the experimental data. More details about the calculation can be found in Ref. [17].

The fitting result is displayed in Fig. 2. We note that within a reasonable range of the cut-off energy, each single rescattering amplitude gives a much larger contribution compared to the experimental data. It seems that to reproduce the line shape of the experimental data, a destructive interference between different rescattering amplitudes is required. The solid line is the fitting result, and we can see that it reproduces the data well. We mention again that the values of some parameters are model dependent, and they also depend on the accuracy of the data for $J/\psi \to \gamma VV$.

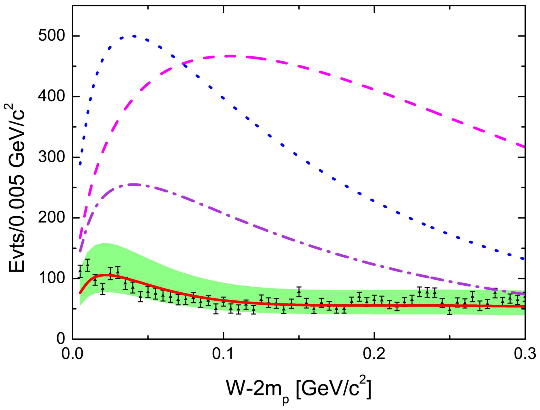

Fig. 2. The $p\bar{p}$ invariant mass spectrum of $J/\psi \to \gamma p\bar{p}$. The dashed, dotted, and dot-dashed lines correspond to contributions from $\rho\rho_{\eta(1405)}$, $\omega\omega_{\eta(1760)}$, and $\rho\rho_{\eta(1760)}$-rescattering, respectively. The solid line is the overall interference with $\Lambda \simeq 1.17$ GeV and $\theta \simeq \pi$, $\phi \simeq -\pi/2$. The lower and upper bound of the shadowed area correspond to $\Lambda = 1.15$ and 1.20 GeV, respectively. The triangle with error bar represents the experimental data from Ref. [1].

Since the model indicates that the VV-rescattering effects are very important in $J/\psi \to \gamma p\bar{p}$, especially in the near threshold region, we need to check whether we have overestimated the amplitude of VV scattering to $p\bar{p}$ or not. Therefore, we use the same effective Lagrangian, form factors, and couplings to investigate the process $p\bar{p} \to VV$, and then compare it with the experimental data, such as the data of proton antiproton annihilation at rest. Considering the uncertainty of the data, we found that the amplitudes reproduce the data well and give the correct order of magnitude.

We also checked this rescattering mechanism in $J/\psi \to \omega p\bar{p}$. Since a lot of processes will contribute to this decay, we will focus on the small $p\bar{p}$ invariant mass region, and examine the role played by the VV-rescatterings via $J/\psi \to \omega\eta(1405)/\omega\eta(1760)$. Interestingly, it shows that in the near-threshold region, the cross section do not exhibit any narrow enhancement as in $J/\psi \to \gamma p\bar{p}$, although the cross sections are compatible with the data. This seems to be consistent with the BES-II observation [16], and indicates a special feature arising from the VV-rescattering. Namely, due to the kinematic change, the interference pattern will also change. It shows that the relatively narrow enhancement in $J/\psi \to \gamma p\bar{p}$ will be attenuated in $J/\psi \to \omega p\bar{p}$. This somehow explains why the enhancement appears special in $J/\psi \to \gamma p\bar{p}$ but not in $\psi' \to \gamma p\bar{p}$, $J/\psi \to \omega p\bar{p}$ or other $p\bar{p}$ production channels [18, 19].

3 Summary

The VV-rescattering effect, i.e. $J/\psi \to \gamma VV \to \gamma p\bar{p}$, may be one of the possible mechanisms to produce the near threshold enhancement observed by BES II in $J/\psi \to \gamma p\bar{p}$. And the fitting result indicates that the enhancement resulted from the destructive interferences between different rescattering amplitudes. The forthcoming BESIII results on $J/\psi(\psi') \to \gamma p\bar{p}$ and $J/\psi(\psi') \to \omega p\bar{p}$ may help us to clarify this phenomenon and the underlying mechanism.

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