Evidence for a $J/\psi p\bar{p}$ Pauli Strong Coupling?

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The couplings of charmonia and charmonium hybrids (generically $\Psi$) to $p\bar{p}$ are of great interest in view of future plans to study these states using an antiproton storage ring at GSI. These low to moderate energy $\Psi p\bar{p}$ couplings are not well understood theoretically, and currently must be determined from experiment. In this letter we note that the two independent $p\bar{p}$ couplings $\gamma_\mu$ and $\sigma_{\mu\nu}$ of the $J/\psi$ and $\psi'$ can be constrained by the angular distribution of $e^+e^-\rightarrow(J/\psi,\psi')\rightarrow p\bar{p}$ on resonance. The unpolarized differential cross section has a twofold ambiguity, and as a result the ratio of the $\gamma_\mu$ to $\sigma_{\mu\nu}$ $p\bar{p}$ couplings is not uniquely determined by this data. This ambiguity can be resolved by a study of the polarized reaction, or of the unpolarized processes $e^+e^-\rightarrow(J/\psi,\psi')\rightarrow\Lambda\bar{\Lambda}$. A comparison of our theoretical results to recent unpolarized data allows estimates of these couplings; in the better determined $J/\psi$ case the data is inconsistent with pure $\gamma_\mu$ coupling, and can be explained by the presence of a $\sigma_{\mu\nu}$ term. This Pauli coupling may significantly suppress the cross section for the PANDA process $p\bar{p}\rightarrow\pi^0J/\psi$ near threshold.

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I. INTRODUCTION

Charmonium is usually studied experimentally through $e^+e^-$ annihilation or hadronic production, notably in $p\bar{p}$ annihilation. The $p\bar{p}$ annihilation process was employed by the fixed target experiments E760 and E835 at Fermilab, which despite small production cross sections succeeded in giving very accurate results for the masses and total widths of the narrow charmonium states $J/\psi$, $\psi'$, $\chi_1$, and $\chi_2$. A future experimental research program on charmonium and charmonium hybrids using $p\bar{p}$ annihilation planned by the PANDA collaboration [1] at GSI is one motivation for this research.

Obviously the strengths and detailed forms of the couplings of charmonium states to $p\bar{p}$ are crucial questions for any experimental program that uses $p\bar{p}$ annihilation to study charmonium; see for example the predictions for the associated production processes $p\bar{p}\rightarrow\Psi\pi^0$ in Refs.[2–4]. (We use $\Psi$ to denote a generic charmonium or charmonium hybrid state, and $\psi$ if the state has $J^{PC}=1^{--}$.)

Unfortunately, these low to moderate energy production reactions involve obscure and presumably rather complicated QCD processes, so for the present they are best inferred from experiment. In Ref.[4] we carried out this exercise by using the measured $p\bar{p}$ partial widths as input to estimate the coupling constants of the $J/\psi,\psi',\eta,\eta',\chi_0$ and $\chi_1$ to $p\bar{p}$, assuming that the simplest Dirac couplings were dominant. These $\Psi p\bar{p}$ couplings were then used in a PCAC-like model to give numerical predictions for several associated charmonium production cross sections of the type $p\bar{p}\rightarrow\pi^0\Psi$.

In this paper we generalize these results for the $J/\psi$ and $\psi'$ by relaxing the assumption of $\gamma_\mu$ dominance of the $\psi p\bar{p}$ vertex. We assume a $\psi p\bar{p}$ vertex with both a $\gamma_\mu$ vector and a Pauli $\sigma_{\mu\nu}$ term, and derive the differential and total cross sections for $e^+e^-\rightarrow\psi\rightarrow p\bar{p}$ given this more general coupling. Both unpolarized and polarized processes are treated.

A comparison of our theoretical unpolarized angular distributions to recent experimental $J/\psi$ results allows estimates of both the vector and Pauli couplings in this case. There is a twofold ambiguity in determining the ratio $\kappa$ of the Pauli to vector $J/\psi p\bar{p}$ couplings from unpolarized data; the larger Pauli solution predicts important Pauli-vector destructive interference in $p\bar{p}\rightarrow\pi^0J/\psi$, which considerably reduces this cross section near threshold. Determining which $\kappa$ solution is correct is important for PANDA, and can be accomplished through measurements of polarized $e^+e^-\rightarrow J/\psi\rightarrow p\bar{p}$ or through studies of the angular distribution of the unpolarized, self-analyzing process $e^+e^-\rightarrow J/\psi\rightarrow\Lambda\bar{\Lambda}$. 

