Charmonium production in $p\bar{p}$ annihilation: Estimating cross sections from decay widths

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The cross sections for the charmonium production processes $p\bar{p} \to m\Psi$, where m is a light meson and Ψ is a charmonium state, are of great interest for the planned $p\bar{p}$ experiment PANDA. In this paper we estimate these cross sections using known results for the decays $\Psi \to mp\bar{p}$, which are related to these reactions by crossing. In lieu of detailed experimental data on the decay Dalitz plots, we assume a constant amplitude as a first approximation; this implies a simple relation between the cross sections and decay widths. The single measured exclusive cross section of this type is $p\bar{p} \to \pi^0 J/\psi$, which was reported by E760 to be 130 ± 25pb near $\sqrt{s} = 3.5$–3.6 GeV. In comparison, our constant amplitude estimate is about 300 pb at this energy. This suggests that our approach is useful as a simple estimate, but should be refined through detailed modeling of resonances and other energy-dependent effects in the $\Psi \to mp\bar{p}$ Dalitz plots.

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I. INTRODUCTION

The proton-antiproton annihilation experiment PANDA, which is planned for the FAIR facility at GSI, is scheduled to begin data taking in the beginning of the next decade. PANDA is an internal fixed target experiment, with a design luminosity of $2 \cdot 10^{32}$ cm^{-2} s^{-1} and a momentum range of $p_{\bar{p}\text{lab}} = 1.5$–$15$ GeV/c. This covers a mass range in which many interesting hadron resonances are anticipated, including glueballs, light hybrids, charmonia and charmonium hybrids [1].

The physics goals of PANDA include a detailed investigation of the spectrum of charmonia and charmonium hybrids, including determinations of masses, widths, quantum numbers and decay properties. Since the known charmonium spectrum is largely characterized by clear, well separated states, unlike the broad, overlapping resonances of light quark hadron spectroscopy, it is anticipated that this will be a relatively clean sector in which to search for higher-mass excitations such as hybrids and other unusual hadron resonances.

Studies of conventional meson spectroscopy using proton-antiproton collisions have a considerable advantage over electron-positron colliders, in that *all* nonexotic quantum numbers can be accessed in formation reactions. Although J^{PC}-exotics cannot be made in formation in $p\bar{p}$ annihilation, they can be made in associated production processes such as $p\bar{p} \to \pi H_c$ (where H_c is a J^{PC}-exotic charmonium hybrid).

Production of the very characteristic J^{PC}-exotic charmonium hybrids is one of the main goals of the PANDA project. These states are predicted to lie at rather high masses; the $J^{PC} = 1^{-+}$ state, which is expected to be the lightest exotic charmonium hybrid, is predicted by the flux tube model [2–5] and lattice QCD [6–8] to have a mass in the range 4.2–4.4 GeV. This exotic resonance could be produced at PANDA together with a light meson m, such as an η or π^0. (Both isospins are allowed in $p\bar{p} \to m\Psi$ because $p\bar{p}$ is a superposition of $I = 0$ and $I = 1$.)

Numerical estimates of charmonium and charmonium hybrid production cross sections are evidently crucial for the PANDA physics program, both to formulate detection strategies and to evaluate luminosity requirements, as well as for detailed detector simulations with theoretically preferred final states. Unfortunately there are few estimates of these cross sections at present, and only one has been measured, $p\bar{p} \to \pi^0 J/\psi$. (This result was reported by the E760 collaboration [9].) The purpose of this paper is to derive and evaluate simple estimates of these cross sections from measurements of charmonium partial widths to $mp\bar{p}$ three-body final states.

The approach we follow in this paper is to use a measured charmonium partial width into a three-body $mp\bar{p}$ final state, $\Gamma_{\Psi\to mp\bar{p}}$, to estimate the corresponding production cross section $\sigma_{p\bar{p}\to m\Psi}$. The (presumably complicated) quark-gluon dynamics is subsumed in the unknown amplitude $\mathcal{M}$, which is common to both processes.

