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The CLEO-c Research Program

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The CLEO-c research program will include studies of leptonic, semileptonic and hadronic charm decays, searches for exotic and gluonic matter, and test for physics beyond the Standard Model. The experiment and the CESR accelerator were modified to efficiently operate at center-of-mass energies between 3 and 5 GeV. Data at the $\psi(3770)$ resonance were recorded with the CLEO-c detector in September 2003 beginning a new era in the exploration of the charm sector.

1 Introduction

The CLEO-c physics program [1] includes a variety of measurements that will improve the understanding of Standard Model processes as well as provide the opportunity to probe physics that lies beyond the Standard Model. The primary components of this program are measurement of absolute branching ratios for charm mesons with a precision of the order of $1-2\%$, determination of charm meson decay constants and of the CKM matrix elements $\mid V_{cs} \mid$ and $\mid V_{cd} \mid$ at the $1-2\%$ level and investigation of processes in charm decays that are highly suppressed within the Standard Model. A 10 nb cross section for $e^+e^- \to D\overline{D}$ is assumed throughout ref. [1].

Since 2003, the CESR accelerator has operated at center-of-mass energies corresponding to $\sqrt{s} \sim 3770$ MeV (ψ''), $\sqrt{s} \sim 4140$ MeV and $\sqrt{s} \sim 3100$ MeV (J/ψ). The design luminosity at these energies ranges from $5 \times 10^{32} cm^{-2}s^{-1}$ down to about $1 \times 10^{32} cm^{-2}s^{-1}$ yielding 3 fb^{-1} each at the ψ'' and at $\sqrt{s} \sim 4140$ MeV above $D_s\bar{D}_s$ threshold and 1 fb^{-1} at the J/ψ. These integrated luminosities correspond to samples of 1.5 million $D_s\bar{D}_s$ pairs, 30 million $D\bar{D}$ pairs and one billion J/ψ decays [1]. These datasets will exceed those of the BESII (Mark III) experiment by factors of 130 (480), 110 (310) and 20 (170), respectively. Additionally, CLEO-c has much better photon energy resolution and particle identification than the BESII and Mark III experiments.

From fall 2001 to spring 2003 CLEO collected a total of 4 fb^{-1} of data on the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(5S)$ which is currently under analysis. These data samples will increase

Table 1: The 3-year CLEO-c run plan [1]

Resonance	Anticipated Luminosity	Reconstructed Events
$\psi(3770)$	~ 3 fb^{-1}	30M $D\bar{D}$
$\sqrt{s} \sim 4140$ MeV	~ 3 fb^{-1}	1.5M $D_s\bar{D}_s$
$\psi(3100)$	~ 1 fb^{-1}	60M radiative J/ψ

the available $b\bar{b}$ bound state data by more than an order of magnitude.

Only modest hardware modifications are required for low energy operation. The transverse cooling of the CESR beams will be enhanced by 16 meters of superconducting wiggler magnets. Half of the full complement of 12 wigglers were installed in summer 2003 with the additional 6 wigglers scheduled for installation in 2004. The CLEO III silicon vertex detector was replaced by a small, low mass inner drift chamber. The solenoidal field was reduced from 1.5 T to 1.0 T. No other modifications are planned. Prior to the installation of the final 6 wigglers, CLEO has accumulated 60.3 pb^{-1} at $\psi(3770)$, 3.1 pb^{-1} at $\psi(2S)$, and 21.0 pb^{-1} of continuum data at $\sqrt{s} = 3.67$ GeV with the new detector configuration.

2 Physics Program

The following sections will outline the CLEO-c physics program. The first section will focus on the Upsilon spectroscopy, the second section will describe the charm decay program, the third section will give an overview about the exotic and gluonic matter studies and the last section will descibe the oportunities to probe physics beyond the Standard Model.

