P-986 Addendum:
Antiproton Annihilation and Open Charm

Daniel M. Kaplan
Illinois Institute of Technology, Chicago, Illinois 60616, USA

February 5, 2009

Abstract

It is possible that the world's most sensitive charm-mixing and *CP*-violation study could be carried out using the Fermilab Antiproton Source. Such a study could potentially discover non-standard model *CP* violation — a goal that to date has eluded the *B* Factories and Tevatron experiments.

1 Summary

We do not yet know whether there is appreciable *CP* violation due to physics beyond the standard model. Such non-SM *CP* violation is a corollary of Sakharov's explanation for the baryon asymmetry of the universe but has yet to be found in *K* or *B* *CP*-violation studies. The LHC*b* and SuperBelle experiments seek to extend such sensitivity but will take some years to do so (and may ultimately be limited by systematics rather than statistics). In the near term, neither experiment is likely to rival the charm sensitivity potentially available at the Fermilab Antiproton Source (see below). In contrast to *K* and *B* studies, new physics in charm *CP* violation is unlikely to be obscured by SM background.

Many SM extensions predict appreciable *CP* violation in charm mixing and decay, as well as appreciable branching fractions for rare decays suppressed in the SM. Both direct and indirect *CP* violation are expected, and both could be sensitive to new physics.[1] Thanks to the *B* factories and CDF, we now know definitively that D^0 and $\overline{D}^0$ mesons mix, albeit at the ≈ sub-percent level [4]. But greater statistics is required in order to ascertain whether *D* mixing and decay also violate *CP*. If they are found to do so, it will most likely represent non-SM *CP* violation. This will be a landmark discovery.

Braaten has recently published [1] a formula by which the $\overline{p}p$ cross section for annihilation into the exclusive final state $D^{*0}\overline{D}^0$ may be estimated. The result is shown in Fig. 1 and is seen to peak at $\approx 1.25\,\mu$b at $\sqrt{s} \approx 4.2\,$GeV. This is a remarkable result in that it represents several billion events produced per year in an experiment at the Fermilab Antiproton Accumulator with $\overline{p}p$ luminosity $\approx 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$. (The details of this estimate are presented below.)

To put this into perspective, the largest extant charm sample is that of Belle, with a total of some 1 billion charm events produced in about $1\,\text{ab}^{-1}$ of integrated luminosity. The

[1] In the standard model, direct charm *CP* violation is expected only in singly Cabibbo-suppressed decays; thus observation of *CP* asymmetry in Cabibbo-favored or doubly Cabibbo-suppressed decays would signal new physics [3].

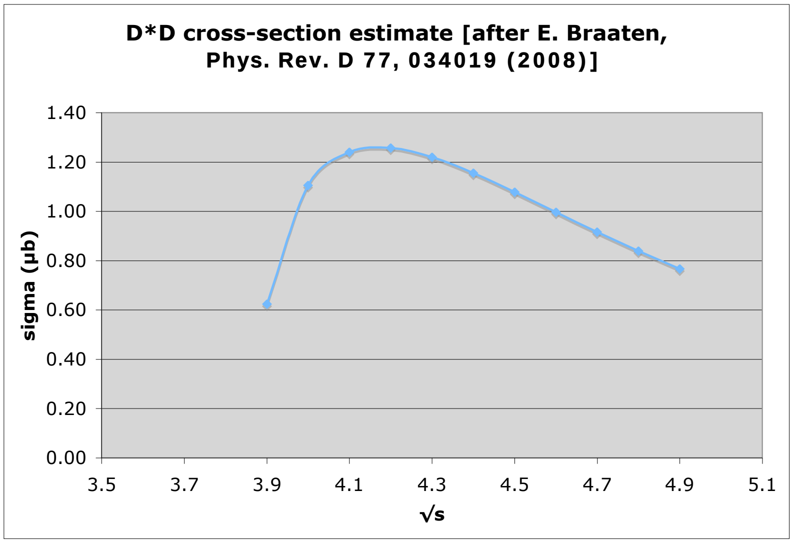

Figure 1: Estimated cross section vs. $\sqrt{s}$ for the exclusive reaction $\overline{p}p \to D^{*0}\overline{D}^0$.

highest-statistics published result from Belle, 1.22×10^6 tagged $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$ events (from $540\,\mathrm{fb}^{-1}$ of e^+e^- data taken at or near the $\Upsilon(4S)$) [2], corresponds to "only" 32 million tagged $\overset{(-)}{D}{}^0$ decays.[2] There thus appears to be the opportunity at the Fermilab Antiproton Source to amass what could be by far the world's largest sample of tagged D^0 decays.