II. RELATING WIDTHS TO CROSS SECTIONS

A. Three-body decay $\Psi \to mp\bar{p}$

The three-body partial width of an initial charmonium state Ψ (Fig. 1) is an average over initial and sum over final polarizations of a squared decay amplitude, multiplied by three-body phase space. The differential decay rate, in the form familiar as a Dalitz plot, is

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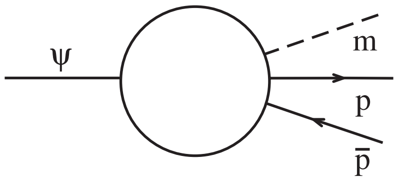

FIG. 1. The three-body charmonium decay process $\Psi \to m p \bar{p}$.

$$d\Gamma_{\Psi\to mp\bar{p}} = \frac{1}{2S_\Psi + 1}\frac{1}{(2\pi)^3}\frac{1}{32M_\Psi^3} \times \left\{\sum |\mathcal{M}|^2\right\} dm_{mp}^2 dm_{p\bar{p}}^2. \quad (1)$$

Here S_X is the spin of particle X, $m_{ij}^2 = (p_i + p_j)^2$ is the invariant mass squared of the two-particle system (i, j) [10], and the squared amplitude in this formula is summed over all $4(2S_\Psi + 1)(2S_m + 1)$ initial and final polarization states. (This summation convention is convenient for relating decays to cross sections.)

As a simple approximation one can assume a constant decay amplitude $\mathcal{M}$, in which case the decay width is proportional to the area A_D of the Dalitz plot;

$$\Gamma_{\Psi\to mp\bar{p}} = \frac{1}{2S_\Psi + 1}\frac{1}{(2\pi)^3}\frac{1}{32M_\Psi^3}\left\{\sum |\mathcal{M}|^2\right\} A_D \quad (2)$$

where

$$A_D = \iint dm_{mp}^2 dm_{p\bar{p}}^2. \quad (3)$$

B. Two-body production reaction $p\bar{p} \to m\Psi$

In the unpolarized two-body production cross section (Fig. 2) the squared amplitude is again averaged over initial and summed over final states. The unpolarized differential cross section is given by [10]

$$\left.\frac{d\sigma}{dt}\right|_{p\bar{p}\to m\Psi} = \frac{1}{256\pi}\frac{1}{|p_{pcm}|^2} s^{-1}\left\{\sum |\mathcal{M}|^2\right\} \quad (4)$$

where t is the Mandelstam variable $t = (p_p - p_m)^2$. A factor of 1/4 has been included for the average over the four initial $p\bar{p}$ polarization states.

The total cross section involves an integral over t between the limits

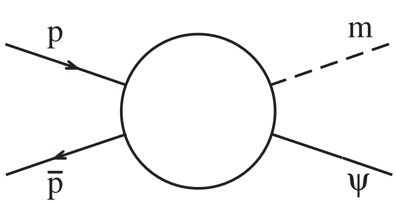

FIG. 2. The related associated charmonium production process $p\bar{p} \to m\Psi$.

$$t_\pm = m_p^2 + m_m^2 - 2(E_p E_m \mp p_p p_m)_{cm}. \quad (5)$$

Assuming a constant amplitude we can trivially evaluate this integral, with the result

$$\sigma_{p\bar{p}\to m\Psi} = \frac{1}{64\pi}\frac{p_{mcm}}{p_{pcm}} s^{-1}\left\{\sum |\mathcal{M}|^2\right\}. \quad (6)$$

C. Connecting charmonium decay and production

The partial width $\Gamma_{\Psi\to mp\bar{p}}$ and the production cross section $\sigma_{p\bar{p}\to m\Psi}$ given above are simply related in the constant amplitude approximation, since both are given by simple kinematic and spin factors times the same spin-summed squared amplitude. Eliminating the common squared amplitude, we find the following relation between the cross section and decay width:

$$\sigma_{p\bar{p}\to m\Psi} = 4\pi^2(2S_\Psi + 1)\frac{M_\Psi^3}{A_D}\Gamma_{\Psi\to mp\bar{p}}\left[\frac{p_{mcm}}{p_{pcm}} s^{-1}\right]. \quad (7)$$

Note that in this approximation all the energy dependence in the cross section comes from the expression in square brackets. A similar approach has been used to estimate charmonium cross sections of relevance to QGP experiments [11].

