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Excited Charmed Mesons

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ABSTRACT

The experimental status of excited charmed mesons is reviewed and is compared to theoretical expectations. Six states have been observed and their properties are consistent with those predicted for excited charmed states with orbital angular momentum equal to one.

Charmed mesons are understood to be bound states of a charmed quark and a lighter anti-quark, $\bar{u}$,$\bar{d}$, or $\bar{s}$ moving in a potential derived from QCD. The lowest mass, or ground state, mesons have quantum numbers:

$\vec{L} = 0$	^1S_o	$\vec{S} = \vec{s_c} + \vec{s_{\bar{q}}} = 0$	D^o, D^+, D_s^+
	$^3S_1$	$\vec{S} = \vec{s_c} + \vec{s_{\bar{q}}} = 1$	D^{*o}, D^{*+}, D_s^{*+}

Table 1: Quantum Numbers of Ground State Charmed Mesons

Excited mesons, often referred to as D^{**}'s, have higher values of the radial or orbital quantum number numbers and have higher mass. The first such excited state was seen by the ARGUS collaboration in 1986 [1)]. Since then, 5 additional excited charmed meson states have been seen [2)]. The main contributors to the experimental observations have been the ARGUS experiment, CLEO, and Fermilab experiments E691 and E687. LEP experiments and Fermilab Experiment 791 are also beginning to contribute to our knowledge of these states.

The outline of this paper is as follows: Section I will be a brief discussion of the theoretical framework used to describe the spectroscopy of the excited charmed mesons, including their quantum numbers, masses and widths, and decay properties; Section II will address briefly some important issues in the detection and analysis of these states; In Section III, we will review the current experimental results on signals, masses, and widths; In Section IV, we discuss the association of quantum numbers to the observed states; Section V uses the excited charm spectrum to predict the spectrum of excited B-mesons, a very interesting topic especially since these excited B's are beginning to be observed; and the last section lists some open questions which need to be addressed in the future.

1 Theoretical Framework

A charm quark and light anti-quark moving in a central potential of the form

$$V = a + bR + \frac{c}{R},$$

motivated by QCD, can be described by the quantum numbers J, L, and S, where $\vec{J}$ is the total angular momentum, which is the sum of the orbital angular momentum $\vec{L}$ and the total spin $\vec{S}$, where $\vec{S} = \vec{s_c} + \vec{s_{\bar{q}}}$.

The first set of excited states are expected to have L = 1 , shown schematically in figure 1. These states all have positive parity. Since the individual quark spins can add to 0 or 1, the total angular momentum can be 0, 1, or 2.

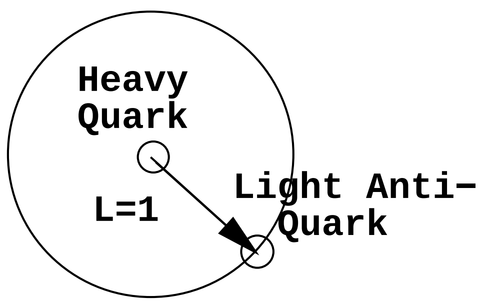


Figure 1: Schematic Representation of an Excited D Meson

Assuming that these states are heavy enough to decay **strongly** into a ground state charmed meson and a pseudoscalar meson (π or K), then conservation rules such as angular momentum, parity, and isospin lead to twelve states with the pattern of quantum numbers and allowed decays shown here:

$^{2S+1}L_J$	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$
$^3P_2$	$D\pi$,$D^*\pi$	$D\pi$,$D^*\pi$	D^*K, DK
$^3P_1$	$D^*\pi$	$D^*\pi$	D^*K
$^3P_0$	$D\pi$	$D\pi$	DK
$^1P_1$	$D^*\pi$	$D^*\pi$	D^*K

Table 2: Quantum Numbers of Excited Charmed Mesons, using total quark spin, orbital angular momentum, and total angular momentum to describe the states.

(One complication is that the two 1^+ states can mix.)

While these quantum numbers may be an 'appropriate choice' for Charmonium where the masses of the two quarks are equal, they may not be 'appropriate' to a 'heavy-light' system. By 'appropriate choice' we mean that the quantum numbers best express the symmetry of the system (leaving the rest as a small perturbation). For example, in the hydrogen atom, we do not worry about the nuclear spin – it largely decouples from the spectroscopy and enters only as a 'hyperfine' effect.

One very relevant symmetry is 'Heavy Quark Symmetry' or HQS which is supported by a 'Heavy Quark Effective Theory' or HQET [3]. According to this, in the limit of infinitely heavy quark mass, the heavy and light degrees of freedom decouple and the light degrees of freedom determine the quantum states, level spacing, and decay rates (and hence widths) of the heavy-light mesons. This same approach leads to relations between the transition matrix elements which appear for example in semileptonic decays of these systems.

The model is expected to be a good approximation when

$$M_Q > \Lambda_{QCD}$$

and, therefore should apply to the b-quark and hopefully the c-quark. Corrections would be expected to be of order $\frac{\Lambda_{QCD}}{M_Q}$.

