$\psi(1\,^1P_1)$ production in $\bar{p}p$ annihilation

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The model dependence of the $\psi(1\,^1P_1)$ production rate in $\bar{p}p$ annihilation is examined. The predicted production rate for $M_{1\,^1P_1}$ ranging between $M_{1\,^3P_0}$ and $M_{1\,^3P_2}$ is presented, and may be tested by an improved experiment at Fermilab.

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The masses of $1\,^1P_1$ states of heavy quarkonia provide important information about the spin-spin interaction between heavy quarks and antiquarks [1,2]. Experimental searches for the $\psi(1\,^1P_1)$ and $\Upsilon(1\,^1P_1)$ states have been tried at many laboratories. The R704 Group at the CERN Intersecting Storage Rings (ISR) claimed a preliminary result for finding a possible candidate of the $\psi(1\,^1P_1)$ state in $\bar{p}p$ annihilation in the $\pi\pi e^+e^-$ channel, but with poor statistics [3]. A theoretical calculation of the production rate in this process was given by Kuang, Tuan, and Yan [4]. They took the simple Cornell Coulomb plus linear potential, and the obtained production rate

$$\Gamma_{\pi\pi e^+e^-} \equiv \Gamma(\psi(1\,^1P_1)\to\bar{p}p) \times B(\psi(1\,^1P_1)\to J/\psi\pi^+\pi^-)B(J/\psi\to e^+e^-)$$

is of the order of 0.1 eV, which is consistent with the preliminary result by the R704 group [3]. Recently, the E760 group at Fermilab has been doing improved experiments, searching for $\psi(1\,^1P_1)$ states in $\bar{p}p$ annihilation. Further examination of how sensitive the theoretical prediction is to the potential model is therefore needed. In this paper we take a better and more QCD-like potential proposed by Chen and Kuang [5] to do the calculation. We shall consider the rate

$$\Gamma_{\psi^0 e^+e^-} \equiv \Gamma(\psi(1\,^1P_1)\to\bar{p}p) \times B(\psi(1\,^1P_1)\to J/\psi\pi^0)B(J/\psi\to e^+e^-) ,$$

as well to include the $\pi^0e^+e^-$ channel. The potential is of a form with explicit $\Lambda_{\overline{\rm MS}}$ dependence (where $\overline{\rm MS}$ denotes the modified minimal subtraction scheme) and natural QCD interpretations, and it fits the $c\bar{c}$ and $b\bar{b}$ spectra very well for $\Lambda_{\overline{\rm MS}}$ in the range 100–500 MeV. We shall see that our new results for $\Gamma(\psi(1\,^1P_1)\to\bar{p}p)$, $B(\psi(1\,^1P_1)\to J/\psi\pi\pi)$, and $B(\psi(1^1P_1)\to J/\psi\pi^0)$ are rather different from those in Ref. [4], but the production rates $\Gamma_{\pi\pi e^+e^-}$ and $\Gamma_{\pi^0e^+e^-}$ are still of the same order of magnitude. The main theoretical uncertainties in the calculation are also discussed, and they do not affect the order of magnitude of the rates.

The potential I proposed by Chen and Kuang [5] takes the form

$$V(r)=kr-\frac{16\pi}{25}\frac{1}{f(r)}\left[1+\frac{2\gamma_E+\frac{53}{75}}{f(r)}-\frac{462}{625}\frac{\ln f(r)}{f(r)}\right] , \quad (1)$$

where γ_E is the Euler constant, $k=0.149\ {\rm GeV}^{-2}$, and

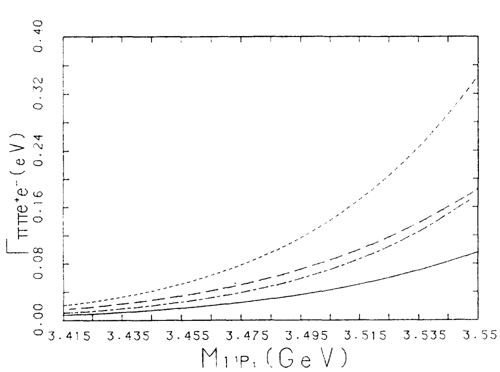

FIG. 1. Production rate $\Gamma_{\pi\pi e^+e^-}$ predicted by the Chen-Kuang potential for $M_{1\,^1P_1}$ ranging between $M_{1\,^3P_0}$ and $M_{1\,^3P_2}$. The solid line ($\alpha_M=\alpha_E$) and the dashed line ($\alpha_M=2\alpha_E$) are obtained by directly using (6) and (7); the dot-dashed line ($\alpha_M=\alpha_E$) and the dotted line ($\alpha_M=2\alpha_E$) are obtained by replacing $\ln(4m_c^2/|4m_c^2-M^2_{1\,^1P_1}|)$ by $\ln(m_cR_c)$ in (6) and (7).

