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CHARM OVERVIEW

Stefano Bianco
Laboratori Nazionali di Frascati
via E. Fermi 40, Frascati 00044, Italy
E-mail: bianco@lnf.infn.it

Abstract

This paper is aimed at giving a complete review of the latest (post-1998 conference) experimental results on charm physics.

1 Introduction

The study of the c–quark generates about 200 papers and 800 measurements per year, for a total of 15 collaborations and 700 physicists involved. Such an effort has led us to a conflicting situation. On one hand, the advent of high-statistics, high-resolution experiments has turned c–quark physics into precision physics. On the other hand, the c–quark mass scale is too large for chiral symmetry methods, while theories based on expansions of heavy quark masses, such as Heavy Quark Effective Theory[1] (HQET) or Operator Product Expansion[2,3] (OPE), are often questionable because m_c may not be large enough. Nonetheless, remarkable agreement is often found when such theories make predictions, most notably on semileptonic decays, lifetimes, and spectroscopy.

The 1998-1999 scenario is full of results – from new experiments (SELEX and BES), experiments that have undergone significant upgrades (FOCUS, CLEO II.V, E835), and others that are planning upgrades for charm physics (HERMES), experiments at their peak publication rate (E791), and experiments (at LEP and HERA) that keep their charm working groups alive and vital. Interesting news comes from the neutrino (CCFR, CHARM II) and heavy-ion (NA50) groups.

In this paper I have tried to present a review of today's scenario rather than pursue the goal of detailed investigation. In setting the physics scenario for each item, I was guided by recent reviews[4–8], from which I borrowed copiously. With such a goal in mind, I apologize in advance to those whose work has been left unmentioned.

2 Production mechanisms

The QCD picture of charm production consists of parton-level hard scattering, which produces the $c\bar{c}$ pair, hadronization of the $c\bar{c}$ into a charmed hadron, and a final stage in which the charmed hadron travels through and interacts with the hadronic matter, followed by decay. Thanks to the generally large momentum transfers involved, the hard scattering is traditionally a good testing ground for perturbative QCD techniques, while the hadronization stage has the complication of matching experimental kinematical distributions of charm hadrons with predictions of a suitable dressing mechanism. Theoretical updates on both topics were given at HQ98 [9,10]. In general, any asymmetry is due to hadronization since $c\bar{c}$ asymmetries in NLO QCD are very small. For a seminal review see ref.[11,12].

A wealth of new results comes from Fermilab fixed-target experiments E791, SELEX and FOCUS (pion, hyperon, and photon beams respectively)[13]. Correlation studies of fully reconstructed hadroproduced $D\bar{D}$ pairs by E791[14] show less correlation

Table 1: Compilation of $\Lambda_c/\bar{\Lambda}_c$ photoproduction asymmetry measurements (adapted from ref.[13]).

Experiment	Asymmetry
FOCUS prel.	0.14 ± 0.02
E687 (93)	0.04 ± 0.08
E691 (88)	0.11 ± 0.09
NA1 (87)	0.14 ± 0.12

than that predicted by the Pythia/Jetset Monte Carlo event generator for $D\bar{D}$ production, which, however, follows the experimental trend better than a pure NLO QCD parton level prediction (Fig.1). Coherently, $D\bar{D}$ correlation in photoproduction is much more pronounced because of a lack of hadronization contributions of the projectile remnants.

New results from E791[15] also report particle-antiparticle production asymmetries for $D^\pm$, $D_s^\pm$ and Λ_c, and a cross-section measurement[16] with a 500-GeV π^- beam on a nuclear target of $\sigma(D^0 + \bar{D}^0; x_F > 0) = 15.4^{+1.8}_{-2.3}\mu$b/nucleon. Asymmetry results show clear evidence for leading effects. Both measurements are in principle sensitive to m_c; in practice it is necessary to first nail down a few other parameters (factorization scale, intrinsic parton momentum k_t, etc). In general, E791 asymmetry results favor $m_c = 1.7\,\text{GeV}/c^2$, while the cross-section measurement is compatible with $m_c = 1.5\,\text{GeV}/c^2$. For the renormalization scale and scheme adopted for the above definitions of m_c the interested reader is referred to reff.[15,16]. SELEX preliminary results[17], which include comparison of Λ_c and $D^\pm$ asymmetries with proton, pion, and hyperon beams, also indicate large leading effects. FOCUS presented clear evidence[13] of Λ_c asymmetry in photoproduction (Tab.1). With a photon beam any asymmetry has to be attributed to the target, and the picture is consistent with $\Lambda_c(cud)$ production being more probable than $\bar{\Lambda}_c$. When comparing results from different photoproduction experiments, it should be also kept in mind how the asymmetry is in general $\sqrt{s}$-dependent, as well as dependent on the exact acceptance kinematics, i.e., the x_F range, etc.

Neutrino charm production also gives estimates of m_c. Results[18] of CCFR (Fermilab) and CHARM II (CERN) experiments provide analysis-dependent values: CCFR (next-to-leading order) and CHARM II find $m_c \sim 1.7\,\text{GeV}/c^2$, while CCFR (leading order) favors $m_c \sim 1.3\,\text{GeV}/c^2$. New data are expected very soon from the successor CCFR experiment, NuTeV.

The HERMES experiment at HERA presented[19] preliminary results (Fig.2) for open and hidden charm photoproduction at threshold. They expect to collect data in 1999 with an upgraded detector, and to provide a measurement of open charm cross section at
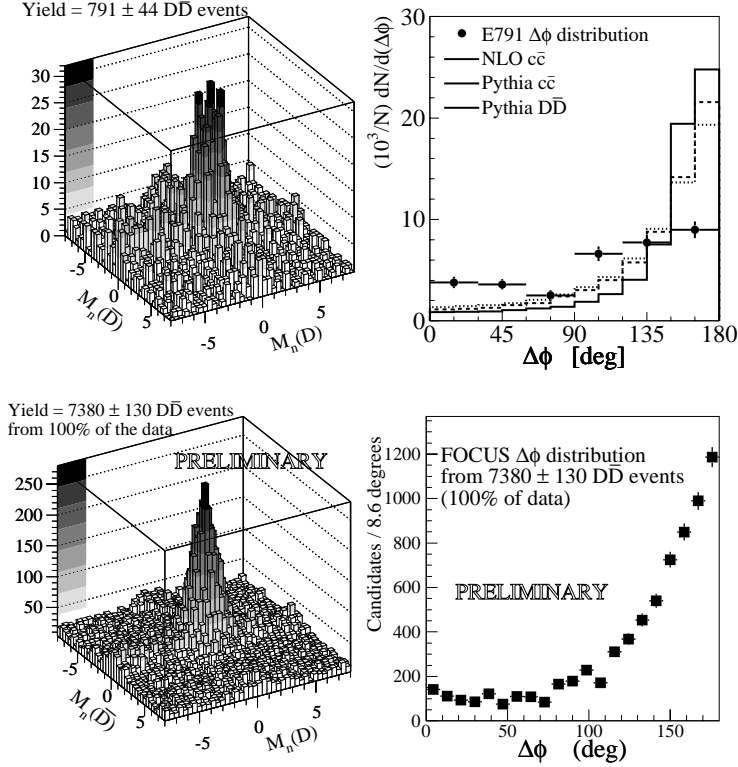
Figure 1: Mass correlation plots (left), and acoplanarity angle distributions (right) for hadro- (E791) and photo-produced (FOCUS) $D\bar{D}$ pairs.

threshold, with the ultimate goal of extracting the gluon momentum distribution $G(x)$. Theoretical predictions of cross sections at threshold suffer from major difficulties (the size of α_S, the role of higher order corrections, etc.). For the case of charmonium production at threshold, NLO predictions do exist[20,21]. New theory results may come from the utilization of novel methods (resummation of NLO logarithms) developed for the high-energy region [22,23].