In this picture, the best choice for the quantum numbers would be the spin of the heavy quark,

$$\vec{S_Q}$$

and the total angular momentum of the light degrees of freedom:

$$\vec{j} = L + \vec{s_{\bar{q}}}.$$

This gives two sets of levels: $j = \frac{3}{2}$ and $j = \frac{1}{2}$. In the heavy quark limit, each level consists of two degenerate states corresponding to the different orientations of the heavy quark spin. For finite (c,b) quark masses, the degeneracy will be broken to the order of $\frac{\Lambda_{QCD}}{M_{b,c}}$. The $j = \frac{1}{2}$, 0^+ state decays via an S-wave therefore is expected to be very broad – with widths of 100 MeV/c or more. The $j = \frac{3}{2}$, 2^+ state goes through a D-wave so it is expected to be relatively narrow. Because the quantum numbers of heavy and light degrees of freedom are independently conserved, HQET predicts that the $j = \frac{1}{2}$, 1^+ state decays purely by S-wave and the $j = \frac{3}{2}$, 1^+ state decays by a D-wave. This means that the $j = \frac{3}{2}$ states are relatively narrow while the $j = \frac{1}{2}$ are quite broad. We shall see later that experimental backgrounds make the identification of broad states very difficult and none has so far been convincingly observed. The rest of this paper will confine its attention to the $j = \frac{3}{2}$ states. To differentiate the two $j = \frac{3}{2}$ states, we refer to them as the 1^+ and the 2^+ from now on. The predicted spectrum is shown in figure 2.

HQS predicts specific relationships between the level spacing of the D^{**}'s and B^{**}'s. Symmetry breaking effects in the Hamiltonian can be used to predict the splitting of the 3/2 and 1/2 states. Attempts have even been made to extend the applicability of the symmetry to strange mesons.

Quantum number restrictions similar to the ones shown above also exist. The non-strange D^{**} 2^+ state can decay into $D^*\pi$ or $D\pi$. The 1^+ only decays through $D^*\pi$. Similarly, the D_s^{**} 2^+ state can decay into D^*K or DK while the 1^+

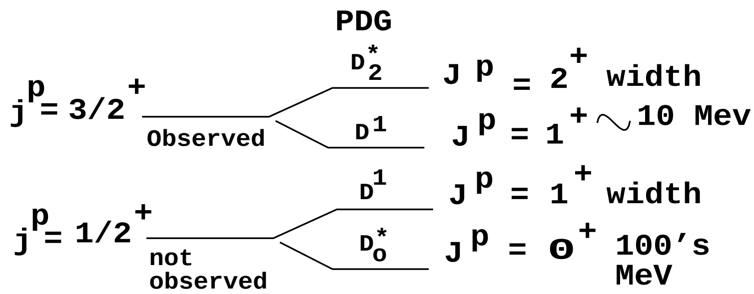


Figure 2: Level Diagram for Quantum States of L = 1 System in HQET. The names given to these states by the Particle Data Group are also shown.

state can only decay through D^*K. In addition, the model makes specific predictions on the decay rates into charm particles and light mesons.

HQS also predicts that the decay rates from each excited state into each final state, such as $D\pi$, $D^*\pi$, $D\rho$, and $D\eta$, are independent of the heavy quark mass.

Decay rates between an excited meson H, with quantum numbers $L_J(j_q)$, to a heavy-light state H', with quantum numbers $L'_{J'}(j'_q)$ and a light meson h are given by:

$$\Gamma_{j_h,l}^{H\rightarrow H'h} = (C_{j_h,J,j_q}^{S_Q,j'_q,J'})^2 p^{2l+1} F_{j_h,l}^{j_q,j'_q}(p^2)$$

The $6-j$ coefficients express the fact that overall angular momentum, the angular momentum of the light degrees of freedom, and the heavy quark spin all have to be conserved. The form factor F is a sort of reduced matrix element which depends only on the quantum numbers of the light quarks in the decaying D^{**} and the daughter heavy-light meson (e.g. D or D^*) and on the orbital angular momentum of the emitted light meson, l, and its total angular momentum, j_h, where $\vec{j_h} \rightarrow \vec{s_h} + \vec{l}$

With this relation and some arguments about the values of the functions F, it is possible to predict the widths of the various excited mesons into various final states and to add them up to get estimates of the total widths. Pionic transitions between any two heavy-light states should be identical independent of the heavy quark mass so charm transitions can be used to predict B transitions. The $6-j$ coefficients can be used to relate the branching fractions from a given parent into various final states. One prediction is that $\frac{\Gamma(D_2^*\rightarrow D\pi)}{\Gamma(D_2^*\rightarrow D^*\pi)}$ is about 1.8.

If one accepts the validity of the model, then relative rates into different final states, total widths, and certain angular correlations can help associate particular mass bumps with particular states predicted by the HQS model.