2.1 Upsilon Spectroscopy

The only established $b\bar{b}$ states below $B\bar{B}$ threshold are the three vector triplet Υ resonances ($^3S_1$) and the six χ_b and χ_b' (two triplets of ^3P_J) that are accessible from these parent vectors via E1 radiative transitions. CLEO will address a variety of outstanding physics issues with the data samples at the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$,
Searches for the η_b and h_b: Most present theories [2] indicate the best search method for the η_b is the hindered M1 transition from the $\Upsilon(3S)$, with which CLEO might have a signal of 5σ significance in 1 fb^{-1} of data. In the case of the h_b, CLEO established an upper limit of $\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- h_b) < 0.18\%$ at 90% confidence level [3]. This result, based on ~ 110 pb^{-1}, tests some theoretical predictions [4,5,6] for this transition which range from $< 0.01 - 1.0\%$.
Observation of 1^3D_J states: The $b\bar{b}$ system is unique as it has states with L = 2 that lie below the open-flavor threshold. These states have been of considerable theoretical interest, as indicated by many predictions of the center-of-gravity of the triplet and by a recent review [7]. In an analysis of the $\Upsilon(3S)$ CLEO data sample the $\Upsilon(1^3D_2)$ state could already be observed in the four-photon cascade $\Upsilon(3S) \to \gamma_1\chi_b' \to \gamma_1\gamma_2\Upsilon(^3D_J) \to \gamma_1\gamma_2\gamma_3\chi_b \to \gamma_1\gamma_2\gamma_3\gamma_4\ell^+\ell^-$. The mass of the $\Upsilon(1^3D_2)$ state is determined to be $10161.1 \pm 0.6 \pm 1.6$ MeV/c^2 [8].
Observation of New Hadronic Υ Decays: Previously, the only hadronic decays of bottomonia experimentally observed were the $\pi\pi$ transitions among vector bottomonium states [3]. In an analysis of the $\Upsilon(3S)$ CLEO data sample the transitions $\Upsilon(3S) \to \gamma\chi_b(2P)_{1,2} \to \gamma(\omega\Upsilon(1S)) \to \gamma(\pi^+\pi^-\pi^0)(\ell^+\ell^-)$ have been observed. The branching ratios $B(\chi_{b1} \to \omega\Upsilon(1S))$ and $B(\chi_{b2} \to \omega\Upsilon(1S))$ are $(1.63^{+0.35+0.16}_{-0.31-0.15})\%$ and $(1.10^{+0.32+0.11}_{-0.28-0.10})\%$, respectively and the ratio of branching ratios is determined to be $0.67^{+0.30}_{-0.22}$ [8].
Glueball candidates in radiative $\Upsilon(1S)$ decays: Signals for glueball candidates in radiative J/ψ decay - a glue-rich environment - might be observed in radiative $\Upsilon(1S)$ decays. Naively one

would expect the exclusive radiative decay to be suppressed in Υ decay by a factor of roughly 40, which implies product branching fractions for Υ radiative decay of $\sim 10^{-6}$. With 1 fb^{-1} of data and efficiencies of around 30% one can expect ~ 10 events in each of the exclusive channels, which would be an important confirmation of the J/ψ studies.

2.2 Charm Decays

The observable properties of the charm mesons are determined by the strong and weak interactions. As a result, charm mesons can be used as a laboratory for the studies of these two fundamental forces. Threshold charm experiments permit a series of measurements that enable direct study of the weak interactions of the charm quark, as well as tests of our theoretical technology for handling the strong interactions.

Leptonic Charm Decays: Measurements of leptonic decays in CLEO-c will benefit from the fully tagged D^+ and D_s decays available at the $\psi(3770)$ and at $\sqrt{s} \sim 4140$ MeV. The leptonic decays $D_s \to \mu\nu$ are detected in tagged events by observing a single charged track of the correct sign, missing energy, and a complete accounting of the residual energy in the calorimeter. The clear definition of the initial state, the cleanliness of the tag reconstruction, and the absence of additional fragmentation tracks make this measurement straightforward and essentially background-free. This will enable measurements of the poorly known leptonic decay rates for D^+ and D_s^+ to a precision of 3 - 4% and will allow the validation of theoretical calculations of the decay constants f_D and f_{D_s} at the 1 - 2 % level. Table 2 summarizes the expected precision in the decay constant measurements.

Table 2: Expected decay constants errors for leptonic decay modes

	Decay Constant Error %	
Decay Mode	**PDG 2000**	**CLEO-c** [1]
$D^+ \to \mu^+\nu$ (f_D)	Upper Limit	2.3
$D_s^+ \to \mu^+\nu$ (f_{D_s})	17	1.7
$D_s^+ \to \tau^+\nu$ (f_{D_s})	33	1.6

Semileptonic Charm Decays: The CLEO-c program will provide a large set of precision measurements in the charm sector against which the theoretical tools needed to extract CKM matrix information precisely from heavy quark decay measurements will be tested and calibrated.