New results on $G(x)$ have come from H1 and ZEUS. H1[24] determines the NLO gluon momentum distribution for $7.5 \cdot 10^{-4} < x < 4 \cdot 10^{-2}$ from DIS and direct detection of D^*'s photoproduced in the final state. Results on $G(x)$ agree with distributions found from scaling violations of the proton structure function. ZEUS[25] finds the D^* differential cross section well described by NLO QCD calculations, with *massless* calculations[26] performing better than *massive* calculations[27,28]. ZEUS also remeasured[29,30] with higher statistics the charm contribution $F_2^{c\bar{c}}$ to the proton structure function F_2, finding that at low-x values a very large ($\sim 30\%$) fraction of DIS events contains open charm states, unlike EMC fixed target results at high-x. For a recent summary of
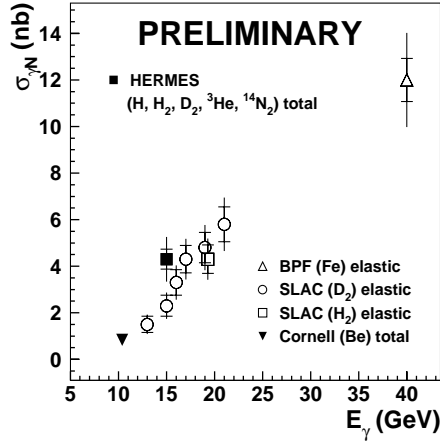
Figure 2: HERMES J/ψ photoproduction cross section.

HERA heavy quark results, see ref.[31]. Finally, a further observable that can be computed by NLO QCD is the probability $g_{c\bar{c}}$ of $c\bar{c}$ pair production by gluon splitting ($e^+e^- \rightarrow q\bar{q}g, g \rightarrow Q\bar{Q}$). New OPAL preliminary results[32] $g_{c\bar{c}} = 3.20 \pm 0.21 \pm 0.38) \times 10^{-2}$ are higher than theoretical estimates, as also recent measurements of $g_{b\bar{b}}$ by ALEPH and DELPHI.

In 1992 the CDF collaboration[33] discovered that the production of J/ψ and ψ' in $p\bar{p}$ collisions was enhanced by a factor of fifty with respect to predictions of the color-singlet model, which stated that produced $c\bar{c}$ pairs would dress into the observed charmonium state by keeping their quantum numbers, i.e., by rearranging their colors without gluon emission. To explain the result, a color-octet model was proposed in which the $c\bar{c}$ pair dressed in a charmonium hadron by emitting a soft gluon. The color-octect model predicts absence of polarization for charmonium production, since the initial polarization of $c\bar{c}$ pairs is destroyed by the radiation of gluons. Data by fixed target (WA92 at CERN), and neutrino (NUSEA) experiments on the polarization of J/ψ do confirm the color-octet prediction, while relevant polarization is observed in the HERA q^2 regimes[31], and at the collider (CDF), in agreement with the color-singlet model. The issue of charmonium production is dealt with in great detail in these proceedings[34].

Charmonium production is also investigated on the very distant field of relativistic heavy ion collisions, where the NA50 experiment[35] using 1996 data (158 GeV/nucleon Pb beams on Pb target) provided circumstancial evidence for charmonium suppression, which may be explained by the onset of a quark-gluon plasma regime. They measure J/ψ production relative to Drell-Yan pair production. After accounting for conventional
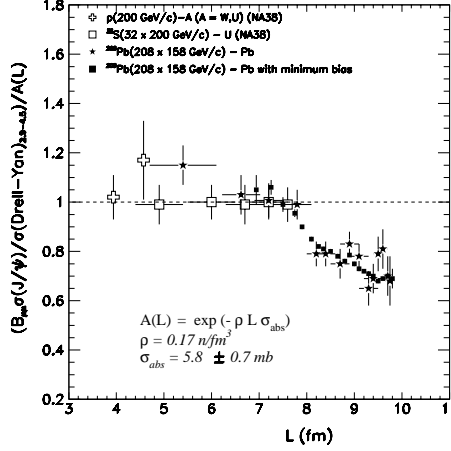
Figure 3: NA50 J/ψ suppression in relativistic heavy ion collisions.

nuclear absorption, their data (Fig.3) show evidence for a suddenly lower production, due to the attracting force between the $c\bar{c}$ quarks being screened by gluons, and fewer $c\bar{c}$ pairs hadronizing into J/ψ.

Those uncorrelated pieces of information taken together confirm the important role of gluons in the context of charmonium production dynamics.

3 Lifetimes

If there were no other diagram but the spectator and no QCD effects causing charm hadrons to decay, we would have one lifetime for all states. The wide range of lifetimes measured (Fig.5) shows the extent to which this is not the case. The total width is written as a sum of the three possible classes of decays

$$\tau \equiv \frac{\hbar}{\Gamma_{Total}} \equiv \frac{\hbar}{\Gamma_{Semilept} + \Gamma_{Nonlept} + \Gamma_{Lept}}$$

The partial width $\Gamma_{Semilept}$ is universal (equal) for D^0 vs D^+ (an assumption experimentally verified within 10%) as a consequence of isospin invariance, and for D_s^+ vs D^0 on the basis of theoretical arguments. The partial width Γ_{Lept} is small due to the helicity suppression. Therefore, all differences experimentally found should be caused by $\Gamma_{Nonlept}$. Lifetimes are a window on decay dynamics: conventional explanations of differences among charm hadrons lie in the interplay among the spectator, W-exchange, and W-annihilation diagrams (Fig.4). The large difference in lifetimes for D^0 and D^+ is conclusively explained as being due to the presence of external and internal spectator diagrams. Instead,
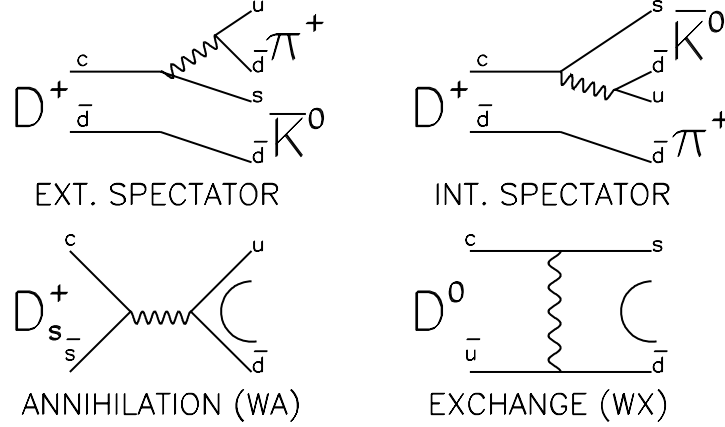
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Figure 4: The two internal and external spectator decays are exclusive of D^+ mesons and, because of the destructive Pauli interference due to the identical $\bar{d}$ quarks in the final state, they enhance the lifetime. The contribution to the total widths of Cabibbo-Favored (CF) W-annihilation and W-exchange diagrams is, among mesons, unique to D_s^+ and D^0, respectively.

the D_S^+ lifetime as it appears in PDG98[36] is only different from D^0 at the 3σ level, i.e., $\tau_{D_s^+}/\tau_{D^0} = 1.12 \pm 0.04$.

The PDG98 measurements of charm lifetimes are dominated by old fixed-target photoproduction E687 experiment results. Besides new results from fixed-target experiments, a new player in the lifetime game in 1998-1999 was the e^+e^- experiment CLEO II.V. Their lifetime measurements[37] (relative to $3.7\,\mathrm{fb}^{-1}$, i.e., about 40% of their present data set) were made possible by the implementation of a double-sided Si vertex detector, which also has the beneficial effect of improving D^*-tagging by a better definition of the soft pion track. New results[42] are shown in Tab.2, with new world averages. Although CLEO II.V precision is at the level of E687, their continuous building up of statistics, a possible better understanding of the systematics of their new detector, and the planned CLEO III implementation of RICH particle ID may help them become competitive with fixed-target experiments in the future.