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II. UNPOLARIZED CASE

The Feynman diagram used to model this process is shown in Fig. 1. We assume a vertex for the coupling of a generic $1^-$ vector charmonium state $\psi$ to $p\bar{p}$ of the form

$$\Gamma_\mu(p\bar{p}) = g(\gamma_\mu + \frac{i\kappa}{2M}\sigma_\mu q_\nu).$$  \hspace{1cm} (1)$$

In this paper $m$ and $M$ are the proton and charmonium mass, $\Gamma$ is the charmonium total width, and we assume massless initial leptons. Following DIS conventions, $q_\nu$ is the four momentum transfer from the nucleon to the electron; thus in our reaction $e^+e^-\rightarrow p\bar{p}$ in the c.m. frame we have $q = (-\sqrt{s}, 0)$. The couplings $g$ and $\kappa$ are actually momentum dependent form factors, but since we only access them very close to the kinematic point $q^2 = M^2$ in the reactions $e^+e^-\rightarrow (J/\psi, \psi')\rightarrow p\bar{p}$, we will treat them as constants.

![Feynman Diagram](image)

**FIG. 1:** The Feynman diagram assumed in this model of the generic reaction $e^+e^-\rightarrow \psi\rightarrow p\bar{p}$.

The unpolarized differential and total cross sections for $e^+e^-\rightarrow \psi\rightarrow p\bar{p}$ may be expressed succinctly in terms of strong $\psi p\bar{p}$ Sachs form factors $G_E = g(1 + ks/4m^2)$ and $G_M = g(1 + \kappa)$. (We assume that $G_E$ and $G_M$ are real but may be of either sign, and use angle brackets to denote an unpolarized quantity.) The unpolarized total cross section is given by

$$\langle \sigma \rangle = \frac{4\pi\alpha^2 M^4}{3f^2_{\psi}} \frac{(1 - 4m^2/s)^{1/2}}{s^2(1 - M^2/s)^2 + \Gamma^2 M^2)} (2m^2 G^2_E + s G^2_M).$$  \hspace{1cm} (2)$$

Exactly on resonance ($s = M^2$) this can be expressed in terms of the $\psi$ partial widths

$$\Gamma_{\psi\rightarrow e^+e^-} = \frac{4\pi\alpha^2 M}{3f^2_{\psi}}$$

and

$$\Gamma_{\psi\rightarrow p\bar{p}} = \frac{(1 - 4m^2/M^2)^{1/2}}{12\pi M} (2m^2 G^2_E + M^2 G^2_M),$$

which gives the familiar result

$$\langle \sigma \rangle |_s=M^2 = \frac{12\pi}{M^2} B_{e^+e^-} B_{p\bar{p}}$$

where $B_{e^+e^-}$ and $B_{p\bar{p}}$ are the $\psi\rightarrow e^+e^-$ and $\psi\rightarrow p\bar{p}$ branching fractions.

Since the (unpolarized) $p\bar{p}$ width and total cross section on resonance involve only the single linear combination $(2m^2 G^2_E + M^2 G^2_M)$, separating these two strong form factors requires additional information, such as the angular distribution. The unpolarized $e^+e^-\rightarrow \psi\rightarrow p\bar{p}$ differential cross section in the c.m. frame is given by

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 M^4}{4f^2_{\psi}} \frac{(1 - 4m^2/s)^{1/2}}{s^2((s - M^2)^2 + \Gamma^2 M^2)} \left\{4m^2 G^2_E(1 - \mu^2) + s G^2_M(1 + \mu^2)\right\}.$$  \hspace{1cm} (6)$$

This angular distribution is often written as $1 + \alpha \mu^2$, where

$$\alpha = \frac{1 - (4m^2/s)(G_E/G_M)^2}{1 + (4m^2/s)(G_E/G_M)^2}.$$  \hspace{1cm} (7)$$

One can evidently extract the magnitude of $G_E/G_M$ from the unpolarized differential cross section, but not the overall sign. This implies a twofold ambiguity in the size of the anomalous strong coupling $\kappa$, which is related to $G_E/G_M$ by $\kappa = (G_E/G_M - 1)/(s/4m^2 - G_M/G_M)$.

