Recent results from CLEOc

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Abstract. In the search for physics beyond the Standard Model, the accuracy with which one can predict hadronic properties plays an important role. This places a new emphasis on studies of charm physics. CLEOc has embarked on a diverse program of research encompassing leptonic decay, semileptonic decay, meson spectroscopy, and many other areas of charm physics.

1. Introduction
The CLEO experiment at the Cornell Electron-positron Storage Ring (CESR) has a 30 year history of quark-flavor research. Measurements were carried out in the \( \Upsilon(1S) \) to \( \Upsilon(5S) \) mass range. Starting in 2003 CESR began operating in the charm-quark region. Twelve beam wigglers were installed in the ring and a new drift chamber replaced the silicon detector in the CLEO detector. The accelerator typically operates at a beam luminosity of 4 pb\(^{-1}\)/day. The experiment has been renamed CLEOc to signify the change in research goals. CLEOc is the only modern \( e^+e^- \) experiment operating in the charm region, and it will remain so until the program ends in April 2008.

The primary advantage of doing charm physics near the charm threshold is that one can produce large samples of charmonium in a low background environment. A case in point is the recent CLEOc measurement (1) of \( \chi_{cJ} \) radiative decay to \( J/\psi \), shown in figure 1. Those data were used to extract the first measurement of the branching fraction \( B(\psi(3770) \to \gamma\chi_{c1}) = (2.8 \pm 0.5 \pm 0.4) \times 10^{-3} \). This low-background environment allows one to study tagged electroweak decays of the \( D \) mesons with unprecedented precision.

The research program at CLEOc is summarized in Table 1. CLEOc presently has the world’s largest data samples at the \( \psi(3770) \), and at 4170 MeV. These then provide the largest samples of \( D \) and \( D_s \) mesons. A record number of \( \psi(2S) \) events, about 30 million, has also been acquired. They provide the data for numerous spectroscopic studies involving charmonium states. Lastly, small amounts of data were recently acquired at several energies near the \( \Upsilon(4260) \) meson. Some of the CLEOc results that are relevant to hadronic research are described below.

2. \( D \) and \( D_s \) leptonic decay
The primary reasons for studying \( D \) and \( D_s \) leptonic decay are to provide high-precision tests of lattice QCD (LQCD) methods and to improve our knowledge of the CKM quark mixing matrix. Lattice QCD has changed dramatically in the last few years. Long-awaited improvements in lattice techniques have resulted in a quantitative theory that is capable of making precise predictions. Selected physical parameters show agreement between theoretical and experimental
Figure 1. Energy of the lower-energy photon in \( \psi(2S) \rightarrow \gamma \chi_{cJ} \rightarrow \gamma \gamma J/\psi \); (a) before and (b) after kinematic constraints.

Table 1. A summary of charm physics research at CLEOc and the expected luminosities at the end of the program.

| Energy (MeV)               | Acquired (pb\(^{-1}\)) | Projected (pb\(^{-1}\)) | Primary Research          |
|----------------------------|------------------------|-------------------------|----------------------------|
| \( \psi(3770) \)           | 280                    | 740                     | \( D \) decay              |
| 4170                       | 320                    | 740                     | \( D_s \) decay            |
| \( \psi(2S) \) (30M sample)| 60                     | no change               | \( \psi(2S), \chi_{cJ}, J/\psi, h_c \) |
| 3970-4260                  | 60                     | no change               | \( Y(4260) \)              |

values at the percent level (2). Reactions involving leptons are particularly good places to test the models because they do not involve large final-state interactions.