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$$f(r)=\ln\left[\frac{1}{\Lambda_{\overline{MS}}r}+4.62-\left[1-\frac{1}{4}\frac{\Lambda_{\overline{MS}}}{\Lambda^{L}_{\overline{MS}}}\right]\left\{1-\exp\left[-225\left[3\frac{\Lambda^{L}_{\overline{MS}}}{\Lambda_{\overline{MS}}}-1\right]^{2}(\Lambda_{\overline{MS}}r)^{2}\right]\right\}\Big/(\Lambda_{\overline{MS}}r)\right]^{2}, \tag{2}$$

with $\Lambda^{L}_{\overline{MS}}=180$ MeV. The quark masses m_c and m_b depend slightly on the value of $\Lambda_{\overline{MS}}$. Numerical results show that the variation of $\Lambda_{\overline{MS}}$ in the range 100–200 MeV causes only a few percent difference in the rate. In this paper we only present the results calculated with $\Lambda_{\overline{MS}}=200$ MeV (the world averaged value [6]). The corresponding quark masses are $m_c=1.48$ GeV and $m_b=4.88$ GeV.

The calculation of the rates is similar to that in Ref. [4]. $\Gamma(\psi(1\,{}^1P_1)\to J/\psi\pi\pi)$, $\Gamma(\psi(1\,{}^1P_1)\to J/\psi\pi^0)$, $\Gamma(\psi(1\,{}^1P_1)\to\bar{p}p)$, and $\Gamma_{\rm tot}(\psi(1\,{}^1P_1))$ are calculated separately.

For the hadronic transition rates $\Gamma(\psi(1\,{}^1P_1)\to J/\psi\pi\pi)$ and $\Gamma(\psi(1\,{}^1P_1)\to J/\psi\pi^0)$, the approaches in Ref. [4] give

$$\Gamma(\psi(1\,{}^1P_1)\to J/\psi\pi\pi)=\frac{4\alpha_E\alpha_M}{2835\pi m_c^2}|f^{101}_{1110}+f^{010}_{1110}|^2(M_{1\,{}^1P_1}-M_{J/\psi})^7\,, \tag{3}$$

$$\Gamma(\psi(1\,{}^1P_1)\to J/\psi\pi^0)=\frac{1}{9}\frac{\alpha_M}{\alpha_E}\left[\frac{\alpha_E}{\alpha_S}\right]^2\left[\frac{\pi}{3}\right]^3\left[\frac{m_d-m_u}{m_d+m_u}f_\pi m_\pi^2\right]^2\left|\frac{f^{101}_{1110}+f^{010}_{1110}}{m_c}\right|^2|\mathbf{p}_{\pi^0}|\,, \tag{4}$$

where

$$f^{1P_iP_f}_{1110}\equiv\sum_n\langle R_{10}|r^{P_f}|R^{v}_{n1}\rangle\langle R^{v}_{n1}|r^{P_i}|R_{11}\rangle/(M_{1\,{}^1P_1}-E^{v}_{n1})\,, \tag{5}$$

in which R_{11} and R_{10} are, respectively, the radial wave functions of $\psi(1\,{}^1P_1)$ and J/ψ; E^{v}_{n1} and R^{v}_{n1} are the energy eigenvalue and radial wave function of the intermediate state. (The rate is not sensitive to the model for the intermediate state [7]. Here we take the string model approach [8,9].) The phenomenological coupling constant α_E can be determined by taking the well-measured rate $\Gamma(\psi'\to J/\psi\pi\pi)$ [6] as input, and in the Chen-Kuang model, $\alpha_E=0.51$. This is close to the commonly accepted value of $\alpha_s(m_\pi)$; thus, we take $\alpha_s(m_\pi)\approx\alpha_E$ in (4). There is no proper input to determine α_M yet. A reasonable theoretical estimate is $\alpha_E\le\alpha_M\le(2-3)\alpha_E$ [4].