For a sufficiently narrow resonance one can replace $4m^2/s$ above by $\tau = 4m^2/M^2$. The coefficient $\alpha$ may then be written in terms of the $\psi p\bar{p}$ vertex parameters of Eq. 1 as

$$\alpha = \frac{(1 - \tau)(r - \kappa^2)}{r(1 + \tau) + 4r\kappa + (1 + \tau)\kappa^2}.$$  \hspace{1cm} (8)$$

III. COMPARISON TO EXPERIMENT

Experimental values of $\alpha$ have been reported by several collaborations. The results for the $J/\psi$ are

$$\alpha = \begin{cases} 1.45 \pm 0.56, & \text{MarkI } [5] \\ 1.7 \pm 1.7, & \text{DASP } [6] \\ 0.61 \pm 0.23, & \text{MarkII } [7] \\ 0.56 \pm 0.14, & \text{MarkIII } [8] \\ 0.62 \pm 0.11, & \text{DM2 } [9] \\ 0.676 \pm 0.036 \pm 0.042, & \text{BES } [10]. \end{cases}$$  \hspace{1cm} (9)$$

and for the $\psi'$

$$\alpha = \begin{cases} 0.67 \pm 0.15 \pm 0.04, & \text{E835 } [11] \\ 0.85 \pm 0.24 \pm 0.04, & \text{BES } [12]. \end{cases}$$  \hspace{1cm} (10)$$

For our comparison with experiment we use the statistically most accurate measurement for each charmonium state, and combine the errors in quadrature. This gives experimental estimates for $\alpha$ of $0.676 \pm 0.055$ and $0.67 \pm 0.155$ for the $J/\psi$ and $\psi'$ respectively.

Initially we will compare these experimental numbers to the “null hypothesis” of no Pauli term, $\kappa = 0$, in which
case $\alpha = (1 - r)/(1 + r)$. This $\kappa = 0$ formula was previously given by Claudson, Glashow and Wise [13] and by Carimalo [14]; the value of $\alpha$ under various theoretical assumptions has been discussed by these references and by Brodsky and LePage [15], who predicted $\alpha = 1$. Fig.2 shows these two experimental values together with the pure vector formula for $\alpha$. The $\psi'$ case is evidently consistent with a pure vector $(\gamma_\mu) \psi' p \bar{p}$ coupling at present accuracy, but the better determined $J/\psi$ distribution is inconsistent with a pure vector $J/\psi p \bar{p}$ coupling at the 4$\sigma$ level.

The discrepancy in Fig.2 may be evidence for a Pauli term ($\kappa \neq 0$) in the $J/\psi p \bar{p}$ vertex. Inspection of our result for $\alpha$ in the general case (Eq.8) shows that one can certainly accommodate this discrepancy by introducing a Pauli term, since the full range of $-1 < \alpha < 1$ is covered (twice) by varying $\kappa$; there are two inequivalent solutions for $\kappa$ for a given $\alpha$, corresponding to the two possible phases of $G_E/G_M$ in Eq.7. These are

$$\kappa = -2\alpha r \pm \sqrt{(1 - \alpha^2)/(1 - r + (1 + r)\alpha)}. \tag{11}$$

The dependence of the predicted $\alpha$ on $\kappa$ at the $J/\psi$ mass (from Eq.8) is shown in Fig.3. The experimental number $\alpha = 0.676 \pm 0.055$ (shown) is consistent with the two values

$$\kappa = \begin{cases} -0.137(32), & \text{solution I} \\ -0.500(11), & \text{solution II}. \end{cases} \tag{12}$$

The overall strength $g$ of the $\psi' p \bar{p}$ coupling for a given $\kappa$ can be determined from the partial width $\Gamma_{\psi' \rightarrow p \bar{p}}$, which was given in Eq.4. In terms of the vertex couplings of Eq.1 this partial width is

$$\Gamma_{\psi' \rightarrow p \bar{p}} = \frac{1}{3} \frac{g^2}{4 \pi} M \sqrt{1 - r} \left(1 + \frac{r}{2} + 3\kappa + \left(1 + \frac{1}{2r}\right)\kappa^2\right)^2, \tag{13}$$

which generalizes the $\kappa = 0$ result in Eq.27 of Ref.[4]. Using the PDG values [16] of $\Gamma_{J/\psi} = 93.4 \pm 2.1$ keV and $\Gamma_{\psi'} = 58.1 \pm 2.2$ keV, we determine $g = (1.95 \pm 0.09) \cdot 10^{-3}$, solution I.

Our estimated uncertainties in $g$ include the errors in the total width, $p \bar{p}$ branching fraction, and $\kappa$. Both solutions for $g$ are somewhat larger than our previous estimate of $g = (1.62 \pm 0.03) \cdot 10^{-3}$ [4], as a result of destructive interference between the vector and Pauli couplings.

### IV. EFFECT ON $\sigma(p \bar{p} \rightarrow \pi^0 J/\psi)$

The possibly large effect of a $J/\psi p \bar{p}$ Pauli term on the $p \bar{p} \rightarrow \pi^0 J/\psi$ cross section may be of considerable importance to the PANDA project, since one might use this process as a “calibration” reaction for associated charmonium production. Although we have carried out this calculation with the vertex of Eq.1 for general masses, the full result is rather complicated; here for illustration we discuss the much simpler massless pion limit.

