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Perspectives on Heavy Quark 98

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Perspectives on Heavy Quark 98

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Abstract. I summarize and comment upon some highlights of *HQ98*, the Workshop on Heavy Quarks (strange, charm, and beauty) at Fixed Target.

HISTORICAL PROLOGUE

Half a century has passed since George Rochester and Clifford Butler announced their discovery of “*vee* particles,” penetrating products of cosmic-ray showers that proved to be *K* mesons, the first strange particles [1]. Through the years, it is striking how thoroughly the study of heavy flavors has defined our progress toward an elegant and comprehensive picture of the fundamental constituents and their interactions. Understanding heavy flavors has been essential to understanding the ordinary stuff of everyday matter.

To kick off *HQ98*, we had the pleasure of hearing reminiscences from Lincoln Wolfenstein [2], Jon Rosner [3], and Tony Sanda [4] on the beginnings of our understanding of strangeness, charm, and beauty. They offered interesting lessons in where we have been, and where we hope to go.

Not all history lies so far in the past. *HQ98* weekend witnessed an important event for the future of Fermilab and of heavy-quark physics. At 17:21 on Saturday, October 10, circulating beam was established for the first time in the Main Injector. This new element in Fermilab’s cascade of accelerators, a proton synchrotron precisely π km around, will play a double role as injector to the Tevatron and as the high-intensity source for a new 120-GeV fixed-target program at Fermilab. On behalf of the participants in *HQ98*, it is my pleasure to salute our colleagues for this fine achievement, and to wish them continued success in commissioning our newest accelerator.

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the degree of $B_d - \bar{B}_d$ mixing. They estimated $x_d \equiv \Delta M_B/\Gamma_B \simeq 0.7$ (where Γ_B is the average lifetime of the heavy and light B^0 states, to be compared with $\Delta M_K/\Gamma_K \simeq 0.5$).

At *HQ98*, we have seen two lovely examples of *time-dependent* $B^0 - \bar{B}^0$ oscillations in the talks by Kevin Pitts [8], representing CDF, and Achille Stocchi [9], representing the four LEP collaborations. These plots, which are based on thousands of clean events, will take their place in textbooks alongside the classic plots of the time evolution of $K^0 - \bar{K}^0$ oscillations. They represent phenomenal progress since the discovery of $B^0 - \bar{B}^0$ mixing in 1987. And this is not all. Through the combined efforts of ALEPH, DELPHI, OPAL, and L3 at LEP, CDF at the Tevatron, and SLD at the Stanford Linear Collider, we now can quote a very precise world average for the mass difference [8]

$$\Delta M_B = 0.475 \pm 0.010_{\text{stat}} \pm 0.014_{\text{sys}} \text{ ps}^{-1}. \quad (3)$$

so that $x_d \approx 0.74$.

This much is solid achievement, but a great deal more is in the works. We expect the frequency of $B_s - \bar{B}_s$ oscillations to be much more rapid than that of $B^0 - \bar{B}^0$. The LEP experiments plus CDF and SLD can now set a lower bound of $\Delta M_{B_s} > 12.4 \text{ ps}^{-1}$ [10], which implies $x_s \equiv \Delta M_{B_s}/\Gamma_{B_s} \gtrsim 18.5$. An observation of $B_s - \bar{B}_s$ mixing would fix the ratio of the quark-mixing matrix elements V_{td} and V_{ts} . While the LEP experiments continue to press their analyses, the greatest reach in the near future will come from CDF and DØ, using the 2 fb^{-1} of data each experiment will accumulate in Run II of the Tevatron Collider. For the baseline detector, CDF anticipates a reach in the range $x_s \approx 30 - 40$; additional upgrades could extend the reach to $x_s \approx 55 - 65$ [8].

In the standard electroweak theory, the dominant contributions to $B - \bar{B}$ mixing come from box diagrams involving loops of W bosons and quarks, most importantly top quarks. These lead to expressions for the mixing parameters,

$$x_d = \frac{\Delta M_B}{\Gamma_B} \propto f_{B_d}^2 |V_{td}^* V_{tb}|^2 B_{B_d} \tau_{B_d} m_t^2 \quad (4)$$

and

$$x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}} \propto f_{B_s}^2 |V_{ts}^* V_{tb}|^2 B_{B_s} \tau_{B_s} m_t^2, \quad (5)$$

that contain many parameters. I think the worst moment in my career as a summary speaker came during that talk at *Heavy Flavours - '87*. When I flashed these formulas on the screen, I suddenly became aware that I could pronounce the name of every parameter, but I didn't know the value of a single one! Our ignorance in 1987 ranged from the uncertain relationship between quark matrix elements and hadronic matrix elements subsumed in

the infamous B parameters to the mass of the top quark and the B -meson lifetimes.