The most relevant new information comes from the E791[39] and FOCUS[40] measurements of D_s lifetime, which reduce the error on the ratio with the D^0 lifetime

$$R_\tau \equiv \tau_{D_s^+}/\tau_{D^0} = 1.22 \pm 0.02 \tag{1}$$

which is now ten standard deviations away from unity, indicating that although not dominant, the WA diagram is significant. In an approach based on Wilson's OPE[2] (where the interaction is factorized into three parts – weak interaction between quarks, perturbative QCD corrections, non-perturbative QCD effects), the decay rate is expanded in the heavy

7

Table 2: Summary of new results in charm hadron lifetimes.

	Experiment	Lifetime (ps)	Events	Year	Technique
D^+	New Average	1.050 ± 0.015			
	CLEO	$1.0336 \pm 0.0221^{+0.0099}_{-0.0127}$	3777	98	e^+e^-
	PDG98	1.057 ± 0.015			
D^0	New Average	0.412 ± 0.003			
	E791	$0.413 \pm 0.003 \pm 0.004$	35k	99	Hadroprod
	CLEO	$0.4085 \pm 0.0041^{+0.0035}_{-0.0034}$	19k	98	e^+e^-
	PDG98	0.415 ± 0.004			
D_s^+	New Average	0.500 ± 0.007			
	FOCUS prel	$0.506 \pm 0.008(stat)$	5668	99	Photoprod
	E791	$0.518 \pm 0.014 \pm 0.007$	1662	99	Hadroprod
	CLEO	$0.4863 \pm 0.0150^{+0.0049}_{-0.0051}$	2167	98	e^+e^-
	PDG98	0.467 ± 0.017			
Λ_c^+	New Average	0.2019 ± 0.0031			
	FOCUS prel	$0.2045 \pm 0.0034(stat)$	8520	99	Photoprod
	SELEX prel	$0.177 \pm 0.010(stat)$	1790	99	Hyperons
	PDG98	0.206 ± 0.012			

quark masses[3]

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\,\pi^3}|KM|^2\Big[A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \mathcal{O}(1/m_Q^4)\Big] \qquad (2)$$

Each term has a simple physical meaning: the leading operator A_0 contains the spectator diagram contribution; A_2 is the spin interaction of the heavy quark with light quark degrees of freedom inside the hadron; A_3, the PI, WA, WX contributions. A description of OPE goes beyond the scope of this review; interested readers are addressed to excellent review[41]. The OPE model predicts $R_\tau = 1.00 - 1.07$ if the WA operator does not contribute. If it does, the maximum effect predicted is $\pm 20\%$, i.e., $R_\tau = (0.8 - 1.27)$. The world average found is presently quite at the limits of the OPE predictions, and it could be used as a constraint to better define the WA operator, which also intervenes in semileptonic beauty decays[43].

In the baryon sector, the SELEX measurement[44] of the Λ_C lifetime disagrees with the PDG98 world average dominated by E687, which is instead preliminarily confirmed by FOCUS[40] new high-statistics measurement. Finally, a more precise measurement of Ω_c and Ξ_c^0 lifetimes is badly needed in order to confirm the lifetime pattern $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$.
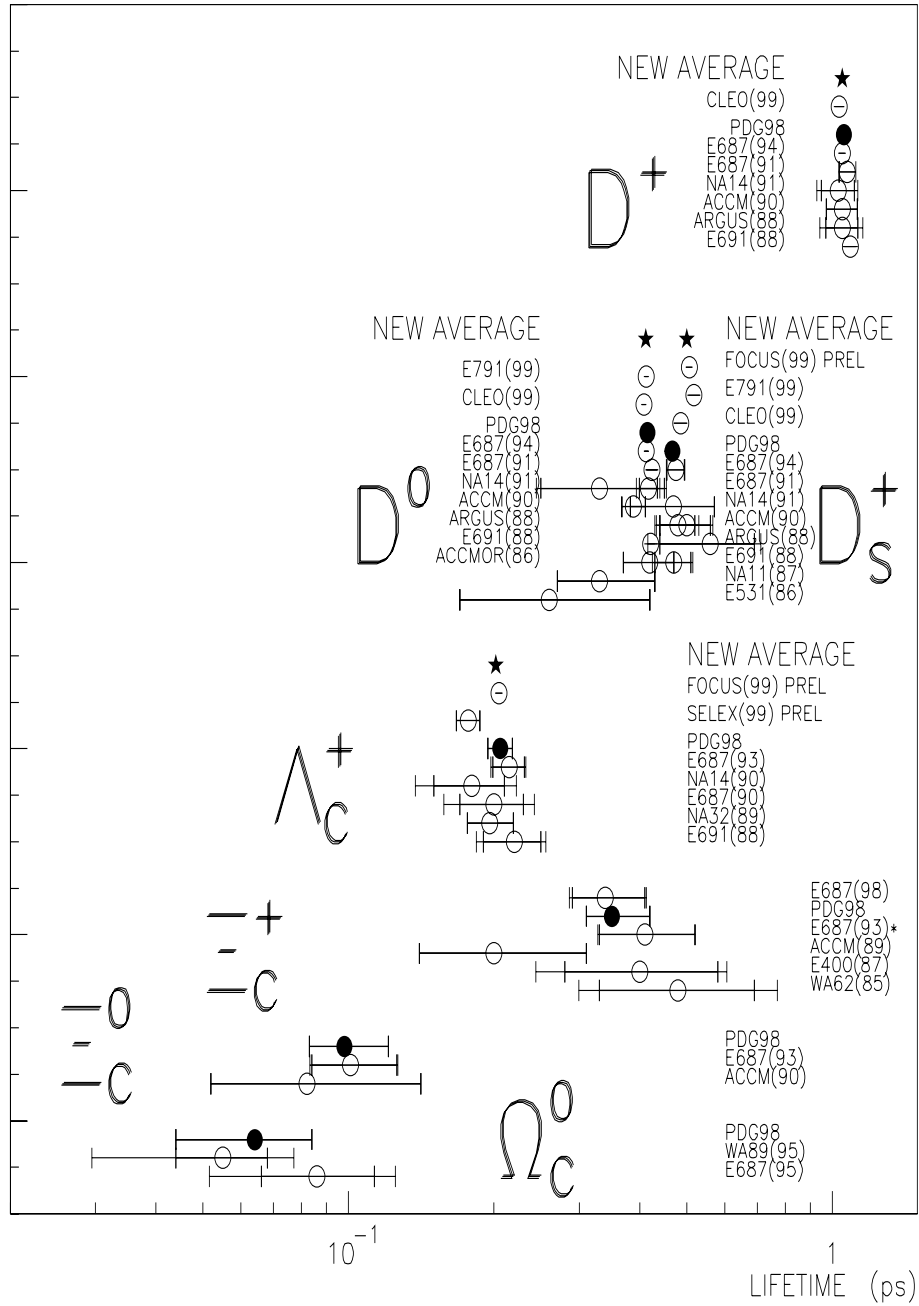
Figure 5: Compilation of charm meson and baryon lifetimes.

4 Nonleptonic weak decays

The highest impact new measurement is the CLEO II.V determination of the $\Lambda_c^+ \rightarrow pK^-\pi^+$ absolute branching fraction. This number, used to normalize all charm baryon branching ratios, consists of the PDG98 average of $(5.0 \pm 1.3)\%$ as an average of two model-dependent measurements, in mutual disagreement at the level of $2-3\,\sigma$. CLEO II.V tags charm events with the semielectronic decay of a D^*-tagged $\bar{D}$, and the Λ_c^+ production with a $\bar{p}$. Their final value is $B(\Lambda_c^+ \rightarrow pK^-\pi^+) = (5.0 \pm 0.5 \pm 1.5)\%$. A full discussion of the analysis technique is reported in these proceedings[81].