2 Issues in Detection and Analysis of Excited Charm Mesons

Extraction of the D^{**} signals proceeds in the following steps:

1. Identify a ground state light charm candidate by reconstructing its mass from its decay products. Decay modes which are relatively large and easy to recon-

struct are

$$D^o \to K^-\pi^+,\ D^o \to K^-3\pi,\ D^+ \to K^-\pi^+\pi^+,\ D^o \to K^-\pi^+\pi^o,$$
$$\text{and } D^* \to D\pi.$$

In photon or hadron experiments, the signal to background is improved by using a vertex detector to chose only those combinations which form a vertex that is well separated from the main interaction vertex;

2. Combine the charm candidate with all appropriate tracks coming from the primary interaction vertex. States of interest would have 'cascade' π or K mesons, neutral or charged, and possibly ρ's or η's;

3. Plot the mass difference, for example,

$$M(D\pi) - M(D) \text{ or } M(D^*\pi) - M(D^*)$$

for each combination. Many measurement errors cancel in the mass difference which gives improved resolution;

4. Identify, fit, and study 'bumps' in the mass difference distribution.

There are two major sources of background to the D^{**} signals:

1. Even under the best of circumstances there will be background in the charm candidate (D or D^*) sample giving false entries into the D^{**} plot. These can be studied or even subtracted out using the sidebands to the charm mass peak. This source of background is illustrated in figure 3a.

2. Each combination of a correctly signed light meson coming from the primary vertex and the charm candidate must be entered into the mass difference plot. This gives rise to a continuous 'combinatoric background' whose statistical fluctuations can obscure a signal (or mimic one!). This background is unavoidable and is expected to be worse in hadroproduction than in photoproduction. This kind of background is shown in figure 3b. It can be studied using 'wrong sign' combinations of the D-meson and the light meson.

There are two other annoying problems:

1. False peaks can be generated in a variety of ways. In particular, D^{**} states with D^* decay products can create false peaks if the π is lost. These states will then enter the D plots but the mass of the true $D^*\pi$ state will appear as a $D\pi$ bump displaced by one pion mass from its true value. While this can easily be identified it does complicate the mass plot and makes it more difficult to fit the distributions to extract signal parameters.

2. Since there are a large number of possible excited states, including some which have L=2 or 3, some which are broad, and some which decay in complicated ways, there are many opportunities to create irregular structure in the mass plots.

The bottom line: backgrounds in these searches are large and irregular! Broad states are very likely to be masked by these backgrounds!

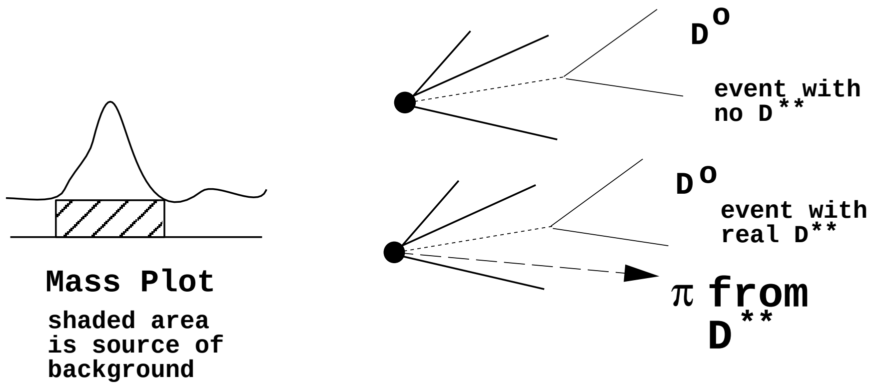


Figure 3: Contributions to backgrounds: (left) from background accompanying the ground state charm candidate; and (right) from random combinations with tracks coming from primary vertex (combinatoric background) with the ground state charm candidate.

3 Signals, Masses, and Widths

The first signal, shown in figure 4a,b, is the invariant mass difference distribution

$$M(D^+\pi^-) - M(D^+) \text{ (and c.c.)}$$

where the D^+ decays into

$$K^-\pi^+\pi^+.$$

Notice the bump at 2460 MeV/c^2 whose width is about 20 MeV/c^2. There are also small wiggles at lower mass about which more will be said later. This state is now called the $D_2^*(2460)$. Its isospin partner should decay into $D^o\pi^+$. That spectrum is shown in figure 4c,d. Note that there is indeed a peak 'near' 2460 MeV/c^2. There is also an impressive structure just 140 MeV/c^2 below this. It turns out that this can be shown to arise mainly from the expected decay of the of D^{**}'s decaying through $D^{*o}\pi^+$ where

$$D^{*o} \rightarrow D^o\pi^o$$

with the π^o going unobserved, an example of the background mechanism described above.