I'm very happy that a decade of progress means I do not have to relive that unsettling moment. Harry Cheung's review of charm and beauty lifetimes [11] presents us with wonderfully precise values for $\tau_{B_d} = (1.556 \pm 0.027)$ ps and $\tau_{B_s} = (1.489 \pm 0.058)$ ps. The top mass, which was entirely unknown in 1987, is now known to very impressive precision. My informal average of the latest results from CDF [12] and DØ [13] yields $m_t = (173.8 \pm 4.8)$ GeV/ c^2 . Andreas Kronfeld reported on the development of lattice QCD calculations of the pseudoscalar decay constants and related parameters [14]. The study of heavy (b and c) quarks on the lattice, which coincidentally began in 1987, is now a mature subject. I think it is fair to say that almost definitive calculations of f_B and f_{B_s} (as well as f_D and f_{D_s}) are in hand, and that convergence on the B_B parameters is on the horizon. It would be incautious of me to record "best values," but I think it is useful to quote *representative values* drawn from Kronfeld's compilation: $f_B \approx 165 \pm 15$ MeV, $f_{B_s} \approx 188 \pm 15$ MeV, $f_D \approx 195 \pm 15$ MeV, and $f_{D_s} \approx 220 \pm 15$ MeV, not including the estimated effects of quark loops, which are thought to increase the values about 10%. Our best experimental test of these calculations comes from the purely leptonic decays $D_s \rightarrow \mu\nu$ and $\tau\nu$, which yield a world average value, $f_{D_s} = 254 \pm 31$ MeV [9]. This is encouragingly close to the calculated value adjusted for quark loops. The "bag factors" B_B are not in such settled condition; the scatter among calculated values still exceeds the uncertainties attributed to the calculations. More work is needed, but I do hope that convergence on reliable values is near. I am encouraged to note that the suitably defined bag factor for the neutral kaon system does seem to have converged to a value near 0.62 (see Ref. [14] for the precise definition), with little sensitivity to the omission of light-quark loops.

The remaining quantities, the quark-mixing matrix elements, are known to reasonable precision if we assume the three-generation picture and invoke unitarity of the CKM matrix to fix their values. (The Particle Data Group advises $|V_{td}| = 0.004$ to 0.013 , $|V_{ts}| = 0.035$ to 0.042 , and $|V_{tb}| = 0.9991$ to 0.9994 [15].) But if we demand a measurement, it is from the study of $B - \bar{B}$ oscillations that we get our best information about $|V_{td}|$ and $|V_{ts}|$. Single-top production in $\bar{p}p$ collisions will give us our first measurement of $|V_{tb}|$.

***CP* Violation in the B System**

One of our very important near-term goals is the observation and detailed study of CP violation in B meson decays. If the observed CP violation in the neutral kaon system indeed arises from the phase in the Cabibbo–Kobayashi–Maskawa quark mixing matrix, then the manifestations of CP violation in B decays will be rich and informative. Distinguishing B^0 from \bar{B}^0 by means of

a same-side-tagging technique, the CDF Collaboration has performed a first measurement of the asymmetry

$$\mathcal{A} = \frac{N(\bar{B}^0 \rightarrow \psi K_S) - N(B^0 \rightarrow \psi K_S)}{N(\bar{B}^0 \rightarrow \psi K_S) + N(B^0 \rightarrow \psi K_S)}, \quad (6)$$

using 200 events in which both muons from the decay $\psi \rightarrow \mu^+ \mu^-$ are reconstructed in the silicon vertex detector. In the standard model, this time-varying CP -violating asymmetry is given by

$$\mathcal{A}(t) = \sin(\Delta M_B t) \cdot \sin 2\beta, \quad (7)$$

where β is the angle in the complex plane between V_{td} and V_{cb}^* . The CDF measurement [8,16],

$$\sin 2\beta = 1.8 \pm 1.1_{\text{stat}} \pm 0.3_{\text{sys}}, \quad (8)$$

is statistics limited. The dominant contribution to the systematic error comes from the uncertainty in the dilution factor. While it is more in the nature of a dress rehearsal than an informative measurement, this CDF exercise is an important step on the path toward the discovery of CP violation in the B system [17].

The search for CP -violating effects in the B system will soon begin in earnest. The fixed-target experiment HERA-B has begun to take data, as we heard from B. Schwingerheuer [18]. Commissioning is well under way at the SLAC B factory, and the BABAR experiment described by G. Bonneaud [19] is approaching completion, with first data expected in 1999. Also in 1999, we expect the first run of BELLE at the KEK B factory [20]. The following year, the upgraded CDF and DØ detectors will profit from the greatly enhanced luminosity that the Main Injector will bring to the Tevatron Collider [8]. Farther in the future are LHCb [21] and the BTeV proposal at Fermilab [22]. A general survey of the promise of forthcoming experiments was presented at *HQ98* by Marina Artuso [23].

While the new experiments prepare themselves for serious data-taking, the highly successful Cornell Electron Storage Ring, which we may regard as a stationary center-of-momentum B factory, continues to produce a rich harvest of physics results in the upgraded CLEO detector. Among the CLEO results presented at *HQ98*, those reported by Peter Gaidarev on rare decays [24] are of special interest to the search for CP violation. The CLEO measurements of the branching fractions for $B^0 \rightarrow K\pi, \pi\pi$, and KK will inform the search for, and interpretation of, a CP asymmetry in the decays $(B^0, \bar{B}^0) \rightarrow \pi^+ \pi^-$. The current values are $B(B^0 \rightarrow K^\pm \pi^\mp) = (1.4 \pm 0.3_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-5}$ and $B(B^0 \rightarrow \pi^+ \pi^-) < 0.8 \times 10^{-5}$ at 90% CL. The small $\pi^+ \pi^-$ branching fraction complicates the program to extract the angle α between V_{ub}^* and V_{td} .

Before leaving the CLEO data on rare decays, let us note that the new measurement of the inclusive $b \rightarrow s\gamma$ branching fraction,

$$B(b \rightarrow s\gamma) = (3.15 \pm 0.35_{\text{stat}} \pm 0.32_{\text{sys}} \pm 0.26_{\text{model}}) \times 10^{-4}, \quad (9)$$

is in good agreement with standard-model expectations, and limits the phase space of models for new physics.