CLEO-c will measure the branching ratios of many exclusive semileptonic modes, including $D^0 \to K^-e^+\nu$, $D^0 \to \pi^-e^+\nu$, $D^0 \to K^-e^+\nu$, $D^+ \to \bar{K}^0e^+\nu$, $D^+ \to \pi^0e^+\nu$, $D^+ \to \bar{K}^{0*}e^+\nu$, $D_s^+ \to \phi e^+\nu$ and $D_s^+ \to \bar{K}^{0*}e^+\nu$. The measurement in each case is based on the use of tagged events where the cleanliness of the environment provides nearly background-free signal samples, and will lead to the determination of the CKM matrix elements $\mid V_{cs} \mid$ and $\mid V_{cd} \mid$ with a precision level of 1.6% and 1.7%, respectively. Measurements of the vector and axial vector form factors $V(q^2)$, $A_1(q^2)$ and $A_2(q^2)$ will also be possible at the $\sim 5\%$ level. Table 3 summarizes the expected fractional error on the branching ratios.

Table 3: Expected branching fractional errors for selected semileptonic decay modes

	BR fractional error %	
Decay Mode	**PDG 2000**	**CLEO-c** [1]
$D^0 \to K\ell\nu$	5	0.4
$D^0 \to \pi\ell\nu$	16	1.0
$D^+ \to \pi\ell\nu$	48	2.0
$D_s \to \phi\ell\nu$	25	3.1

HQET provides a successful description of the lifetimes of charm hadrons and of the absolute semileptonic branching ratios of the D^0 and D_s [9]. Isospin invariance in the strong forces implies $\Gamma_{SL}(D^0) \simeq \Gamma_{SL}(D^+)$ up to corrections of $\mathcal{O}(\tan^2\theta_C) \simeq 0.05$. Likewise, $SU(3)_{Fl}$ symmetry relates $\Gamma_{SL}(D^0)$ and $\Gamma_{SL}(D_s^+)$, but a priori would allow them to differ by as much as 30%. However, HQET suggests that they should agree to within a few percent. The charm threshold region is the best place to measure absolute inclusive semileptonic charm branching ratios, in particular $\mathcal{B}(D_s \to X\ell\nu)$ and thus $\Gamma_{SL}(D_s)$.

Implications for CKM Triangle: The CLEO-c program of leptonic and semileptonic measurements has two components: one of calibrating and validating theoretical methods for calculating hadronic matrix elements, which can then be applied to all problems in CKM extraction in heavy quark physics; and one of extracting CKM elements directly from the CLEO-c data. The direct results of CLEO-c are the precise determination of $\mid V_{cd} \mid$, $\mid V_{cs} \mid$, f_D, f_{D_s}, and the semileptonic form factors. The precision knowledge of the decay constants f_D and f_{D_s}, together with the rigorous calibration of theoretical techniques for calculating heavy-to-light semileptonic form factors, are required for the direct extraction of CKM elements from CLEO-c. This also drives the indirect results, namely the precision extraction of CKM elements from experimental measurements of the B_d mixing frequency, the B_s mixing frequency, and the $B \to \pi\ell\nu$ decay rate measurements which will be performed by BaBar, Belle, CDF, D0, BTeV, LHCb, ATLAS and CMS. In Table 4 the combined projections are presented [1]. In the determination of the CKM elements $\mid V_{cd} \mid$ and $\mid V_{cs} \mid$ from B and B_s mixing $\mid V_{tb} \mid = 1$ is used. The tabulation also includes improvement in the direct measurement of $\mid V_{tb} \mid$ expected from the Tevatron experiments [10].

