

CHARM*

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New results on properties and decays of open charm and charmonium states are reviewed. The emphasis is on examples that illustrate the various aspects through which studies of charm physics impact the field.

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1. Introduction

The charm sector provides a unique testing ground for understanding the strong interaction. The large data samples of open charm and charmonium decays now available facilitate detailed theory-experiment comparisons. Moreover, many lessons learned from charm can be transferred to the bottom sector. Perturbative methods are applicable when charm decay is concerned; yet it is also possible to explore relativistic effects due to the light (in comparison with bottom) charm-quark mass.

The immediate goals of the analyses presented here¹ are to study charm for its own sake, to treat it as a calibration ground for methods developed for heavier systems, and to use it as a production site for light-quark systems.

2. Open charm

2.1. Leptonic and semileptonic decays

Leptonic and semileptonic decays allow the study of the effect that QCD has in weak decays where the interaction between the quarks modifies the decay rates induced by the weak process.

For leptonic decays such as $D \rightarrow \ell \nu$, the goal is a precision branching fraction measurement which, via the relation $\Gamma(D^+ \rightarrow \ell^+ \nu) \propto f_D^2 |V_{cd}|^2$, can be turned into a measurement of the decay constant f_D , with the external

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input of the CKM matrix element V_{cd} . Similar relations hold for leptonic D_s , B , and B_s decays. Measurements of f_D and f_{D_s} can be compared to calculations, thereby validating computation techniques that can then confidently be applied in the B system, where entities quantifying the effects of strong interaction must be provided as an external input in order to arrive at *e.g.* V_{td} . The experimental precision currently achieved is about 5% on f_D (CLEO [1]) and 8% on f_{D_s} (CLEO [2] and BaBar [3]). The CLEO measurements are absolute determinations, while the BaBar result is obtained relative to the decay $D_s \rightarrow \phi\pi$ which entails a dependency on the normalization branching fraction. A recent lattice QCD (LQCD) calculation [4] is in broad agreement with the measured results given the experimental uncertainties but quotes a superior precision of 1–2%.

For semileptonic decays, for example $D \rightarrow \pi\ell\nu$, a different kinematic variable enters, namely the momentum transfer q^2 to the outgoing hadron. The differential rate for decay to a pseudoscalar, $d\Gamma/dq^2(D \rightarrow P\ell\nu)$, is proportional to $|V_{cq}|^2 \times |f_+(q^2)|^2 \times p_P^3$. The modification of the weak decay by the strong force present between the ingoing quark, outgoing quark, and spectator quark is described by the pseudoscalar form factor $f_+(q^2)$. The value of p_P is determined by kinematics, and also the form factor shape does not require additional external information. For normalization, experiment can access the product $V_{cq} \times f_+(0)$, and therefore input of either V_{cq} or the form factor normalization $f_+(0)$ is required to determine the other one.

Experimental progress has seen drastic improvements in accuracy for all branching fractions, and some new ones observed for the first time, such as $D^0 \rightarrow (K^-\pi^+\pi^-)e^+\nu$ [5] at 4σ statistical significance, $\mathcal{B}(D^0 \rightarrow (K^-\pi^+\pi^-)e^+\nu) = (2.8_{-1.1}^{+1.4} \pm 0.3) \times 10^{-4}$. The decay is seen to proceed dominantly through a $K_1^-(1270)$.

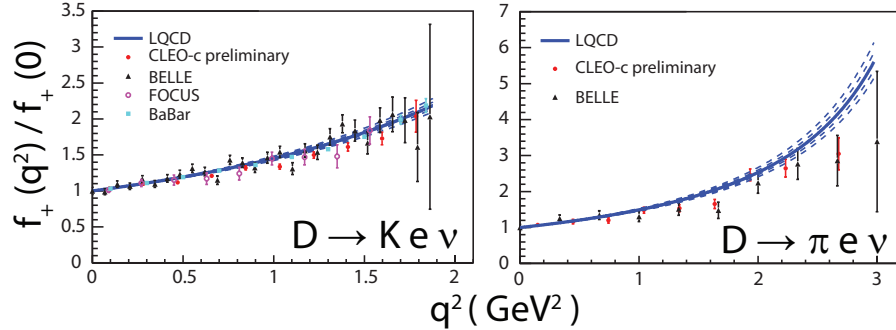


Fig.1. World data on $D \rightarrow K\ell\nu$ and $D \rightarrow \pi\ell\nu$ form factors, with an LQCD prediction [6] overlaid.