For a massless pion the ratio of the unpolarized cross section $\langle \sigma(p \bar{p} \rightarrow \pi^0 J/\psi) \rangle$ with a Pauli term to the pure vector result ($\gamma_\mu$ only) is

$$\frac{\langle \sigma(p \bar{p} \rightarrow \pi^0 J/\psi) \rangle/(\kappa)}{\langle \sigma(p \bar{p} \rightarrow \pi^0 J/\psi) \rangle/(0)} \bigg|_{m_{\pi} = 0} = 1 + 2\kappa + \frac{\kappa^2}{2} (1 + \frac{M^2}{4m^2})$$

$$+ \frac{\kappa^2}{4m^2} \frac{(s - M^2)}{\ln \left((1 + \beta)/(1 - \beta)\right)} \tag{15}$$

where $\beta = \sqrt{1 - 4m^2/s}$ is the velocity of the annihilating $p$ and $\bar{p}$ in the c.m. frame.

Note that there is destructive interference between the vector and Pauli terms near threshold for negative $\kappa$, which is largest at $\kappa = -2/\left(1 + M^2/4m^2\right)$ ($\approx -0.54$ for...
the $J/\psi$). At this value of $\kappa$ the near-threshold cross section is reduced to $(1 - r)/(1 + r) \approx 0.46$ of the pure vector result. Since this $\kappa$ is rather close to our “solution II”, $\kappa = -0.500(11)$, there is a possibility that the Pauli coupling in $J/\psi p\bar{p}$ may strongly suppress the unpolarized $p\bar{p} \to \pi^0 J/\psi$ cross section near threshold. (“Solution I” in contrast has a much smaller effect.) For this reason it will be important to establish which of the two solutions best describes the $J/\psi p\bar{p}$ coupling.

V. POLARIZED CASE

Establishing which of the two sets of $J/\psi p\bar{p}$ couplings (solutions I, II above) is preferred experimentally is possible through a study of the polarization process $e^+e^- \to J/\psi \to p\bar{p}$.

As each of the external particles in this reaction has two possible helicity states, there are 16 helicity amplitudes. All the amplitudes to the final $p\bar{p}$ helicity states $|p(\pm)\bar{p}(\pm)|$ are proportional to $G_E$, whereas all $|p(\pm)\bar{p}(\pm)|$ helicity amplitudes are proportional to $G_M$. In the unpolarized case these are squared and summed, which leads to a cross section and proportional to $G_E^2$, whereas in the polarized case it is necessary to determine nonzero helicity amplitudes, and for massless leptons constraints of parity and C-parity reduce this set to 6 independent helicity amplitudes, and for massless leptons constraints of parity and C-parity reduce this set to 6 independent nonzero helicity amplitudes.

For simplicity we introduce normalized polarization observables, $Q_{\epsilon_+\epsilon_-\epsilon_p\epsilon_{\bar{p}}}/Q(0,0,0,0)$, where $Q(0,0,0,0)$ is the unpolarized differential cross section. The (nonzero) polarization observables for this process satisfy the relations

$$Q_{0000} = Q_{xxyy} = Q_{yxyy} = Q_{zz00} = 1,$$
$$Q_{xx00} = Q_{y00y} = Q_{0yy0} = -Q_{zzyy},$$
$$Q_{z00z} = Q_{00z0} = -Q_{yyxz} = Q_{rzyy} =$$
$$-Q_{0zx0} = -Q_{00xz} = -Q_{zyxz} = -Q_{zxyy},$$
$$Q_{zzz0} = -Q_{zz0z} = -Q_{xyzx} = -Q_{zxyz},$$
$$Q_{00xz} = Q_{zzxz} = Q_{zyxx} = Q_{zzxx} =$$
$$-Q_{zxzx} = -Q_{zxyy} = -Q_{zzzz} = Q_{00zz}. \quad (16)$$

Explicit expressions for these observables are given in Table I. All single-polarization and triple-polarization observables vanish, so the only measurable polarization dependences in the angular distributions arise from having two or all four particles polarized.

FIG. 4: Axes used to define the polarization observables.