First observation[45] (confirmed shortly thereafter[46]) of Cabibbo-Suppressed (CS) $\Xi_c^+ \rightarrow pK^-\pi^+$ decay by the fixed-target, hyperon-beam experiment SELEX (Fig.6) provided information on the interplay of the external W-spectator decay and final-state interactions (FSI). These are interactions which occur in a space-time region where the final state particles have already been formed by the combined action of weak and strong forces, but are still strongly interacting while recoiling from each other. In charm meson decays, FSI are particularly problematic because of the presence of numerous resonances in the mass region interested[49]. The CS branching ratio, measured by SELEX relative to four–body CF decay

$$B(\Xi_c^+ \rightarrow pK^-\pi^+)/B(\Xi_c^+ \rightarrow \Sigma^+(pn)\,K^-\pi^+) = 0.22 \pm 0.06 \pm 0.03$$

is (once corrected for phase space) compatible with the branching ratio for the only other CS decay well measured, $\Lambda_c^+ \rightarrow pK^-K^+$, relative to three–body CF decay $\Lambda_c^+ \rightarrow pK^-\pi^+$. This is different from the charm meson case, where branching ratios depend heavily on the multiplicity of the final state, and is interpreted as confirmation of the fact that for charmed baryons, contrary to mesons, FSI do not play a relevant role. Finally, first evidence of DCS decay $D^+ \rightarrow K^+K^-K^+$ was reported[47] by FOCUS (Fig.6c), which measures

$$\Gamma(D^+ \rightarrow K^+K^-K^+)/\Gamma(D^+ \rightarrow K^+\pi^-\pi^+) = (1.41 \pm 0.27) \times 10^{-4} \qquad (3)$$

Such a decay cannot proceed via a spectator diagram, since the $\bar{d}$ initial state quark disappears in the final state. Possible mechanisms are pure WA, or Long-Distance (LD) processes including a light meson which strongly couples to KK. In either case, a Dalitz analysis would be of extreme interest to possibly investigate the decay resonant structure. For a DCSD, in the simplest picture one has $\Gamma_{DCSD}/\Gamma_{CF} \propto \tan^4\theta_C \simeq 2 \times 10^{-3}$. Any deviation from this value is due to effects such as interference, hadronization, FSI, etc.

Although in principle accessible (with an important *caveat* being the treatment of FSI) by means of lattice methods, nonleptonic decays lack an organic theoretical framework rigorously descending from first principles, while the most interesting (two-body)

10

decays are still largely undetected[49]. A theoretical approach that has been pointed to as comprehensive is ref.[50],[51], which has the merit of fully incorporating FSI in the prediction of two-body nonleptonic decays and also formulates CP-violation (CPV) asymmetries and CP-eigenstate lifetime differences.

5 Semileptonic decays

Comprehensive older reviews of leptonic and semileptonic decays are in [52,53]. Form factors describe dressing of $Q\bar{q}$ into a daughter hadron at the hadronic W-vertex of the spectator decay (Fig.7a). In the simplest case of a charmed pseudoscalar meson decaying to a light pseudoscalar meson, lepton, and antineutrino, the differential decay rate is

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cq}|^2 P^3}{24\pi^3} \left\{ |f_+(q^2)|^2 + |f_-(q^2)|^2 \mathcal{O}(m_\ell^2) + ... \right\} \tag{4}$$

where P is the momentum of the pseudoscalar meson in the reference frame of the charmed meson, and the $Wc\bar{q}$ vertex is described by only two form factors $f_\pm(q^2)$. Parameterizations for $f_\pm(q^2)$ form factors inspired respectively by a pole dominance model and HQET[54] are

$$f_\pm(q^2) = f_\pm(0)(1 - q^2/M_{pole}^2)^{-1} \qquad \text{(Pole)} \tag{5}$$

$$f_\pm(q^2) = f_\pm(0)e^{\alpha q^2} \qquad \text{(HQET)} \tag{6}$$

The value for M_{pole} is somehow arbitrarily chosen such as to be the closest $Q\bar{q}$ state with the same J^P as the hadronic weak current (Fig.7a). Unfortunately (Fig.7b from ref.[8]), there is little or no difference between a pole or an exponential form in the range of small q^2 accessible by CF $K\ell\nu$ decays, while maximal sensitivity is allowed for CS decay $\pi\ell\nu$. FOCUS should be able to finally measure the q^2 dependance by making use of the collected sample of 5,000 $\pi\ell\nu$ semileptonic decays.

In the case of a pseudoscalar-to-vector decay there are four form factors $(V, A_{1,3})$, q^2-dependent. After assuming a nearest-pole dominance model, they are customarily expressed via the ratios $r_V \equiv V(0)/A_1(0)$, $r_2 \equiv A_2(0)/A_1(0)$, with $A_3(0)$ becoming negligible in the (questionable) limit of zero lepton mass. E791 has presented new measurements[55] of form-factor ratios for $D_s^+ \to \phi\ell^+\nu_\ell$, with $(\ell = e, \mu)$, which investigate the extent to which the SU(3) flavor symmetry is valid by comparing form factors with what was measured in $D^+ \to K^{*0}\ell^+\nu_\ell$ previously, where a spectator $\bar{d}$ quark is replaced by a spectator $\bar{s}$ quark. Measurements are based on a sample of 144 electron decays and 127 muon decays: r_V is consistent with the expected SU(3) flavor symmetry between D_s and D^+ semileptonic decays, while r_2 appears inconsistent (Fig.8).
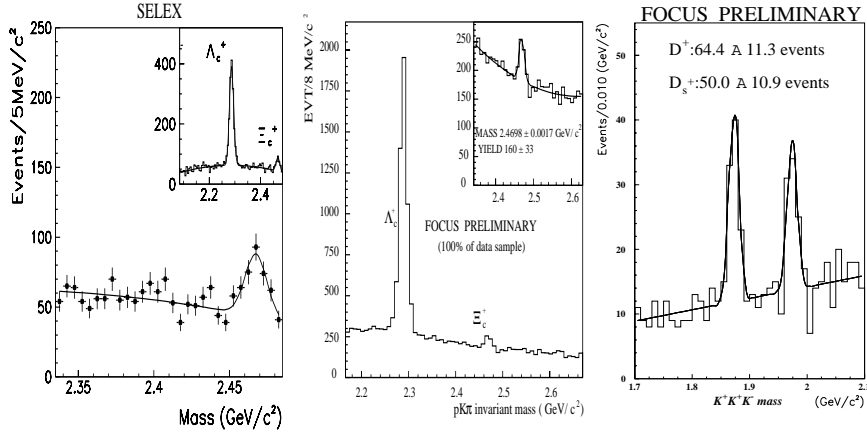
Figure 6: Observation of CS decay $\Xi_c^+ \to pK^-\pi^+$ (left and center), and DCS decay $D^+ \to K^+K^-K^+$ (right).
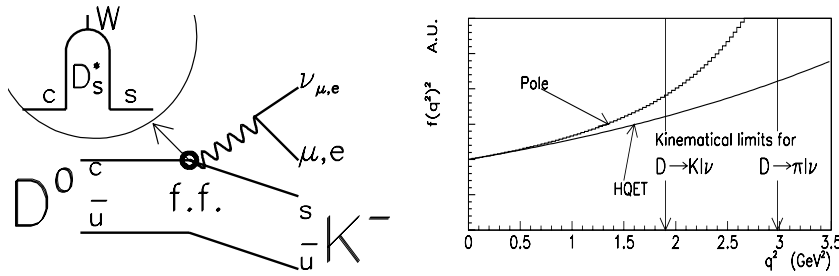