A comparison between calculated and measured form factor normalizations shows experiment still ahead of theory in terms of precision. As to $D \rightarrow P$ form factor shapes, data currently can accommodate the modified pole model [9] or the series parametrization [10]. World data agree on the form factor shape within the current error levels; the shape predicted from an unquenched LQCD calculation in Ref. [6] agrees with the data for $D \rightarrow K\ell\nu$ (Fig. 1 left) but seems to trend towards values larger than the data at upper q^2 in $D \rightarrow \pi\ell\nu$ (Fig. 1 right).

2.2. Hadronic decays

The hadronic decay rate can give insight into a more intricate interplay between manifestations of the strong interaction. An added complication is, with several hadrons produced, that final state interactions take place which are hard to quantify.

Branching fraction measurements have an especially far-reaching impact for channels that are used as normalization modes. One such example is $D^0 \rightarrow K^-\pi^+$, for which both CLEO [7] and BaBar [8] have new measurements using very different techniques. The relative precisions achieved by both are about 2%, dominated by systematic uncertainties. At this level of sensitivity, estimating the uncertainty on final state radiation corrections is an important task as these contributions are not negligible. CLEO also measured absolute branching fractions for other Cabibbo-favored D^0 and D^+ decays [7]: most of these results are the most precise to date.

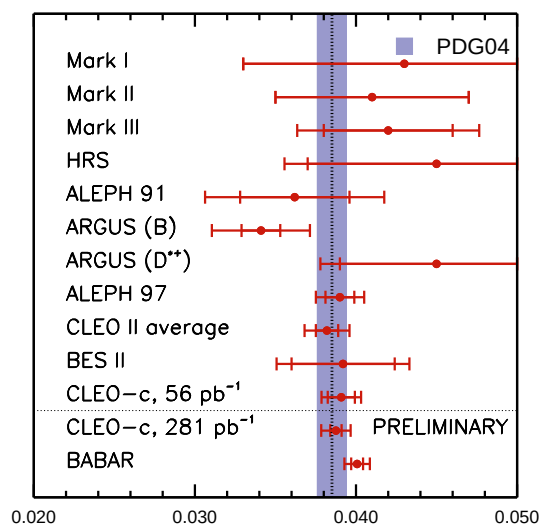


Fig. 2. Measurements of the branching fraction $\mathcal{B}(D^0 \rightarrow K^-\pi^+)$.

A comparison of the rates for the Cabibbo-favored decay $D^0 \rightarrow K^- \pi^+$ with the Cabibbo-suppressed ones $D^0 \rightarrow \pi^- \pi^+$ and $D^0 \rightarrow K^- K^+$ found that, after adjusting for phase space, the measured rates [11] do not behave as expected, namely proportionally to the squares of the CKM matrix element ratios involved: $(V_{cd}/V_{cs})^2 \approx 0.05$ for $\pi^- \pi^+ : K^- \pi^+$, $K^- K^+ : K^- \pi^+$, and unity for $\pi^- \pi^+ : K^- K^+$. Instead, one finds, for $\pi^- \pi^+ : K^- \pi^+$, $K^- K^+ : K^- \pi^+$, and $K^- K^+ : \pi^- \pi^+$ the values [13] 0.034 ± 0.001 , 0.111 ± 0.002 , 3.53 ± 0.12 . Both Belle [12] and BaBar [13] extended this study to see if the same imbalance would hold for three-body decays, in which a π^0 was added to each of the above channels. Those measurements support the expectation at the level of 30%.

CLEO [14] performed a systematic search for ten $D_S \rightarrow P_1 P_2$ decays where modes with $P_1 = K^+$ or π^+ and $P_2 = \eta, \eta, \pi^0, K_S$ or K_L are studied. This comprises all decays to a pair of mesons from the lowest-lying pseudoscalar meson nonet. The analysis measures Cabibbo-suppressed branching fractions relative to those of the corresponding Cabibbo-favored mode. The suppression ratio is, again, expected to be of order $|V_{cd}/V_{cs}|^2$, which is confirmed by the data. Signals are seen in all modes except for the isospin-forbidden decay $D_S \rightarrow \pi^+ \pi^0$.

