$N\bar{N}$ annihilation at the open charm threshold

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We discuss the $p\bar{p}$ annihilation into a pair of charmed D mesons not far from the threshold of the reaction. An interesting interference pattern in the differential cross section is predicted to arise from the existence of both t-channel charmed-baryon exchange and s-channel Ψ'' charmonium resonance amplitudes. We argue that the experimental study of this process would provide new and valuable information about the unknown $p\bar{p}\Psi''$ and $\Lambda_c ND$ couplings. These are important to know to solve the long-standing puzzle of the heavy flavor content of baryons and to test the semilocal duality.

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There exist many meson states which couple to the $N\bar{N}$ system. These states then appear as the poles in the amplitudes of the $N\bar{N}$ interaction and this, in principle, can lead to observable effects. However, the common situation in the light quark sector is that the widths of the resonances are large; they therefore overlap and interfere. The necessity to account, in addition, for an interference with the (generally unknown) t-channel exchange amplitudes further complicates the situation, making a clean and detailed analysis an extremely difficult task.

In this sense a rather uncommon situation is encountered in the $p\bar{p}$ annihilation into a pair of D mesons close to the threshold. The s-channel resonance here is the $\Psi''(3770)$ charmonium state with a relatively small width of $\Gamma \simeq 23.6$ MeV. The nearest charmonia are too far and narrow to cause any appreciable interference effects, so the pole corresponding to Ψ'' can, to a good accuracy, be considered as isolated. In addition, there exist of course nonresonant t-channel amplitudes, corresponding to the exchange of the states with the quantum numbers of charmed baryon(s). The relation between the strengths of the resonant and nonresonant amplitudes depends on two couplings, $N\bar{N}\Psi''$ and $N_c ND$. Almost nothing is known at present about the values of the corresponding coupling constants, apart from a few rather controversial predictions [1–5]. A possible admixture of the light-quark–antiquark pairs in the wave function of the Ψ'' can further complicate the situation, giving rise to a nonperturbative contribution to the $p\bar{p} \to \Psi''$ amplitude. Another interesting issue concerning the $N_c ND$ coupling is that the knowledge of its value is desirable to solve the problem of the intrinsic heavy flavor content of the baryons [6,7]. The arguments listed above indicate that the study of the $p\bar{p} \to D\bar{D}$ reaction is interesting, but at the same time leave seemingly little chance to make a reliable prediction for the relative importance of s- and t-channel exchange amplitudes.

There exists, however, an attractive theoretical scheme which, when applied to our situation, gives a definite answer—the (semilocal) duality [8–11]. Namely, the semilocal duality implies that the averages (over a finite-energy segment) of cross sections corresponding to the sum of all possible amplitudes in s and t channels, respectively, should be approximately the same.

We therefore can expect the appearance of an interesting interference pattern in the vicinity of the Ψ'' resonance, arising from the competing s- and t-channel amplitudes of comparable size. To see in more detail how this pattern can appear, we shall try to calculate directly the cross section of the $p\bar{p} \to D\bar{D}$ process.

The s-channel resonant amplitude is given by

$$T^{(s)} = -\frac{A(\Psi'' \to p\bar{p})A(\Psi'' \to D\bar{D})}{s - M_R^2 + iM_R\Gamma_R} , \quad (1)$$

where M_R and Γ_R are the resonance mass and width and $A(\Psi'' \to X)$ stands for the resonance decay amplitude. For what concerns the t-channel amplitude, we shall model it by the Λ_c charmed-hyperon exchange. We choose the effective Lagrangian of $\Lambda_c ND$ interaction as

$$\not{L}_{\rm int} = ig(\bar{\Phi}_{\gamma_5}\Psi)\Phi , \quad (2)$$

where $g \equiv g_{\Lambda_c ND}$ is the corresponding coupling constant, Φ is the field of the D meson, and Ψ is the Dirac spinor of the baryon. The interaction (2) induces the t-channel exchange amplitude of the form

$$T^{(t)} = \frac{ig^2}{t - M^2}\bar{v}(\hat{q} + \Delta)u , \quad (3)$$

where M and m are the charmed hyperon and nucleon masses, respectively, $\Delta = M - m$, and q is the c.m. system (c.m.s.) momentum of the D meson (in what follows we shall keep the notation and metric conventions of Bjorken and Drell [12]).

The initial- and final-state interactions must also be

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taken into account. If $S_{p\bar{p}}$ and $S_{D\bar{D}}$ are the S-matrix elements describing the interaction in the initial and final channels, respectively, then the total transition S-matrix element can be represented as [13]

$$S_{if} = \sqrt{S_{p\bar{p}}}\tilde{S}_{if}\sqrt{S_{D\bar{D}}} \ , \tag{4}$$

where $\tilde{S}_{if}$ is the transition matrix element induced by the amplitudes (1) and (3).

A fair description of the $p\bar{p}$ interaction in the energy range of interest for us is given by the so-called Frahn-Venter (spin-dependent) model [14]. It has been successfully applied to describe the $p\bar{p}$ scattering [15] and initial-state interaction in the $p\bar{p} \to \Lambda\bar{\Lambda}$ reaction [16]. We thus feel free to introduce the initial-state interaction in exactly the same way as it was done in [16]. The main effect of the initial-state interaction is to damp the cross section by a factor of $\sim 10^{-2}$–10^{-3}, depending on the partial waves involved.

The properties of the $D\bar{D}$ interaction are essentially unknown; it nevertheless seems natural that it is much weaker than the strongly absorptive $p\bar{p}$ interaction. In what follows we shall put $S_{D\bar{D}} = 1$, thus neglecting the final-state scattering.

We now have to consider the amplitudes of Ψ'' decay entering into the resonant amplitude (1). A natural (though not necessarily true—see [17]) assumption is that the Okubo-Zweig-Iizuka- (OZI-) allowed $D\bar{D}$ mode dominates the Ψ'' decay; this fixes the $A(\Psi'' \to D\bar{D})$ amplitude by the relation $\Gamma(\Psi'' \to D\bar{D}) \simeq \Gamma_R$.

The partial width $\Gamma(\Psi'' \to p\bar{p})$ is presently unknown; we thus have to make use of available theoretical predictions [1–5]. They are quite contradictory: while Refs. [2,3] predict the value of $\Gamma(\Psi'' \to p\bar{p})$ to be in the range of 3–8 eV, and [1] the value of $\simeq 40$ eV, Ref. [5] claims a value as high as 500 ± 150 eV. Keeping in mind the controversial character of these theoretical predictions, we shall use a rather conservative value of $\simeq 7$ eV, arising from the appropriate scaling of the J/ψ and Ψ' partial decay widths to the $p\bar{p}$ channel [2,3]. The corresponding resonant part of the $p\bar{p} \to D\bar{D}$ cross section at the peak (without taking into account any of the interference effects) can therefore be estimated as

$$\sigma^{\rm res}(p\bar{p} \to D\bar{D}) \simeq \frac{12\pi}{M_R^2 - 4m^2}\frac{\Gamma(\Psi'' \to p\bar{p})}{\Gamma_R} \sim 0.5 \text{ nb} \ . \tag{5}$$

The last ingredient that has to be fixed is the value of the $\Lambda_c pD$ coupling constant. To the best of our knowledge, it has not been evaluated previously. Our first SU(4)-motivated guess for it is

$$\frac{g^2_{\Lambda_c pD}}{4\pi} \simeq \frac{g^2_{\Lambda pK}}{4\pi} \simeq 13.9 \pm 2.6 \ , \tag{6}$$

where the last value is taken from Martin's analysis [18] of kaon-nucleon scattering data using the forward dispersion relation techniques. The values extracted by other authors from the analyses of kaon-nucleon scattering [19], kaon photoproduction [20], hyperon-nucleon potential [21], and the $p\bar{p} \to \Lambda\bar{\Lambda}$ reaction [22] are consistent with this result.

The evaluation of the amplitude (3) is more conveniently performed in the helicity basis. The two helicity amplitudes corresponding to the values of the total helicity $\Lambda = \lambda_p - \lambda_{\bar{p}}$ equal to $\Lambda = 0$ and $\Lambda = 1$, respectively, are

$$T^{(t)}_{++} = \frac{ig^2}{t - M^2}\left(\Delta\frac{p}{m} + q\cos\theta\right) \ , \tag{7a}$$

$$T^{(t)}_{+-} = \frac{ig^2}{t - M^2}\left(\frac{-E}{m}q\sin\theta\right) \ , \tag{7b}$$

where p and $E = \sqrt{p^2 + m^2}$ are the momentum and energy of the (anti) proton in the c.m.s., and θ is the angle between the directions of the incoming antiproton and outcoming D^- or D^0 meson.

The machinery of the evaluation of the amplitudes (7) is standard [23,24], and includes the decomposition of the helicity amplitudes into components with definite total momentum. It is further convenient to expand the denominator

$$\frac{1}{(t - M^2)} = -\frac{1}{2pq}\frac{1}{z - \cos\theta} \ ,$$

where

$$z = \frac{1}{pq}\left[\frac{1}{2}(M^2 - m^2 - M_D^2) + \frac{s}{4}\right]$$

(M_D is the D-meson mass, and s is the c.m.s. energy squared), using the Heine formula

$$(z - \cos\theta)^{-1} = \sum_{m=0}^{\infty}(2m + 1)P_m(\cos\theta)Q_m(z) \ ,$$

with P_m being the Legendre polynomials and Q_m the Legendre functions of the second kind.

We now have to correct for the initial-state interaction. The S-matrix elements of the $p\bar{p}$ scattering that enter formula (4) are parametrized [15,16] in the $\{LSJ\}$ basis, where L and S refer to the orbital momentum and total spin in the $p\bar{p}$ system. To implement the initial-state interaction one has therefore to make the transformation of the partial-wave helicity amplitudes into $\{LSJ\}$ ones, which can be done easily:

$$T^J_{L=J-1} = \sqrt{\frac{2}{2J+1}}(\sqrt{J}T^J_{++} + \sqrt{J+1}T^J_{+-}) \ , \tag{8a}$$

$$T^J_{L=J+1} = \sqrt{\frac{2}{2J+1}}(-\sqrt{J+1}T^J_{++} + \sqrt{J}T^J_{+-}) \ . \tag{8b}$$

The parity conservation allows only the transitions ($J = L\pm 1, S = 1) \to (l = J)$, where l is the orbital momentum in the $D\bar{D}$ system.

Adding the s-channel resonant amplitude (1) to the t-channel one, we find ourselves in a position to calculate

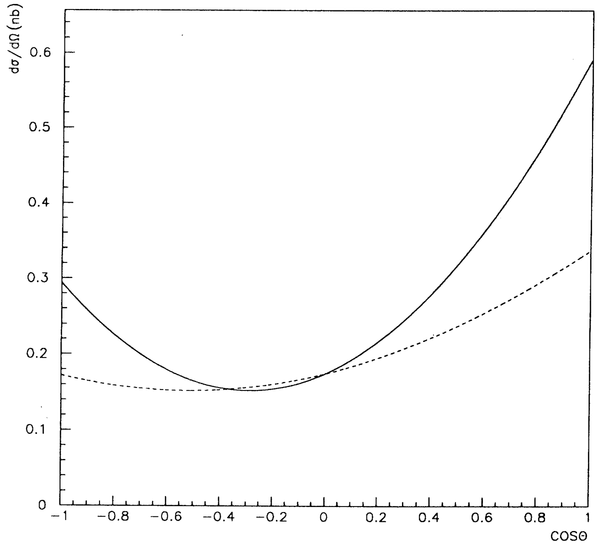

FIG. 1. The differential cross section of the $p\bar{p} \to D\bar{D}$ reaction at $\sqrt{s} = 3.79$ GeV. The dashed line corresponds to the contribution of the t-channel exchange diagrams only; the solid line is the result of full calculation with the contribution from the Ψ'' resonance taken into account.

the cross section.[1] The use of the SU(4)-motivated value (6) for the $\Lambda_c pD$ coupling constant leads to a t-channel contribution which is three orders of magnitude larger than that of the s-channel Ψ'' resonance, thus leading to a result that is in strong contradiction with the semilocal duality. We do expect, however, that due to the large difference in the masses of charmed and strange quarks the SU(4) is severely broken, and the value (6) is largely overestimated.

To perform an estimate of the cross section, we can, however, proceed in a different way, choosing the magnitude of the $\Lambda_c pD$ coupling so that the energy-averaged contributions of the s- and t-channel amplitudes become equal, according to the semilocal duality [8,9]. The resulting value is about

$$\frac{g^2_{\Lambda_c pD}}{4\pi} \simeq 0.5 \ , \tag{9}$$

which is some 30 times less than the SU(4)-motivated value (6). A very interesting interference pattern then appears in the differential cross section.

As a typical example of our results we show in Fig. 1 the differential cross section of the $p\bar{p} \to D\bar{D}$ reaction at $\sqrt{s}$=3.79 GeV, i.e., 20 MeV above the $\Psi''(3.77)$ mass. One can clearly see how the $\cos\theta$ distribution of the D mesons arising from the decay of the Ψ'' resonance is distorted by the asymmetric t-channel exchange amplitude. The magnitude of the cross section that we find is of the same order as found by [25,26] in a different framework.

The appearance of the interference pattern is extremely sensitive to the relative strength of the $p\bar{p}\Psi''$ and $\Lambda_c ND$ couplings; its very existence requires these couplings to be of the same order of magnitude, in agreement with the semilocal duality.

To summarize, we have calculated the differential cross section of the $p\bar{p} \to D\bar{D}$ reaction close to its threshold. We have found an interesting structure in the angular distributions of D mesons, arising from the interference between the resonant s-channel and nonresonant t-channel amplitudes. The very appearance of this interference pattern requires, however, the strength of the two amplitudes to be approximately the same, as is required by semilocal duality. Moreover, we find that the shape of the angular distributions and the value of the total cross section altogether allow one to determine the $p\bar{p}\Psi''$ and $\Lambda_c ND$ couplings unknown at present. The latter are important to know since they are possibly driven by nonperturbative effects sensitive to the heavy flavor contents of baryons and/or to the light-quark–antiquark component of the Ψ''.

An additional interest in the production of charmed mesons in $N\bar{N}$ annihilation not far from the threshold arises from the possible existence [27] of exotic diquark-antidiquark resonances with hidden charm, which would manifest themselves as additional s-channel resonances. We therefore consider the experimental measurement of the $p\bar{p} \to D\bar{D}$ reaction as very desirable.

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[1]Summing the s- and t-channel amplitudes seems to contradict the idea of duality and could lead to double counting in computing the total reaction cross section. Nevertheless, it is clear that an interference between these amplitudes should manifest itself in the differential cross section in the vicinity of a resonance.

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