If this state is to be identified as the 2^+ state, there should be a corresponding peak in the $D^{*+}\pi^-$ spectrum. That spectrum should also reveal the 1^+ state. Figure 5 shows that spectrum, namely

$$M(D^{*+}\pi^-) - M(D^{*+}) \text{ (and c.c.)}$$

where the D^{*+} decays into

$$D^o\pi^+ \text{and/or to } D^+\pi^o$$

and the $D^o(D^+)$ is reconstructed through its decays to

$$K^-\pi^+ \text{ or } K^-\pi^+\pi^-\pi^+ \, (K^-\pi^+\pi^+)$$

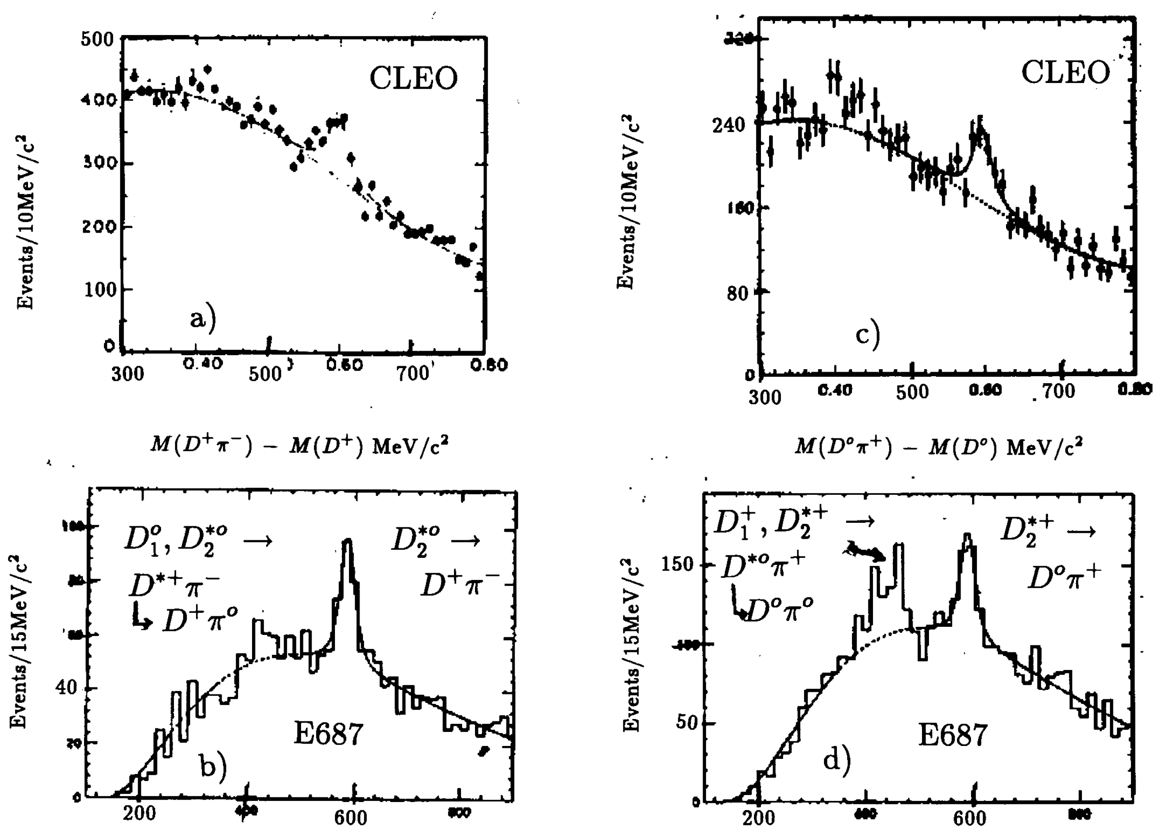


Figure 4: Mass Spectra for $D^+\pi^-$ from a) CLEO; and b) E687 and $D^o\pi^+$ from c) CLEO; and d) E687.