Table 4: CKM elements at present and after CLEO-c [1]

Present Knowledge $\to$ After CLEO-c		
$\delta V_{ud}/V_{ud} = 0.1\% \to 0.1\%$	$\delta V_{us}/V_{us} = 1\% \to 1\%$	$\delta V_{ub}/V_{ub} = 25\% \to 5\%$
$\delta V_{cd}/V_{cd} = 7\% \to 1\%$	$\delta V_{cs}/V_{cs} = 16\% \to 1\%$	$\delta V_{cb}/V_{cb} = 5\% \to 3\%$
$\delta V_{td}/V_{td} = 36\% \to 5\%$	$\delta V_{ts}/V_{ts} = 39\% \to 5\%$	$\delta V_{tb}/V_{tb} = 29\% \to 15\%$

Hadronic Charm Decays: The CLEO and ALEPH experiments by far provide the most precise measurements for the decay $D^0 \to K^-\pi^+$. They use the same technique by looking at $D^{*+} \to \pi^+ D^0$ decays and taking the ratio of the D^0 decays into $K^-\pi^+$ to the number of decays with only the π^+ from the D^{*+} decay detected. The dominant systematic uncertainty is the background level in the latter sample. In both experiments, the systematic errors exceed the statistical errors. The D^+ absolute branching ratios are determined by using fully reconstructed

Table 5: Expected branching fractional errors for hadronic decay modes [1]

	BR fractional error %	
Decay Mode	**PDG 2000**	**CLEO-c** [1]
$D^0 \to K\pi$	2.4	0.6
$D^+ \to K\pi\pi$	7.2	0.7
$D_s \to \phi\pi$	25	1.9

D^{*+} decays, comparing $\pi^0 D^+$ with $\pi^+ D^0$ and using isospin symmetry. Hence, this rate cannot be determined any better than the absolute D^0 decay rate using this technique. The D_s^+ absolute branching ratios are determined by comparing fully reconstructed $B \to D^{(*)} D_s^{*+}$ to the partially reconstructed $B \to D^{(*)} D_s^{*+}$ requiring only the γ from the D_s^{*+} decay. Here the dominant systematic uncertainty is due to the background shape in the partially reconstructed sample. By reconstructing both D mesons in $D\overline{D}$ decays, the background can be reduced to almost zero and the branching ratio fractional error can be improved significantly (see Table 5).

2.3 Exotic and Gluonic Matter

The approximately one billion J/ψ produced at CLEO-c will be a glue factory to search for glueballs and other glue-rich states via $J/\psi \to gg \to \gamma X$ decays. The region of $1 < M_X < 3$ GeV/c^2 will be explored with partial wave analyses for evidence of scalar or tensor glueballs, glueball-$q\bar{q}$ mixtures, exotic quantum numbers, quark-glue hybrids and other new forms of matter predicted by QCD. This includes the establishment of masses, widths, spin-parity quantum numbers, decay modes and production mechanisms for any identified states, a detailed exploration of reported glueball candidates such as the scalar states $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$, and the examination of the inclusive photon spectrum $J/\psi \to \gamma$X with < 20 MeV photon resolution and identification of states with up to 100 MeV width and inclusive branching ratios above 1×10^{-4}.

In addition, spectroscopic searches for new states of the $b\bar{b}$ system and for exotic hybrid states such as $cg\bar{c}$ will be made using the 4 fb^{-1} $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(5S)$ data. Analysis of $\Upsilon(1S) \to \gamma X$ will play an important role in verifying any glueball candidates found in the J/ψ data.

2.4 Charm Beyond the Standard Model

CLEO-c has the opportunity to probe for physics beyond the Standard Model. Three highlights - rare charm decays, $D^0 - \bar{D}^0$-mixing and CP violation - are discussed in the following sections.
Rare Charm Decays: Rare decays of charmed mesons and baryons provide “background-free” probes of new physics effects. In the framework of the Standard Model (SM) these processes occur only at one loop level. SM predicts vanishingly small branching ratios for processes such as $D \to \pi/K^{(*)}\ell^+\ell^-$ due to the almost perfect GIM cancellation between the contributions of strange and down quarks. This causes the SM predictions for these transitions to be very uncertain. In addition, in many cases annihilation topologies also give sizable contribution. Several model-dependent estimates exist indicating that the SM predictions for these processes are still far below current experimental sensitivities [11,12].
$\mathbf{D^0 - \bar{D}^0}$ Mixing: Neutral flavor oscillation in the D meson system is highly suppressed within the Standard Model. The time evolution of a particle produced as a D^0 or $\overline{D}^0$, in the limit of CP conservation, is governed by four parameters: $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$ characterize the mixing matrix, δ the relative strong phase between Cabibbo favored (CF) and doubly-Cabibbo suppressed (DCS) amplitudes and R_D the DCS decay rate relative to the CF decay rate [13]. Standard Model based predictions for x and y, as well as a variety of non-Standard Model expectations, span several orders of magnitude [14]. It is reasonable to assume that $x \approx y \approx 10^{-3}$ in the Standard Model. The mass and width differences x and y can be measured in a variety of ways. The most precise limits are obtained by exploiting the time-dependence of D decays [13]. Time-dependent analyses are not feasible at CLEO-c; however, the quantum-coherent $D^0\overline{D}^0$ state provides time-integrated sensitivity to x, y at $\mathcal{O}(1\%)$ level and $\cos\delta \sim 0.05$ [1,15]. Although CLEO-c does not have sufficient sensitivity to observe Standard Model charm mixing the projected results compare favorably with current experimental results; see Fig. 1 in Ref. [13].
CP Violation: Theoretical predictions for the rate of CP violation in the Standard Model have significant uncertainties. Standard Model predictions for the rate of CP violation in charm mesons are as large as 0.1% for D^0 decays and as large as 1% for certain D^+ and D_s^+ decays [16].