The rate $\Gamma(\psi(1\,{}^1P_1)\to\bar{p}p)$ can be related to the measured rate $\Gamma(\eta_c\to\bar{p}p)$ by [4]

$$\Gamma(\psi(1\,{}^1P_1)\to\bar{p}p)=\frac{\dfrac{320}{9\pi}\alpha_s^3\dfrac{|\psi'_{1\,{}^1P_1}(0)|^2}{M^4_{1\,{}^1P_1}}\ln(4m_c^2/|4m_c^2-M^2_{1\,{}^1P_1}|)}{\frac{8}{3}\alpha_s^2|\psi_{\eta_c}(0)|^2/M^2_{\eta_c}}\Gamma(\eta_c\to\bar{p}p)\,, \tag{6}$$

where $\psi_{\eta_c}(0)$ and $\psi'_{1\,{}^1P_1}(0)$ are , respectively, the wave function at the origin of η_c and the derivative of the wave function at the origin of $\psi(1\,{}^1P_1)$, and the QCD coupling constant α_s at the scale $M_{1\,{}^1P_1}$ is taken to be $\alpha_s(M_{1\,{}^1P_1})=0.22$, corresponding to $\alpha_s(M_\Upsilon)=0.17$ [4].

To calculate $\Gamma_{\rm tot}(\psi(1\,{}^1P_1))$, we need to know the rates for the main decay channel of $\psi(1\,{}^1P_1)$. Following Ref. [4], we have

$$\Gamma(\psi(1\,{}^1P_1)\to\text{light hadrons})=\frac{\dfrac{320}{9\pi}\alpha_s^3\dfrac{|\psi'_{1\,{}^1P_1}(0)|^2}{M^4_{1\,{}^1P_1}}\ln(4m_c^2/|4m_c^2/|4m_c^2-M^2_{1\,{}^1P_1}|)}{\dfrac{40}{81\pi}(\pi^2-9)\alpha_s^3|\psi_{J/\psi}(0)|^2/M^2_{J/\psi}}\Gamma(J/\psi\to3g)\,, \tag{7}$$

$$\Gamma(\psi(1\,{}^1P_1)\to\gamma+\text{light hadrons})=\frac{16}{5}\frac{\alpha}{\alpha_s}\Gamma(\psi(1\,{}^1P_1)\to3g) \tag{8}$$

(from Ref. [10]), where α is the fine-structure constant and

$$\Gamma(J/\psi\to3g)=\Gamma_{\rm tot}(J/\psi)[1-(2+R)B(J/\psi\to e^+e^-)]$$

(from Ref. [4]).

The estimate of the radiative transition rate $\Gamma(\psi(1\,{}^1P_1)\to\gamma\eta_c)$ is uncertain. Following Ref. [4], we estimate $\Gamma(\psi(1\,{}^1P_1)\to\gamma\eta_c)\simeq330$ keV, which is one-half of the value predicted by the nonrelativistic potential model [11]. With all these, we have

TABLE I. Rates predicted by the two potential models. The numbers in the parentheses are obtained from replacing $\ln(4m_c^2/|4m_c^2-M^2_{1\,^1P_1}|)$ by $\ln(m_cR_c)$ in (6) and (7). The results of the Cornell model are calculated with new experimental data [6].

Rates	Chen-Kuang model	Cornell model
$\Gamma(\psi(1\,^1P_1)\rightarrow J/\psi\pi\pi)$ (keV)		
$\alpha_M=\alpha_E$	7.1	4.7
$\alpha_M=2\alpha_E$	14.2	9.3
$\Gamma(\psi(1\,^1P_1)\rightarrow J/\psi\pi^0)$ (keV)		
$\alpha_M=\alpha_E$	0.58	0.29
$\alpha_M=2\alpha_E$	1.16	0.57
$\Gamma(\psi(1\,^1P_1)\rightarrow \bar{p}p)$ (keV)	0.044 (0.080)	0.15 (0.14)
$\Gamma(\psi(1\,^1P_1)\rightarrow \text{hadrons})$ (keV)	19.3 (35)	51 (51)
$\Gamma(\psi(1\,^1P_1)\rightarrow \gamma+\text{hadrons})$ (keV)	2.1 (3.7)	5.7 (5.5)
$\Gamma_{\text{tot}}(\psi(1\,^1P_1))$ (keV)		
$\alpha_M=\alpha_E$	360 (377)	392 (391)
$\alpha_M=2\alpha_E$	367 (384)	398 (397)
$\Gamma(\psi(1\,^1P_1)\rightarrow \bar{p}p)B(\psi(1\,^1P_1)\rightarrow J/\psi\pi^+\pi^-)B(J/\psi\rightarrow e^+e^-)$ (eV)		
$\alpha_M=\alpha_E$	0.061 (0.11)	0.12 (0.12)
$\alpha_M=2\alpha_E$	0.120 (0.21)	0.25 (0.23)
$\Gamma(\psi(1\,^1P_1)\rightarrow \bar{p}p)B(\psi(1\,^1P_1)\rightarrow J/\psi\pi^0)B(J/\psi\rightarrow e^+e^-)$ (eV)		
$\alpha_M=\alpha_E$	0.005 (0.009)	0.008 (0.007)
$\alpha_M=2\alpha_E$	0.010 (0.017)	0.015 (0.014)

