Associated Charmonium Production in $p\bar{p}$ Annihilation

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Abstract. In this paper we summarize our recent results for low energy associated charmonium production cross sections, using 1) crossing symmetry, and 2) an explicit hadronic model. These predictions are of relevance to the planned charmonium and charmonium hybrid production experiment PANDA at GSI.

1. Introduction
The clear spectrum of states observed in the charmonium system and the straightforward identification of low-lying states with the predictions of simple $c\bar{c}$ potential models make this an ideal sector for the search for unusual “extra” states such as charmonium hybrids. The PANDA experiment [1] at GSI plans to exploit this possibility in a search for charmonia, charmonium hybrids, and other similar states in a $p\bar{p}$ annihilation experiment.

Of course planning for this experiment would be greatly facilitated by experimental data on and theoretical estimates of these cross sections. Unfortunately, remarkably little is known at present. There are a few data points for the single reaction $p\bar{p} \rightarrow \pi^0 J/\psi$ from the E760 [4] and E835 [5, 6] experiments at Fermilab, which suggest a scale of roughly 100 pb near 3.5 GeV, but nothing is known about the cross sections to other charmonium states. Here we give results for two estimates of these cross sections, based on two different theoretical approaches. Where they allow common predictions, we find that these methods are reassuringly in agreement to within about a factor of two, and the explicit hadronic model shows a similar level of agreement with the data. The following discussion summarizes these predictions in more detail.

2. Crossing
This approach was developed by Lundborg et al. [2]. The close kinematic proximity of certain charmonium processes with identical underlying amplitudes, such as the production process $p\bar{p} \rightarrow \pi^0 J/\psi$ and the experimentally well studied three body decay $J/\psi \rightarrow \pi^0 p\bar{p}$, suggests that knowledge of the decay can be used to estimate the numerical scale of the production cross section. This is illustrated by Fig.1 in which it is evident that an extrapolation from the decay Dalitz plot to the production regime may well be feasible.

The differential decay rate and differential production cross section are the following functions (with an implicit polarization sum) of the same invariant amplitude $M$;
Figure 1. Kinematically allowed regimes for the charmonium production reaction $p\bar{p} \rightarrow \pi^0 J/\psi$ and the related decay $J/\psi \rightarrow \pi^0 p\bar{p}$.

$$d\Gamma_{\Psi \rightarrow m p \bar{p}} = \frac{1}{2S_{\Psi} + 1} \frac{1}{(2\pi)^3} \frac{1}{32M^3} |M|^2 dm_{12}^2 dm_{23}^2, \quad (1)$$

$$\frac{d\sigma_{p\bar{p} \rightarrow \Psi}}{dt} = (2S_{\Psi} + 1)(2S_{m} + 1) \frac{1}{64\pi s} \frac{1}{|p_{1\text{cm}}|^2} |M|^2, \quad (2)$$

Here $m$ is a generic meson with spin $S_{m}$ and $\Psi$ is a generic charmonium (or related) state. Ideally one can develop a detailed model of $M$ from a study of the decay Dalitz plot, which can then be extrapolated to predict the charmonium production cross section. However a much simpler qualitative cross section estimate can be written if the Dalitz plot does not show much structure, which is the constant amplitude approximation. If we assume that $|M|^2$ is constant, it can be eliminated between the decay and cross section formulas, which gives a very simple cross section estimate in terms of the three-body decay rate:

$$\sigma_{p\bar{p} \rightarrow m \Psi} = \frac{12\pi^2 M^3}{A_D} \Gamma_{\Psi \rightarrow m p \bar{p}} \frac{p_{3\text{cm}}}{p_{1\text{cm}} s} \quad (3)$$

where $A_D$ is the area of the decay Dalitz plot.

This simple constant-amplitude prediction for the cross section for $p\bar{p} \rightarrow \pi^0 J/\psi$ is shown in Fig.2. This is the single experimentally measured case; as we noted previously, there are a few data points for this cross section from the E760 \cite{4} and E835 \cite{5,6} experiments at Fermilab, which are also shown in the figure. Evidently there is indeed rough agreement between theory and experiment, which suggests that extrapolation from data on generic decays of the form $\Psi \rightarrow m p\bar{p}$ to the corresponding associated production cross section $p\bar{p} \rightarrow m \Psi$ is a useful approach.

