The Future of Charm Physics

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Abstract. The CLEO-c and BESIII detectors at the CESR and BEPC accelerators, respectively, will collect in the near term large data sets of $e^+e^- \to c\bar{c}$ events in the energy range $\sqrt{s} = 3-5\,\text{GeV}$. These data sets will correspond to a huge fractional increase over the size of current ones. The physics goals and unique advantages of running at charm threshold production are discussed.

Charm Threshold Running

Over the next 3-5 years, the CLEO-c (CESR) and BESIII (BEPC) experiments will accumulate large statistics ($\int Ldt \geq 1\,\text{fb}^{-1}$) of $e^+e^- \to c\bar{c}$ events produced in charm threshold reactions in the energy range $\sqrt{s} = 3-5\,\text{GeV}$. Running at charm threshold production has distinct advantages over continuum $e^+e^- \to c\bar{c}$ production at colliders running at $\sqrt{s} = \Upsilon(4S)$. For example, the charged and neutral multiplicities in $\Psi(3770)$ events are only 5.0 and 2.4, respectively, reducing combinatorics and leading to high detection efficiencies and low systematic errors. Additionally, charm events at threshold are pure $D\bar{D}$, including the $\Psi(4140)$ decaying into $D\bar{D}^*$, $D_s\bar{D}_s$ and $D_s\bar{D}_s{}^*$. No additional particles from fragmentation are produced.

Low multiplicity events and pure $D\bar{D}$ states, coupled with the relatively high branching fractions typical of D decays, permit the efficient implementation of "double tag" studies where one D is fully reconstructed and the other is studied in a bias free fashion. This permits the determination of absolute branching fractions with very low backgrounds. The quantum coherence of the $D\bar{D}$ states produced in $\Psi(3770) \to D\bar{D}$ and $\Psi(4140) \to \gamma D\bar{D}$ decays permit relatively simple techniques[1] for measuring $D\bar{D}$ mixing parameters and direct CP violation.

This report summarizes estimates of the physics reach of the existing CLEO-c detector based on extensive monte carlo simulation. Similar physics topics can also be addressed by the soon-to-be-upgraded BESIII detector.

Absolute Branching Fractions

The combination of pure $D\bar{D}(D_s\bar{D}_s)$ at $\sqrt{s} = \Psi(3770)$ ($\sqrt{s} = 4140\,\text{MeV}$), typical charm branching fractions of $(1-15)\%$, and a high reconstruction efficiency for D-mesons, lead to a high net D-meson tagging efficiency of $\sim 15\%$ for CLEO-c. Key selection criteria for D candidates include constraints on the energy difference between the D candidate and the beam energy, the beam constrained mass of the D candidate, and particle identification cuts.

TABLE 1. Branching fraction precision of key D decay modes projected for $3\,fb^{-1}$ of CLEO-c data compared to PDG 2003 values.

Mode	$\sqrt{s}$ (GeV)	$(\frac{\delta Br}{Br})_{PDG}$	$(\frac{\delta Br}{Br})_{CLEO-c}$
$D^0 \to K^-\pi^+$	3770	2.4%	0.6%
$D^+ \to K^-\pi^+\pi^+$	3770	6.8%	0.7%
$D_s \to \phi\pi$	4140	25%	1.9%

TABLE 2. Charm decay constant precision expected with $3\,fb^{-1}$ of CLEO-c data compared to PDG 2002 values.

Decay Constant	Mode (GeV)	$(\frac{\delta f}{f})_{PDG}$	$(\frac{\delta f}{f})_{CLEO-c}$
f_{D_s}	$D_s^+ \to \mu\nu$	16%	1.9%
f_{D_s}	$D_s^+ \to \tau\nu$	17%	1.7%
f_D	$D^+ \to \mu\nu$	Upper limit	2.3%

The technique for tagging a single D candidate can clearly be extended to the second D-meson candidate in $e^+e^- \to c\bar{c}$ threshold production events by essentially applying the single-tag technique twice. Using a modified version of a technique developed at MARK III[2], CLEO-c can then precisely measure absolute hadronic charm meson branching fractions using double-tag events. Table 1 compares the branching fraction precision for some key D decay modes anticipated with $3\,\text{fb}^{-1}$ of CLEO-c data and the corresponding PDG 2003 values.

Leptonic and Semileptonic Decays

Precision measurements of leptonic and semileptonic decays in the charm sector are vital for determining CKM matrix elements that describe the mixing of flavors and generations induced by the weak interaction. The lowest order expression for the leptonic branching fraction of a D-meson is given by[3]

$$\mathscr{B}(D_q \to l\nu) = \frac{G_F^2}{8\pi} m_{D_q} m_l^2 (1 - \frac{m_l^2}{m_{D_q}^2})\, f_{D_q}^2 |V_{cq}|^2 \tau_{D_q}, \qquad (1)$$

where f_{D_q} is the parameter that encapsulates the strong physics of the process and $|V_{cq}|$ is the CKM matrix parameter that encapsulates the weak physics and quantifies the amplitude for quark mixing. Measurements of leptonic branching fractions can then be used to extract f_{D_q} and, with additional semileptonic measurements, $|V_{cq}|$. Table 2 compares with PDG 2002 values the expected precision for D-meson decay constants with $3\,\text{fb}^{-1}$ of data and assuming 3 generation unitarity.

The differential semileptonic decay rate for a D-meson to a pseudoscalar P is given by[4]

TABLE 3. Expected precision in the branching fraction $\mathscr{B}$ for important semileptonic decays with CLEO-c and the comparison with PDG 2003 values.