Baryogenesis

Together with the existence of fundamental processes that violate baryon number and a departure from thermal equilibrium during the epoch in which baryon-number-violating processes were important, microscopic CP violation is a necessary condition for generating a nonvanishing baryon number from an initially symmetrical universe. As Peter Arnold reviewed in his talk at *HQ98* [25], the CP violation we attribute to a phase in the quark mixing matrix does not appear capable of generating a baryon-to-photon ratio nearly as large as the value

$$n_B/n_\gamma \approx 10^{-9 \pm 1} \quad (10)$$

inferred from astronomical observations. Nevertheless, we hope that lessons learned from the study of CP -violating phenomena in the domain of heavy quarks will inform our eventual understanding of the baryon number of the universe. One of the most active areas of recent theoretical work has been to elaborate the possibility that baryogenesis occurs on the scale of electroweak symmetry breaking. In this scenario, it is not possible to generate a large enough baryon-to-photon ratio in the minimal electroweak theory with a single Higgs doublet. The feat can be accomplished in a supersymmetric theory, but only if the lightest Higgs boson is very light, $M_h \lesssim 105 \text{ GeV}/c^2$, and the stop squark weighs no more than the top quark [26]. Under these conditions, both h and \tilde{t} should be accessible soon at LEP200 and the Tevatron Collider, and we can expect departures from the standard-model CP phenomenology in the B mesons.

HEAVY-FLAVOR SPECTROSCOPY

Excited Mesons

For many years, the principal focus of charm and beauty physics has been on the weak decays of states stable against strong or electromagnetic decay. From these, we have learned important lessons about the structure of the weak charged current and about the interplay between the strong and weak interactions. Over the past five years or so, the study of excited states—especially excited meson resonances—has taken on a new interest, as high-statistics experiments with excellent mass resolution have attained maturity.

We now know a good deal about the meson states $c\bar{q}$, $c\bar{s}$, $b\bar{q}$, and $b\bar{s}$ beyond the ground-state (0^{-+} and 1^{--}) doublet.

The gross structure of the spectra of heavy-light mesons is rather well understood, from a combination of potential-inspired intuition and heavy-quark effective theory. The fine structure of the spectra is not an unambiguous prediction of HQET; thus, experimental results may provide some surprises and some new insights. To give an example, the separation of the centroids of the $j_q = 3/2$ (1^{++} and 2^{++}) and $j_q = 1/2$ (0^{++} and 1^{++}) doublets is not a robust prediction of the heavy-quark theory [27]. We believe that HQET and the chiral quark model do give us the tools we need to describe the strong-interaction transitions among mesonic states with precision, as described by Estia Eichten in his talk at *HQ98* [28]. The $j_q = 3/2$ states are expected to be narrow; the charmed states are thoroughly known, and the beauty states are under investigation in a number of experiments. Franz Muheim [29] showed what the LEP experiments have been able to achieve in analyses that rely to varying degrees on the predictions [30] of heavy-quark effective theory. The experimental observations are in broad agreement with HQET, and indicate that a significant fraction of B mesons (25 to 40%) are produced through the p -wave B^{**} states. This conclusion holds great interest for the same-side tagging of B flavor for studies of CP violation.

The $j_q = 1/2$ levels have not been established yet. They are expected to be broad, but theorists are only beginning to endow that label with a numerical meaning. At *HQ98*, Jorge Rodriguez [31] presented CLEO's evidence for the $D_1^*(j_q = 1/2)$ state near $2461 \text{ MeV}/c^2$, with a total width of about $200 - 400 \text{ MeV}$. This seems considerably broader than the theoretical expectation [28,32] that $\Gamma(0^+ \rightarrow 0^-\pi) \approx \Gamma(1^+ \rightarrow 1^-\pi) \approx 85 \text{ MeV}$. In the B system, an L3 analysis reported by Muheim [29] suggests that the B_1^* has a mass of $5675 \pm 12 \pm 4 \text{ MeV}/c^2$ and a width of $78 \pm 28 \pm 15 \text{ MeV}$, in the range suggested by chiral-quark-model calculations. We can expect both theoretical and experimental progress by the time of *HQ2000*.

The DELPHI Collaboration [33] recently reported an excess of events in the $D^{*+}\pi^+\pi^-$ mass spectrum at a mass of $2637 \pm 2 \pm 6 \text{ MeV}$, which is consistent with expectations for the first radial excitation of the D^* meson. The width of the excess is quite small, consistent with their experimental resolution. Both OPAL (see Muheim, Ref. [29]) and CLEO (see Rodriguez, Ref. [31]) have presented upper limits that are inconsistent with the DELPHI observation.

Charmed Baryons

In $SU(4)_{\text{flavor}}$ symmetry, the ground-state baryons include 20 $1/2^+$ states, of which 12 contain one or more charmed quarks, and 20 $3/2^+$ states, of which 10 contain one or more charmed quarks. All nine of the singly-charmed $1/2^+$ states and four of the six singly-charmed $3/2^+$ states have been observed.

Only the Σ_c^{*+} and Ω_c^* remain undetected. Sajjad Alam [34] reviewed CLEO's extensive contributions to charmed-baryon spectroscopy, while Eric Vaandering [35] summarized the achievements of Fermilab Experiment E687 and the promise of its successor, FOCUS. The multiply charmed baryons (and, more generally, heavy-heavy-light baryons) remain tempting experimental targets, in part for the analogy in HQET to heavy-light mesons [28].