D. Experimental $\Psi \to mp\bar{p}$ decay widths

The estimate of the charmonium production cross sections $\sigma_{p\bar{p}\to m\Psi}$ in Eq. (7) requires the three-body decay partial widths $\Gamma_{\Psi\to mp\bar{p}}$. These branching fractions (and hence partial widths) have been measured for about 10 $mp\bar{p}$ decay modes to date, all from J/ψ or ψ' initial states at e^+e^- colliders. PDG values for the branching fractions are given in Table I. Since the PDG compilation, new measurements of J/ψ and ψ' branching fractions to $mp\bar{p}$ have been reported by BESII [12] and CLEO-c [13]; these are summarized in Table II.

Unfortunately, branching fractions of $J^{PC} \neq 1^{--}$ charmonia to $mp\bar{p}$ final states have not yet been reported.

TABLE I. Experimental charmonium partial widths to $mp\bar{p}$ final states. These numbers combine the PDG [10] total widths with the reported branching fractions.

Decay	$\Gamma_{mp\bar{p}}$ [eV]	Experiment
$J/\psi \to \pi^0 p\bar{p}$	99.2 ± 8.9	MRK2, MRK1, DASP
$J/\psi \to \eta p\bar{p}$	190 ± 18	MRK2, MRK1, DASP
$J/\psi \to \rho^0 p\bar{p}$	<28	MRK2
$J/\psi \to \omega p\bar{p}$	118 ± 23	MRK2, MRK1
$J/\psi \to \eta' p\bar{p}$	82 ± 37	MRK2, MRK1
$J/\psi \to \phi p\bar{p}$	4.1 ± 1.4	DM2
$\psi' \to \pi^0 p\bar{p}$	39 ± 14	MRK2
$\psi' \to \omega p\bar{p}$	22 ± 9	BES
$\psi' \to \phi p\bar{p}$	<7.4	BES

TABLE II. $\psi' \to mp\bar{p}$ partial widths recently reported by BESII [12] and CLEO-c [13]. These numbers combine the PDG [10] total width with the reported branching fractions.

Decay	$\Gamma^{(BES)}_{mp\bar{p}}$ [eV]	$\Gamma^{(CLEO)}_{mp\bar{p}}$ [eV]
$\psi' \to \pi^0 p\bar{p}$	37.1 ± 5.5	—
$\psi' \to \eta p\bar{p}$	16.3 ± 3.8	22 ± 12
$\psi' \to \rho^0 p\bar{p}$	—	14 ± 6
$\psi' \to \omega p\bar{p}$	—	17 ± 8
$\psi' \to \phi p\bar{p}$	—	<6.7

Results for $C = (+)$ states such as the η_c and χ_{cJ} would be very interesting, as these may couple to $mp\bar{p}$ through a different mechanism than $C = (-)$ charmonia, perhaps with significantly larger amplitudes. This possibility is suggested by the known four-body partial widths to $\pi^+\pi^- p\bar{p}$, which are larger on average for the χ_J states than for the J/ψ and ψ'.

E. Previous Estimates

The only previous estimate of near-threshold associated charmonium production cross sections we have found in the literature is the PCAC calculation of Gaillard, Maiani and Petronzio [14]. This reference considers the process $\Psi \to \pi^0 p\bar{p}$, where Ψ is a generic charmonium state, and notes that the cross section is proportional to the peak on-resonance cross section for $p\bar{p} \to \Psi \to all$ if one assumes that pion emission in the decay takes place from the p or $\bar{p}$ line in a two-step process, $\Psi \to p\bar{p} \to \pi^0 p\bar{p}$. Assumption of the usual PCAC coupling between nucleons and pions gives a relation between the two cross sections,

$$\sigma_{p\bar{p}\to\pi^0\Psi} = \frac{1}{4\pi}\left(\frac{g_A}{f_\pi}\right)^2 \Gamma_\Psi^{tot} \sigma_{CP} \sigma^{\max}_{p\bar{p}\to\Psi\to\text{all}} p_{\pi\,\text{cm}}. \quad (8)$$

