Production of Bound States with Hidden Charm at J-PARC and JLab

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Abstract
The cross sections of the production of bound states with hidden charm in reactions induced by pions and photons are presented. To facilitate the experimental efforts to determine the $J/\Psi$-$N$ interactions, we present results for $J/\Psi$ production on the deuteron.

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I. INTRODUCTION

In a recent paper [1], we presented predictions of photo-production of bound states $[^3He]_{J/Ψ}$ on $^4He$ target and $[q^6]_{J/Ψ}$ on $^3He$ target. In this work we apply the same approach to predict the production cross sections for these bound states with pion beams. Our predictions depend on a potential model of $J/Ψ-N$ interaction $v_{J/Ψ}$. All theoretical calculations of $v_{J/Ψ}$, based on the effective field theory method [2–5], the Pomeron-quark coupling model [6], and the Lattice QCD [7], give an attractive feature. However the resulting strength of $v_{J/Ψ}$ is rather uncertain. Here we present results on the deuteron target to facilitate the experimental tests of these models.

II. PRODUCTION OF BOUND STATES $[^3He]_{J/Ψ}$ AND $[q^6]_{J/Ψ}$

The calculations in Ref. [1] are based on the impulse approximation mechanism illustrated in Fig.1. The same approach can be used to perform calculations with incident pions by simply replacing the $γ+N → J/Ψ+N$ amplitude by the $π+N → J/Ψ+N$ amplitude. Following the approach of Refs. [1] and [4], we calculate the $π+N → J/Ψ+N$ amplitude from the $ρ$-exchange mechanism calculated from the following Lagrangian

$$L = L_{J/Ψ, ρπ} + L_{ρNN}$$

with

$$L_{J/Ψ, ρπ} = \frac{g_{J/Ψ, ρπ}}{m_{J/Ψ}} e^{\alpha_3 ρπ} \sigma_{αβ} φ_{J/Ψ,β} \partial_{α} p_{ν} \cdot \vec{ρ},$$

$$L_{ρNN} = \bar{ψ}_N[γ_γ - \frac{κ_ρ}{2m_N} σ^{σδ} ] \bar{ρ}_γ \cdot \frac{τ}{2} \psi_N,$$

where $g_{J/Ψ, ρπ} = 0.032$ is determined from the width of $J/Ψ → ρ + π$, $g_{ρNN} = 6.23$ and $κ_ρ = 1.825$ are taken from a dynamical model of $πN$ scattering.

For the calculations of $π + ^4He → [^3He]_{J/Ψ} + N$, we need to calculate the bound state wavefunction from a $[^3He]_{J/Ψ}$ potential $V_{3,J/Ψ} = α_3 e^{-μ \rho}$. Here we use $α_3 = 0.33$ and $μ = 257$ MeV determined [1] from the Pomeron-quark coupling model of Brodsky, Schmidt, and de Teramond [6]. For the calculations of $π + ^3He → [q^6]_{J/Ψ} + N$, the probability of finding a six-quark cluster $q^6$ in $^3He$ is determined by using the Compound Bag model [9] of $NN$ interaction. The relative wavefunction of $J/Ψ-q^6$ is constrained by reproducing the $^3He$ charge form factor, as detailed in Ref. [1].

The results from pion and photon beams are compared in Fig.2 for the $[^3He]_{J/Ψ}$ production on a $^4He$ target and in Fig.3 for $[q^6]_{J/Ψ}$ production on a $^3He$ target. We see that the cross sections from pions are about a factor of 2-3 larger than those from photons. We also see that the detections of these bound states with hidden charm are favored at energies near the production threshold.