Other questions to be addressed with hadronic multi-body decays are the production of intermediate resonances and their properties, or suppression patterns of certain channels. The description of the multi-body final state is dependent on the formalism used and introduces model dependencies that cannot be removed. Points of debate are the existence of a sound theoretical basis (as opposed to just achieving a satisfactory description of the data), quality control (what constitutes a satisfactory description), knowledge of inferred or expected intermediate states (in particular, consistency with scattering experiments), and the importance and treatment of final state interactions. Similar questions arise in the B system.

FOCUS [15] analyzed $D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ events, first determining the branching fraction relative to $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$, which is the most precise to date and in agreement with data from CLEO-c, but then moving to an amplitude analysis. Two important motivations, aside from the fact that for this decay it had not been done before, are to examine the importance of final state interactions (which are expected to be greater in four-body than in three-body decays); and developing an understanding of intermediate resonances such as the $a_1(1260)$, expected to be relevant in $B^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$. The FOCUS model incorporates ten baseline components: $D^0 \rightarrow a_1(1260)^+ \pi^-$ with $a_1(1260)^+ \rightarrow \rho^0 \pi^+$ (S and D wave) and $a_1(1260)^+ \rightarrow \sigma \pi^-$, $D^0 \rightarrow \rho^0 \rho^0$ in three helicity states, and $D^0 \rightarrow \pi^+ \pi^- + \mathcal{R}$ with $\mathcal{R} = \sigma, \rho^0, f_0(980), f_2(1270)$. The fit returns the $a_1(1260)$ a dominant contributor with a fit fraction of about 60%, as is the case also in

$K^-\pi^+\pi^-\pi^+$ and $K^0\pi^+\pi^-\pi^+$. The group $\rho^0\rho^0$ yields a fit fraction of 25%, and the rest, $\pi^+\pi^- + \mathcal{R}$, contributes about 11%. While these components get the gross features of kinematic distributions right, the confidence level is low and cannot be improved by inclusion of further signal amplitudes. This can either imply that the model is too simplistic, and/or that final state interactions cannot be ignored.

The information on the mass and the width of the $a_1(1260)$ extracted from the fit result is more precise than the current PDG average and agrees with theoretical predictions (of similar precision).

2.3. Open-charm spectroscopy

The production of pairs of open-charm mesons can be observed in e^+e^- scattering, and particularly interesting features are observed near threshold. The production cross-sections as a function of center-of-mass energy show structure that can either directly be interpreted as bound states in the charmonium system, or as the effect of interference from several resonance at nearby energies. Since the bound states decay to different pairs of mesons depending on their quantum numbers and mass, in order to obtain a complete picture it is important to measure the production cross-section for different pairs of mesons, not just the inclusive or just, for example, D^+D^- . Predictions for the production of D pairs can be found for example in [16].

Production cross-section data do exist from CLEO ($e^+e^- \rightarrow D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$, $D_s^+D_s^-$, $D_s^{*+}D_s^-$, $D_s^{*+}D_s^{*-}$ at a center-of-mass energy $E_{\text{CM}} \sim 4 \text{ GeV}$) as well as Belle and BaBar ($e^+e^- \rightarrow \gamma + D\bar{D}$, $D^{*+}D^-$, $D^{*+}D^{*-}$ at $E_{\text{CM}} \sim 10 \text{ GeV}$ [17]); both agree on the rough features. A comparison between the sum of the CLEO channels with an inclusive measurement (with the uds continuum subtracted) reveals multi-body contributions of the type $D^*D\pi$.

The characteristic enhancements in the inclusive cross-section between 3.7 and 4.5 GeV are commonly associated with the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ states of charmonium. Their mass and widths were determined in earlier experiments. A re-evaluation by BES of scan data in the region of 2–5 GeV [18] applying a model that takes interference between the resonances into account leads to, in some cases, substantially altered parameters for the mass, width, and electronic coupling, owing to the fact that the three higher resonances are broad, and, consequently, interference effects become visible. The $\psi(3770)$ results are in line with earlier results of more focused scans (BES [19]).

There are many other members of the charmonium system above open-flavor threshold that have not yet been observed. Many of them cannot be identified in direct e^+e^- production because of their quantum numbers; $p\bar{p}$ scattering or transition from a higher-mass state offer additional avenues. It is important to continue searching for those states in order to compare with and refine predictions for the spectrum of quarkonium states.