Figure 7: Semileptonic decays of the D^0 meson, illustrating coupling of a virtual $D_s^*(c\bar{s})$ vector state which originates the nearest-pole dominance model (left); $|f_+(q^2)|^2$ as a function of q^2 for pole and HQET parameterizations. The kinematic limits for $K\ell\nu$ and $\pi\ell\nu$ are drawn with vertical lines (adapted from ref.[8]).
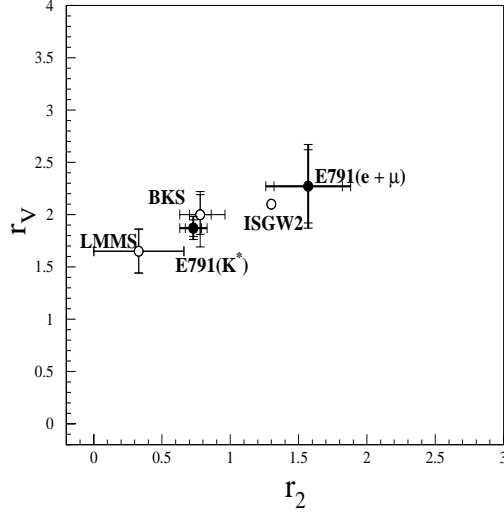
Figure 8: E791 semileptonic vector form-factor ratios for D^+ and D_s^+, and comparison with predictions.

In the e^+e^- sector, OPAL has recently produced the first measurement[56,57] of the semileptonic branching ratio of charm hadrons produced in $Z^0 \to c\bar{c}$ decays, finding $B(c \to \ell) = 0.095 \pm 0.006^{+0.007}_{-0.006}$, in good agreement with the ARGUS lower energy data.

6 Decay constants f_D and f_{D_s} in charm leptonic decays

No experimental results have emerged on leptonic decays. Theoretical activity on the main reasons for these studies (i.e., the pseudoscalar decay constants f_D and f_{D_s}) is very intense[58]. Lattice calculations have now converged to $f_{D_S} \sim 220 \pm 15\,\mathrm{MeV}$, to be compared with the world average $254 \pm 31\,\mathrm{MeV}$. On the contrary, the lattice result $f_D \sim 195 \pm 15\,\mathrm{MeV}$ can only be compared with the 1988 MARK III limit of $f_D < 290\,\mathrm{MeV}$. An experiment able to study the challenging decay $D \to \ell\nu_\ell$ is badly needed. An alternative model-dependent technique[59] relates the $D^{*+} - D^{*0}$ mass isosplittings to f_D, via the wavefunction at the origin $|\psi(0)|^2$. The value inferred from the best isosplit measurement [60] is $f_D = (290 \pm 15)\,\mathrm{MeV}$, very distant from the lattice computation.

7 Rare and forbidden decays, CP violation.

In the charm sector, Flavor-Changing Neutral Current processes such as $D^+ \to h^+ \mu^+ \mu^-$, $D^0 \to \mu^+ \mu^-$, etc, are suppressed in the SM via the GIM mechanism, with predictions spanning an enormous range $10^{-9} - 10^{-19}$. Lepton Family Number Violating $D^+ \to h^+ \ell_1^+ \ell_2^-$, and Lepton Number Violating $D^+ \to h^- \ell_1^+ \ell_{1,2}^+$ processes are instead strictly forbidden. This is why charm rare decays can provide unique information. E791 has presented [62] a set of new limits that improve the PDG98 numbers by a factor of 10, reaching approximately the 10^{-5} region.

CP-violation asymmetries in D decays are expected to occur via the interplay of weak phases stemming from penguin, Single-Cabibbo-Suppressed diagrams, and a (strong) FSI phase, and are predicted at the 10^{-3} level[50]. FOCUS presented preliminary results[63] on CPV asymmetries in the two most accessible modes ($D^+ \to K^- K^+ \pi^+$ and $D^0 \to K^- K^+$), which improve the current limits down to the 10^{-2} level. CPV in the charm sector still has to be discovered. The availability of large clean samples of fully reconstructed $D^+ \to K^- K^+ \pi^+$ decays entitles one to investigate CPV by comparing phases and amplitudes found in the two CP conjugate Dalitz plots[47].

8 $D^0 \bar{D}^0$ mixing

Important new results have been presented on $D^0 \bar{D}^0$ mixing (for an updated review see [64]). It is useful to recall the key features of particle-antiparticle mixing [65]. Because of weak interactions, flavor $f = s, c, b$ of a generic pseudoscalar neutral meson P^0 is not conserved. Therefore it will try and decay with new mass eigenstates $P_{1,2}^0$ which no longer carry definite flavor f: they are new states with different mass and lifetime $|P_{1,2}^0\rangle \propto (p|P^0\rangle \pm q|\bar{P}^0\rangle)$ where complex parameters p and q account for any CPV. The time evolution of $|P^0(t)\rangle$ is given by the Schrödinger equation. After a time t the probability of finding the state P^0 transformed into $\bar{P}^0$ is

$$|\langle \bar{P}^0 | P^0(t)\rangle|^2 \propto \left|\frac{q}{p}\right|^2 e^{-\Gamma_1 t}[1 + e^{\Delta \Gamma t} + 2e^{\frac{\Delta \Gamma}{2} t} \cos(\Delta m t)] \qquad (7)$$

with definitions $\Delta m \equiv m_1 - m_2$, $\Delta \Gamma = \Gamma_1 - \Gamma_2$ and $\bar{\Gamma} \equiv (\Gamma_1 + \Gamma_2)/2$. The two states will oscillate with a rate expressed by Δm and $\Delta \Gamma$, which are naturally expressed when calibrated by the average decay rate within the parameters $x \equiv \Delta m / \bar{\Gamma}$ and $y \equiv \Delta \Gamma / (2\bar{\Gamma})$.

In the case of charm mesons[66], because of the Cabibbo-favored decay mechanism and the large phase space available for their decay, decay widths are very similar ($y \ll 1$),
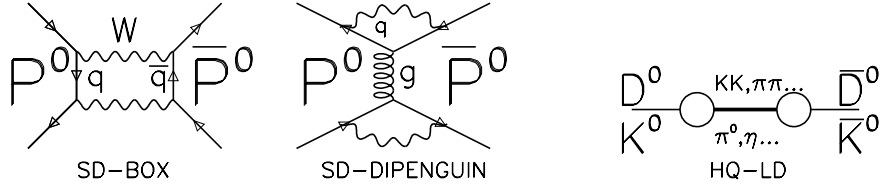
Figure 9: Box (proportional to $(m_q^2 - m_d^2)^2/m_W^2 m_{s,c,b}^2$), penguin, and long-distance diagrams for mixing.

Table 3: Box diagram contributions to mixing.

