One-pion-exchange final-state interaction and the $p\bar{p}$ near threshold enhancement in $J/\psi \to \gamma p\bar{p}$ decays

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For the $N\bar{N}$ system, the one-pion-exchange (OPE) interaction gives the largest attractive force for $N\bar{N}$ with an isospin $I=0$ and spin $S=0$, while a near-threshold enhancement was observed for $p\bar{p}$ with $I=0$ and $S=0$ in $J/\psi \to \gamma p\bar{p}$ decays. With a K-matrix approach, we find that the OPE final-state interaction makes an important contribution to the near-threshold enhancement in the $p\bar{p}$ mass spectrum in $J/\psi \to \gamma p\bar{p}$ decays.

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Recently the BES Collaboration has observed a near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from the radiative decays $J/\psi \to \gamma p\bar{p}$ [1]. The enhancement can be fitted with either an S- or P-wave Breit-Wigner resonance function. No similar structure is seen in $J/\psi \to \pi^0 p\bar{p}$ decays. In the S-wave case, the peak mass is below $2M_p$ around $M=1859$ MeV with a total width $\Gamma<30$ MeV. These observations together with other similar results in the decays of B mesons [2] have stimulated further investigations of the quasibound nuclear baryonium or multiquark resonance near the $2M_p$ threshold. What is the origin of the $p\bar{p}$ enhancement at $M_{p\bar{p}} \approx 2M_p$ in the radiative decays $J/\psi \to \gamma p\bar{p}$? Datta *et al*. [3] describe the enhancement as the formation of a zero baryon number, ‘‘deuteronlike’’ singlet $^1S_0$ state. Does it come from any quasibound nuclear baryonium or multiquark resonance near the $2M_p$ threshold? In order to draw a conclusion we must study other dynamics which might affect the spectrum of the outgoing proton and antiproton.

The question of possible nucleon-antinucleon ($N\bar{N}$) bound states was raised many years ago, in particular by Fermi and Yang [4]. In the 1960's, explicit attempts were made to describe the spectrum of ordinary mesons as $N\bar{N}$ bound states. It was noticed [5], however, that the $N\bar{N}$ picture hardly reproduces the observed pattens of the meson spectrum. Encouraged by evidence from many intriguing experimental investigations, new types of mesons with a mass near the $N\bar{N}$ threshold and specific decay properties were proposed [6,7]. However, at the time when several candidates for baryonium were proposed, the quasinuclear approach was seriously challenged by a direct quark picture. Stimulated by the success of the quark models, exotic multiquark configurations were studied extensively [8]. The observation of the pentaquark state [9] has stimulated further searches for other multiquark bound states.

It was noticed [10–12] that for a multiquark or quasi-bound hadronic system close to its dissociation threshold, two hadrons will experience their long-range interaction, in particular the pion exchange. ‘‘Hadronic molecule’’ states might be formed. Because of its long-range nature, pion exchange plays a crucial role in achieving the binding of some configuration, especially for two hadrons in a relative S state. In a chiral unitary approach it was also found [13] that solving the coupled-channel Bethe-Salpeter equations is crucial for explaining observations in meson-meson and meson-baryon interactions. Similarly, the outgoing proton and antiproton from the radiative decays $J/\psi \to \gamma p\bar{p}$ will experience the long-range final-state interaction before they are detected. In order to better understand the nature of the experimental observation of the near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from the radiative decays $J/\psi \to \gamma p\bar{p}$ one has to evaluate the final-state-interaction (FSI) contribution to the invariant mass spectrum near $M_{p\bar{p}} \approx 2M_p$.

In this note, with the one-pion-exchange (OPE) potential between the proton and antiproton, we study the FSI of $p\bar{p}$ by the K-matrix approach for radiative decays $J/\psi \to \gamma p\bar{p}$.