3. Charmonium

3.1. Spectroscopy

In contrast to the somewhat hazy situation of charmonium states above open-flavor threshold, all states below have been observed [11]. Large samples exist for the J/ψ and $\psi(2S)$, which are well-studied. The experimental focus is now on comparing the two states, identifying rare decays, and investigating the resonant substructure in multibody states. As for open charm, this provides information on the intermediate states produced and gives insight into the decay dynamics. The masses and widths are known well. A scan of the $\psi(2S)$ by E385 [20] led to the current best results on $\Gamma(\psi(2S))$ and $\Gamma(\psi(2S)) \times \mathcal{B}(\psi(2S) \rightarrow p\bar{p})$. The process used was $p\bar{p} \rightarrow \psi(2S)$ with $\psi(2S) \rightarrow e^+e^-$ or $\psi(2S) \rightarrow XJ/\psi \rightarrow Xe^+e^-$. The analysis makes use of the beam energy spread that is comparable to the structure investigated as opposed to the MeV range that e^+e^- machines are limited to.

The χ_{cJ} states can be studied using the reaction $\psi(2S) \rightarrow \gamma\chi_{cJ}$, where they are produced at a branching ratio of order 10% each. This implies that the χ_{cJ} data are not far behind the $\psi(2S)$ in statistical power, and similar studies as for the $\psi(2S)$ are being conducted. Once the transition photon is identified, the χ_{cJ} are easy to handle experimentally. The transition rates are affected by relativistic corrections, and thus measuring them accurately is important to guide theory. A variety of approaches and models exist; the experimental precision is currently well below the spread of predictions [21]. The $\eta_c(1, 2S)$ and the h_c are less well known, and studies to learn more about their properties and decays are underway.

3.2. Hadronic decays

Based on the observations that to date much fewer radiative decays have been observed for the $\psi(2S)$ than for the J/ψ , and that the ones seen all have branching fractions at the level of 10^{-4} or 10^{-5} while a naive scaling leads to the expectation of about 1% for the sum $\psi(2S) \rightarrow \gamma gg$, BES executed a survey of multi-body decay modes with pions and kaons [22]. They found many more signals but all in the same range as the ones previously measured. This raises the question whether modes with even higher multiplicity matter as much as to raise the sum to 1%, or whether the naive scaling prediction is insufficient.

3.3. Ties to lighter systems

Decay or transitions between charmonia provide a lab within which to study the properties of light mesons. BES [23] searched for the decay $\eta(') \rightarrow$ undetectable final states, where the $\eta(')$ is produced in the reaction $J/\psi \rightarrow \phi\eta(')$. The ϕ as a narrow resonance is readily identified via its decay into a charged kaon pair, and kinematics constrain the recoiling $\eta(')$ to a narrow

region in the missing momentum. No signal is seen; an upper limit is placed on the decay of $\eta(\prime)$ to invisible final states relative to decay into two photons, which translate into absolute branching fractions of $\eta, \eta(\prime) \rightarrow \text{invisible}$ of order 10^{-3} and 10^{-4} , respectively.

CLEO used the transition $\psi(2S) \rightarrow \eta J/\psi$ with $J/\psi \rightarrow \ell^+ \ell^-$ to study the η meson. Branching fractions and ratios thereof [24] were determined for $\eta \rightarrow \gamma\gamma, \pi^+ \pi^- \pi^0, 3\pi^0, \pi^+ \pi^- \gamma$, and $e^+ e^- \gamma$, a first for such a suite of modes within the same experiment. Deviations from previous determinations were observed for $\pi^+ \pi^- \gamma$ and $e^+ e^- \gamma$ at the level of three standard deviations. The kinematic properties of the decay and CLEO's resolution allow to use the invariant mass of the η decay products (except $e^+ e^- \gamma$, which has too few events) to determine the η mass [25] as a by-product. The precision achieved is comparable to that of dedicated experiments (Fig. 3).

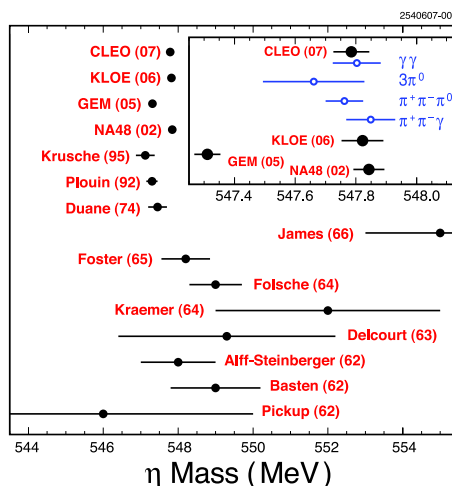


Fig. 3. World data on the η mass.