σ_{CP} is a dimensionless function of the c.m. energy and the initial $p\bar{p}$ quantum numbers. Gaillard *et al.* estimated σ_{CP} numerically at a single pion energy, $E_\pi = 230$ MeV, but did not evaluate it analytically. We have carried out this calculation using the angular distributions given in their Eqs. (25–28). Defining $\xi_{m,n} = (1/4)\int_{-1}^{1} d\cos(\theta)\sigma_{m,n}$ analogous to their Eq. (38) for σ_{CP}, we find

$$\xi_{0,0} = 1 + \frac{1}{\gamma^2} - \frac{\gamma_\pi^2 + 1}{\gamma^2} f(\beta), \quad (9)$$

$$\xi_{1,0} = -\frac{1}{2\gamma^2(1-\beta^2)} + \frac{1}{\beta_p^2} - \left(\frac{1}{\gamma_p^2 - 1} + \frac{1}{2\gamma^2}\right) f(\beta), \quad (10)$$

$$\xi_{1,1} = -\frac{1}{2\gamma^2(1-\beta^2)} - \frac{1}{2(\gamma_p^2-1)} + \frac{1+\beta_p^2}{2(\gamma_p^2-1)} f(\beta) \quad (11)$$

where $\beta = \beta_\pi \beta_p$, $\gamma = \gamma_\pi \gamma_p$ and $f(x) = \tanh^{-1}(x)/x$. The coupling σ_{CP} is a linear combination of these ξ functions. For example, for a pure S-wave $\pi^0 J/\psi$ system one requires a $CP = -$, ${}^1\text{P}_1$ 1^{+-} $p\bar{p}$ initial state, for which $\sigma_{CP=-} = \xi_{0,0}$. For a $CP = +$, spin-triplet initial state, $\sigma_{CP=+}$ is a linear combination of $\xi_{1,0}$ and $\xi_{1,1}$,

$$\sigma_{CP=+} = (1 - \langle S_3^2 \rangle)\xi_{1,0} + \langle S_3^2 \rangle \xi_{1,1}. \quad (12)$$

The spin matrix element $\langle S_3^2 \rangle$ depends on the mix of L = J ± 1 waves in the initial $p\bar{p}$ state, and satisfies $0 \le \langle S_3^2 \rangle \le 1$. (For an initial ${}^3S_1$ $p\bar{p}$ state, $\langle S_3^2 \rangle = 2/3$.)

Numerical results for $\sigma_{p\bar{p}\to\pi^0 J/\psi}$ using both this PCAC approach and the constant amplitude formula of Eq. (7) are given below.

III. NUMERICAL RESULTS FOR $\sigma_{p\bar{p}\to m\Psi}$

A. Method

Using Eq. (7) and the partial widths given in Tables I and II, we have generated constant amplitude estimates for $\sigma_{p\bar{p}\to m\Psi}$ for all cases with measured Ψ partial widths to $mp\bar{p}$ final states. The J/ψ cross section estimates use PDG branching fractions and decay widths, and the ψ' cross sections were calculated using BESII branching fractions for $m = \pi^0$ and η and CLEO-c branching fractions for ρ, ω and ϕ. Our results, including combined errors from the total widths and branching fractions, are given in Table III.

B. The case $p\bar{p} \to \pi^0 J/\psi$

The process $p\bar{p} \to J/\psi\pi^0$ is of special interest because this is the single associated charmonium production reaction in $p\bar{p}$ annihilation for which we have an experimental measurement of the cross section. This reaction was studied by the E760 Collaboration at Fermilab [9], who observed a few $p\bar{p} \to \pi^0 J/\psi$ events as a background in their searches for ${}^1\text{P}_1$ h_c and 2^3S_1 η_c' charmonia.

TABLE III. Charmonium cross sections from Eq. (7), given the $\Psi \to mp\bar{p}$ partial widths of Tables I and II. The size and energy of the cross section maximum and the area of the $\Psi \to mp\bar{p}$ Dalitz plot are given. These cross sections may be overestimated if the corresponding Ψ decay Dalitz plot is dominated by baryon resonances (see text).