The leptonic width for charged \( D \) decay is proportional to a quark annihilation decay constant times the CKM matrix element,

\[
\Gamma \propto f_{D^+}^2|V_{cd}|^2
\]

In this expression \( V_{cd} \) is known at the one percent level from unitarity of the CKM matrix. Therefore a precise measurement of the leptonic width results in a precise determination of the decay constant. One expects that LQCD should be able to predict \( f_{D^+}^2 \) at a similar level of accuracy. More importantly, once LQCD has been tested in this way it can be applied with confidence to the analogous cases of \( f_{B_d} \) and \( f_{B_s} \), where experimental knowledge is poor (3). Theoretical decay constants are used to determine some heavy-quark CKM matrix elements. For example, the neutral \( B \) mixing rate, which is known at the one percent level, is proportional to \( f_{B_d} \),

\[
\Delta m_d \propto f_{B_d}^2 |V_{tb}V_{td}|^2
\]

The theoretical error bar on \( f_{B_d} \) is large and that determines how well the CKM matrix elements can be constrained by the mixing measurements (4). Smaller errors on the theoretical values for \( f_{B_d} \) and \( f_{B_s} \) will lead to higher precision in \( V_{td} \) and \( V_{ts} \).

At CLEOc charged \( D \) decay is studied by using correlated \( D^+D^- \) decay of \( \psi(3770) \), as depicted in figure 2. Events are tagged by the hadronic decay of one \( D \) and the muon is detected from the leptonic decay of the other \( D \) (5). This method yields a very clean missing
mass spectrum, shown in figure 3. A total of 158k tagged events have been analyzed, yielding $f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-3.4} \text{MeV})$ (5). This is the most precise experimental value for $f_{D^+}$ obtained to date. It is in good agreement with recent LQCD predictions (6). With the addition of future CLEOc data the ultimate experimental accuracy for $f_{D^+}$ will be about four percent.

![Figure 2](image1.png)

**Figure 2.** Depiction of hadronic tagging of leptonic $D$ decay. The measurements are charge symmetric and several hadronic tags are used. The tagging efficiency is about ten percent.

![Figure 3](image2.png)

**Figure 3.** Missing mass squared showing the neutrino peak (inset) from $D \rightarrow \mu \nu$. The background peak at 0.25 GeV$^2$ is from $D \rightarrow \pi K^0$.

CLEOc has also made a preliminary analysis of charged $D_s$ leptonic decay (7). The initial production of $D_s \bar{D}_s^*$ at 4170 MeV is tagged by the radiative decay of $D_s^*$ to $D_s$ followed by hadronic decay of $D_s$. Approximately 200pb$^{-1}$ of data have been analyzed to date, yielding a total of 100 events. In this case the missing mass spectrum, shown in figure 4 includes contributions from $D_s \rightarrow \mu \nu$ as well as $\tau$ modes such as $D_s \rightarrow \tau \nu, \tau \rightarrow \pi \nu$. A cut on calorimeter energy selects weighted samples of each decay channel which are then combined by assuming lepton universality. The preliminary value for the decay constant is $f_{D_s^+} = (280 \pm 12 \pm 6 \text{MeV})$. This is the only high-precision measurement of $f_{D_s^+}$. Recent LQCD predictions for the decay constant yield a slightly lower value, $f_{D_s^+} = (249 \pm 3 \pm 7 \pm 11 \pm 10 \text{MeV})$ (6).

3. $D$ semileptonic decay
The motivation for studying $D$ semileptonic decay is similar to that for leptonic decay. The differential rate for pion production takes the form,

$$d\Gamma(D \rightarrow \pi e^+ \nu_e) \propto f_+(q^2)^2 |V_{cd}|^2$$

3
Therefore a precise measurement of the rates can be used to test the theoretical form factor, or new constraints can be deduced for $V_{cd}$. Since the form factors for $D \to \pi e \nu$ and $B \to \pi e \nu$ are related by heavy-quark symmetry, tests in the charm sector indirectly yield improvements in the determination of $V_{ub}$ (4).