4. Conclusions

Charm continues to provide many interesting avenues to enhance the understanding of the strong interaction whether as an open-charm meson or a charmonium state. Charm allows to investigate the impact of presence of the strong force in weak decays. The system of states provides information about the underlying potential, and hence confirming the existence of expected states and determining spectroscopic parameters is important in both cases. Studying transition and decays provides further insight into the production mechanism and properties of lighter hadrons generated in the reaction. Techniques can be refined in the charm system where large data samples are available while external input allows to overconstrain the prob-

lems, thereby affording a calibration ground for theory techniques which can then be applied to heavier systems. It is mandatory to exploit the charm data samples now for maximal impact at future facilities.

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REFERENCES

- [1] M. Artuso *et al.* [CLEO Collaboration], *Phys. Rev. Lett.* **95**, 251801 (2005).
- [2] M. Artuso *et al.* [CLEO Collaboration], *Phys. Rev. Lett.* **99**, 071802 (2007).
- [3] B. Aubert *et al.* [BaBar Collaboration], *Phys. Rev. Lett.* **98**, 141801 (2007).
- [4] E. Follana *et al.* [HPQCD Collaboration], *Phys. Rev. Lett.* **100**, 062002 (2008).
- [5] M. Artuso *et al.* [CLEO Collaboration], *Phys. Rev. Lett.* **99**, 191801 (2007).
- [6] C. Aubin *et al.*, *Phys. Rev. Lett.* **95**, 122002 (2005).
- [7] D.G. Cassel, [arXiv:hep-ex/0702021](#).
- [8] B. Aubert *et al.* [BaBar Collaboration], *Phys. Rev. Lett.* **100**, 051802 (2008).
- [9] D. Becirevic, A.B. Kaidalov, *Phys. Lett.* **B478**, 417 (2000).
- [10] R.J. Hill, [arXiv:hep-ph/0606023](#).
- [11] W.M. Yao *et al.* [Particle Data Group], *J. Phys.* **G33**, 1 (2006) and 2007 partial update for edition 2008.
- [12] K. Abe *et al.* [Belle Collaboration], [arXiv:hep-ex/0610062](#).
- [13] B. Aubert *et al.* [BaBar Collaboration], *Phys. Rev.* **D74**, 091102 (2006).
- [14] G.S. Adams *et al.* [CLEO Collaboration], *Phys. Rev. Lett.* **99**, 191805 (2007).
- [15] J.M. Link *et al.* [FOCUS Collaboration], *Phys. Rev.* **D75**, 052003 (2007).
- [16] E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane, T.M. Yan, *Phys. Rev.* **D21**, 203 (1980).
- [17] K. Abe *et al.* [BELLE Collaboration], *Phys. Rev. Lett.* **98**, 092001 (2007).
- [18] M. Ablikim *et al.* [BES Collaboration], *Phys. Lett.* **B660**, 315 (2008).
- [19] M. Ablikim *et al.* [BES Collaboration], *Phys. Rev. Lett.* **97**, 121801 (2006);
M. Ablikim *et al.* [BES Collaboration], *Phys. Lett.* **B652**, 238 (2007).
- [20] M. Andreotti *et al.* [Fermilab E835 Collaboration], *Phys. Lett.* **B654**, 74 (2007).
- [21] E. Eichten, S. Godfrey, H. Mahlke, J.L. Rosner, [arXiv:hep-ph/0701208](#), accepted by *Rev. Mod. Phys.*
- [22] M. Ablikim *et al.* [BES Collaboration], *Phys. Rev. Lett.* **99**, 011802 (2007).
- [23] M. Ablikim *et al.* [BES Collaboration], *Phys. Rev. Lett.* **97**, 202002 (2006).
- [24] A. Lopez *et al.* [CLEO Collaboration], *Phys. Rev. Lett.* **99**, 122001 (2007).
- [25] D.H. Miller *et al.* [CLEO Collaboration], *Phys. Rev. Lett.* **99**, 122002 (2007).