Charmonium Spectroscopy

Todd Pedlar reported on Fermilab experiment E835 [36], the study of charmonium spectroscopy in resonant $\bar{p}p$ annihilations. E835 is conducted in what we think of as the Fermi National *D*eaccelerator Laboratory, when the Antiproton Accumulator decelerates antiprotons from 8.9 GeV/*c* to the momenta required for resonant formation of $c\bar{c}$ states, in the range 4 – 7 GeV/*c*. E835 reports the first evidence for formation of the 1^3P_0 state χ_0 in $\bar{p}p$ annihilations. The resonance parameters, $M(\chi_0) = (3415_{-1.7}^{+2.1})$ MeV/*c*² and $\Gamma(\chi_0) = (13.9_{-3.9}^{+5.3})$ MeV, are in good agreement with Particle Data Group averages [15]. The $\bar{p}p$ branching fraction, while consistent with the preëxisting upper bound, is tantalizingly large:

$$B(\chi_0 \rightarrow \bar{p}p) = (4.24_{-0.70}^{+0.96} \pm 1.16) \times 10^{-4}. \quad (11)$$

The BES Collaboration has just published the first determination of this branching fraction in e^+e^- collisions at the $\psi(2S)$ [37]; their value is $(1.59 \pm 0.43 \pm 0.53) \times 10^{-4}$.

Despite assiduous efforts, the E835 Collaboration has not been able to find any sign of the expected pseudoscalar radial excitation η'_c (2^1S_0). The old Crystal Ball claim of a state at 3594 MeV/*c*², which was too distant from the ψ' for theoretical comfort, is rather decisively ruled out, but it is somewhat maddening that the real η'_c has not shown itself. What are we missing?

Production of Heavy Flavors

A wealth of information about the production of heavy quarks was presented at *HQ98*. Fred Olness [38] presented an excellent summary of the outstanding theoretical and experimental issues. A key point is that heavy-quark production processes are both challenging and interesting for our understanding of perturbative QCD because they typically involve two large scales: the heavy-quark mass, or threshold, and the typical large-momentum scale that encourages the application of perturbative techniques. Once we have reliable predictions for the kinematic distributions of the heavy quarks, we need to understand how those are reflected in the kinematic distributions of the hadrons that contain those quarks. The current state of understanding in the

Lund string-fragmentation approach was reported to *HQ98* by Emanuel Norrbin [39]. Fermilab Experiment E791's new measurements of the production asymmetries $A \equiv (\sigma_X - \sigma_{\bar{X}})/(\sigma_X + \sigma_{\bar{X}})$ for D^\pm , D_s^\pm , and Λ_c baryons and antibaryons, presented by Kevin Stenson [40], offer empirical insight into the fragmentation process. The HERMES experiment at HERA has completed three years of successful data taking that includes a measurement of the cross section for J/ψ photoproduction and a clear open charm signal [41], still under analysis. We also look forward to the operation of the COMPASS experiment at CERN [42].

Collider data on charmonium production have forced us to look more broadly for the right physical picture of the process than the color-singlet mechanism in which the observed charmonium state has the quantum numbers of the produced $c\bar{c}$ pair. Since the discovery by the CDF Collaboration [43] that the direct production of both J/ψ and ψ' occur at some fifty times the color-singlet-model rate, our attention has been drawn to a color-octet mechanism in which the produced $c\bar{c}$ pair evolves into a color-singlet hadron by emitting a soft gluon. For this reason, it is sometimes called the color-evaporation mechanism. At *HQ98*, Andrzej Zieminski [44] presented recent results from the DØ Collaboration that test the color-octet picture of J/ψ production into the regime of large rapidity and small transverse momentum. Within uncertainties, the color-octet model describes the pseudorapidity dependence of J/ψ production at all angles. An interesting production-mechanism diagnostic is the polarization of the produced charmonium state. In a thorough report on charm and beauty production in CERN Experiment WA92, Dario Barberis [45] showed that in 350-GeV/c π^- -A collisions, the J/ψ polarization is small, in agreement with the color-octet picture. Ting-Hua Chang [46] similarly reported that in 800-GeV/c p Cu collisions, the NUSEA Collaboration (Fermilab Experiment E866) observes no polarization in the J/ψ decay angular distribution integrated over all production angles (represented by x_F).

Models for charmonium production need also to confront the photoproduction data shown by Beate Naroska [47] in her summary of heavy-flavor work at H1 and ZEUS. The HERA measurements, taken in a kinematic regime where diffraction dominates, are described very well by a next-to-leading-order color singlet model, and do not demand a significant color-octet contribution. The link between nonperturbative parameters set by CDF data and the consequences for diffractive production at HERA involves some subtleties that need further work to resolve.

In heavy-ion collisions, charmonium suppression—beyond the normal nuclear absorption long observed in hadron-nucleus and light-ion collisions—has been predicted as a diagnostic for the creation of a quark-gluon plasma, *i.e.*, a deconfined state of hadronic matter. A sudden drop in the J/ψ yield as a function of the product of target and projectile mass numbers has been observed in Pb-Pb collisions by the NA50 Collaboration at CERN, as we heard in the heavy-ion summary by Carlos Lourenço [48]. The effect is large: the

measured point lies some 4.5σ below the extrapolation from smaller values of the mass product. It is clearly a tantalizing hint.

The CCFR Collaboration at Fermilab has used the production of one heavy quark, charm, to investigate the population of another heavy quark, strange, in the nucleon. Todd Adams [49] presented the results of their next-to-leading-order fits to the charm production cross section in $(\nu_\mu, \bar{\nu}_\mu)N$ deeply inelastic scattering. They confirm the expectation (and the conclusion of earlier experiments) that the nucleon sea is not $SU(3)$ -symmetric, and find that the inferred value of the charm quark mass is analysis dependent. The successor experiment, NuTeV, has an improved data sample that will permit more incisive analyses.