2 Tagged D's from D^*'s

The charm cross section at medium energies is unmeasured and difficult to estimate reliably from theory. However, recent papers present a few approaches that are probably indicative of the order of magnitude.

2.1 Cross-section estimates

Braaten's formula [1],

$$\sigma[p\overline{p} \to D^{*0}\overline{D}^0; s] \approx \left(\frac{m_{D^*} + m_D}{\sqrt{s}}\right)^6 \frac{\lambda^{1/2}(s^{1/2}, M_{D^*}, M_D)}{[s(s - 4m_p^2)]^{1/2}} \times (4800\,\mathrm{nb}), \tag{1}$$

where $\lambda(x, y, z) = x^4 + y^4 + z^4 - 2(x^2y^2 + y^2z^2 + z^2x^2)$, applies to the $D^{*0}\overline{D}^0$ exclusive final state, which however does not yield tagged D^0 decays, since the slow π^0 or gamma emitted in the D^{*0} decay to D^0 is not flavor-specific. To assess the reach in tagged-D^0 events, we must consider such exclusive final states as $D^{*+}D^-$, $D^{*+}D^{*-}$, $D^{*+}D^-\pi^0$, $D^{*+}D^0\pi^-$, $D^{*+}D^0\pi^-\pi^0$, etc. (and Hermitian-conjugate modes). Two-thirds of all D^{*+} decays are in the flavor-specific π^+D^0 mode, in which the charge of the slow pion tags the initial charm flavor of the D meson.

[2]The Belle analysis includes the requirement $p_{D^*} > 2.5\,\mathrm{GeV}/c$, in order to suppress combinatorics and the large background of charm from B decays.

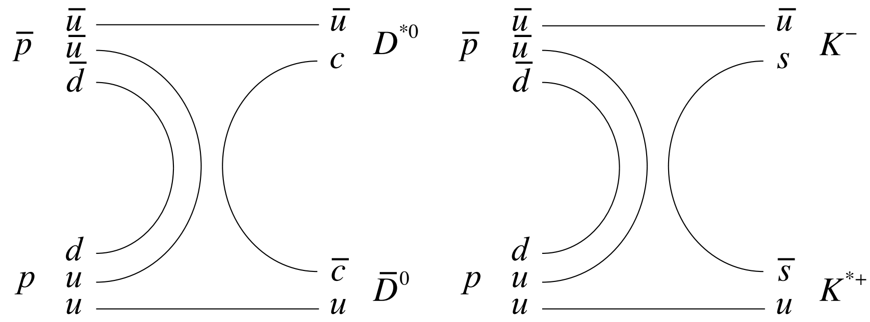

Figure 2: Comparison of leading Feynman diagrams for $\overline{p}p \to D^{*0}\overline{D}^0$ and $\overline{p}p \to K^{*+}K^-$; they differ only in the replacement of final-state charm quarks with strange quarks.

Braaten's interest in the $\overline{p}p \to D^{*0}\overline{D}^0$ cross section stems from his contention that the most plausible explanation for the unusual properties of the $X(3872)$ particle discovered by Belle [5] is that it is a $D^{*0}\overline{D}^0$ molecule. However, no measurements are available of the $\overline{p}p \to D^{*0}\overline{D}^0$ cross section — nor, for that matter, of *any* medium-energy-antiproton charm-production cross section. (LEAR had insufficient energy, the bubble-chamber experiments had insufficient statistics, and E760/835 had no magnet.) Braaten therefore relates this cross section to that for $\overline{p}p \to K^{*+}K^-$ (see Fig. 2), for which measurements are available from the Crystal Barrel experiment at LEAR [6] and from earlier bubble-chamber experiments [7]. This involves a kinematic extrapolation from well above threshold (where the exclusive cross section has fallen by an order of magnitude from its peak value) to the peak of the cross section. He estimates the uncertainty as a factor of 3 in either direction.

Following his example, the best way to estimate the cross section for $D^{*\pm}$ production is to relate it to measured $\overline{p}p$-annihilation cross sections to final states including K^{*0} (see Fig. 3). Some of these are available in Ganguli *et al.* [7] (see Table 1). Their sum of $(860 \pm 60)\,\mu$b substantially exceeds the $(460 \pm 50)\,\mu$b observed for $K^{*+}K^-$ by Crystal Barrel as well as the $(400 \pm 20)\,\mu$b observed by Ganguli *et al.* for that mode. Since other final states containing K^{*0} are also possible, we take this as only a "subtotal," i.e., the inclusive K^{*0} cross section should be larger than this. (Similarly, the inclusive D^{*+} cross section could be larger than estimated here, both because of additional final states and due to the extrapolation uncertainty in Braaten's formula.)

