Production of vector mesons in pentaquark states resonance channel in $p$-$Au$ ultraperipheral collisions

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Abstract

Ultraperipheral collisions (UPCs) of proton and nucleus are important to study the photoproduction of vector mesons and exotic states. Photoproduction of vector mesons in pentaquark resonance channel in $p$-$Au$ UPCs at Relative Heavy Ion Collider (RHIC) are investigated employing STARlight package. The cross sections of vector mesons via pentaquark state resonances channel are obtained using effective Lagrangian method. Pseudo-rapidity and rapidity distributions of $J/\psi$ and $\Upsilon(1S)$ are given in $p$-$Au$ UPCs at RHIC. These predictions can be applied to identity pentaquark states in $p$-$Au$ UPCs at RHIC.

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I. INTRODUCTION

Ultraperipheral collisions (UPCs) are important tools to investigate photoproduction at high energies\cite{1,2}. UPCs can probe two-photon and \( p-A \) interactions, for example, vector meson production and dijet production\cite{3}. UPCs are studied at Large Hadron Collider (LHC) and Relative Heavy Ion Collider (RHIC) for photoproduction of several vector mesons, such as \( \rho, \omega, \phi, J/\psi \). The photoproduction of exotic particles have also been investigated at UPCs\cite{4,5}.

Recently, several narrow pentaquark states named \( P_c(4312), P_c(4440), P_c(4457) \) were observed in \( \Lambda_b \rightarrow J/\psi pK \) by the LHCb Collaboration \cite{6,7}, which is an important progress in the search for exotic hadrons. A lot of theoretical models are proposed to explain the internal natural of the pentaquark states \( P_c \) after they are discovered\cite{8-18}.

Since the intermediate particles in the above reaction process satisfy the on-shell condition, the contribution of triangular singularities in the \( \Lambda_b \rightarrow J/\psi pK \) reaction cannot be ignored\cite{19}. This means that it is currently difficult for us to determine whether these \( P_c \) states are genuine state. However, one can observe and study the \( P_c \) state through other scattering processes (such as photoproduction processes), which can effectively avoid the influence of triangular singularities to confirm whether the \( P_c \) state is a genuine state. In Ref.\cite{20,21}, combined with the latest experimental results, an in-depth study of the \( P_c \) state production via \( \gamma p \) or \( \pi^- p \) was carried out. After that, the GlueX Collaboration reported their first measurement of the \( \gamma p \rightarrow J/\psi p \) process\cite{22}. Though GlueX group did not find the photoproduction of pentaquark states with present precision\cite{22}, a very meaningful upper limit of production cross sections, and hence a model dependent upper limit of branching ratios \( \mathcal{B}(P_c \rightarrow J/\psi p) \), a few percents at most, were suggested by their data. The size of the branching ratio of \( P_c \rightarrow J/\psi p \) given in the experiment is basically consistent with the results in\cite{21}. In Ref.\cite{23}, based on the theoretical predictions of the mass and width of the hidden bottom pentaquark \( P_b \) state\cite{24,25}, a systematic study of the photoproduction of the \( P_b \) state was conducted. These photoproduction results of \( P_c \) and \( P_b \) are very important foundations for studying the production of pentaquark states via UPCs.

STARlight is a Monte-Carlo package for simulation in UPCs\cite{26}. It is widely applied in \( AA \) and \( pA \) UPCs at LHC and RHIC. The cross section of photon-proton to vector mesons are needed in STARlight package. We will employ the STARlight package in simulating vector meson in the pentaquark resonance \( s \)-channel and pomeron exchange \( t \)-channel.

The aim of this paper is to study the production of hidden charm/bottom pentaquark states in UPCs. The relevant results will provide an important theoretical basis for finding \( P_c \) and \( P_b \) states through UPCs experiments in the future. This paper is organized as follows. Theoretical framework is presented in Sec.\textbf{II}. The numerical results are given in Sec.\textbf{III} closed with a summary in Sec.\textbf{IV}.

II. THEORETICAL FRAMEWORK

In UPCs, the photon emitted from one nucleus interacts with a nucleus from another side. Because the photon number is proportional to number of charge of nucleus and proton, the photon flux emitted from proton can be neglected comparing the photon flux emitted from nucleus in \( p-A \) UPCs, for example gold and Lead. Thus, in \( p-A \) UPCs, we can neglect the photon emitted from proton. We only consider the photon from nucleus. The processes scheme diagrams are shown in Fig.\textbf{I}. There are two channels in vector meson production.
In $s$-channel, the vector mesons are produce via pentaquark states resonance. In $t$-channel, the photon interacts with proton via pomeron exchange. As the cross section of $t$-channel is dominant in photon-proton interaction, the cross section of $t$-channel be viewed as a background of the pentaquark resonance $s$-channel.

![Diagram](image)

FIG. 1. The processes of vector mesons production in $p$-$A$ UPCs through $s$-channel (left graph) and $t$-channel (right graph).

The cross section of vector mesons in UPCs is computed using integration of photon flux and photon-proton cross sections. The photon flux can be obtained in QED calculations. The photon-proton cross section for vector meson can be calculate in models now. In $p$-$A$ UPCs, the cross section of $pA \rightarrow pAV$ is given as follow [26]

$$\sigma(pA \rightarrow pAV) = \int dk \frac{dN_\gamma(k)}{dk} \sigma_{\gamma p \rightarrow pV}(W).$$

(1)

where $k$ is the momentum of the photon emitted from nucleus, $W$ is the center of mass (c.m.) energy of the photon and proton system. The photon emitted from nucleus is presented as [27]

$$\frac{dN_\gamma(k)}{dk} = \frac{2Z^2\alpha}{\pi k} \left( XK_0(X)K_1(X) - \frac{X^2}{2} [K_1^2(X) - K_0^2(X)] \right).$$

(2)

where $X = b_{min} k / \gamma_L$, $b_{min} = R_A + R_p$ is sum of radius of proton and nucleus. $\gamma_L$ is the Lorentz boost factor. $K_0(x)$ and $K_1(x)$ are the Bessel functions. Employing the cross section of vector meson in $p$-$A$ UPCs, we can get the total cross section in $p$-$Au$ UPCs at RHIC experiments. In order to get the final states proton and vector meson distributions, we must investigate the angle distributions in pentaquark states decaying into proton and vector meson. In previous paper, we have study the angle distributions in $P_c$ decaying into proton and $J/\psi$.

In Ref. [21, 23], the cross section of $\gamma p \rightarrow P_c \rightarrow J/\psi p$ and $\gamma p \rightarrow P_b \rightarrow \Upsilon(1S)p$ via $s$-channel were calculated based on the effective Lagrangian method and vector-meson-dominance (VMD) model. In the photoproduction calculation, the branching ratio of $P_c(4312) \rightarrow J/\psi p$ was taken as 3%, and the decay width of $P_b(11080) \rightarrow \Upsilon(1S)p$ was taken as 0.38 MeV predicted in Ref. [25]. The numerical result shown that the average value of the cross section from the $P_c(4312)$ or $P_b(11080)$ produced in the $\gamma p$ scattering reaches at least 0.1 nb with a bin of 0.1 GeV. In this work, the result of $P_c/P_b$ photoproduction in Ref. [21, 23] will be employed to calculate the production of $P_c/P_b$ via UPCs.

For the contribution of $t$-channel Pomeron exchange, the cross section of $\gamma p \rightarrow Vp$ is given as [26],

$$\sigma^t_{\gamma p \rightarrow Vp}(W) = \sigma_p \left( 1 - \frac{(m_p + m_V)^2}{W^2} \right) \cdot W^\epsilon,$$

(3)
with \(\sigma_p=4.06\) nb and \(\epsilon = 0.65\) for \(J/\psi\) and \(\sigma_p=6.4\) pb and \(\epsilon = 0.74\) for \(\Upsilon(1S)\), which are determined by the experimental data of \(\gamma p \rightarrow Vp\).

Employing the cross sections in \(s\)-channel and \(t\)-channel, we can get the vector meson cross sections in \(p-A\) UPCs. With the Monte-Carlo package STARlight, we can simulate the vector meson production processes and get the four momentum of final states. Then, we can obtain the spectrum of vector mesons in two channels.

### III. NUMERICAL RESULT

In this paper, the cross section of the vector meson \(J/\psi\) and \(\Upsilon(1S)\) in \(t\)-channel can be calculated as Eqs. (1)-(3). Meantime, we use the same calculation progress of vector mesons in \(s\)-channel as [21, 23]. STARlight package are employed to calculate the vector mesons through \(t\)-channel and \(s\)-channel in \(p-Au\) UPCs at RHIC and give the final states distributions.

Firstly, we calculate the \(J/\psi\) and \(\Upsilon(1S)\) cross sections in \(s\)-channel and \(t\)-channel. The cross sections are listed in Table. I, where the masses and decay widths are also presented. The event numbers are also listed in the Table I, which can be applied to estimate event number for one-year running.

| Resonance | Properties | \(s\)-channel | \(t\)-channel |
|-----------|------------|----------------|---------------|
| \(P_c(4312)\) | Mass: \(4311.9 \pm 0.7_{-0.6}^{+0.8}\) MeV | \(J/\psi\) cross section: \(1.8\) nb | \(2.2\) \(\mu\)b |
|         | Decay width: \(9.8 \pm 2.7_{-4.5}^{+3.4}\) MeV | Event Number: \(8.1\) K | \(9.9\) M |
| \(P_b(11080)\) | Mass: \(11080\) MeV | \(\Upsilon(1S)\) cross section: \(0.10\) nb | \(1.2\) nb |
|         | Decay width: \(1.58\) MeV | Event Number: \(0.45\) K | \(5.4\) K |

**TABLE I. Cross sections \(J/\psi\) and \(\Upsilon(1S)\) in \(pAu \rightarrow pVAu\) in \(s\)-channel.** The luminosity of the \(p-Au\) is \(4.5\) pb\(^{-1}\) [28].