III. PRODUCTION ON DEUTERON TARGET

To facilitate the experimental determination of the $J/Ψ-N$ interaction, we make predictions of the cross sections of $γ/π + d → J/Ψ + n + p$. In the impulse approximation,
FIG. 1: The impulse approximation mechanism of $\gamma/\pi + A \rightarrow N + [B]_{J/\psi}$ reaction. $A$ is a nucleus with mass number $A$ and $B$ could be a nucleus with mass number $(A-1)$ or a $[q^3(A-1)]$ multi-quark cluster.

FIG. 2: Production cross sections of $\gamma/\pi + ^4He \rightarrow [^3He]_{J/\psi} + n$.

the amplitude of this process is the coherent sum of the three mechanisms illustrated in Fig.4. The $\pi + N \rightarrow J/\Psi + N$ amplitudes needed in the calculations are computed from the $\rho$-exchange mechanism, as described in section II. The $\gamma + N \rightarrow J/\Psi + N$ amplitude is taken from Ref.[1], $NN \rightarrow NN$ amplitudes are generated from the Bonn potential, and $J/\Psi + N \rightarrow J/\Psi + N$ amplitudes are generated from a potential $v_{J/\Psi-N} = -\alpha e^{-\mu r}$. With $\mu = 630$ MeV, the strength $\alpha$ determines the s-wave scattering lengths $a$. In presenting our results, we use $a$ to indicate the strength of the considered $J/\Psi$-N potential model.

We find that the kinematics favoring the determination of $v_{J/\Psi,N,J/\Psi}$ is in the region where the outgoing proton is in the $\theta_p = 0$ forward angle. In Fig.5, we compare the predicted differential cross section of the outgoing proton at $\theta_p = 0$, where $\kappa_{J/\Psi}$ denotes the relative momentum of the outgoing $J/\Psi$-n pair. We see that cross sections for pion beam are larger than that for the photon beams in the low $\kappa_{J/\Psi}$ region where the $J/\Psi$-N relative motion is slow. We also see that the predicted magnitudes depend on the scattering length $a$ of the $J/\Psi$-N potential model. The results for $a = -8.83$ fm(left) are about a factor of 10 larger than those for $a = -0.24$ fm(right).

In Fig.6, we show the relative importance between the different mechanisms illustrated in Fig.4. For the case with photon beams (left), the $J/\Psi$-N re-scattering term (Fig.4(c)) dominants in the considered kinematic region. Thus the measured cross section (solid curve) can be used to sensitively test the considered $J/\Psi$-N potential models. For the results with pion beams (right), determinations of $J/\Psi$-N interaction clearly need an accurate calcula-
FIG. 3: Production cross sections of $\gamma/\pi + ^3\text{He} \rightarrow [q^6]_{J/\Psi} + n$

tion of the impulse term (Fig. 4(a)), which is comparable to the $J/\Psi$-N re-scattering term (Fig. 4(c)).

FIG. 4: The mechanisms of $\gamma + d \rightarrow J/\Psi + p + n$.

IV. DISCUSSIONS

If the predicted bound states $[^3\text{He}]_{J/\Psi}$ and $[q^6]_{J/\Psi}$ can be detected, it will provide useful information to understand the role of the gluon field in determining nuclear properties. Thus the experiments on $\gamma/\pi + ^4\text{He}[^3\text{He}] \rightarrow N +[^3\text{He}]_{J/\Psi} ([q^6]_{J/\Psi})$ will be very interesting to perform at J-PARC and JLab. However, the data can be analyzed properly only when we have information to determine the basic $J/\Psi$-N interactions. Our predictions on the cross sections for $\gamma/\pi + d \rightarrow J/\Psi + n + p$ can facilitate the future experimental efforts in this direction.
FIG. 5: The differential cross sections of $\gamma/\pi + d \rightarrow J/\Psi + n + p$

FIG. 6: Relative importance between the contributions from three mechanisms illustrated in Fig.4 to the differential cross sections of $\gamma/\pi + d \rightarrow J/\Psi + n + p$. Imp: Fig.4(a), NN: Fig.4(b), $J/\Psi N$: Fig.4(c).
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