For this "continuum" charm running, we anticipate using a moderate-A target, such as an aluminum wire, rather than the hydrogen gas jet used in E760 and E835. At high energies it is well established that heavy-quark production cross sections scale as $A^{1.0}$ [8], while the total inelastic cross section scales as $A^{0.71}$ [9]. The use of e.g. aluminum thus increases the signal-to-background ratio by a factor $27^{0.29} = 2.6$.[3] This also halves the $\overline{p}p$ interaction rate and adds an equal rate of $\overline{p}n$ interactions. Figure 3 suggests that $D^{*\pm}$ production in $\overline{p}n$ interactions should be similar in rate to that in $\overline{p}p$ interactions.

Titov and Kämpfer have published [10] an alternative calculation of charm exclusive cross sections. They use a Regge approach, with the values of various free parameters determined from measured $\overline{p}p \to K\overline{K}$ and $\overline{p}p \to$ hyperon-antihyperon cross sections. Their focus

[3]A higher-A target than aluminum would provide a larger charm enhancement but might also reduce the integrated luminosity by eliminating stored antiprotons via dE/dx loss and multiple Coulomb scattering. The optimal target material will need to be established in actual running; however, materials in the range Al through Ti were found to be optimal in HERA-B [11].

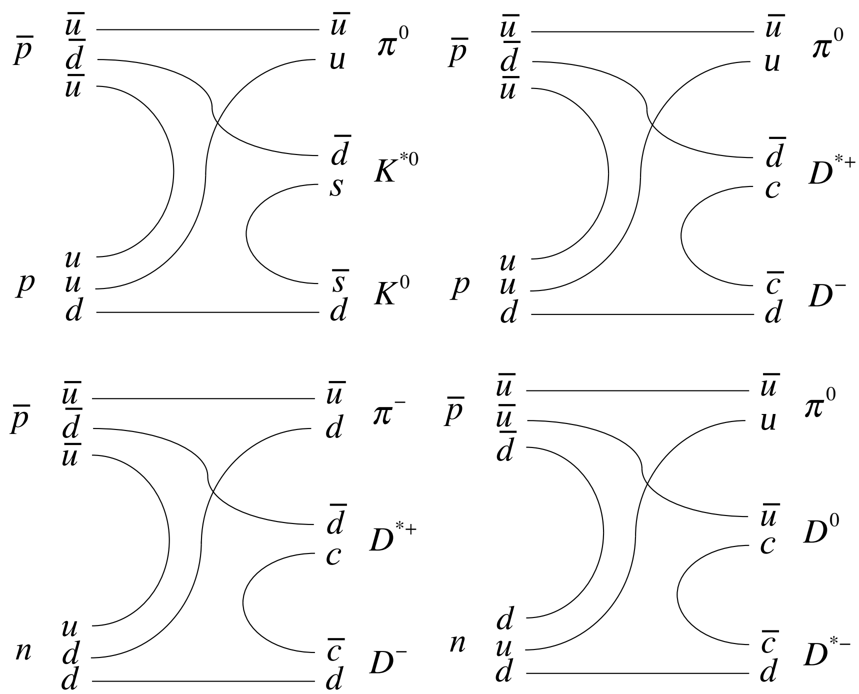

Figure 3: Some leading Feynman diagrams for $\overline{p}p \to K^* K\pi$, $\overline{p}p \to D^* D\pi$, and $\overline{p}n \to D^* D\pi$; note that compared with those of Fig. 2, these diagrams require only one pair of initial-state quarks to annihilate.

Table 1: Various exclusive $\overline{p}p$ cross sections to final states containing K^{*0} (from [7]) at $\approx 750\,\text{MeV}$ $\overline{p}$ kinetic energy. (Note that K_L was unobserved in [7]; we assume the cross sections for K_L and K_S are equal.)

Mode	σ (μb)	error (μb)
$K^{*0}K_S$	150	20
$K^{*0}K_L$	150*	20*
$K^{*0}K_S\pi^0$	70	10
$K^{*0}K_L\pi^0$	70*	10*
$K^{*0}K^{\pm}\pi^{\mp}$	240	40
$K^{*0}\overline{K}^{*0}$	180	25
Sum	860	57

*assumed.