$$\Gamma_{\text{tot}}(\psi(1\,^1P_1))\simeq\Gamma(\psi(1\,^1P_1)\rightarrow\gamma\eta_c)+\Gamma(\psi(1\,^1P_1)\rightarrow J/\psi\pi\pi)+\Gamma(\psi(1\,^1P_1)\rightarrow J/\psi\pi^0)$$
$$+\Gamma(\psi(1\,^1P_1)\rightarrow\text{light hadrons})+\Gamma(\psi(1\,^1P_1)\rightarrow\gamma+\text{light hadrons})\ . \tag{9}$$

For any given value of $M_{1\,^1P_1}$, we can obtain all the above rates by taking the experimental data [6] $\Gamma_{\text{tot}}(\psi')=243\pm43$ keV, $B(\psi'\rightarrow J/\psi\pi\pi)=(50.8\pm5.3)\%$, $\Gamma_{\text{tot}}(J/\psi)=68\pm10$ keV, $B(J/\psi\rightarrow e^+e^-)=(6.9\pm0.91)\times10^{-3}$, $\Gamma_{\text{tot}}(\eta_c)=10.3^{+3.8}_{-3.4}$ MeV, and $B(\eta_c\rightarrow\bar{p}p)=(1.04\pm0.19)\times10^{-3}$ as inputs. The center-of-gravity value M_{COG} of $\psi(1\,^3P_J)$ states is $M_{\text{COG}}=3.5254\pm0.0005$ GeV [6]. The calculated rates for $M_{1\,^1P_1}=M_{\text{COG}}$ are listed in Table I. We see that some rates are rather model dependent. The Chen-Kuang potential predicts a larger $\Gamma(\psi(1\,^1P_1)\rightarrow J/\psi\pi\pi)$, but a much smaller $\Gamma(\psi(1\,^1P_1)\rightarrow\bar{p}p)$, so that the obtained production rate $\Gamma_{\pi\pi e^+e^-}$ is smaller than that in the Cornell model by approximately a factor of 2. This is mainly due to the logarithm factor in (6) and (7), $\ln(4m_c^2/|4m_c^2-M^2_{1\,^1P_1}|)$, which is sensitive to the value of m_c ($m_c=1.48$ GeV in the Chen-Kuang model, while $m_c=1.84$ GeV in the Cornell model). To avoid the singularity in $\ln(4m_c^2/|4m_c^2-M^2_{1\,^1P_1}|)$ at $M_{1\,^1P_1}=2m_c$, Remiddi suggested to estimate it by $\ln(m_cR_c)$, where R_c is the radius of the $\psi(1\,^1P_1)$ state [12]. In Table I we list the rates with $\ln(4m_c^2/|4m_c^2-M^2_{1\,^1P_1}|)$ replaced by $\ln(m_cR_c)$ in (6) and (7) in the parentheses. We see that the final production rates predicted by the two potential models are close to each other with this replacement.

The main theoretical uncertainties in this calculation are due to (a) lack of a reliable determination of α_M/α_E, (b) different possible estimates of the logarithm factor in (6) (model dependent), and (c) lack of a reliable estimate of $\Gamma(\psi(1\,^1P_1)\rightarrow\gamma\eta_c)$. Each of them may cause an uncertainty about a factor of 2 (cf. Table I), and the last uncertainty may be reduced if relativistic and coupled-channel corrections are carefully taken into account [13]. Anyway, both the model dependence and the above uncertainties do not affect the order of magnitude of the predicted production rates $\Gamma_{\pi\pi e^+e^-}$ and $\Gamma_{\pi^0e^+e^-}$, which are of the order of 0.1 and 0.01 keV, respectively, for $M_{1\,^1P_1}=M_{\text{COG}}$.

The production rate $\Gamma_{\pi\pi e^+e^-}$ for $M_{1\,^1P_1}$ ranging between $M_{1\,^3P_0}$ and $M_{1\,^3P_2}$ is given in Fig. 1. This is expected to be compared with the improved experiment at Fermilab.

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