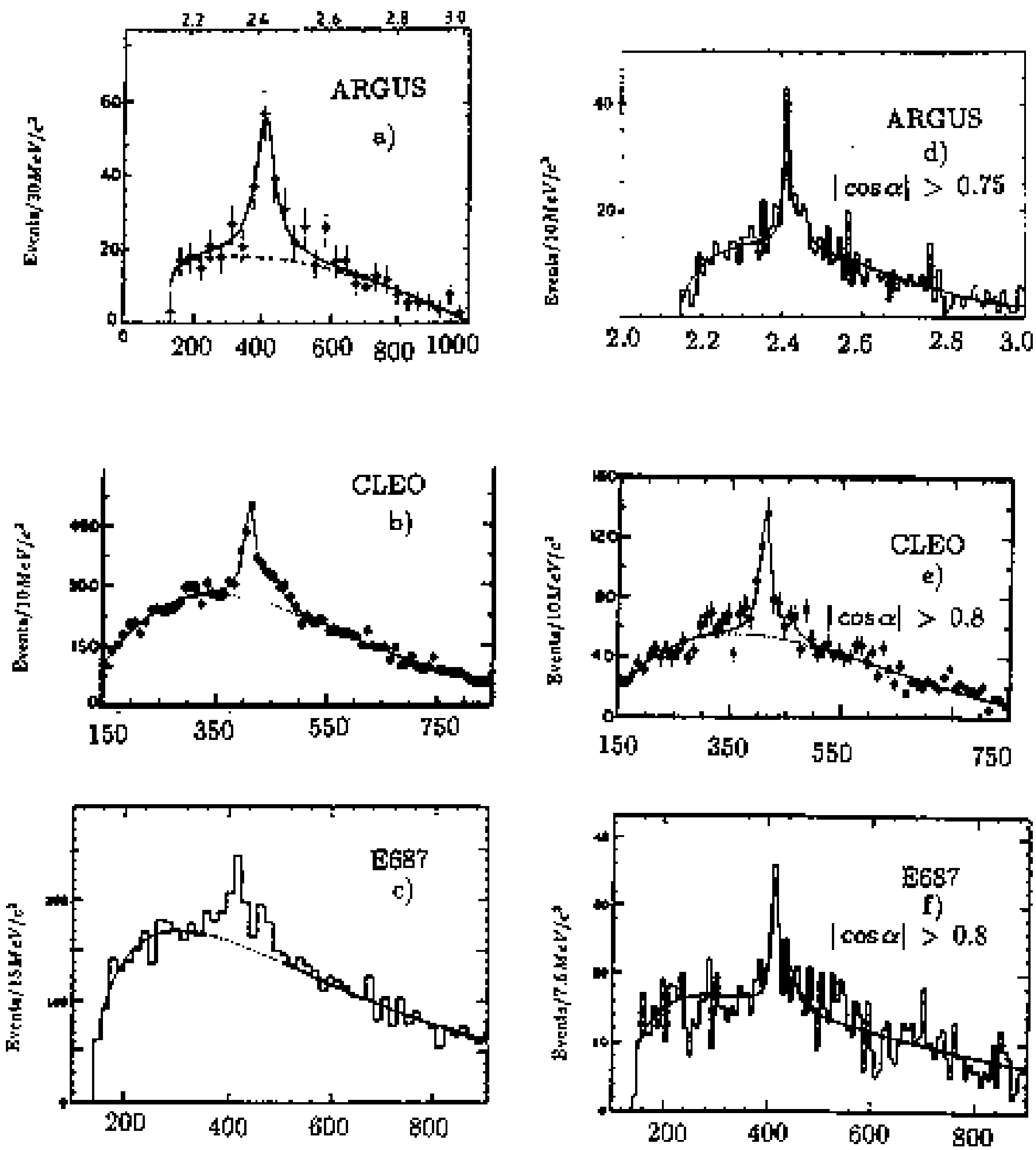


Figure 5: Mass Spectra for $D^{*+}\pi^-$ from a) ARGUS; b) CLEO; and c) E687 and for $|\cos\alpha| > 0.75$ from d) ARGUS; for $|\cos\alpha| > 0.80$ e) CLEO; and f) E687. All plots are mass differences in MeV/c^2 except for d) where the axis values show the total mass in GeV/c^2.

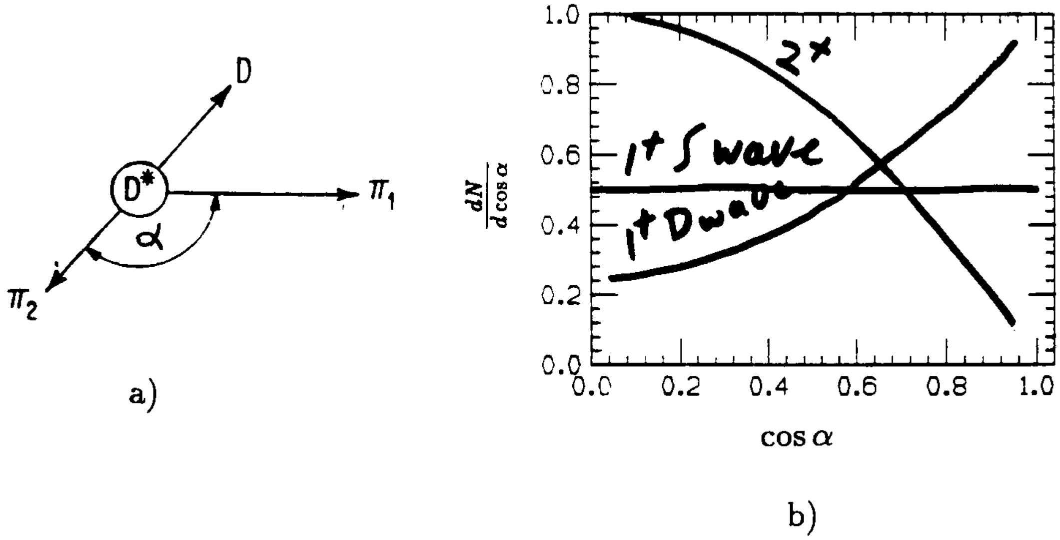


Figure 6: a) Definition of helicity angle in $D^*\pi$ decay; b) Angular distribution for various quantum numbers of parent D^{**}.

Instead of seeing two peaks, we see one very broad peak (or perhaps a suggestion of two poorly resolved peaks) which covers the 2460 region.