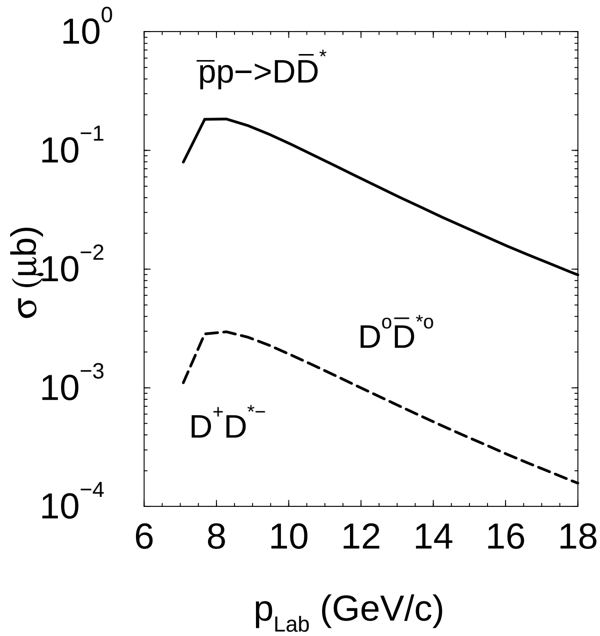

Figure 4: Total cross sections for $\overline{p}p \to D^0\overline{D}^{*0}$ (solid) and $\overline{p}p \to D^+\overline{D}^{*-}$ (dashed) from Regge calculation of Titov and Kämpfer [10, 12] vs. antiproton momentum. As with Braaten's formula [1], the $D^0\overline{D}^{*0}$ cross section peaks at $p_{\overline{p}} \approx 8\,$GeV; however the estimated cross section is a factor of 6 smaller.

on FAIR led them to consider 15 GeV/c antiprotons rather than the 8.9 GeV/c which is the maximum $\overline{p}$ momentum available at the Accumulator, but Titov has recently provided [12] exclusive total cross-section predictions vs. antiproton momentum, shown in Fig. 4. For $D^0\overline{D}^{*0}$ these are lower than obtained using Braaten's formula by a factor of 6. (Given the uncertainties of low-momentum-transfer, non-perturbative QCD, Braaten views this as agreement with his estimate [13].)

Since several other low-multiplicity final states containing a D^{*+} or D^{*-} are accessible in antiproton annihilation at this energy, we take these arguments as indicative of the likelihood that the total $D^{*\pm}$ cross section in 8 GeV $\overline{p}N$ annihilation is of order 1–10 μb. This is sufficiently large that a measurement is of great interest.

2.2 Acceptance and efficiency

We note that $\sqrt{s} = 4.2\,$GeV is approximately the maximum center-of-mass (CM) energy accessible at the Antiproton Accumulator since 8 GeV antiproton kinetic energy corresponds to $\sqrt{s} = 4.30\,$GeV. At this energy the CM frame moves in the lab with a boost factor $\gamma = 2.3$, comparable to the boost for charm events at the B factories. Preliminary simulation studies indicate acceptance for $D^{*+} \to \pi^+ D^0$ decays of $\approx 50\%$. Furthermore, the mean charged multiplicity in $\overline{p}p$ interactions at these energies is ≈ 3. Thus the combinatorial background that underlies the D mass peak in high-energy hadroproduction experiments should be much reduced. We therefore speculate that cuts required to suppress the background can be relatively mild and similar in efficiency to those used at the B factories. At present this guess still needs to be backed up with additional work; we are studying MIPP antiproton data to try to quantify this efficiency.

3 The $X(3872)$ as a D Factory

We next assume (for the sake of discussion) that the $X(3872)$ is indeed a $D^{*0}\overline{D}^0$ (plus Hermitian-conjugate) molecule — arguably the leading interpretation of this mysterious, charmonium-related state. Then with a sufficiently narrow beam-momentum distribution, the process $\overline{p}p \to X(3872)$ may be competitive in charm new-physics reach with the continuum production discussed above.[4] The statistics obtainable in this fashion depends on unknowns (about which the experiment considered here would appreciably improve our knowledge) including the $X(3872)$ total width, $\overline{p}p$ partial width, and branching ratios, as well as the beam-momentum distribution. Assuming plausible values for these [1, 13], we can estimate the number of produced $X(3872) \to D^{*0}\overline{D}^0$ per year at about 10^8 — some two orders of magnitude below the continuum-production estimate of Table 2. However, analogously to the $\psi(3770) \to D\overline{D}$ decay, these events are $D^{*0}\overline{D}^0$ pairs produced in a known (most likely, $J^{PC} = 1^{++}$) quantum state, which thus correlates the subsequent D and D^* decays. (Because the D^{*0} decays to both γD^0 and $\pi^0 D^0$, giving D^0 mesons with opposite C-parities, one would want the calorimeter to be capable of distinguishing these modes with some degree of reliability.)