Reaction	$\sigma^{\max}_{p\bar{p}\to m\Psi}$ [pb]	$E^{\max}_{\text{cm}}$ [GeV]	A_D[GeV^4]
$p\bar{p} \to \pi^0 J/\psi$	420 ± 40	4.28	9.265
$p\bar{p} \to \eta J/\psi$	1520 ± 140	4.57	4.520
$p\bar{p} \to \rho^0 J/\psi$	<450	4.80	2.114
$p\bar{p} \to \omega J/\psi$	1900 ± 400	4.80	2.053
$p\bar{p} \to \eta' J/\psi$	3300 ± 1500	4.99	0.765
$p\bar{p} \to \phi J/\psi$	280 ± 90	5.06	0.452
$p\bar{p} \to \pi^0 \psi'$	55 ± 8	5.14	30.500
$p\bar{p} \to \eta \psi'$	33 ± 8	5.38	20.984
$p\bar{p} \to \rho^0 \psi'$	38 ± 17	5.59	14.953
$p\bar{p} \to \omega \psi'$	46 ± 22	5.60	14.778
$p\bar{p} \to \phi \psi'$	<28	5.84	9.118

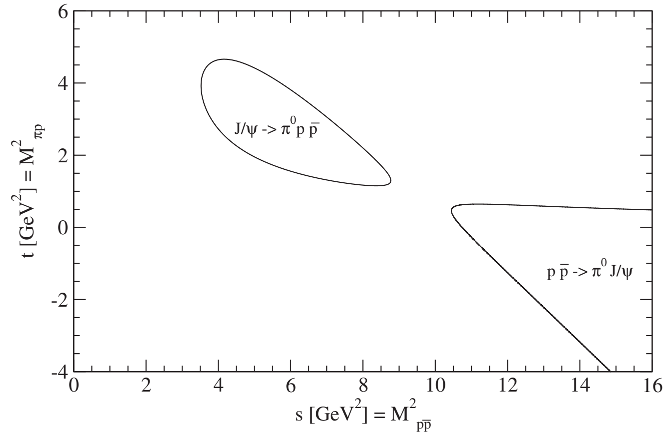

FIG. 3. Kinematically allowed regions for the three-body decay $J/\psi \rightarrow \pi^0 p\bar{p}$ and the related charmonium production reaction $p\bar{p} \rightarrow \pi^0 J/\psi$.

The observed events correspond to a cross section of 99 ± 40pb just below 3.525 GeV and 156 ± 36pb at 3.61 GeV. This has also been quoted as a combined value of 130 ± 25pb [15]. The E760 measurements are shown in Fig. 4 together with the theoretical predictions.

The constant amplitude cross section of Eq. (7) is also shown in Fig. 4. This approximation predicts $\sigma = 299$pb at 3.52 GeV and 336pb at 3.61 GeV, which overestimates the cross section at these energies by about a factor of 2–3. This suggests that the constant amplitude approximation is useful as a first estimate, but should be improved through a more detailed description of the amplitude, for example, by incorporating the contributions of individual resonances to the decay Dalitz plot. The importance of baryon resonances in this decay and in related $\Psi \rightarrow mp\bar{p}$ decays has been discussed previously in both experimental [12,16,17] and theoretical [18,19] references.

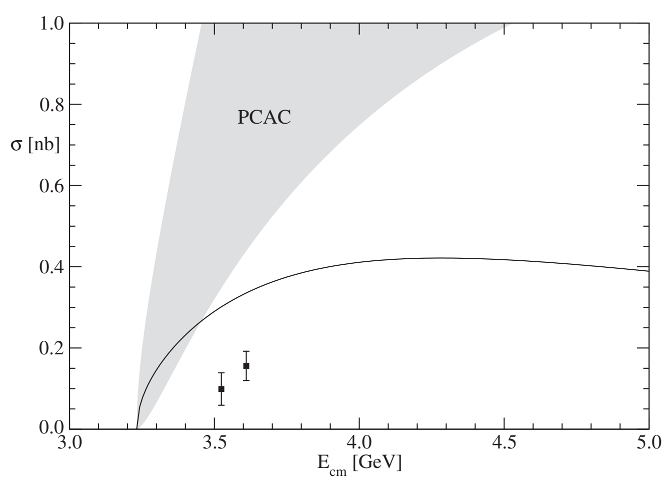

FIG. 4. Theoretical and experimental cross sections for $p\bar{p} \rightarrow \pi^0 J/\psi$. The theoretical predictions are the constant amplitude result Eq. (7) (solid) and the range of PCAC cross sections, from Eq. (8) (filled). The experimental points are from E760 [9].