If the spectrum indeed consists of two overlapping peaks, corresponding to the 1^+ and 2^+ states, then the angular distribution of the 'cascade' pion in the D^* rest frame can be used to help separate the two states. In the HQS picture, the 1^+ and 2^+ will both decay through a D-wave. The angular distribution for this state into a D-wave is $1 + 3\cos^2\alpha$ whereas the 2460, if it is the 2^+, will decay like $\sin^2\alpha$. The angle α is the angle between the two pions in the D^* rest frame. This angle is defined in figure 6a. Figure 6b shows the various angular distributions. A cut on large $|\cos\alpha|$ favors the 1^+ relative to the 2^+ state.

Figures 5d,e,f show the result of a cut of $|\cos\alpha| > 0.8$ on the $D^{*+}\pi^-$ spectrum. After the cut, a relatively narrow peak remains on the low side of the original structure while the excess of events around the 2460 has mostly disappeared. The low mass peak has a value around 2420 MeV/c^2 and does not appear in the $D^+\pi^-$ spectrum. It is therefore identified as the 1^+ state while the bump at 2460, which seems to appear in both $D^{*+}\pi^-$ and $D^+\pi^-$ is identified as the 2^+ state.

The isospin splitting of the 2460 states is measured to be

$$0 \pm 4 \pm 3\ (E687);\ 2 \pm 4 \pm 4\ (CLEO);\ \text{and}\ 14 \pm 5 \pm 8\ (ARGUS)$$

CLEO has also measured the isospin splitting of the $J^P = 1^+$:

$$-4^{+2}_{-3} \pm 4$$

The funny structures seen in the D^+ spectrum can now be understood as due to incompletely reconstructed (missing π from the D^*) decays of the 2^+ and 1^+ into $D^*\pi$.

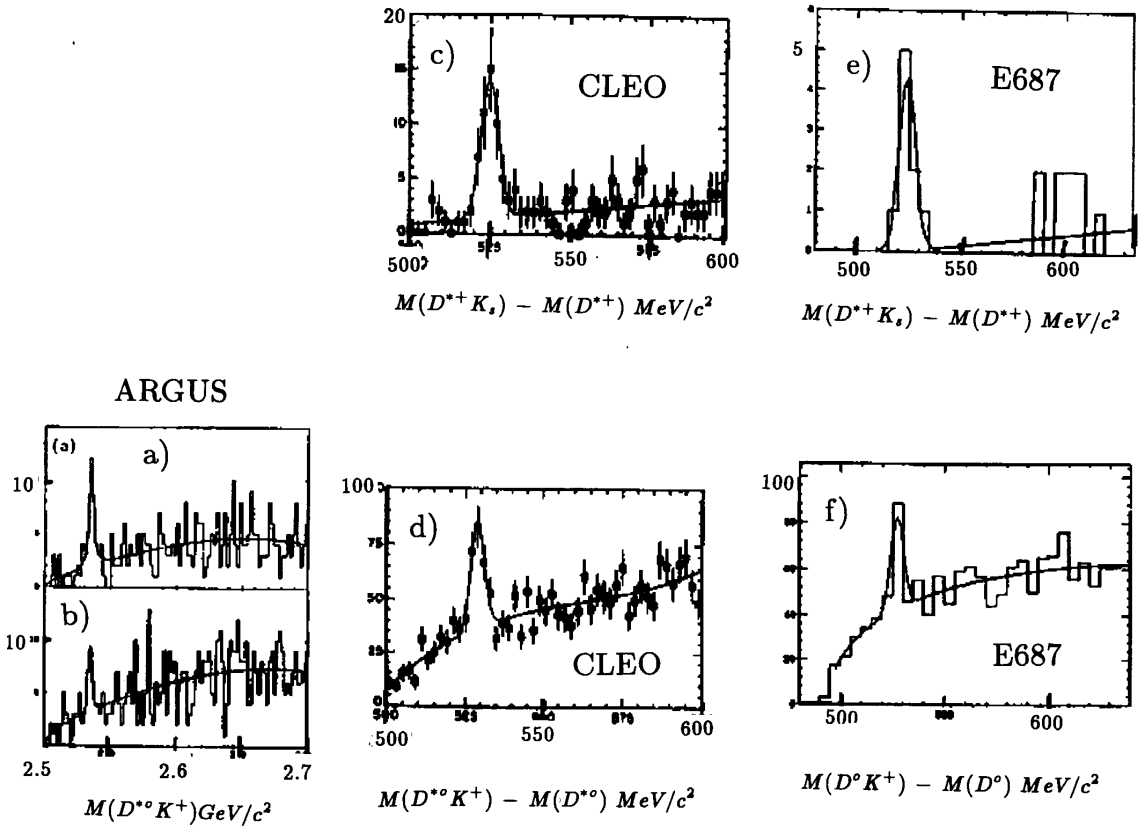


Figure 7: $D_s^{**}, 1^+$ signals from ARGUS a) and b), from CLEO c) and d), and from E687 e) and f). The signal in f) is compatible with the decay $D^{*o}K^+$ where the D^{*o} decays to $D^o\pi^o$ since the π^o is not reconstructed in this analysis. A direct decay into D^oK would show up at a much higher mass difference. CLEO seems to rule out such a decay mode for the state near 2535.