Mode	$(\frac{\delta\mathscr{B}}{\mathscr{B}})_{PDG}$	$(\frac{\delta\mathscr{B}}{\mathscr{B}})_{CLEO-c}$
$D^0 \to K^- e^+ \nu$	5%	0.4%
$D^0 \to \pi^- e^+ \nu$	16%	1.0%
$D^+ \to \pi^0 e^+ \nu$	48%	2.0%
$D_s \to \phi e^+ \nu$	25%	3.1%

TABLE 4. Expected precision in V_{cq} matrix elements with CLEO-c and the comparison to PDG 2002 values.

$\frac{\delta V}{V}$	CLEO-c	PDG 2002
$\frac{\delta V_{cd}}{V_{cd}}$	1.6%	7%
$\frac{\delta V_{cs}}{V_{cs}}$	1.7%	11%

$$\frac{d\Gamma(D \to Pl\nu)}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cq}|^2 p_P^3 |f(q^2)|^2, \tag{2}$$

where the form factor $f(q^2)$ encapsulates the strong physics. Form factor measurements are a key means to test theory's description of heavy quark decays. Precision measurements in inclusive semileptonic decays can strenuously test heavy quark effective theory (HQET)[5] while exclusive decays are a rigorous testbed for Lattice QCD (LQCD) calculations[6]. Table 3 shows the expected precision in branching fraction $\mathscr{B}$ for some important semileptonic decays with CLEO-c for an integrated luminosity of $3\,\text{fb}^{-1}$ and the comparison with PDG 2003 values.

The absolute branching fraction for a semilptonic D decay to a pseudoscalar can be combined with a measurement of the D lifetime τ_D to yield the total decay width:

$$\Gamma(D \to Pl\nu) = \frac{\mathscr{B}(D^0 \to Pl\nu)}{\tau_D} = \beta_{cq} V_{cq}, \tag{3}$$

with β_{cq} given by theory. Using eqs. 1, 2 and 3 and combining measurements from leptonic and semileptonic decays make it possible to measure charm decays constants directly, without the assumption of 3-generation unitarity, and to then determine the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$, also without the unitarity assumption. Table 4 shows the expected precision in V_{cd} and V_{cs} for CLEO-c with $3\,\text{fb}^{-1}$ of integrated luminosity.

BESIII and CLEO-c will probe the low-energy nonperturbative structure of QCD with new precision. QCD predicts the existence of bound hadronic states in the mass range $\sim (1.5-2.5)\,\mathrm{GeV/c^2}$ in which gluons are both constituents and the source of the binding force. Both fully gluonic "glueballs" and quark-gluon "hybrids" are novel forms of matter whose existence has yet to be unambiguously demonstrated. Their detection and study will be a major focus of J/Ψ running. With an expected CESR luminosity of $\mathscr{L} = 2\times 10^{32}\,\mathrm{cm^2/sec^{-1}}$ at $\sqrt{s} = J/\Psi$, CLEO-c expects to collect 1×10^9 J/Ψ events. BESIII should collect even more.

Radiative J/Ψ decays are a fruitful environment to search for glue rich hadronic matter[7] and CLEO-c, for example, will collect roughly 60 million $J/\Psi \to \gamma X$ decays with its projected $1\,\mathrm{fb^{-1}}$ of integrated luminosity from J/Ψ running. With this projected data set and if the branching fraction measurements from BES[8] are indeed correct for the putative glueball candidate $f_J(2220)$, then CLEO-c will see many thousands of events in a variety of exclusive $f_J(2220)$ decay modes, $J/\Psi \to \gamma f_J(2220)$, $f_J(2220) \to \pi\pi, KK, p\bar{p}$. Firmly establishing or debunking the existence of the $f_J(2220)$ is a CLEO-c and BESIII priority.

The inclusive photon spectrum from radiative J/Ψ decays is also a powerful means to search for new glue-rich hadronic states. Due to its nearly hermetic structure (93% of 4π), the CLEO-c detector is highly efficient at rejecting events of the type $J/\Psi \to \pi^0 X$ where one of the photons from the π^0 gets lost. With its projected data set of 10^9 J/Ψ events, CLEO-c should be able to detect any narrow resonances in radiative J/Ψ decays with a branching fraction of $\mathscr{O}(10^{-4})$ or larger.

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REFERENCES

1. M. Gronau *et al*, hep-ph/0103110.
2. MARK III Collaboration, R.M. Baltrusaitis *et al*, Phys. Rev. Lett. **56**, 89 (1988).
3. J.L. Rosner, Phys. Rev. D **42**, 3732 (1990).
4. B.Grinstein *et al*, Phys. Rev. Lett. **56**, 298 (1986); F.J. Gilman and R.L. Singleton, Phys Rev. D **41**, 142 (1990); K. Hagiwara *et al*, Nucl. Phys B **327** 569 (1989).
5. I.I. Bigi *et al*, Ann. Rev. Nucl. Part. Sci. **47**, 591 (1997) and references therein.
6. Cornell Workshop on High-Precision Lattice QCD, January 2001.
7. T. Appelquist *et al*, Phys. Rev. Lett. **34**, 365 (1975); M.S. Chanowitz, Phys. Rev. D **12**, 918 (1975).
8. BES Collaboration, J.Z. Bai *et al*, Phys. Rev. Lett. **76**, 3502 (1996).