CLEOc has made several recent measurements in this area (8; 9; 10). Our (preliminary) analysis with the highest statistics, incorporating 282 pb$^{-1}$ of data, is shown in figure 5. Overlapping data samples (40 percent shared events) were studied by two methods. In one the $D$ mass squared is constructed as the difference of the squared beam energy and the squared momenta of the decay products. In the other the signal is the difference between the missing energy and missing momentum of the decay, corresponding to the neutrino mass. Clear signals with low background are observed in each case. Using LQCD values (11) for $f_+(0)$ and the measured rates yields the values for $|V_{cd}|$ shown in Table 2. Good agreement was obtained between the data for each decay mode, and with the values tabulated by the PDG (12). Good agreement was also observed between the two methods of analysis. Theoretical uncertainties dominate the analysis.

4. $Y(4260)$

The CLEO experiment has made numerous spectroscopic studies, including measurements of the $Y(4260)$ meson. The latter are particularly interesting because $Y(4260)$ may have exotic structure. After its original discovery by BaBar (13) in ISR production of $\pi^+\pi^-J/\psi$, it was confirmed by Belle at a slightly higher mass (14). Its observation by ISR strongly suggests that the $Y(4260)$ is a vector meson. In direct production CLEOc also observed the $Y(4260)$ decaying to $\pi^0\pi^0J/\psi$ and to $K^+K^-J/\psi$ (15). Although one suspects that there is now sufficient data to allow an interpretation of the $Y(4260)$ based on its decay properties, the present state of

![Figure 4. Missing mass squared for $D_s$ leptonic decay. A cut on calorimeter energy selects event samples near zero missing mass that are primarily from a) $D_s \to \mu \nu$, b) $D_s \to \tau \nu$, and c) $D_s \to e \nu$. The largest component, from $D_s \to \mu \nu$, is seen as a peak at zero missing mass corresponding to the neutrino.](image)
 neutrino reconstruction

Table 2. Preliminary CLEOc results from the analysis of untagged $D \to$ hadrhonev.

| Decay Mode   | $|V_{cd}| \pm (stat) \pm (sys) \pm (theory)$ | PDG06     |
|--------------|-------------------------------------------|-----------|
| $D^0 \to K^\pm e^\nu$ | 1.006±0.007 ± 0.013 ± 0.103               | 0.957 ± 0.017 ± 0.093 |
| $D^0 \to \pi^\pm e^\nu$ | 0.221±0.013 ± 0.004 ± 0.028               | 0.230 ± 0.011 |
| $D^\pm \to K^0 e^\nu$   | 0.984±0.042 ± 0.017 ± 0.101               | 0.957 ± 0.017 ± 0.093 |
| $D^\pm \to \pi^0 e^\nu$ | 0.235±0.016 ± 0.006 ± 0.029               | 0.230 ± 0.011 |

hadronic theory is not up to the task. The strongest statement one can make is that some particular model predictions are disfavored (15).

A recent analysis of ISR data from CLEO also confirms $Y(4260)$ in $\pi^+\pi^-J/\psi$ decay (16). The mass, $4284_{-16}^{+17}$ ± 4 MeV/$c^2$, lies between the two previous measurements. Figure 6 shows the spectrum. Recent (quenched) LQCD calculations predict an exotic $J^{PC} = 1^{++}$ hybrid meson at about 4.4 GeV/$c^2$, and Dudek’s contribution to this conference gives a value below 4.3 GeV/$c^2$ for this exotic meson. One expects the hybrid vector state to mix with other vector charmonium states, but since no conventional charmonium vectors are expected at this mass, one can speculate that a significant portion of the hybrid strength will remain at about 4.3 GeV/$c^2$. This suggests that the $Y(4260)$ may be dominantly a hybrid meson.

5. Summary and outlook
There has been a resurgence in charm physics research due to new initiatives at CLEOc and elsewhere. Measurements of $D$ and $D_s$ leptonic and semileptonic decay are providing unprecedented tests of LQCD methods. The expected improvements in hadronic theory will significantly reduce the uncertainties in the CKM matrix elements $V_{cd}, V_{cs}, V_{td}, V_{ts}$, and $V_{ub}$. 
Recent spectroscopic discoveries have opened a new area of research, exotic charmonium. Further improvements in these areas will result from the completion of the CLEOc program and from future research at BES-III and Super-B.

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