STRANGE-PARTICLE DECAYS

Search for Direct CP Violation

CP violation can arise from a small impurity in the mass eigenstates of the K^0 - \bar{K}^0 complex, or from a “direct” CP -violating contribution to the decay amplitudes, or from interference between the two. If CPT is a good symmetry, the mass eigenstates can be written as

$$|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle, \quad |K_L\rangle = p|K^0\rangle - q|\bar{K}^0\rangle. \quad (12)$$

If CP invariance held, we would have $q = p = 1/\sqrt{2}$, so that K_S would be CP -even and K_L CP -odd. In a convenient phase convention [50], we can express CP violation in K^0 - \bar{K}^0 mixing through the parameter ε ($|\varepsilon| \approx 2.28 \times 10^{-3}$, with a phase near 45°),

$$\frac{p}{q} = \frac{(1 + \varepsilon)}{(1 - \varepsilon)}. \quad (13)$$

CP violation in the decay amplitudes gives rise to an inequality—a phase difference—in the amplitudes $A(K^0 \rightarrow \pi\pi(I))$ and $A(\bar{K}^0 \rightarrow \pi\pi(I))$, where I is the isospin of the $\pi\pi$ system. It is conventional to express the CP -violating observables in terms of the parameters ε and ε' , the latter defined through

$$\begin{aligned} \eta_{+-} &\equiv \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \varepsilon + \varepsilon', \\ \eta_{00} &\equiv \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} = \varepsilon - 2\varepsilon'. \end{aligned} \quad (14)$$

The observable $|\eta_{+-}|^2/|\eta_{00}|^2 \approx 1 + 6 \operatorname{Re}(\varepsilon'/\varepsilon)$ is very close to unity. In the electroweak theory, a tiny deviation from one arises from the phase in the

quark mixing matrix. In the electroweak theory, it seems most likely that ε'/ε should be on the order of 10^{-3} , or perhaps smaller [51].

Published measurements of ε'/ε have already reached a remarkable level of precision, with E731 at Fermilab reporting $(0.74 \pm 0.52 \pm 0.29) \times 10^{-3}$ [52] and the NA31 experiment at CERN quoting $(2.3 \pm 0.65) \times 10^{-3}$ [53]. If we take both of these beautiful results at face value, then both the existence and perforce the magnitude of a direct CP -violating amplitude remain in doubt. Three experiments now in progress aim at a precision that will settle the issue. NA48 at CERN and KTeV at Fermilab have already logged very significant data sets. Augusto Ceccucci reported [54] that NA48 anticipates a result based on their 1997 data in time for the winter conferences. The statistical uncertainty on $\text{Re}(\varepsilon'/\varepsilon)$ should be around $(4 - 5) \times 10^{-4}$, and the systematic error should be still smaller. According to Mike Arenton [55], KTeV is nearing a final result based on 20% of the data they recorded in 1996 and 1997. They expect a statistical uncertainty of about 3×10^{-4} , and are currently studying systematic effects. And we learned from G. Bencivenni that when the ϕ factory DAΦNE operates at full luminosity, the KLOE experiment should be able to probe $\text{Re}(\varepsilon'/\varepsilon)$ to 10^{-4} [56].

CP Violation in Hyperon Decay?

To understand the origin of CP violation, it is a matter of urgent interest to find CP -violating phenomena outside the neutral-kaon system. A natural place to look is in the decays of other strange particles, notably the hyperons of the baryon octet. HYPERCP at Fermilab, described at *HQ98* by Cat James [57], is the first experiment dedicated to the search for CP violation in hyperon decay. HYPERCP uses a high-rate spectrometer to compare the decay chains

$$\begin{array}{l} \Xi^- \rightarrow \Lambda\pi^- \\ \quad \quad \quad \downarrow \\ \quad \quad \quad p\pi^- \end{array}$$

and

$$\begin{array}{l} \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+ \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \bar{p}\pi^+ \end{array}$$

The decay angular distribution of the proton in the Λ rest frame,

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Lambda\alpha_\Xi \cos\theta), \tag{15}$$

where θ is the angle between the proton momentum and the Λ polarization vector, is characterized by the asymmetry parameters of the sequential hyperon decays. HYPERCP aims to measure the CP -violating asymmetry,

$$\mathcal{A} = \frac{\alpha_\Lambda\alpha_\Xi - \alpha_{\bar{\Lambda}}\alpha_{\bar{\Xi}}}{\alpha_\Lambda\alpha_\Xi + \alpha_{\bar{\Lambda}}\alpha_{\bar{\Xi}}} \approx A_\Lambda + A_\Xi, \tag{16}$$

with a sensitivity of one part in 10^4 , adding data from the 1999 run to the data in hand from 1997. Published predictions for the joint asymmetry range from about 10^{-5} to a few times 10^{-4} , whereas the superweak model predicts no asymmetry.

Direct Observation of T -Violation

Perhaps the most satisfying new result presented at *HQ98* was the KTeV observation [55] of a time-reversal-violating asymmetry in the rare decay $K_L \rightarrow \pi^+\pi^-\epsilon^+\epsilon^-$. The best evidence that the $\pi^+\pi^-\epsilon^+\epsilon^-$ mode qualifies as rare is that it had not been reported until this year [58]. An analysis of about 60% of KTeV's 1997 data set now allows a precise determination of the branching fraction as $(3.32 \pm 0.14 \pm 0.28) \times 10^{-7}$. The interest in this decay mode derives from the fact that the underlying process, $K_L \rightarrow \pi^+\pi^-\gamma$, proceeds through both CP -conserving and CP -violating mechanisms. A Bremsstrahlung component is associated with the CP -violating $K_L \rightarrow \pi^+\pi^-$ decay, while a direct-emission component arises from a CP -conserving M1 transition. The interference between amplitudes with different CP properties can lead to a CP -violating effect in the photon polarization. The $K_L \rightarrow \pi^+\pi^-\epsilon^+\epsilon^-$ channel, which represents the internal conversion of the photon to an electron-positron pair, analyzes the virtual photon polarization through the orientation of the $\epsilon^+\epsilon^-$ plane relative to the $\pi^+\pi^-$ plane [59].