It is well known [14] that for the NN system, the central OPE potential is attractive for $(S,I)=(0,1)$ (deuteron) or $(S,I)=(1,0)$ and repulsive for $S=I=0$ (strong) or $S=I=1$ (weak). For the $N\bar{N}$ system, the meson-exchange interaction is related to the corresponding one for the $N\bar{N}$ system by the G-parity transformation, and the OPE potential gets an additional negative sign due to the negative G parity of the pion. Hence the central OPE potential gives the largest attractive force for $N\bar{N}$ with $S=I=0$. The attractive force is 3 times stronger than the corresponding one for the deuteron. The near-threshold narrow enhancement observed in the $J/\psi \to \gamma p\bar{p}$ happens to have quantum numbers $S=I=0$ preferred [1]. From the one-pion-exchange theory [14,15], the nucleon-antinucleon potential can be written as

$$V^{\pi}_{p\bar{p}} = \frac{C^{SI} f_\pi^2}{\vec{q}^{\,2}+m_\pi^2}, \tag{1}$$

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with $C^{00}=-3$ for $S=I=0$, $C^{11}=-1/3$, and $C^{10}=C^{01}=1$. Here f_π is the πNN coupling constant $f_\pi^2/4\pi \simeq 0.08$ and m_π the mass of the π meson. $\vec{q}$ is the three-momentum transfer between the proton and antiproton. The $p\bar{p}$ with $I=S=L=0$ from the radiative decays $J/\psi \to \gamma p\bar{p}$ will experience the largest attractive long-range OPE final-state interaction. From the one-pion-exchange potential, in principle, one could calculate the two-body $N\bar{N}$ scattering amplitude by solving the Bethe-Salpeter equation

$$\bar{T}=V+VG\bar{T}. \tag{2}$$

Here G is the loop function of a proton and an antiproton propagator. It has been shown [16] that the K-matrix formalism provides an elegant way of expressing the unitarity of the S matrix for processes of the type $a+b\to c+d$. In the K-matrix approach the invariant S-wave $p\bar{p}$ scattering T matrix can be expressed as

$$\bar{T}=\frac{K_s}{1-iK_s\rho_{p\bar{p}}}, \tag{3}$$

where $\rho_{p\bar{p}}$ is the phase space factor for the $p\bar{p}$ system:

$$\rho_{p\bar{p}}=\frac{M_p^2 k}{\pi\sqrt{s}}, \tag{4}$$

with s the invariant mass squared of the $p\bar{p}$ system and $k=\sqrt{s/4-M_p^2}$ the momentum magnitude of the proton in the proton-antiproton c.m. system. Following a usual approach for the strong interaction in the K-matrix formalism [17,18], the K_s is taken as the S-wave projection of the $N\bar{N}$ potential—i.e.,

$$K_s=\frac{1}{4k^2}\int_{-4k^2}^{0} dt V_{p\bar{p}}^{\pi}(t), \tag{5}$$

where $t=-\vec{q}^{\,2}$. For the $I=S=0$ case, K_s can be easily evaluated from Eq. (5) as

$$K_s=-\frac{3f_\pi^2}{4k^2}\ln\left(1+\frac{4k^2}{m_\pi^2}\right). \tag{6}$$

In this approach, by considering the OPE FSI of the proton and antiproton, the T matrix for $J/\psi\to\gamma p\bar{p}(^1S_0)$ decays can be written as

$$T_{J/\psi\to\gamma p\bar{p}}=\frac{T^{(0)}_{J/\psi\to\gamma p\bar{p}}}{1-i\rho_{p\bar{p}}K_s}=\frac{T^{(0)}_{J/\psi\to\gamma p\bar{p}}}{1+i\dfrac{3M_p^2}{k\sqrt{s}}\dfrac{f_\pi^2}{4\pi}\ln\left(1+\dfrac{4k^2}{m_\pi^2}\right)}. \tag{7}$$

Here $T^{(0)}_{J/\psi\to\gamma p\bar{p}}$ is the T matrix of the bare $J/\psi\to\gamma p\bar{p}(^1S_0)$ without considering the FSI. Conservation of parity and total angular momentum requires the orbital angular momentum between γ and the $p\bar{p}(^1S_0)$ to be $L=1$, so that the $T^{(0)}$ is proportional to the momentum of the photon K_γ in the J/ψ rest system—i.e.,

$$T^{(0)}_{J/\psi\to\gamma p\bar{p}}=CK_\gamma. \tag{8}$$

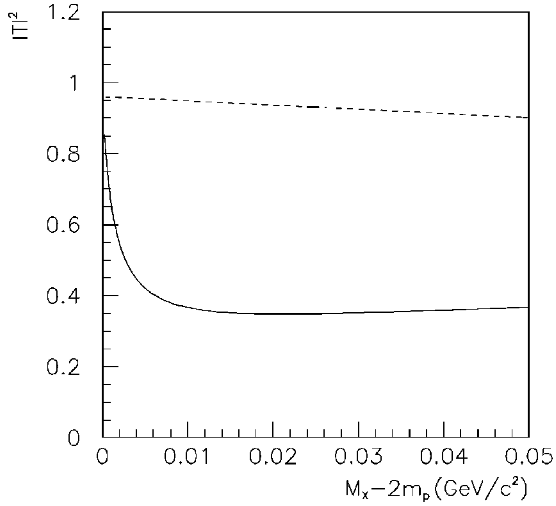

FIG. 1. T matrix squared with (solid line) and without (dashed line) OPE FSI's, with an arbitrary normalization.

In reality, C should be an s-dependent function. Here to illustrate the OPE FSI effect, we assume C as a constant. In Fig. 1 we show the T matrix squared as a function of the invariant mass of the proton and antiproton for the $J/\psi\to\gamma p\bar{p}(^1S_0)$ process. The solid line corresponds to that with the FSI and the dashed line is that without the FSI. We find that the final-state interaction has an important contribution to the $p\bar{p}$ enhancement near $M_{p\bar{p}}=2M_p$ in $J/\psi\to\gamma p\bar{p}$ decays. Compared with plateau region well above threshold, the OPE FSI enhancement factor at the $p\bar{p}$ threshold is larger than 2. The phenomenon of a narrow near-threshold peak due to the t-channel pion exchange is not new. For example, the striking narrow peak near $p\omega$ threshold in the $\gamma p\to\omega p$ process is found to be produced by the t-channel pion exchange [19].

It is well known that there is a very large production of two gluon system with $J^{PC}=0^{-+}$ below $2M_p$ from the J/ψ radiative decays [20–26]. So C should at least have some broad resonance peaks below $2M_p$, which have not been well understood. It is quite possible that interference of those components plus the narrow OPE FSI structure could explain the $p\bar{p}$ near threshold enhancement in the $J/\psi\to\gamma p\bar{p}$ process. Note that the FSI through an s-channel subthreshold resonance has $K_S=g^2/(M_R^2-s)$, which is always negative and interferes with the t-channel attractive (repulsive) force constructively (destructively).

For $J/\psi\to\pi^0 p\bar{p}$ decays, the dominant mechanism is expected to be $J/\psi\to\bar{p}N^*+\text{H.c.}$ with $N^*\to p\pi^0$ [27]. So the p and $\bar{p}$ are not produced from the same hadronic vertex, hence should experience much less FSI than in the case of $J/\psi\to\gamma p\bar{p}$ where $p\bar{p}$ come from the same hadronic vertex.

Moreover, because of the isospin and *G*-parity conservation, the $p\bar{p}$ system must have isospin 1 and spin 1 for the near-threshold S wave. The corresponding t-channel pion exchange $p\bar{p}$ interaction is a factor of 9 weaker than for the isoscalar $p\bar{p}(^1S_0)$ system. Hence one should find negligible near-threshold $p\bar{p}$ enhancement. In the decays of B mesons, $B^0 \to D^0 p\bar{p}$ and $B^{\pm} \to K^{\pm} p\bar{p}$, the isospin of the $p\bar{p}$ system has isospin 0. The enhancement of the low-mass $p\bar{p}$ systems in B decays may also be understood by the FSI. The very narrow proton-antiproton atomic states observed by LEAR experiments [28] at $p\bar{p}$ threshold may also play some role in various narrow structures observed recently near $p\bar{p}$ threshold.

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