P^0	q	$x \equiv \Delta m/\Gamma$
K^0	c	0.48
D^0	s	$\ll 1$
B_d^0	t	0.75
B_s^0	t	> 22

and the time-integrated ratio of mixed and nonmixed rates is

$$r \equiv \frac{\Gamma(D^0 \to \bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f)} = \left|\frac{q}{p}\right|^2 \frac{x^2 + y^2}{2} \tag{8}$$

Theoretical estimates of x fall into two main categories, short distance (SD) and heavy quark/long distance (HQ-LD): the former arise from the box diagram[67] (Fig.9a), with GIM mechanism suppressing the charm case (Tab.3) or the dipenguin diagram[68], the latter come from QCD diagrams[69] and FSI[67] such as rescattering of quarks with known intermediate light states (Fig.9c). An important comment was made recently[70] on the possibility of measuring y separately from x. Indeed, $x \neq 0$ means that mixing is genuinely produced by $D^0 \bar{D}^0$ transitions (either SD or HQ-LD, or both), while $y \neq 0$ means that the fast-decaying component D_1^0 quickly disappears, leaving the slow-decaying component D_2^0 behind, which is a mixture of D^0 and $\bar{D}^0$. Infinite discussion is active on the extent to which the three contributions are dominant: consensus seems to exist on the HQ–LD being, in the case of charm mesons, larger than the SD, and in any case utterly small. Standard Model predictions are[72]

$$x, y < 10^{-7} - 10^{-3} \qquad r^{SM} < 10^{-10} - 10^{-4} \tag{9}$$

still below the PDG98 limit[75] $r < 5 \times 10^{-3}$. Any observation of $D^0 \bar{D}^0$ mixing above the predicted level, once HQ–LD effects are understood, is a signal that new physics contributions are adding to the box diagrams[71]. Traditionally, $D^0 \bar{D}^0$ mixing is searched for by means of event-counting techniques, while advances in event statistics now allow studies of the y parameter.

15

8.1 Wrong sign vs right sign counting

Mixing is searched for in the decay chains

$$D^{*+} \to \pi^+, \qquad D^0 \to \bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^+\pi^-, K^+\ell^-\bar{\nu}_\ell \tag{10}$$

with the particle/antiparticle nature of D^0 at production and at decay given by the sign of π^+ and K^- respectively.

In the case of a hadronic final state, life is complicated by pollution of the mixing by the Doubly-Cabibbo-Suppressed Decay $D^0 \to K^+\pi^-$, proportional to $\tan^4\theta_C$. The measurable r_{WS} – the rate of wrong-sign events – has therefore contributions[73] from DCSD, interference, and mixing

$$r_{WS} = \frac{\Gamma(D^0 \to f)}{\Gamma(\bar{D}^0 \to f)} = \frac{e^{-\bar{\Gamma}t}}{4}|\langle f|H|D^0\rangle|^2_{CF}\left|\frac{q}{p}\right|^2(X + Yt + Zt^2) \tag{11}$$

$$X \equiv 4|\lambda|^2 \quad Y \equiv 2\Re(\lambda)\Delta\Gamma + 4\Im(\lambda)\Delta m \quad Z \equiv (\Delta m)^2 + (\Delta\Gamma)^2/4 \tag{12}$$

$$\lambda \equiv \frac{p}{q}\frac{\langle f|H|D^0\rangle_{DCS}}{\langle f|H|\bar{D}^0\rangle_{CF}} \tag{13}$$

The X term (pure DCS) is characterized by an exponential decay time behavior, unlike the Z term (pure mixing), and this feature can in principle be used to suppress the DCS pollution. The Y (interference) term receives contributions from $\Im(\lambda)$, which can be nonzero if a) CPV is present, thus introducing a phase φ in p/q; and/or b) a strong phase δ is present, due to different FSI in the DCS and CF decays. By assuming CP conservation, i.e., $|p/q| = 1$, defining

$$e^{i\varphi} \equiv \frac{p}{q} \qquad e^{i\delta}\sqrt{r_{DCS}} \equiv \frac{\langle f|H|D^0\rangle_{DCS}}{\langle f|H|\bar{D}^0\rangle_{CF}} \tag{14}$$

and measuring t in units of $\bar{\Gamma}$ one can write[70] a simpler expression for r_{WS}

$$r_{WS} \propto e^{-t}[r_{DCS} + t^2(r/2) + t\sqrt{2rr_{DCS}}\cos\phi] \tag{15}$$

where the interference angle is given by $\phi = \arg(ix + y) - \varphi - \delta$. Equation 15 shows how a meaningful quote of the r result must specify which assumptions where made on the CPV and strong angles φ and δ. If one assumes CP invariance ($\varphi = 0$), then

$$r_{WS} \propto e^{-t}\{r_{DCS} + (r/2)t^2 + (y'\sqrt{r_{DCS}})t\} \tag{16}$$

$$y' \equiv y\cos\delta - x\sin\delta \qquad x' \equiv x\cos\delta + y\sin\delta \tag{17}$$

The alternative option in counting techniques is the use of semileptonic final states $K\ell\nu$, which do not suffer from DCSD pollution but are harder experimentally.

Table 4: Synopsis of recent mixing results. CPV phase is φ, strong phase is δ, interference angle is $\phi = \arg(ix + y) - \varphi - \delta$.

	Assumptions	Mode	N_{RS}	Result (%)
ALEPH[74]	No mix	$K\pi$	1.0k	$r_{DCS} = 1.84 \pm .59 \pm .34$
(95% CL)	$\varphi = 0, \cos\phi = 0$			$r < 0.92$
	$\varphi = 0, \cos\phi = +1$			$r < 0.96$
	$\varphi = 0, \cos\phi = -1$			$r < 3.6$
E791[75]	$\varphi = 0$	$K\ell\nu$	2.5k	$r = 0.11^{+0.30}_{-0.27} \quad (r < 0.50)$
(90% CL)				
E791[76]	No mix	$K\pi$	5.6k	$r_{DCS} = 0.68^{+0.34}_{-0.33} \pm 0.07$
(90% CL)	No mix	$K3\pi$	3.5k	$r_{DCS} = 0.25^{+0.36}_{-0.34} \pm 0.03$
	$\varphi \neq 0$ in Y			$r = 0.39^{+0.36}_{-0.32} \pm 0.16$
				$(r < 0.85)$
		$K\pi$		$r_{DCS} = 0.90^{+1.20}_{-1.09} \pm 0.44$
		$K3\pi$		$r_{DCS} = -0.20^{+1.17}_{-1.06} \pm 0.35$
	None			$r(\bar{D}^0 \rightarrow D^0) = 0.18^{+0.43}_{-0.39} \pm 0.17$
	None			$r(D^0 \rightarrow \bar{D}^0) = 0.70^{+0.58}_{-0.53} \pm 0.18$
	No Y			$r = 0.21^{+0.09}_{-0.09} \pm 0.02$
E791[77]	$\varphi = 0, \delta = 0$	KK	6.7k	$\Delta\Gamma = 0.04 \pm 0.14 \pm 0.05 \, \text{ps}^{-1}$
(90% CL)		$K\pi$	60k	$(-0.20 < \Delta\Gamma < 0.28) \, \text{ps}^{-1}$
				$y = 0.8^{+2.9}_{-1.0} \quad (-4 < y < 6)$
CLEO[78]	$\varphi = 0, \delta = 0$	$\pi\pi$	475	
(90% CL)		KK	1.3k	$y = -3.2 \pm 3.4 \quad (-7.6 < y < 1.2)$
5.6 fb^{-1}		$K\pi$	19k	
CLEO[79]	No mix	$K\pi$	16k	$r_{DCS} = 0.34 \pm 0.07 \pm 0.06$
(95% CL)	$\varphi = 0, \delta \neq 0$			$r_{DCS} = 0.50^{+0.11}_{-0.12} \pm 0.08$
9 fb^{-1}	$\varphi = 0, \delta \neq 0, x' = 0$			$y' = -2.7^{+1.5}_{-1.6} \pm 0.2$
				$(-5.9 < y' < 0.3)$
	$\varphi = 0, \delta \neq 0, y' = 0$			$x' = 0 \pm 1.6 \pm 0.2$
				$|x'| < 3.2 \quad (r < 0.05)$

8.2 Lifetime difference measurements

The y parameter can be determined directly by measuring the lifetimes of CP=+1 and CP=−1 final states, assuming CP conservation, i.e., that D_1^0 and D_2^0 are indeed CP eigenstates. This would allow in principle, along with an independent measurement of r, limits to be set on x. The experimentally most accessible CP-eigenstates are K^+K^- and $\pi^+\pi^-$ (CP=+1), $K_S\phi$ (CP=−1), and $K^-\pi^+$ (mixed CP).