The process $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ produces an eigenstate of $CP+$, in the first step, since the $\psi(3770)$ has J^{PC} equal to 1^{--}. Now consider the case where both the D^0 and the $\bar{D}^0$ decay into CP eigenstates. Then the decays $\psi(3770) \to f_+^i f_+^j$ *or* $f_-^i f_-^j$ are forbidden, where f_+ denotes a $CP+$ eigenstate and f_- denotes a $CP-$ eigenstate. This is because $CP(f_\pm^i\, f_\pm^j) = (-1)^\ell = -1$ for the $\ell = 1$ $\psi(3770)$. Hence, if a final state such as $(K^+K^-)(\pi^+\pi^-)$ is observed, one immediately has evidence of CP violation. Moreover, all $CP+$ and $CP-$ eigenstates can be summed over for this measurement. The expected sensitivity to direct CP violation is $\sim 1\%$.

This measurement can also be performed at higher energies where the final state $D^{*0}\bar{D}^{*0}$ is produced. When either D^* decays into a π^0 and a D^0, the situation is the same as above. When the decay is $D^{*0} \to \gamma D^0$ the CP parity is changed by a multiplicative factor of -1 and all decays $f_+^i f_-^j$ violate CP [17]. Additionally, CP asymmetries in CP even initial states depend linearly on x allowing sensitivity to CP violation in mixing of $\sim 3\%$ [1].

Dalitz Plot Analyses: A Dalitz plot analysis of multibody final states measures amplitudes and phases rather than the rates and so may provide greater sensitivity to CP violation. In the limit of CP conservation, charge conjugate decays will have the same Dalitz distribution. Although the D^+ and D_s^+ decays are self-tagging, there have been no reported Dalitz analyses that search for CP violation with charged D's. The decay $D^0 \to K_S\pi^+\pi^-$ proceed through intermediate states that are $CP+$ eigenstates, such as $K_S f_0$, $CP-$ such as $K_S\rho$ and flavor eigenstates such as $K^{*-}\pi^+$ [18]. It is noteworthy that for uncorrelated D^0 the interference between $CP+$ and $CP-$ eigenstates integrates to zero across the Dalitz plot but for correlated D the interference between $CP+$ and $CP-$ eigenstates is locally zero. The Dalitz plots for $\psi(3770) \to D^0\overline{D}^0 \to f_+K_S\pi^+\pi^-$ and $\psi(3770) \to D^0\overline{D}^0 \to f_-K_S\pi^+\pi^-$ will be distinct and the Dalitz plot for the untagged sample $\psi(3770) \to D^0\overline{D}^0 \to XK_S\pi^+\pi^-$ will be distinct from that observed with uncorrelated D's from continuum production at ~ 10 GeV [18]. The sensitivity at CLEO-c to CP violation with Dalitz plot analyses has not yet been evaluated.

3 Summary

The high-precision charm and quarkonium data will permit a broad suite of studies of weak and strong interaction physics as well as probes of new physics. In the threshold charm sector measurements are uniquely clean and make possible the unambigous determinations of physical quantities discussed above. The advances in strong interaction calculations enabled by CLEO-c will allow advances in weak interaction physics in all heavy quark endeavors and in future explorations for physics beyond the Standard Model.

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