To be explicit, let $\hat{\mathbf{n}}_\pi = (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-})/|\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-}|$ be the normal to the pion plane and $\hat{\mathbf{n}}_e = (\mathbf{p}_{e^+} \times \mathbf{p}_{e^-})/|\mathbf{p}_{e^+} \times \mathbf{p}_{e^-}|$ be the normal to the electron plane, and define the azimuthal angle φ through $\cos \varphi = \hat{\mathbf{n}}_\pi \cdot \hat{\mathbf{n}}_e$. The decay angular distribution is of the form $d\Gamma/d\varphi = \Gamma_1 \cos^2 \varphi + \Gamma_2 \sin^2 \varphi + \Gamma_3 \sin \varphi \cos \varphi$. We can express $\sin \varphi = (\hat{\mathbf{n}}_\pi \times \hat{\mathbf{n}}_e) \cdot \hat{\mathbf{z}}$, where $\hat{\mathbf{z}} = (\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-})/|\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-}|$. Under the action of the charge conjugation operator C , we have $\mathbf{p}_{\pi^\pm} \rightarrow \mathbf{p}_{\pi^\mp}$ and $\mathbf{p}_{e^\pm} \rightarrow \mathbf{p}_{e^\mp}$, so that $\hat{\mathbf{n}}_\pi \rightarrow -\hat{\mathbf{n}}_\pi$, $\hat{\mathbf{n}}_e \rightarrow -\hat{\mathbf{n}}_e$, and $\hat{\mathbf{z}} \rightarrow \hat{\mathbf{z}}$. Either the parity operator P or the time-reversal operator T takes $\mathbf{p}_{\pi^\pm} \rightarrow -\mathbf{p}_{\pi^\pm}$ and $\mathbf{p}_{e^\pm} \rightarrow -\mathbf{p}_{e^\pm}$, so that $\hat{\mathbf{n}}_\pi \rightarrow \hat{\mathbf{n}}_\pi$, $\hat{\mathbf{n}}_e \rightarrow \hat{\mathbf{n}}_e$, and $\hat{\mathbf{z}} \rightarrow -\hat{\mathbf{z}}$. Accordingly, P and T take $\sin \varphi \rightarrow -\sin \varphi$ and $\cos \varphi \rightarrow \cos \varphi$, while C leaves both $\sin \varphi$ and $\cos \varphi$ unchanged. The presence of a $\sin \varphi \cos \varphi$ term in the decay angular distribution, *i.e.*, of a nonzero value of Γ_3 , is direct evidence for time-reversal noninvariance and, since C leaves the decay angular distribution unchanged, for CP violation. Indirect CP violation—the same physics that produces a nonzero value of ε —induces a T -violating asymmetry in the decay-angular distribution whose size is determined by $\text{Im}(\varepsilon)$. The effect is large, because the CP -violating contribution to the $K_L \rightarrow \pi^+\pi^-\epsilon^+\epsilon^-$ decay amplitude occurs at a lower order in chiral perturbation theory than the CP -conserving contribution. Sehgal and Wanninger [60] have computed a forward-backward asymmetry $A = (14.3 \pm 1.3)\%$.

KTeV's full 1997 data set leads to a sample of 1811 ± 42 events, enough to

study the decay angular distributions in detail. The preliminary asymmetry presented at *HQ98* is

$$A = (13.5 \pm 2.5_{\text{stat}} \pm 3.0_{\text{sys}})\%, \quad (17)$$

which represents direct evidence for a violation of time-reversal symmetry. This is the largest particle-antiparticle asymmetry so far observed. The measured value is in good agreement with theoretical expectations.

During the week of *HQ98*, the CPLEAR Collaboration at CERN reported on the first observation of time-reversal symmetry violation through a comparison of the probabilities for the transformations $\bar{K}^0 \leftrightarrow K^0$ as a function of the neutral-kaon proper time [61]. In their experiment, the strangeness of the neutral kaon at the moment of its creation, $t = 0$, was tagged by observing the kaon charge in the formation reaction $\bar{p}p \rightarrow K^\pm \pi^\mp (K^0, \bar{K}^0)$ at rest, while the strangeness of the neutral kaon at the time of its semileptonic decay, $t = \tau$, was tagged by the charge of the final-state lepton. The time-average decay-rate asymmetry, measured over the interval $1 \times \tau_s < \tau < 20 \times \tau_s$, is

$$\left\langle \frac{\Gamma(\bar{K}^0|_0 \rightarrow e^+ \pi^- \nu|_\tau) - \Gamma(K^0|_0 \rightarrow e^- \pi^+ \bar{\nu}|_\tau)}{\Gamma(\bar{K}^0|_0 \rightarrow e^+ \pi^- \nu|_\tau) + \Gamma(K^0|_0 \rightarrow e^- \pi^+ \bar{\nu}|_\tau)} \right\rangle = (6.6 \pm 1.3_{\text{stat}} \pm 1.0_{\text{sys}}) \times 10^{-3}. \quad (18)$$

This asymmetry is a direct manifestation of T -violation. If CPT is a good symmetry in semileptonic decays and the $\Delta S = \Delta Q$ rule is exact, then the observed asymmetry (18) is identical to

$$\frac{\mathcal{P}(\bar{K}^0 \rightarrow K^0) - \mathcal{P}(K^0 \rightarrow \bar{K}^0)}{\mathcal{P}(\bar{K}^0 \rightarrow K^0) + \mathcal{P}(K^0 \rightarrow \bar{K}^0)}, \quad (19)$$

where \mathcal{P} is a probability for strangeness oscillation. The observed result is in good agreement with the theoretical expectation, $4 \text{Re}(\varepsilon) = (6.63 \pm 0.06) \times 10^{-3}$.