8.3 Mixing results and projections

The most recent mixing results in Tab.4 are compiled from ALEPH (out of 4×10^6 hadronic Z decays) and E791 (2×10^5 reconstructed decays) recently published results, as well as CLEO II.V preliminary results (lifetime difference $(5.6 \, fb^{-1})$ and hadronic

counting $(9.0 \ fb^{-1})$). Once compared with the same assumptions, measurements are consistent, with the exception of a mild discrepancy in the ALEPH measurement of r_{DCS}. CLEO II.V's best limit on y' corresponds to $r < 0.05\%$ if $x' = 0$. Progress should come from CLEO II.V (semileptonic counting and lifetime differences including the $K_S\phi$ decay mode) and FOCUS, which both project sensitivities around $y' < 1\%$, corresponding to $r < 0.005\%$. A compilation of predictions on $D^0\bar{D}^0$ mixing was recently presented[80], and it was pointed out how the CLEO II.V limit already rules out a lot of them.

It is clear that, in order to further reduce the limit on r, one should await results from B-factories. Mixing and CPV are the very topics which sorely experience the lack of a concrete project of τ–charm factory.

9   Spectroscopy

A specialized review of the many new results available and their implications for Heavy Quark Symmetry predictions was given at the conference[81], so I shall present only an overall picture, referring the interested reader to details in D. Besson's paper.

With the high-statistics, high-mass resolution experiments attaining maturity, focus has been shifted from the ground state (0^- and 1^-) $c\bar{q}$ mesons and ($1/2^+$ and $3/2^+$) cqq baryons to the orbitally- and, only very recently, radially-excited states[1]. An organic and consistent theoretical framework for the spectrum of heavy-light mesons is given by the ideas of Heavy Quark Symmetry (HQS), later generalized by Heavy Quark Effective Theory in the QCD framework. The basic idea (mediated from the JJ coupling in atomic physics) is that in the limit of infinite heavy quark mass: a) the much heavier quark does not contribute to the orbital degrees of freedom, which are completely defined by the light quark(s) only; and b) properties are independent of heavy quark flavor. The extent to which the infinite heavy quark mass limit is appropriate for charm hadrons is the subject of infinite discussion; however, things seem to work amazingly well. For recent experimental reviews see [87–89].

9.1   Mesons

Heavy Quark Symmetry provides explicit predictions on the spectrum of excited charmed states[82,83]. In the limit of infinite heavy quark mass, the spin of the heavy quark $\mathbf{S_Q}$ decouples from the light quark degrees of freedom (spin $\mathbf{s_q}$ and orbital $\mathbf{L}$), with $\mathbf{S_Q}$ and $\mathbf{j_q} \equiv \mathbf{s_q} + \mathbf{L}$ the conserved quantum numbers. Predicted excited states are formed by combining $\mathbf{S_Q}$ and $\mathbf{j_q}$. For $L = 1$ we have $j_q = 1/2$ and $j_q = 3/2$ which, combined

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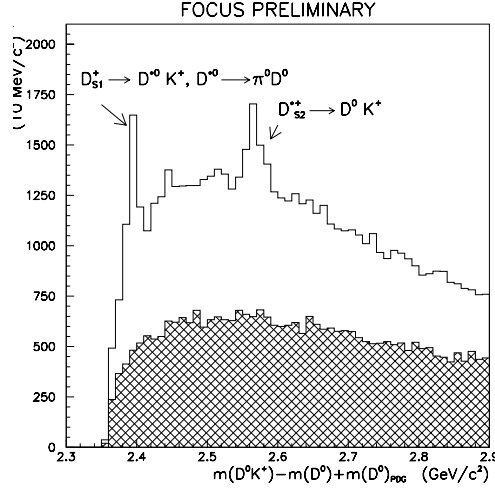[1]In the past, these excited states were called generically and improperly D^{**}.

Figure 10: The $D^0 K^+$ invariant mass spectrum, showing the D^*_{s2} peak along with the $D_{s1}(j_q = 3/2)$ reflection peak due to an undetected π^0. Wrong-sign $(D^0 K^-)$ background is shown shaded.

with S_Q, provide prediction for two $j_q = 1/2$ (J=0,1) states, and two $j_q = 3/2$ (J=1,2) states. These four states[2] are named respectively D^*_0, $D_1(j_q = 1/2)$, $D_1(j_q = 3/2)$ and D^*_2. Finally, parity and angular momentum conservation force the $(j_q = 1/2)$ states to decay to the ground states via S-wave transitions (broad width), while $(j_q = 3/2)$ states would decay via D-wave (narrow width).

Such a pattern was recently beautifully borne out by the CLEO evidence for the $D_1(j_q = 1/2)$ broad state[79]. An open question remains the 1997 DELPHI observation[91] of first radial excitation $D^{*\prime+}$ in the $D^{*+}\pi^-\pi^+$ final state, not confirmed either by OPAL [92] or by CLEO[93], and questioned by theory predictions[94]. The situation of our present knowledge of excited D mesons is shown in tab.5. A major confirmation for HQS would also be the observation of the missing $(L = 1, j_q = 1/2, J^P = 0^+)$ D^*_0 broad state. Finally, very little is known on excited $(c\bar{s})$ states (Fig.10).

9.2 Baryons

In the framework of SU(4) at ground state we expect nine cqq $J^P = 1/2^+$ baryons (all of them detected after the recent CLEO II.V observation of Ξ'_c) and six cqq $J^P = 3/2^+$ baryons (Σ^{*+}_c and Ω^{*0}_c remain undetected; they are expected to decay via the experimen-

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[2] Common nomenclature for excited states is $D^{*(\prime,\prime\prime,...)}_J$, where J is the total angular momentum (spin+orbital), $(\prime,\prime\prime,...)$ indicates radial excitations, and $*$ indicates natural $(0^+, 1^-, 2^+, ...)$ J^P assignment.

Table 5: Experimental status of (L=1, n=1) and (L=0, n=2) $c\bar{q}$ and $c\bar{s}$ mesons (adapted from ref.[87]). Not well established states are shown in bold. Units are MeV/c^2. Spin-parity assignment for D_{s2}^* is not pinned down yet, therefore this state is quoted as $D_{sJ}(2573)$ in PDG98. Theory predictions are taken from ref.[81,93].

j_q	1/2	1/2	3/2	3/2	1/2	1/2
J^P	0^+	1^+	1^+	2^+	0^-	1^-
L	1	1	1	1	0	0
n	1	1	1	1	2	2
	$\mathbf{D_0^*}$	$\mathbf{D_1}$	D_1	D_2^*	$\mathbf{D'}$	$\mathbf{D^{*\prime}}$
Mass exp.		$2461^0 \, {}^{+42}_{-35}$	$2422^0, 2427^\pm$	$2459^{0,\pm}$		2637 ± 6
Mass th.	2400	2490	2440	2500	2580	2640
Width exp.		$290^0 \, {}^{+104}_{-83}$	$19^0, 28^\pm$	$23^0, 25^\pm$		< 15
Width th.	> 170	> 250	$20 - 40$	$20 - 40$		$40 - 200$
Decay Mode	$D\pi$	$D^*\pi$	$D^*\pi$	$D\pi, D^*\pi$		$D^*\pi\pi$
	$\mathbf{D_{s0}^*}$	$\mathbf{D_{s1}}$	D_{s1}	D_{s2}^*	$\mathbf{D_s'}$	$\mathbf{D_s^{*\prime}}$
Mass exp.			$2535^\pm$	$2573^\pm$		
Mass th.	2480	2570	2530	2590	2670	2730
Width exp.			$< 2.3^\pm$	$15^\pm$		
Width th.			< 1	$10 - 20$		
Decay Mode			D^*K	DK		

tally difficult channels $\Sigma_c^{*+} \to \pi^0 \Lambda_c^+$ and $\Omega_c^{*0} \to \gamma\Omega_c^0$). All the ccq and ccc states remain undiscovered[95]. In the HQS framework, cq_1q_2 baryons are considered as a system made of a heavy quark and a light diquark. Conserved numbers are the heavy quark spin $\mathbf{S_Q}$ and the diquark angular momentum $\mathbf{j}_{q_1q_2} \equiv \mathbf{L} + \mathbf{s}_{q_1q_2}$, where $\mathbf{L}$ is the diquark orbital momentum and $\mathbf{s}_{q_1q_2} \equiv \mathbf{s}_{q_1} + \mathbf{s}_{q_2} + \mathbf{l}_{12}$ the diquark total momentum[3].