The corresponding results for a range of $J/\psi$ and $\psi'$ decays are given in Ref.\cite{2}. One concern in applying this approach is that some decay processes may be dominated by strong $N^*$ resonance bands, in which case extrapolation to the production cross section would be inaccurate. An example is $J/\psi \rightarrow \eta p\bar{p}$, which presumably has large contributions from the $N^*(1535)$. Extrapolation of this and other decay processes to production cross section should generally be accompanied by careful studies of the decay Dalitz plot which allow $N^*$ resonance contributions.
3. Hadronic Model

An attractively simple dynamical model which we have recently developed \cite{7} assumes that the associated production of a charmonium or charmonium hybrid state $\Psi$ with a $\pi^0$ in $p\bar{p}$ annihilation takes place through pion emission from an incoming $p$ or $\bar{p}$ line. The process $p\bar{p} \to \pi^0\Psi$ at leading order then involves the two Feynman diagrams of Fig. 3, in which the only a priori unknown quantity is the $\Psi - p\bar{p}$ vertex.

![Feynman diagrams](image)

**Figure 3.** Feynman diagrams assumed in this model of the generic reaction $p\bar{p} \to \pi^0\Psi$.

The use of a similar model, with a PCAC axial vector coupling for the $pp\pi^0$ vertex, was earlier suggested by Gaillard, Maiani and Petronzio \cite{3}.

We have used this model (with a simpler pseudoscalar $pp\pi^0$ vertex) to calculate the cross sections for $pp \to \pi^0\Psi$ for a much wider range of light charmonia, $\Psi = \eta_c, J/\psi, \chi_0, \chi_1$ and $\psi'$. Numerical results for these cross sections require the strength of the coupling $\Psi - p\bar{p}$, which we take from the measured annihilation widths to $p\bar{p}$. (We do not consider the $\chi_2$ because of the more complicated vertex, and other charmonium states do not have known $p\bar{p}$ couplings.) Analytical results for all these total and differential cross sections and the numerical results shown here are given in Ref.\cite{7}.

Our results for these cross sections are shown in Fig. 4. First, note that the single measured case of $p\bar{p} \to \pi^0J/\psi$ is indeed in rough (factor of two) agreement with the predictions of this dynamical model. This suggests that the simple Feynman diagrams of Fig. 3 may well give a reasonably accurate description of these processes, which is very encouraging. Application of the model to other charmonium and charmonium hybrid states only requires knowledge of the coupling $\Psi - p\bar{p}$.
Figure 4. Predicted unpolarized total cross sections for the processes $pp \rightarrow \pi^0 \Psi$, where $\Psi = \eta_c, J/\psi, \chi_0, \chi_1$ and $\psi'$. The data points are the E760 (filled) and E835 (open) experimental results for $\Psi = J/\psi$.

Figure 5. The corresponding angular distribution for the reaction $pp \rightarrow \pi^0 \eta_c$, for $E_{cm} = 3.2 - 5.0$ GeV in steps of 0.2 GeV.

The most remarkable predictions of the model are the very large cross sections for the associated production of the $\eta_c$ and $\chi_0$ states relative to the $J/\psi$ (see Fig.4). In particular, the cross section for $pp \rightarrow \pi^0 \eta_c$ is predicted to be about a factor of 30 larger than the $pp \rightarrow \pi^0 J/\psi$ cross section in the range of $\sqrt{s}$ relevant to PANDA. The reason for the large $\eta_c$ and $\chi_0$ couplings to $pp$ is not known, but it may be that $pp$ annihilation through $gg$ final states is significantly larger than the $ggg$ states that couple to the $J/\psi$. This suggests that production of some hybrid states may be enhanced at PANDA over $c\bar{c}$, since $gg$ can couple to the hybrid basis state $c\bar{c}g$ more easily than to $c\bar{c}$ itself [8].

This model also gives interesting predictions for the angular distributions of charmonia produced in $pp$ associated with a $\pi^0$. As an example, the c.m. frame angular distribution for the largest cross section, $pp \rightarrow \pi^0 \eta_c$, is shown in Fig.5. This angular distribution has a very characteristic node at $\theta = \pi/2$, due to a $t \leftrightarrow u$ antisymmetry in this model. Since the angular distributions we find for $pp \rightarrow \pi^0 \Psi$ are sensitive to the quantum numbers of the charmonium
state $\Psi$, they could be used as tests of the accuracy of this simple hadronic model.

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