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Angular distributions in $J/\psi \to p\bar{p}\pi^0(\eta)$ decays

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ABSTRACT

The differential decay rates of the processes $J/\psi \to p\bar{p}\pi^0$ and $J/\psi \to p\bar{p}\eta$ close to the $p\bar{p}$ threshold are calculated with the help of the $N\bar{N}$ optical potential. The same calculations are made for the decays of $\psi(2S)$. We use the potential which has been suggested to fit the cross sections of $N\bar{N}$ scattering together with $N\bar{N}$ and six pion production in e^+e^- annihilation close to the $p\bar{p}$ threshold. The $p\bar{p}$ invariant mass spectrum is in agreement with the available experimental data. The anisotropy of the angular distributions, which appears due to the tensor forces in the $N\bar{N}$ interaction, is predicted close to the $p\bar{p}$ threshold. This anisotropy is large enough to be investigated experimentally. Such measurements would allow one to check the accuracy of the model of $N\bar{N}$ interaction.

1. Introduction

The cross section of the process $e^+e^- \to p\bar{p}$ reveals an enhancement near the threshold [1–4]. The enhancement near the $p\bar{p}$ threshold has been also observed in the decays $J/\psi \to \gamma p\bar{p}$, $B^+ \to K^+ p\bar{p}$, and $B^0 \to D^0 p\bar{p}$ [5–7]. These observations led to numerous speculations about a new resonance [5], $p\bar{p}$ bound state [8–10] or even a glueball state [11–13] with the mass near two proton mass. This enhancement could appear due to the nucleon–antinucleon final-state interaction. It has been shown that the behavior of the cross sections of $N\bar{N}$ production in e^+e^- annihilation can be explained with the help of Jülich model [14,15] or slightly modified Paris model [16,17]. These models also describe the energy dependence of the proton electromagnetic form factors ratio $|G_E^p/G_M^p|$. A strong dependence of the ratio on the energy close to the $p\bar{p}$ threshold is a consequence of the tensor part of the $N\bar{N}$ interaction.

Another phenomenon has been observed in the process of e^+e^- annihilation to mesons. A sharp dip in the cross section of the process $e^+e^- \to 6\pi$ has been found in the vicinity of the $N\bar{N}$ threshold [18–22]. This feature is related to the virtual $N\bar{N}$ pair production with subsequent annihilation to mesons [23,24]. In Ref. [24] a potential model has been proposed to fit simultaneously the cross sections of $N\bar{N}$ scattering and $N\bar{N}$ production in e^+e^- annihilation. This model describes the cross section of the process $e^+e^- \to 6\pi$ near the $N\bar{N}$ threshold as well. A qualitative description of this process was also achieved using the Jülich model [23].

In this paper we investigate the decays $J/\psi \to p\bar{p}\pi^0$ and $J/\psi \to p\bar{p}\eta$ taking the $p\bar{p}$ final-state interaction into account. Investigation of these processes has been performed in Refs. [25,26] using the chiral model [27]. However, the tensor part of the $p\bar{p}$ interaction was neglected in that paper. To describe the $p\bar{p}$ interaction we use the potential model proposed in Ref. [24], where the tensor forces play an important role. The account for the tensor interaction allows us to analyze the angular distributions in the decays of J/ψ and $\psi(2S)$ to $p\bar{p}\pi^0(\eta)$ near the $p\bar{p}$ threshold. The parameter of anisotropy is large enough to be studied in the experiments.

2. Decay amplitude

Possible states for a $p\bar{p}$ pair in the decays $J/\psi \to p\bar{p}\pi^0$ and $J/\psi \to p\bar{p}\eta$ have quantum numbers $J^{PC} = 1^{--}$ and $J^{PC} = 1^{+-}$. The dominating mechanism of the $p\bar{p}$ pair creation is the following. The $p\bar{p}$ pair is created at small distances in the $^3S_1$ state and acquires an admixture of $^3D_1$ partial wave at large distances due to the tensor forces in the nucleon–antinucleon interaction. The $p\bar{p}$ pairs have different isospins for the two final states under consideration ($I = 1$ for the $p\bar{p}\pi^0$ state, and $I = 0$ for the $p\bar{p}\eta$ state), that allows one to analyze two isospin states independently. Therefore, these decays are easier to investigate theoretically than the process $e^+e^- \to p\bar{p}$, where the $p\bar{p}$ pair is a mixture of different isospin states.