During 1998, CLEO[96] presented evidence for the two $1/2^+$ missing states $\Xi_c^{0\prime}$ and $\Xi_c^{+\prime}$, respectively $c\{sd\}$ and $c\{su\}$, through the radiative decay $\Xi_c\gamma$. Masses measured are compatible with predictions[95,97].

Only a few of the orbitally excited P-wave ($L = 1$) baryons have been observed. The first doublet $\Lambda_{c1}(2593)$ $(1/2^-)$ and $\Lambda_{c1}^*(2625)$ $(3/2^-)$ was observed several years ago by CLEO II.V, ARGUS, and E687. In 1999 CLEO II.V presented evidence[98] for the charmed-strange baryon analogous to $\Lambda_{c1}^*(2625)$, called $\Xi_{c1}^*(2815)$, in its decay to $\Xi_c\pi\pi$ via an intermediate Ξ_c^* state. The presence of intermediate Ξ_c^* instead of Ξ_c' is an indication of $3/2^-$ assignment, while HQS explicitly forbids a direct transition to the $\Xi_c\pi$ ground state, because of angular momentum and parity conservation.

The last topic of this section is the mass difference between isospin states of charmed

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[3]I adopt for excited baryon states the nomenclature in [12]. Thus, members of 3/2 multiplets are given a ($*$), the subscript is the orbital light diquark momentum $\mathbf{L}$, and ($\prime$) indicates symmetric quark wavefunctions $c\{q_1q_2\}$ with respect to interchange of light quarks, opposed to antisymmetric wavefunctions $c[q_1q_2]$.

Table 6: Isospin mass splittings.

	$M(\Sigma_c^{++} - \Sigma_c^0)\,\mathrm{MeV}$
FOCUS prel.	$0.28 \pm 0.31 \pm 0.15$
PDG98	0.57 ± 0.23
E791	$0.38 \pm 0.40 \pm 0.15$
CLEO II	$1.1 \pm 0.4 \pm 0.1$
CLEO	$0.1 \pm 0.6 \pm 0.1$
ARGUS	$1.2 \pm 0.7 \pm 0.3$

baryons (isosplits). Lately, interest in this issue was revamped[99,100] led by the consideration that, while for all well-measured isodoublets one increases the baryon mass by replacing a u–quark with a d–quark, the opposite happens in the case of the poorly measured $\Sigma_c^{++}(cuu) - \Sigma_c^0(cdd)$ isosplit. Besides the u/d quark mass difference, isosplits are in general sensitive to em effects, and spin–spin hyperfine interactions. New FOCUS results[101] are consistent with E791, and mildly inconsistent with CLEO II (Tab.6). Finally, first measurement of the Σ_c width was presented at this conference – full details in D. Besson's review.

In the baryon sector, the discovery of double-charm states would be of fundamental importance. A recent theoretical work[102] shows how a (nearly) model–independent approach based on the Feynman-Hellman theorem is able to compute heavy-flavor hadron masses in very good agreement with experiments, and to make predictions for double-charm states. As an example, the mass of the Ξ_{cc}^+ is predicted at $\sim 3.7\,\mathrm{GeV}/c^2$, and dominant decay modes are $D^+\Sigma^+$ and $D^+\Lambda^0$. Such a discovery does not seem within reach of either CLEO, or present fixed-target experiments.

9.3 Charmonium

Charmonium states are produced at e^+e^- storage rings and through $p\bar{p}$ annihilation. The e^+e^- annihilation proceeds, at first order, via a virtual photon and only $J^{PC} = 1^{--}$ states can be directly formed. Nonvector states such as the χ_J states can be observed only via two–step processes as $e^+e^- \to \psi' \to (c\bar{c}) + \gamma$, or higher order processes. On the contrary, in $p\bar{p}$ annihilations all J^{PC} quantum numbers are accessible.

New data come from e^+e^- BES[103] and $p\bar{p}$ E835[104]. Results include measurements of masses and widths of χ_{c0}, χ_{c2}, η_c. A 3σ disagreement remains between their η_c mass determinations. Moreover, the width $\Gamma(\eta_c \to \gamma\gamma)$ measured by E835 is nearly a factor of two narrower than the PDG98 world average, with which, instead, recent data from L3, OPAL, and BES agree.

The most intriguing puzzle in charmonium physics seems to remain the case for the pseudoscalar radial excitation $\eta'_c \, (2^1 S_0)$. Claimed in 1982 by Crystal Barrel at $3.594 \, \mathrm{GeV}/c^2$, it was not confirmed by either DELPHI or E835 extensive searches ($30 \, \mathrm{pb}^{-1}$ in the range 3.666 to $3.575 \, \mathrm{GeV}/c^2$). The E835 data-taking period at the end of 1999 sees the search for the η'_c approved as prioritary.

10 Conclusions and outlook

The major news this year in charm physics comes from the advances in lifetime measurement technology. The D_s^+ lifetime is now conclusively measured as being larger than D^0, and the lifetime ratio can be used (along with the new measurements of DCSD branching ratios) to constrain the sizes of the WA and WX operators. New limits on $D^0 \bar{D}^0$ mixing also come mainly from the novel capability of measuring the lifetimes of opposite CP eigenstates. The other field where impressive news comes from is spectroscopy, with HQS predictions being spectacularly confirmed by the observation of an excited broad meson state, while the puzzles of meson radial excitations and the very existance of the η'_c still elude us. At the opening of the third millenium, besides results from E791, FOCUS, SELEX, CLEO II.V, E835, and BES, we should expect first data on $D^0 \bar{D}^0$ mixing from the BaBar and BELLE B-factories.

The future of post-Y2K charm physics is less clear. No new fixed-target data-taking periods for charm studies are planned either at Fermilab, or at CERN for the near future (COMPASS commissioning is scheduled to begin in 2000, with a busy physics programme which includes charm muonproduction, DIS spin-physics, gluon structure functions, and light-quark hadronic physics). Despite the significant upgrade planned, it is not clear whether CLEO III will retain competitivity with respect to B-factories. Future experiments at high-energy hadron machines (Hera-B, BTeV, LHC-B) will need to tame huge backgrounds in order to contribute to charm physics. Intense workshop activity[105] on a $e^+ e^-$ τ-charm factory has not translated into an actual proposal — perhaps the operational experience coming from low-energy, high-luminosity ($\approx 10^{33} \mathrm{cm}^2 \mathrm{s}^{-1}$) machines such as Frascati DAΦNE is needed. Interesting ideas come from a proposal for a $p\bar{p}$ collider operating at the open charm threshold[106]. On the other hand, a few specialized efforts have been approved, in the form of experiments undertaking upgrades for specific study of open charm physics (HERMES, NA50). The distant future will probably see charm ν-production from muon storage rings. Next year, the Lisbon conference will be an appropriate time to verify whether such a scenario had evolved.

Acknowledgments

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