These two new results confirm our expectation that time-reversal invariance is violated in neutral-kaon decays, as must be the case if CPT holds and CP is not respected. In quantitative terms, the newly observed T -violations occur at just the level required to compensate for the CP violation known since 1964 to occur in the decay $K_L \rightarrow \pi^+ \pi^-$.

Plenty of Nothing

One of the most beautiful results of the year past was the observation by Brookhaven Experiment 787 [62] of a single, very clean, example of the decay

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}, \quad (20)$$

corresponding to a branching fraction of $(4.2_{-3.5}^{+9.7}) \times 10^{-10}$ that is consistent with the standard-model expectation, $0.6 \times 10^{-10} \leq B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \leq 1.5 \times 10^{-10}$. What is most impressive to me is not the one beautiful candidate event, but the extremely low level of background: the event occurs on an empty field. In the report presented to *HQ98* by Steve Kettell [63], we learned that preliminary indications from the analysis of 1995–1997 data are that the background rejection is three times better, with an increased acceptance. Over the next two years, the E787 sensitivity should provide a thorough survey of the standard-model regime. Brookhaven proposal 949 [64] would increase the sensitivity to 10^{-11} , and the CKM proposal at Fermilab [65] aims at a sensitivity of 10^{-12} . As long as the experimental sensitivity fell far short of standard-model expectations, the principal interest of searching for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ was to probe non-standard-model physics. With detection achieved near the band of standard-model predictions, the branching ratio takes on additional importance as a determination of $|V_{td}|$.

A little less nothing has been achieved by KTeV in its search for the companion process, $K_L \rightarrow \pi^0 \nu \bar{\nu}$. With a small expected background of 0.12 event in the signal region for the Dalitz-decay final state $(e^+ e^- \gamma) \nu \bar{\nu}$, they observe no events, and can quote an upper limit $B(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-7}$ at 90% confidence level [66]. Dedicated experiments to measure the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ branching fraction are being planned at Fermilab and Brookhaven [67,68]. These would provide an unambiguous determination of $\text{Im}(V_{td})$.

Rarest of Them All

Two formerly rare decays are now being studied with impressive statistical power. KTeV has detected 275 candidates for the decay $\pi^0 \rightarrow e^+ e^-$ over an expected background of 21 events, for a preliminary branching fraction $B(\pi^0 \rightarrow e^+ e^-) = (6.09 \pm 0.40_{\text{stat}} \pm 0.23_{\text{sys}}) \times 10^{-8}$ [66]. This is in good agreement with theoretical expectations [69]. Brookhaven Experiment E871 now has accumulated over 6200 candidates for the decay $K_L \rightarrow \mu^+ \mu^-$ [70]. That, too, is in good agreement with theoretical expectations [71]. They also hold the record sensitivity for the forbidden decay $K_L \rightarrow \mu^\pm e^\mp$, and can quote an upper limit on the branching fraction, $B(K_L \rightarrow \mu^\pm e^\mp) < 4.8 \times 10^{-12}$.

E871 holds the further distinction of measuring the smallest branching fraction of them all, with their observation of four candidates for the decay $K_L \rightarrow e^+ e^-$ [70]. These four events lead to a branching fraction $B(K_L \rightarrow e^+ e^-) = (8.7_{-4.1}^{+5.7}) \times 10^{-12}$, in close agreement with modern calculations based on chiral perturbation theory [71]. This is a very impressive achievement indeed.

Since 1995, Brookhaven experiment E865 has collected data on many rare and formerly rare decays [72]. Among their targets is the lepton-flavor-violating decay $K^+ \rightarrow \pi^+ \mu^+ e^-$, for which they have already set a 90% CL

upper limit of 2.1×10^{-10} . The projected single-event sensitivity is 10^{-11} .

Spinoffs

Although the focus of KTeV is the precision study of neutral kaon decays, the KTeV spectrometer is also well-matched to a number of other important physics goals. Doug Jensen [73] presented a preliminary measurement of the branching fraction $B(\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e)$ based on 153 ± 13 events that fit the pattern

$$\begin{array}{l} \Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e \\ \quad \quad \quad \downarrow \\ \quad \quad \quad p\pi^0, \end{array}$$

upon a background of 6 ± 2 events. The preliminary branching fraction is $(2.5 \pm 0.2 \pm 0.3) \times 10^{-4}$, in excellent accord with the theoretical expectation of 2.61×10^{-4} .

In a similar spirit, the SELEX experiment, which is mainly concerned with the study of charmed particles produced in a Σ^- beam, has obtained interesting new results on hyperon properties [74]. They have determined the Σ^- charge radius to be $\langle r^2 \rangle = (0.60 \pm 0.08_{\text{stat}} \pm 0.08_{\text{sys}}) \text{ fm}^2$, measured the $\Sigma^- p$ total cross section to be about 36 mb at 600 GeV/c, and set a new upper bound on the U -spin-forbidden transition rate, $\Gamma(\Sigma(1385)^- \rightarrow \Sigma^- \gamma) < 12 \text{ keV}$ at 95% CL.