Secondary, the pseudo-rapidity distributions corresponding angle distributions of two vector mesons are illustrated in Fig. 2. It can be seen that \(J/\psi\) and \(\Upsilon(1S)\) in \(s\)-channel are totally covered by \(t\)-channel distributions. Because the cross section of \(t\)-channel is much larger than the \(J/\psi\) cross section through pentaquark exchange \(s\)-channel. The sum of \(s\)-channel and \(t\)-channel is the same to \(t\)-channel. As a result, it is difficult to identify the pentaquark signal through \(J/\psi+p\) invariant mass spectrum in pseudo-rapidity distributions. On the other hand, in \(\Upsilon(1S)\) production, the \(s\)-channel signal is significant to identify the pentaquark states \(P_b(11080)\) state through \(\Upsilon(1S) + p\) invariant mass spectrum in pseudo-rapidity distributions.

Moreover, we also give the rapidity distributions of two vector mesons in \(p-Au\) UPCs in Fig. 3. We can see that in the rapidity space, the vector mesons in \(s\)-channel are not totally covered by the vector mesons distributions in \(t\)-channel. These results are different from the rapidity distributions in Ref. [5]. The rapidity distributions of \(J/\psi\) rapidity distributions in \(s\)-channel are totally covered by \(t\)-channel \(J/\psi\) rapidity distributions in Ref. [5]. Meantime it can be seen that the rapidity distributions are different from the pseudo-rapidity distributions because the energies are different in the same pseudo-rapidity region from Fig. 2 and Fig. 3.

Summary, the productions of \(J/\psi\) and \(\Upsilon(1S)\) are presented for \(p-Au\) UPCs at RHIC. The cross sections in \(s\)-channel and \(t\)-channel are listed in tables, which can predict the
FIG. 2. (Color online) Pseudo-Rapidity distributions of $J/\psi$ and $\Upsilon(1S)$ produced from pomeron exchange $t$-channel (black solid curve) and pentaquark resonance $s$-channel (red dashed curve) $p$-$Au$ UPCs at $\sqrt{s} = 200$ GeV at RHIC.

FIG. 3. (Color online) Rapidity distributions of $J/\psi$ and $\Upsilon(1S)$ produced from pomeron exchange $t$-channel (black solid curve) and pentaquark resonance $s$-channel (red dashed curve) $p$-$Au$ UPCs at $\sqrt{s} = 200$ GeV at RHIC.

total detected event numbers at RHIC. The pseudo-rapidity and rapidity distributions of $J/\psi$ and $\Upsilon(1S)$ in two channels are illustrated for $p$-$Au$ at RHIC. We can see that the pseudo-rapidity distributions and rapidity distributions are different. These results can help us to identify the pentaquark states in $p$-$Au$ UPCs at RHIC.

IV. CONCLUSION

In this paper, we study the production of vector meson including $J/\psi$ and $\Upsilon(1S)$ production in pentaquark resonance channel in $p$-$Au$ UPCs at RHIC. The cross sections of $\gamma p \rightarrow Vp$ are computed in two channels. The vector mesons and proton production in $s$-channel can be used to reconstruct pentaquark states. The vector mesons and proton production in $t$-channel is viewed as a background of $s$-channel production. The cross sections of $\gamma p \rightarrow J/\psi p$ and $\gamma p \rightarrow \Upsilon(1S)p$ in $s$-channel are calculated in effective Lagrangian method. We apply STARlight package to simulate the vector meson production in $p$-$Au$ UPCs at RHIC and obtain the several distributions of $J/\psi$ and $\Upsilon(1S)$. The pseudo-rapidity and ra-
pidity distributions of $J/\psi$ and $\Upsilon(1S)$ are illustrated in this work. From the pseudo-rapidity and rapidity distributions, it can concluded that the $P_c(4312)$ state is difficult to identity through $J/\psi + p$ invariant mass spectrum in $p$-$Au$ UPCs at $\sqrt{s} = 200$ GeV at RHIC. However, the $P_b(11080)$ may be discovered in $\Upsilon(1S) + p$ invariant mass spectrum at $p$-$Au$ UPCs at $\sqrt{s} = 200$ GeV at RHIC, although a small energy bin width is necessary. Consequently, it is important to detect the $\Upsilon(1S)$ production at $p$-$Au$ UPCs at RHIC, which can help us to discover the pentaquark $P_b(11080)$.

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