The PCAC result for the cross section for $J/\psi \rightarrow \pi^0 p\bar{p}$, Eq. (8), is also shown in Fig. 4. Here we have assumed (rounded) PDG values of $g_A = 1.27$ and $f_\pi = 0.131$ GeV, PDG masses and widths, and a peak on-resonance cross section of $\sigma^{\max}_{\bar{p}\rightarrow J/\psi \rightarrow \text{all}} = 5.0\mu b$ [20]. Since the result depends on the initial $p\bar{p}$ quantum numbers assumed, we show the full set of values that follow from the range $0 \leq \langle S_3^2 \rangle \leq 1$ in Eq. (12). Evidently this PCAC prediction is also somewhat larger than the experimental E760 cross section in the 3.5–3.6 GeV region where we have data, and is rather similar to the constant amplitude result near threshold. The disagreement of PCAC with experiment may simply imply that other important processes interfere destructively with the nucleon pole diagram.

C. Other channels

Our constant amplitude predictions for all $p\bar{p} \rightarrow m\Psi$ cross sections are summarized in Table III.

The $p\bar{p} \rightarrow m\psi'$ cross sections are typically predicted to be 10s of pb, at least an order of magnitude smaller than the corresponding J/ψ cross sections. There is no indication of an enhancement of isoscalar m final states in this case. Although the ψ' couplings are relatively weak, the decay $\psi' \rightarrow \pi^0 p\bar{p}$ (and the corresponding reaction $p\bar{p} \rightarrow \pi^0\psi'$) may be the most interesting to study in the near future. As is evident in Fig. 5, the region of phase space sampled by this decay is much larger than in $J/\psi \rightarrow \pi^0 p\bar{p}$, so more baryon resonance contributions can be investigated, and their effects on the extrapolation to the physical region for $p\bar{p} \rightarrow \pi^0\psi'$ can be studied once data on this reaction becomes available. BESII [12] has recently reported results on this ψ' decay mode.

It is notable that quite large maximum cross sections of 1–3 nb are predicted for $\Psi = J/\psi$ and $m = \eta, \omega, \eta'$. This suggests that it may be interesting for PANDA to consider reactions in which m is a light isoscalar meson. This is also

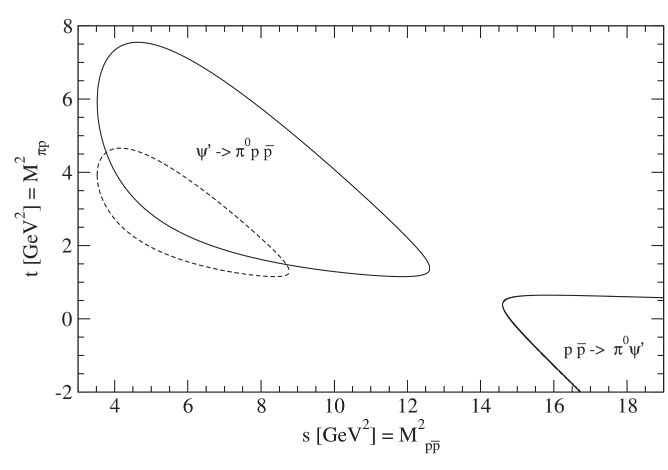

FIG. 5. Allowed regions for $\psi' \rightarrow \pi^0 p\bar{p}$ and $p\bar{p} \rightarrow \pi^0\psi'$. The smaller physical region for $J/\psi \rightarrow \pi^0 p\bar{p}$ is shown for comparison (dashed, from Fig. 3).

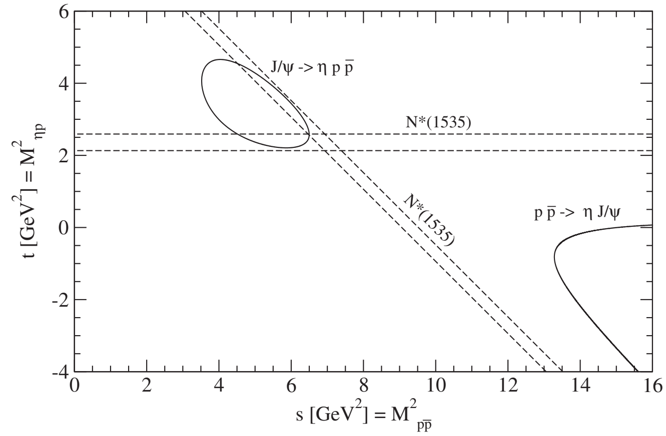

FIG. 6. Allowed regions for $J/\psi \to \eta p\bar{p}$ and $p\bar{p} \to \eta J/\psi$, showing $N^*(1535)$ bands. ($M \pm \Gamma/2$ limits are shown.)