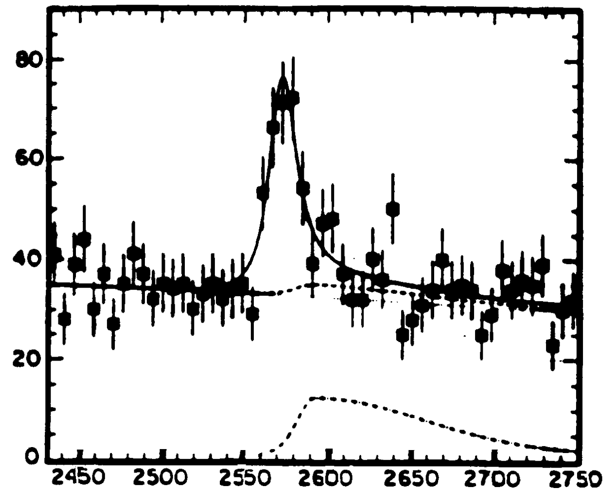
Next, we show evidence in figure 7 for a D_s^{**} state decaying into $D^{*+}K^o$ and $D^{*o}K^+$.

This state has a mass of around 2535 MeV/c^2 and is very narrow. No corresponding state appears in the D^oK^+ channel. This state is identified as 1^+ because it only decays into D^*'s and because the 1^+ is predicted to be very narrow.

CLEO has recently reported the observation of the 2^+ state through its DK mode. The spectrum is shown in figure 8. This state is not seen in D^*K^o, presumably because it is suppressed by phase space considerations. E687 has offered some preliminary confirmation of this state.

3.1 Summary of Masses and Widths

Tables 3 and 4 summarize the present knowledge of the masses and widths of the six $j = \frac{3}{2}$ excited mesons which have been observed. While the overall picture is satisfactory, there are differences in the the mass values that seem outside of the quoted statistical and systematic uncertainties. This is attributed to the large and



$M(D^oK^+)$ MeV/c^2

Figure 8: $D_s^{**}, 2^+$ signals

highly structured backgrounds. The structures limit the region over which fits can be performed. In some cases, subtle variations of the fit near the signal region can cause shifts in the mass values. In general, the authors feel that the quoted systematic errors tend to be optimistic.

These results may be compared to theoretical models, for example those of Godfrey and Kokowski [5] or of Eichten and Quigg [4]. Agreement is generally OK, with level spacings being somewhat more reliable than absolute scales.

4 More on Quantum Number Determination

Quantum numbers of the states are determined by several methods:

1. Observing the pattern of decays into various final states and exploiting the differences caused by the conservation laws and various predictions concerning relative widths;

2. Matching the observations up against predicted mass values and widths;

3. Detailed angular correlation analysis of the $D^*\pi$ states where the helicity angle distribution of the decay indicates the quantum numbers of the parent.

The results of an angular correlation analysis by CLEO [6] for both the 2^+ and 1^+ states is shown in figure 9. The results of fits demonstrate that the angular distribution for the state at 2420 is indeed only consistent with the decay of an object with total angular momentum 1 through a D-wave. This is a very impressive result. The state at 2460 is consistent with an angular momentum 2 object decaying through a D-wave, but because of the low statistics, isotropic decay (which is consistent with the decay of a spin 1 object) cannot be ruled out.

Table 3: Properties of the 2^+ States

experiment	Mass (MeV/c^2)	Width (MeV/c^2)
$D^{**o} \to D^+\pi^-$:		
E687	$2453 \pm 3 \pm 2$	$25 \pm 10 \pm 5$
E691	$2459 \pm 3 \pm 2$	$20 \pm 10 \pm 5$
ARGUS	$2455 \pm 3 \pm 5$	$15\ ^{+13+5}_{-10-10}$
CLEO 1.5	$2461 \pm 3 \pm 1$	$20\ ^{+9+9}_{-12-10}$
CLEO II	$2465 \pm 3 \pm 3$	$28\ ^{+8}_{-7} \pm 6$
$D^{**+} \to D^o\pi^+$:		
E687	$2453 \pm 3 \pm 2$	$23 \pm 9 \pm 5$
ARGUS	$2469 \pm 4 \pm 6$	27 ± 12
CLEO II	$2463 \pm 3 \pm 3$	$27\ ^{+11}_{-8} \pm 5$
$D_s^{**+} \to D^oK^+$:		
CLEO II	$2573.3\ ^{+1.7}_{-1.6} \pm 0.9$	$16\ ^{+5}_{-4} \pm 3$