WEAK INTERACTIONS OF CHARM AND BEAUTY

Lifetimes

The lifetimes of hadrons containing c and b quarks have important engineering value and give us insight into the interplay between the strong and weak interactions. With the development of the heavy-quark expansion, theorists now have well-defined expectations for the hierarchy of b -hadron lifetimes that high-precision data can confront. At *HQ98*, Harry Cheung [11] presented a survey of recent progress in lifetime measurements. Speaking for the E791 Collaboration at Fermilab, Nader Coptly [75] presented a new precise measurement of the D_s lifetime, $\tau_{D_s} = 0.518 \pm 0.014 \pm 0.007 \text{ ps}$. This is considerably larger than the Particle Data Group average, $\langle \tau_{D_s} \rangle_{\text{PDG}} = 0.467 \pm 0.017 \text{ ps}$ [15]. Combined with the PDG average lifetime for the D^0 , $\langle \tau_{D^0} \rangle_{\text{PDG}} = 0.415 \pm 0.004 \text{ ps}$, the E791 value gives a ratio $\tau_{D_s}/\tau_{D^0} = 1.25 \pm 0.04$, a six-standard-deviation difference from unity. [Harry Cheung's world average, including the new data from E791, is $\tau_{D_s}/\tau_{D^0} = 1.193 \pm 0.027$.] This represents a substantial change from the PDG98 value of 1.125 ± 0.042 . We expect further improvements in our knowledge of charm lifetimes from CLEO analyses using the new silicon

vertex detector and the forthcoming FOCUS data described by Jonathan Link [76] and Eric Vaandering [35], which will be statistically dominant over the next few years.

The CDF Collaboration has recently used semileptonic decays to determine the lifetime of the B_c meson as $\tau_{B_c} = 0.46_{-0.16}^{+0.18} \pm 0.03$ ps [77], very close to the value expected in the spectator picture [78].

Semileptonic decays

The semileptonic decays of charm and beauty are of interest for the light they can shed on quark mixing matrix elements and on the dynamics embodied in hadronic form factors. We want to both test and exploit the predictions of heavy-quark effective theory for the behavior of form factors and for the connection between D and B decays.

The study of semileptonic B decays constrains the parameters $|V_{cb}|$ and $|V_{ub}|$ that will be crucial for interpreting CP -violating effects in B decays. Karl Ecklund [79] reported recent CLEO results on the exclusive reconstruction of $B \rightarrow D\ell\nu$ and $B \rightarrow \rho\ell\nu$, and presented a new moment analysis of inclusive semileptonic B decays that may reduce the uncertainties in extracting V_{cb} .

Fermilab Experiment E791 has made important strides in the study of form factor ratios in the decays $D^+ \rightarrow \bar{K}^*\ell^+\nu_\ell$ and $D_s^+ \rightarrow \phi\ell^+\nu_\ell$. Daniel Mihalcea [80] showed the evolution of these measurements, which now offer a worthy challenge for theory based on lattice QCD. Fermilab Experiment E687 has made competitive measurements of semileptonic form factors in the past. Will Johns [81] reviewed these contributions and demonstrated that the successor experiment, FOCUS, will yield thirty to forty times the number of events used in the E687 semileptonic analyses. The gigantic event sample raises the prospect of high-precision studies of Cabibbo-suppressed semileptonic decays of charm.

More Promises and Prospects

The SELEX experiment at Fermilab is a new spectrometer that took data in 1996–1997 with 600-GeV/ c Σ^- and π^- and 540-GeV/ c proton beams. They are just beginning to produce preliminary results on their large sample of charm decays. Alex Kushnirenko [82] reported the first observation of the Cabibbo-suppressed decay $\Xi_c^+ \rightarrow pK^-\pi^+$.

Mitsuhiro Nakamura [83] presented new limits on $\nu_\mu \rightarrow \nu_\tau$ oscillations from the emulsion experiment CHORUS at CERN. They have been able to move the exclusion plot (in the $\Delta m^2 - \sin 2\theta$ plane) near $\sin 2\theta = 10^{-3}$, a significant increase in sensitivity over previous experiments. Of particular interest to the heavy-quark community are the remarkable advances that have been achieved in automated emulsion scanning. Another order of magnitude in scanning power should be in hand by *HQ2000*.

Rare decays

Gustavo Burdman [84] presented an elegant summary of the potential of rare K , D , and B decays to probe the structure of the electroweak theory at one-loop level. By looking for effects that derive from higher-order processes in the standard model, we may hope to probe momentum scales at or above the scale of electroweak symmetry breaking. The theoretical art lies in identifying processes in which the dominant contributions are from short-distance (high momentum scale) processes.

The experimental status of searches for rare decays and CP violation in the charm system was summarized by Simon Kwan [85]. No CP violation has been observed, with a sensitivity of a few percent. The current limits on rare and forbidden D decays are at the level of one part in 10^5 . The current experimental limits on flavor changing neutral current processes are still orders of magnitude above the standard-model expectation, so there is a large window for the discovery of new physics. In the immediate future, the greatest sensitivity to CP violation in the charm sector will come from the B factory experiments, BABAR, BELLE, and CLEO III.

SUMMARY REMARKS

It is a glorious time for heavy-quark physics. The results presented at *HQ98* reflect dramatic progress over the past decade and offer immense promise for the years ahead. For each of the heavy quarks—strange, charm, and beauty—that have occupied our attention at this workshop, experiments in progress and under construction will decisively improve the quality and amount of information available to us. And let us not forget the torrent of new information about the top quark that the next run of the Tevatron Collider will bring [86]. Theoretical advances make it ever clearer that we will be able to interpret the new experimental findings to get at the essence of the interactions of heavy quarks. I look forward, with eager anticipation, to *HQ2000* and beyond.

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