To evaluate the physics reach of such a data sample will require a detailed simulation study; however, the power of quantum-correlated D decays to precisely probe charm mixing is a key aspect of the BES-III physics program — also with an estimated 10^8 events. The $X(3872)$ may be able to play a similar role for a $\overline{p}p$ facility.

4 Conclusions

If we assume charm-continuum running at $\mathcal{L} = 2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ on an aluminum target, acceptance of 50%, efficiency after cuts of 10%, and the central value derived from Braaten's exclusive cross-section formula, $1.25\,\mu$b, we reconstruct some 27 million tagged $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$ events per year of operation (Table 2), to be compared with 1.22 million at present and about 2 million when the full Belle sensitivity of $\approx 1\,\mathrm{ab}^{-1}$ is analyzed. Estimates for medium-energy charm cross sections are available only for exclusive final states. The inclusive cross section may well be significantly larger than this, but clearly it could also be smaller, perhaps by as much as a factor of 3. Given the low multiplicity of events in 8 GeV antiproton annihilation, the assumed 10% cut efficiency may be feasible, but additional studies are required in order to confirm this.

At this preliminary stage of consideration, a magnetic-spectrometer experiment at the Antiproton Accumulator seems potentially capable of reconstructing the world's largest charm samples and making a high-impact measurement: the first observation of new physics in charm CP violation. More work to evaluate the reach is clearly called for. If after this work, the efficiencies estimated here remain plausible, mounting a simple experiment at the Antiproton Accumulator to test these estimates would seem to be both highly desirable and urgent.

[4] This would require running with a hydrogen target, in order not to degrade the center-of-mass energy precision via beam dE/dx loss or target Fermi motion, but it is straightforward to outfit the AP-50 experimental area with both a hydrogen target and a metal target.

Table 2: Assumed values and sensitivity-benchmark estimate of tagged $\overset{(-)}{D}{}^0 \to K^\mp\pi^\pm$ events per year. (Caveats: As discussed in text, the reliability of some of these values remains to be established. They are based on exclusive cross-section estimates, so the inclusive production rate could be significantly higher, but the cross section, luminosity, or efficiency could also be lower.)

Quantity	Value	Unit
Running time	2×10^7	s/y
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Target A	27	
$A^{0.29}$	2.6	
$\sigma(\overline{p}p \to D^{*+}X)$	1.25	μb
# $D^{*\pm}$ produced	2.1×10^{10}	events/y
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.5	
Efficiency	0.1	
Total	2.7×10^7	events/y

*Assumes ≈ 15% of running time is devoted to antiproton-beam stacking.

References

[1] E. Braaten, Phys. Rev. D **77**, 034019 (2008).

[2] M. Staric *et al.* [Belle Collaboration], Phys. Rev. Let. **98**, 211803 (2007).

[3] See e.g. D. M. Kaplan, hep-ex/0111044 (2001) and references therein.

[4] See http://www.slac.stanford.edu/xorg/hfag/charm/ICHEP08/results_mix+cpv.html and E. Barberio *et al.*, arXiv:0808.1297 [hep-ex].

[5] S. K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91**, 262001 (2003).

[6] C. Amsler *et al.*, Phys. Lett. B **639** (2006) 165.

[7] S. N. Ganguli *et al.*, Nucl. Phys. B **183**, 295 (1981).

[8] M. J. Leitch *et al.*, Phys. Rev. Lett. **72**, 2542 (1994).

[9] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).

[10] A. I. Titov and B. Kämpfer, Phys. Rev. C **78**, 025201 (2008).

[11] K. Ehret, Nucl. Instr. Meth. A **446**, (2000) 190.

[12] A. Titov, private communication.

[13] E. Braaten, private communication. Indeed, he has also described an alternative calculation, also based on Phys. Rev. D **77**, 034019 (2008), that, at 250 nb, is expected to be an underestimate but agrees even more closely with Titov's.