Table 4: Properties of the 1^+ States

experiment	Mass (MeV/c^2)	Width (MeV/c^2)
$D^{**o} \to D^{*+}\pi^-$:		
ARGUS	$2414 \pm 2 \pm 5$	$13\ ^{+6+10}_{-6-5}$
CLEO 1.5	$2428 \pm 3 \pm 2$	$23\ ^{+8+10}_{-6-4}$
CLEO II	$2421\ ^{+1}_{-2} \pm 2$	$20\ ^{+6+3}_{-5-3}$
E687	$2422 \pm 2 \pm 2$	$15 \pm 8 \pm 4$
$D^{**+} \to D^{*o}\pi^+$:		
CLEO II	$2425 \pm 2 \pm 2$	$26\ ^{+8}_{-7} \pm 4$
$D_s^{**+} \to D^{*o}K^+$:		
ARGUS	$2535.5 \pm 0.4 \pm 1.3$	<3.9 (90%CL)
CLEO II	$2535.1 \pm 0.2 \pm 0.5$	<2.3 (90%CL)
E687	$2535.0 \pm 0.6 \pm 1.0$	<3.2 (90%CL)

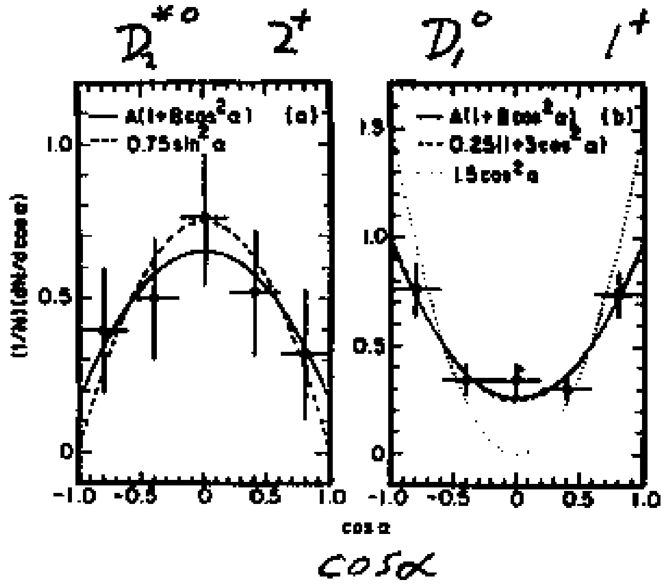


Figure 9: Angular correlation analysis for a) the $D^{*+}\pi^-$ decay of the state at 2460 and for b) the $D^{*+}\pi^-$ decay of the state at 2420

5 Prediction of Excited B meson spectra from Excited Charm Meson Spectra

Following Eichten, Quigg, and Hill [4], we write the equations for the mass difference between the ground state and excited state strange and charm mesons as:

$$
\begin{aligned}
M(2P_2)_K - M(1S)_K &= E(2P) + \frac{C(2P_2)}{m_s} \\
M(2P_1)_K - M(1S)_K &= E(2P) + \frac{C(2P_1)}{m_s} \\
M(2P_2)_D - M(1S)_D &= E(2P) + \frac{C(2P_2)}{m_c} \\
M(2P_1)_D - M(1S)_D &= E(2P) + \frac{C(2P_1)}{m_c}
\end{aligned}
$$

This leaves 5 unknowns: $E(2P)$, $C(2P_2)$, $C(2P_1)$, and m_s and m_c. The charm mass was fixed at various values and particular states were used to determine the mass splittings on the left side of the equations. This leaves four equations in four unknowns.

The parameters so determined are used to predict the $j = \frac{3}{2}$ excited B meson states. The results are given in table 5 [4]:

New data are now available on excited B mesons [7]. These may be compared to the charm states and to the model calculations to check the validity of HQS.

The significance of the B^{**}'s is that they will provide an excellent laboratory for the study of HQS and, as some have suggested [8], may provide a 'flavor tag'

Meson Family	K	D	B	D_s	B_s
M(1S)	794.3	1973.2	5313.1	2074.9	5403.0
M($2^+(\frac{3}{2})$)	1429 ± 6	2459.4 ± 2.2	5771	2561	5861
M($1^+(\frac{3}{2})$)	1270 ± 10	2424 ± 6	5759	2526	5849
M($2^+(\frac{3}{2})$)-M($1^+(\frac{3}{2})$)	159	35	12	35	12

Table 5: Masses (in MeV) predicted for the $2P(\frac{3}{2})$ levels of the B, D_s, and B_s systems. Underlined entries are Particle Data Group averages used as inputs.

for B decays that can be exploited in the search for CP asymmetries.

6 Remaining questions

While all six $j = \frac{3}{2}$ states have been identified, there are still open questions that will be addressed in future experiments: better statistics on everything; production characteristics including a study of polarization which can shed light on the hadronization process [9]; search for decays involving ρ's and η's; more accurate branching fractions and to more modes; detailed angular analysis; the 'broad' $j = \frac{1}{2}$ states; search for higher radial and orbital excitations; and detailed comparison with B^{**}'s.

Given the experimental difficulties described above, this is a challenging program of measurements. Backgrounds will have to be much better understood, perhaps by studying D^{**}'s coming from semileptonic B decays. We may expect many of these measurements will be done over the next few years.

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