supported by the relatively large branching fractions observed for charmonium decays to $\pi^+\pi^- p\bar{p}$. Although an enhancement of $p\bar{p} \to m\Psi$ cross sections with light isoscalar m is an interesting possibility, one should note that the Dalitz plot for the decay $J/\psi \to \eta p\bar{p}$ (as one example) is crossed by $N^*(1535)$ bands (Fig. 6), and this baryon resonance contribution may be the reason for the large branching fraction. This is supported by results from BESII [17]. As these $N^*(1535)$ bands lie far outside the physical region for $p\bar{p} \to \eta J/\psi$, it appears likely that the constant amplitude approximation Eq. (7) will seriously overestimate this cross section.

IV. SUMMARY AND FUTURE

We have used the partial decay widths of charmonia into $mp\bar{p}$ final states (where m is a light meson) and a constant amplitude approximation to estimate cross sections for the reactions $p\bar{p} \to m\Psi$, which are of great interest for the planned PANDA experiment. The single experimentally measured cross section of this type is $p\bar{p} \to \pi^0 J/\psi$, which was reported by E760 to be $130 \pm 25 pb$ near 3.5–3.6 GeV. In comparison we predict a cross section of about 300 pb at this energy. Application of this constant amplitude approximation to other $p\bar{p} \to mJ/\psi$ reactions suggests enhanced peak cross sections of as large as 1–3 nb for light isoscalar m. This prediction may however be an artifact of large baryon resonance contributions to these specific $J/\psi \to mp\bar{p}$ decays. These resonances need not contribute significantly to the production cross section if the decay resonance bands lie far from that region of phase space (see, for example, Fig. 6). The corresponding ψ' decays do not show evidence of an enhancement of isosinglet m final states; the estimated $p\bar{p} \to m\psi'$ cross sections are 10s of pb.

A next important step in these calculations will be to model the contributions of individual baryon resonances to the decays. In low-energy processes involving a single π^0, such as $J/\psi \to \pi^0 p\bar{p}$ and $p\bar{p} \to \pi^0 J/\psi$ (Fig. 3), one may find dominance of the decay Dalitz plot by a few baryon resonances. In such cases, extrapolation of the amplitude to the reaction region may be relatively straightforward. Studies of the corresponding ψ' processes may be instructive, since the region of phase space accessible to the decay is much larger (Fig. 5), and new data is expected from BESII and CLEO-c. In contrast, relating decays and production cross sections for heavier mesons such as the η is clearly problematic, since the decay Dalitz plot provides a smaller window on the amplitude, and the extrapolation from decay to production covers a much larger kinematic range (Fig. 6). For vector mesons such as the ω we encounter the additional complication that the couplings of baryon resonances to ωN are not well established. The $N*$ experimental program at TJNAF, which has a goal of determining these ωN and related baryon resonance decay couplings, may also be useful in interpreting $\Psi \to mp\bar{p}$ decays and clarifying their relation to charmonium production cross sections.

The constant amplitude approximation is of course only a simple first estimate, and it will be of interest in future to develop a model of associated charmonium production that incorporates realistic hadronic couplings and form factors. In particular one might consider the effect of including a $pp\pi^0$ form factor on the relation between the partial width $\Gamma_{J/\psi \to \pi^0 p\bar{p}}$ and the cross section $\sigma_{p\bar{p} \to \pi^0 J/\psi}$ (shown in Fig. 4). Suppression of the cross section due to this form factor may significantly modify the predicted $\sqrt{s}$ dependence of this cross section [21].

Future measurements of $mp\bar{p}$ branching fractions of $C = (+)$ charmonia such as the $\{\chi_J\}$ and η_c will be especially interesting, as these will allow estimates of their $p\bar{p} \to m\Psi$ production cross sections. As $C = (+)$ charmonia employ different production mechanisms than the $C = (-)$ states, for example gg rather than ggg intermediaries, they may have quite different production cross sections.

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