To show how the relative phase of $G_E$ and $G_M$ can be established in polarized scattering, it is useful to introduce the polarization observables defined by Paschke and Quinn [17]. These are differences of angular distributions for particles polarized along versus opposite to specified axes. For example, for our reaction $e^+e^- \to p\bar{p}$, $Q(0,0,z,0)$ is the difference $(d\sigma/d\Omega)_{p_1} - (d\sigma/d\Omega)_{p_1}$. Here we use $x$ and $y$ for the two transverse axes and $z$ for the longitudinal axis (see Fig. 4): $\hat{x}$ and $\hat{z}$ vary with the particle, and $\hat{y}$ is chosen to be common to all. An entry of 0 signifies an unpolarized particle. Since there are four possible arguments for each particle, 0, $x$, $y$, and $z$, there are $4^4 = 256$ polarization observables for this process. Of course there is considerable redundancy, since they are all determined by the 16 helicity amplitudes. The constraints of parity and C-parity reduce this set to 6 independent helicity amplitudes, and for massless leptons (as we assume here) this is further reduced to 3 independent nonzero helicity amplitudes.

| Pol. Observable | Result           |
|-----------------|-----------------|
| $Q_{0000}$      | 1               |
| $Q_{xx00}$      | $2(1 - y^2)\sin^2\theta/F$ |
| $Q_{z00z}$      | $4y\sin\theta/F$ |
| $Q_{zz0z}$      | $4\cos\theta/F$ |
| $Q_{zzz0}$      | 1               |
| $Q_{zzzz}$      | $-2(1 + y^2)\sin^2\theta/F$ |
| $Q_{00zz}$      | $-4y\sin\theta\cos\theta/F$ |

Note that the polarization observables given in Table I all have definite parity in $y = (2m/M)(G_E/G_M)$. Since we wish to resolve the $G_E/G_M$ sign ambiguity we found in the unpolarized cross section, it is evidently necessary to measure a polarization observable that is odd in $y$. These odd observables are $Q_{z00z}, Q_{00zz}$, and their equivalents (in the 3rd and 7th expressions in Eq. 16).

Determining an odd-$y$ observable involves measuring cross section differences with either two or all four particles polarized. In the two-particle cases, either one initial and one final are polarized (such as $e^- p$) or both final particles ($p$ and $\bar{p}$) are polarized. In the first case the relevant observables (such as $Q_{z00z}$) require the initial lepton to have longitudinal ($\pm \hat{z}$) polarization, which is difficult to achieve experimentally. In the second case of both final particles polarized the beams can be unpolarized, and one need simply measure cross section differences for polarized $p$ and $\bar{p}$, with one transverse and
one longitudinal. This case, unpolarized $e^+e^-$ to TL-polarized $p$ and $\bar{p}$, appears to be the most attractive experimentally.

Another interesting experimental possibility is to resolve the ambiguity in unpolarized $e^+e^- \rightarrow p\bar{p}$ scattering using the closely related reaction $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\Lambda$, which has recently been studied using ISR by BABAR [18]. Since the $\psi p\bar{p}$ and $\psi \Lambda \bar{\Lambda}$ couplings are identical in the SU(3) flavor symmetry limit, a determination of $J/\psi \Lambda\bar{\Lambda}$ couplings could be used to select the most plausible of our $J/\psi p\bar{p}$ solutions I,II. This approach has experimental advantages; as the $\Lambda$ and $\bar{\Lambda}$ decays are self-analyzing, no rescattering of the final baryons is required to determine their polarization. In addition no beam polarization is required, since it suffices to measure the odd-$y$ polarization observable $Q_{00xz}$. One may also measure the even-$y$ observables $Q_{00xx}$ and $Q_{00z}$ as a cross-check of the result for $|y|$. 

VI. SUMMARY AND CONCLUSIONS

The unpolarized angular distribution for the process $e^+e^- \rightarrow J/\psi \rightarrow p\bar{p}$, measured recently by the BES Collaboration, is inconsistent with theoretical expectations for a pure Dirac $J/\psi$-$p\bar{p}$ coupling. In this paper we have derived the effect of an additional Pauli-type $J/\psi$-$p\bar{p}$ coupling, and find that this can accommodate the observed angular distribution. There is an ambiguity in determining the relative Pauli and Dirac $J/\psi$-$p\bar{p}$ couplings from the unpolarized $e^+e^- \rightarrow J/\psi \rightarrow p\bar{p}$ data; we note that this can be resolved through measurements of the polarized angular distributions, and that at least two of the particles must be polarized. Detecting both final ($p$ and $\bar{p}$) polarizations appears to be the most useful approach. It may also be possible to use self-analyzing processes such as $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\Lambda$ to resolve this ambiguity. This Pauli coupling may significantly affect the cross section for the charmonium production reaction $p\bar{p} \rightarrow \pi^0 J/\psi$, which will be studied at PANDA.

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