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We derive the formulas for the decay rate of the process $J/\psi \to p\bar{p}x$, where x is one of the pseudoscalar mesons π^0 or η. The following kinematics is considered: $\boldsymbol{k}$ and ε_k are the momentum and the energy of the x meson in the J/ψ rest frame, $\boldsymbol{p}$ is the proton momentum in the $p\bar{p}$ center-of-mass frame, M is the invariant mass of the $p\bar{p}$ system. The following relations hold:

$$
\begin{aligned}
p &= |\boldsymbol{p}| = \sqrt{\frac{M^2}{4} - m_p^2}\,, \\
k &= |\boldsymbol{k}| = \sqrt{\varepsilon_k^2 - m^2}\,, \\
\varepsilon_k &= \frac{m_{J/\psi}^2 + m^2 - M^2}{2m_{J/\psi}}\,,
\end{aligned} \tag{1}
$$

where m is the mass of the x meson, $m_{J/\psi}$ and m_p are the masses of a J/ψ meson and a proton, respectively, and $\hbar = c = 1$. Since we consider the $p\bar{p}$ invariant mass region $M - 2m_p \ll m_p$, the proton and antiproton are nonrelativistic in their center-of-mass frame, while ε_k is about 1 GeV.

The spin-1 wave function of the $p\bar{p}$ pair in the center-of-mass frame has the form [17]

$$
\boldsymbol{\psi}_\lambda^I = \mathbf{e}_\lambda u_1^I(0) + \frac{u_2^I(0)}{\sqrt{2}}\left[\mathbf{e}_\lambda - 3\hat{\boldsymbol{p}}(\mathbf{e}_\lambda \cdot \hat{\boldsymbol{p}})\right], \tag{2}
$$

where $\hat{\boldsymbol{p}} = \boldsymbol{p}/p$, $\mathbf{e}_\lambda$ is the polarization vector of the spin-1 $p\bar{p}$ pair,

$$
\sum_{\lambda=1}^{3} \mathrm{e}_\lambda^i \mathrm{e}_\lambda^{j*} = \delta_{ij}\,, \tag{3}
$$

$u_1^I(r)$ and $u_2^I(r)$ are the components of two independent solutions of the coupled-channels radial Schrödinger equations

$$
\begin{aligned}
&\frac{p_r^2}{m_p}\chi_n + \mathcal{V}\chi_n = 2E\chi_n\,, \\
&\mathcal{V} = \begin{pmatrix} V_S^I & -2\sqrt{2}\,V_T^I \\ -2\sqrt{2}\,V_T^I & V_D^I - 2V_T^I + \dfrac{6}{m_p r^2} \end{pmatrix}, \qquad \chi_n = \begin{pmatrix} u_n^I \\ w_n^I \end{pmatrix}.
\end{aligned} \tag{4}
$$

Here $E = p^2/2m_p$, V_S^I and V_D^I are the $N\bar{N}$ potentials in S- and D-wave channels, and V_T^I is the tensor potential. Two independent regular solutions of these equations are determined by their asymptotic forms at large distances [17]

$$
\begin{aligned}
u_1^I(r) &= \frac{1}{2ipr}\left[S_{11}^I\, e^{ipr} - e^{-ipr}\right], \\
u_2^I(r) &= \frac{1}{2ipr} S_{21}^I\, e^{ipr}, \\
w_1^I(r) &= -\frac{1}{2ipr} S_{12}^I\, e^{ipr}, \\
w_2^I(r) &= \frac{1}{2ipr}\left[-S_{22}^I e^{ipr} + e^{-ipr}\right],
\end{aligned} \tag{5}
$$

where S_{ij}^I are some functions of energy. The formula (2) corresponds to the Jost approximation, which is the near-threshold limit of the DWBA [28].

The Lorentz transformation for the spin-1 wave function of the $p\bar{p}$ pair can be written as

$$
\tilde{\boldsymbol{\psi}}_\lambda^I = \boldsymbol{\psi}_\lambda^I + (\gamma - 1)\hat{\boldsymbol{k}}(\boldsymbol{\psi}_\lambda^I \cdot \hat{\boldsymbol{k}})\,, \tag{6}
$$

where $\tilde{\boldsymbol{\psi}}_\lambda^I$ is the wave function in the J/ψ rest frame, $\hat{\boldsymbol{k}} = \boldsymbol{k}/k$, and γ is the γ-factor of the $p\bar{p}$ center-of-mass frame. The component collinear to $\boldsymbol{k}$ does not contribute to the amplitude of the decay under consideration because the amplitude is transverse to $\boldsymbol{k}$. As a result, the dimensionless amplitude of the decay with the corresponding isospin of the $p\bar{p}$ pair can be written as

$$
T_{\lambda\lambda'}^I = \frac{\mathcal{G}_I}{m_{J/\psi}}\boldsymbol{\psi}_\lambda^I\,[\boldsymbol{k} \times \boldsymbol{\epsilon}_{\lambda'}]\,. \tag{7}
$$

Here $\mathcal{G}_I$ is an energy-independent dimensionless constant, $\boldsymbol{\epsilon}_{\lambda'}$ is the polarization vector of J/ψ,

$$
\sum_{\lambda'=1}^{2} \epsilon_{\lambda'}^i \epsilon_{\lambda'}^{j*} = \delta_{ij} - n^i n^j\,, \tag{8}
$$

where $\boldsymbol{n}$ is the unit vector collinear to the momentum of electrons in the beam. The amplitude $T_{\lambda\lambda'}^I$ is the effective operator which should be linear with respect to the wave functions of each particle ($\boldsymbol{\psi}_\lambda^I$ for $p\bar{p}$ pair and $\boldsymbol{\epsilon}_{\lambda'}$ for J/ψ meson). Only the wave functions depend on the polarization indexes λ and λ'. This is why the constant $\mathcal{G}_I$ is independent of λ and λ'.

The decay rate of the process $J/\psi \to p\bar{p}x$ can be written in terms of the dimensionless amplitude $T_{\lambda\lambda'}^I$ as (see, e.g., [29])

$$
\frac{d\Gamma}{dM d\Omega_p d\Omega_k} = \frac{pk}{2^9\pi^5 m_{J/\psi}^2}\left|T_{\lambda\lambda'}^I\right|^2, \tag{9}
$$

where Ω_p is the proton solid angle in the $p\bar{p}$ center-of-mass frame and Ω_k is the solid angle of the x meson in the J/ψ rest frame.

Substituting the amplitude (7) in Eq. (9) and averaging over the spin states, we obtain the $p\bar{p}$ invariant mass and angular distribution for the decay rate

$$
\begin{aligned}
\frac{d\Gamma}{dM d\Omega_p d\Omega_k} = \frac{\mathcal{G}_I^2 pk^3}{2^{11}\pi^5 m_{J/\psi}^4}\Big\{&\left|u_1^I(0) + \tfrac{1}{\sqrt{2}}u_2^I(0)\right|^2 \\
&+ \left|u_1^I(0) - \sqrt{2}u_2^I(0)\right|^2 (\boldsymbol{n}\cdot\hat{\boldsymbol{k}})^2 \\
&+ \frac{3}{2}\left[\left|u_2^I(0)\right|^2 - 2\sqrt{2}\,\mathrm{Re}\left(u_1^I(0)u_2^{I*}(0)\right)\right] \\
&\times\left[(\boldsymbol{n}\cdot\hat{\boldsymbol{p}})^2 - 2(\boldsymbol{n}\cdot\hat{\boldsymbol{k}})(\boldsymbol{n}\cdot\hat{\boldsymbol{p}})(\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{k}})\right]\Big\}.
\end{aligned} \tag{10}
$$

The invariant mass distribution can be obtained by integrating Eq. (10) over the solid angles Ω_p and Ω_k:

$$
\frac{d\Gamma}{dM} = \frac{\mathcal{G}_I^2 pk^3}{2^5\, 3\pi^3 m_{J/\psi}^4}\left(\left|u_1^I(0)\right|^2 + \left|u_2^I(0)\right|^2\right). \tag{11}
$$

The sum in the brackets is the so-called enhancement factor which equals to unity if the $p\bar{p}$ final-state interaction is turned off.

More information about the properties of $N\bar{N}$ interaction can be extracted from the angular distributions. Integrating Eq. (10) over Ω_p we obtain

$$
\begin{aligned}
\frac{d\Gamma}{dM d\Omega_k} = \frac{\mathcal{G}_I^2 pk^3}{2^9\pi^4 m_{J/\psi}^4}&\left(\left|u_1^I(0)\right|^2 + \left|u_2^I(0)\right|^2\right) \\
&\times\left[1 + \cos^2\vartheta_k\right],
\end{aligned} \tag{12}
$$

where ϑ_k is the angle between $\boldsymbol{n}$ and $\boldsymbol{k}$. However, the angular part of this distribution does not depend on the features of the $p\bar{p}$ interaction. The proton angular distribution in the $p\bar{p}$ center-of-mass frame is more interesting. To obtain this distribution we integrate Eq. (10) over the solid angle Ω_k: