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A Study of Excited States of Charmed Mesons

by

Jae-Chul Yun

A thesis submitted to the Faculty of Graduate Studies and Research in
partial fulfilment of the requirements for the degree of Doctor of Philosophy.

Department of Physics

Carleton University

Ottawa, Ontario

October 1987

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in partial fulfilment of the requirements

for the degree of Doctor of Philosophy

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Abstract

The results from a study of excited charmed mesons produced in e^+e^- annihilation are presented. The data for this analysis is taken from a 10 GeV center-of-mass energy e^+e^- experiment performed using the ARGUS detector at DESY (Deutsches Elektronen Synchrotron), Hamburg, West Germany.

Very strong evidence of a resonance was observed near 2420 MeV c^2 [1], which we call $D^{*0}(2420)$, which decays to $D^{*+}\pi^-$. The observed mass and width are (2419 ± 6) MeV/ c^2 and (41^{+22}_{-14}) MeV/ c^2 , respectively. The fragmentation function is found to be hard, as expected for a state containing a leading charm quark produced by non-resonant e^+e^- annihilation. This object is consistent with being one of the P state charmed mesons according to theoretical mass predictions. A spin parity analysis was attempted in order to constrain the quantum numbers of the object. Due to lack of statistics no decisive discrimination was possible.

Also, the decay modes ($D\pi$) were searched for in order to constrain the spin-parity of the object and the charged partner of the object was searched for in a less efficient decay mode ($D^{*+}\pi^0$). Finally the production rate was calculated.

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Chapter 1

Introduction

The prediction and discovery of the J/ψ particle [2], which is believed to be made up of a pair of charm and anti-charm quarks, confirmed the validity of the quark hypothesis. Also the quark model has been so successful in explaining hadron spectroscopy that the existence of quarks is no longer an issue. Up to now five kinds of quarks are believed to exist. The properties are shown in Table 1.1.

quark type	mass (GeV/c^2)	electrical charge
u	0.2	$2/3$
d	0.2	$-1/3$
c	1.63	$2/3$
s	0.42	$-1/3$
t	> 22	$2/3$
b	4.98	$-1/3$

Table 1.1: Quarks discovered up to now. Values for quark masses are taken from [3]. t quark is theoretically predicted but not observed yet [33].

A theoretical method of describing the quark-quark interaction is QCD (Quantum Chromo-Dynamics) which is based on the force arising from the exchange of, so called, gluons between colour charged quarks. The gluons themselves carry colour charges and they can emit and absorb more gluons. This self-interaction of gluons makes numerical calculations with QCD extremely difficult.

An empirical method of describing the quark-quark force is to look for quark-quark potentials that fit the experimental results of particle spectra. This is more easily done using the meson spectra because there are only two quarks involved. To establish the theory, a fit can be made to the mass and decay widths of experimental meson spectrum. This provides the coupling constants which show the strength of the quark-gluon and gluon-gluon interaction.

A typical potential between quarks is shown in Figure 1.1. A potential that varies as $1/r$ at small r and as $\log(r)$ or r at large r provides a good fit to radially excited states of $\Psi(c\bar{c})$ and $\Upsilon(b\bar{b})$ families.

It is always important to test models whenever new experimental information is available such as new mesons with one heavy quark and a light quark. This system is especially interesting because as the heavy quark mass increases, its motion decreases, so meson properties will be governed increasingly by the dynamics of the light quark and will approach an universal limit. The quantum numbers for a system of a heavy quark and a light anti-quark are shown in Figure 1.2.

Figure 1.1: Potential between quarks. Also shown are the distances between quarks for mesons. From reference [3].

$$J = L + S$$

$$P = (-1)^{L+1}$$

Figure 1.2: Quantum numbers for a system of a quark(Q) and an anti-quark($\bar{q}$).

Figure 1.3: e^+e^- annihilation to fermion and anti-fermions. Fermions include leptons (e, μ, τ) and quarks (u, d, c, s). The production rate is proportional to colour factors (1 for leptons, 3 for quarks) and the square of their charge.

So far only the lowest lying $L=0$ states have been discovered for charmed mesons such as $D^0(c\bar{u})$, $D^-(c\bar{d})$, $D^{*0}(c\bar{u})$, $D^{*+}(c\bar{d})$, $D_s^+(c\bar{s})$ and $D_s^{*+}(c\bar{s})$ and the charge conjugate states of these. The investigation of $L \neq 0$ states is expected to provide us with valuable information about the long range force between quarks.

Electron-positron experiments have been known as very powerful factories for producing a large amount of heavy mesons with relatively low background as compared to fixed target experiments. In e^+e^- experiments, the electron and positron annihilate into a virtual photon which can couple to a fermion-antifermion pair (spin $1/2$ particles) with a relative production rate proportional to the square of the fermion's electrical charge as shown in Figure 1.3.

For charmed meson production, the virtual photon converts to a charmed quark-antiquark pair. Then the pair fragments into hadrons by picking up

Figure 1.4: Fragmentation of primary quark. From reference 5.

u,d or s quark pairs from the vacuum as shown in Figure 1.4. During this process it is believed that a meson containing a primary quark (charm quarks in this case) retains a large portion of the momentum of the primary quark [4]. Experimentally observed momentum distributions of charmed particles such as the $D^{*+}(2010)$ confirms this concept and is described in terms of a 'hard' fragmentation function [29]. Also see section 4.3.3.

This thesis is based on an experiment which was carried out at the DESY laboratory (Deutsches Elektronen Synchrotron) using a magnetic detector known as ARGUS. The ARGUS detector is located at one of two interaction regions of the DORIS II storage ring where e^-e^- beams interact at about 10 GeV (Υ region) center of mass energy. The experiment was conducted by a multi-national collaboration of institutions from Canada, West Germany,

Russia, Sweden, U.S.A. and Yugoslavia. The ARGUS group started taking data in 1982 and has accumulated an integrated luminosity of 255 pb^{-1} by the end of 1986. This corresponds to about 2 million multi-hadronic events. The division of luminosity into various energy regions is tabulated in table 1.2.

Resonances	Energy Range (GeV)	Integrated Luminosity(pb^{-1})
$\Upsilon(1s)$	9.45 - 9.47	46
$\Upsilon(2s)$	10.01 - 10.03	38
$\Upsilon(4s)$	10.56 - 10.60	105
Continuum	near the resonances	66
Total		255

Table 1.2: Integrated luminosity taken by the ARGUS detector by the end of 1986.

The major objective of this analysis is to search for excited states of the $D(c\bar{u}, c\bar{d})$ meson and to determine their quantum numbers. Analogous to the excited states of mesons composed of a *strange* quark and lighter u or d quarks, excited charmed mesons are expected and explicit predictions for the masses of these states are shown in Table 2.1

In this analysis we observed for the first time a significant enhancement in the $D^* \pi$ mass distribution near $2420 \text{ MeV}/c^2$.¹ We interpret this enhancement as evidence for a hadronic decay of new excited D^* meson (labelled as $D^{*0}(2420)$) decaying into the $D^{*-}(2010) - \pi^-$ channel. The details of this analysis are described in chapter 4. This decay channel was

¹References in this thesis to a specific charged state are to be interpreted as implying the charge conjugate state too. Also D^* represents $D^*(2420)$ if not other wise specified.

the most promising decay chain in which to observe a new state because we can select a very clean sample of D^{*+} candidates. This enhancement is most likely due to one of, or a mixture of, the P states (angular momentum one between quarks) according to the theoretical mass predictions (Figure 2.2). To determine the spin-parity for the state, we have studied the decay angular distributions for the $D^{*+} \pi^-$ decay chain. For a consistency check we looked for a charged partner.

$$X \rightarrow D^{*-} \pi^0$$

To constrain the quantum numbers of the state we did further analysis with direct decay modes,

$$\begin{aligned} X &\rightarrow D^0 \pi^- \\ &\rightarrow D^- \pi^+ \end{aligned}$$

The plan for the rest of the thesis is as follows. Chapter 2 contains theoretical background on $q\bar{q}$ systems with emphasis on $L=1$ meson spectra. Potential models for mesons with a heavy quark and a light quark are discussed in detail. Decay properties according to the one pion emission model are discussed.

Components of the ARGUS detector are described in chapter 3. Also, the trigger set-up, data collection, data reduction and Monte-Carlo simulation of detector are discussed.

In chapter 4 a search for excited charmed mesons is described. A description of the observation of the $D^*(2420)$ which decays to $D^{*+} \pi^-$ is given. Theoretical predictions of decay angular distributions of sequential decays are reviewed and experimental results are discussed. Other possible decay

modes of $L=1$ mesons are searched for in order to provide upper limits on the production of the modes.

Finally, in chapter 5, discussions and conclusions are made on the basis of our observations.

Chapter 2

Theoretical Background

The hydrogen atom is a system consisting of an electron and a proton bound by the electromagnetic interaction. Similarly, the hadron is a system consisting of quarks bound by the strong interaction. Quarks combine in three different ways to form hadrons. Three quarks combine to form a subset of hadrons known as baryons, three anti-quarks combine to form anti-baryons and a quark can combine with an anti-quark to form a meson.

By measuring the quantum numbers for these mesons, we may constrain important theoretical parameters and broaden our knowledge about the interaction between a heavy quark and a light anti-quark.

2.1 Potential Model for an $L=1$ Meson.

The mass of a meson is determined by the masses of its two constituents (quarks) and the interaction between two quarks by gluon exchange. At zeroth order approximation the mass of a ground state meson is the sum

of two quark masses such as

$$M_0 = m_1 + m_2.$$

where the m 's are masses of quarks. Of course this is only a very crude approximation because it neglects the interaction between quarks. In the following, we draw heavily on an excellent review article by J. Rosner [6].

$Q\bar{q}$ interaction terms can be put into various categories according to their dependence on spin and angular momentum. First, the spin independent part can be written in the form

$$\Delta H^{SI} = ar - \frac{4}{3} \frac{\alpha_s(r)}{r}, \quad (2.1)$$

where a is a constant, r is the distance between quarks and α_s is the coupling constant of the strong interaction, the strength of which depends on the distance between the two quarks of the meson. This equation has a linear confinement term and a coulomb type term as shown in Figure 1.1. The coupling constant of strong interaction α_s , in lowest order QCD has the form

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f)\ln(Q^2/\Lambda^2)} \quad (2.2)$$

where Q^2 is the square of momentum transfer and N_f is the number of light quark flavours (i.e. those with masses much less than $Q/2$), and Λ is a cut-off parameter, typically 3 and 200 MeV, respectively. Figure 2.1 shows the relation between Q and α_s , [3]. The mass of the charmed meson corresponds to $Q \simeq 2$ GeV. At $Q=2$ GeV, α_s is about 0.3 and it approaches 0.2 as Q becomes very large.

Figure 2.1: Relation between Q and α_s in first order QCD with $\Lambda = 200\text{MeV}$. Dotted curve shows the α_s without saturating effect. From reference [3].

Secondly, the spin dependent part of the interaction is

$$\Delta H^{SD} = C_1 \mathbf{L} \cdot \mathbf{S}_1 + C_2 \mathbf{L} \cdot \mathbf{S}_2 + C_T (3\mathbf{S}_1 \cdot \mathbf{r} \mathbf{S}_2 \cdot \mathbf{r} - \mathbf{S}_1 \cdot \mathbf{S}_2) + C_H \mathbf{S}_1 \cdot \mathbf{S}_2 \quad (2.3)$$

where the first two terms are spin-orbit interaction terms, the third one is a tensor interaction term and the fourth is a spin-spin (or contact) interaction term. The constants are given by:

$$C_1 = \left(\frac{1}{2m_1^2} - \frac{1}{m_1 m_2} \right) \frac{4\alpha_s}{3r^3} - \frac{1}{2m_1^2} \frac{\partial H}{\partial r} \quad (2.4)$$

$$C_2 = \left(\frac{1}{2m_2^2} - \frac{1}{m_1 m_2} \right) \frac{4\alpha_s}{3r^3} - \frac{1}{2m_2^2} \frac{\partial H}{\partial r} \quad (2.5)$$

$$C_T = \frac{1}{m_1 m_2} \left(\frac{4\alpha_s}{3r^3} \right) \quad (2.6)$$

$$C_H = \frac{8\pi}{3m_1 m_2} \left(\frac{\alpha_s}{r^3} \right) \delta^3(r). \quad (2.7)$$

Because the observed resonance is most likely a P state charmed meson, we concentrate the theoretical review on the P state case only. For the L=1 case, four states are possible: a spin singlet ($J^P = 1^-$) and three spin triplets ($2^-, 1^+, 0^-$). Because the two quarks of the meson are different, charge conjugation is not conserved and therefore the two 1^- states can mix. The corresponding mass scheme is,

$$M(^3P_2) = \bar{M} - \frac{1}{10}C_T + \frac{1}{2}(C_1 + C_2) + \frac{1}{4}C_H \quad (2.8)$$

$$M \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \bar{M} + \frac{1}{2}(C_T - C_1 - C_2) + \frac{1}{4}C_H & \frac{1}{\sqrt{2}}(C_1 - C_2) \\ \frac{1}{\sqrt{2}}(C_2 - C_1) & \bar{M} - \frac{3}{4}C_H \end{pmatrix} \begin{pmatrix} ^3P_1 \\ ^1P_1 \end{pmatrix} \quad (2.9)$$

$$M(^3P_0) = \bar{M} - C_T - (C_1 + C_2) - \frac{1}{4}C_H \quad (2.10)$$

where $\bar{M}$ is the mass term of the spin independent part. The observable 1^+ mesons, α and β , are mixtures of two 1^+ states.

If the masses of two quarks in a meson are different from each other and in the limit $m_2 \rightarrow \infty$, (approximately true for the D mesons), the simplification is considerable: The terms $\bar{C}_2$, C_T and C_H becomes negligible in comparison with C_1 and the formulae become

$$M(^3P_2) = \bar{M} - \frac{1}{2}C_1 \quad (2.11)$$

$$M_{\beta}^{\alpha} = \begin{pmatrix} \bar{M} - \frac{1}{2}C_1 & \frac{1}{\sqrt{2}}C_1 \\ -\frac{1}{\sqrt{2}}C_1 & \bar{M} \end{pmatrix} \begin{matrix} ^3P_1 \\ ^1P_1 \end{matrix} \quad (2.12)$$

$$M(^3P_0) = \bar{M} - C_1 \quad (2.13)$$

where

$$C_1 \rightarrow \frac{1}{2m_1^2} \left(\frac{4\alpha_s}{3r^3} - \frac{b}{r} \right) \quad (2.14)$$

This provides us with a very simplified prediction on the mass splitting between 3P_2 and 3P_0 states for the charmed meson based on the previous experimental data on the strange mesons. Assuming that the relationship $m_2 \gg m_1$ is also true for the strange mesons and the parameter C_1 is the same for charmed and strange mesons.

$$\Delta M(^3P_2 - ^3P_0)_c \sim \Delta M(^3P_2 - ^3P_0)_s \simeq 80 \text{ MeV } C^2 \quad (2.15)$$

where the subscript shows the heavy quark content of the meson.

Because of the complex nature of mixing, a similarly simple prediction is not so easy for the α and β case. Many theoretical predictions were made with a more realistic approach. In Figure 2.2 a predicted spectra of charmed mesons ($c\bar{u}$, $c\bar{d}$) from theoretical predictions is shown. The mass of the observed resonance ($2420 \text{ MeV}/c^2$) is close to that of the P state

Figure 2.2: Mass spectra of charmed mesons ($c\bar{u}$, $c\bar{d}$) from theoretical predictions 3. Experimentally measured masses are shown as shaded region.

charmed meson. Also the radially excited state (2^1S_0) is not very far from the observed mass.

More predictions for P wave charmed mesons are shown in Table 2.1. In Table 2.1, mass predictions for most of the P state charmed mesons range from 2200 to 2500 MeV/c^2 . The magnitude of the splitting is about 100 to 150 MeV/c^2 for each reference. All of the predictions in the table show the 2^+ state as the highest mass state and 0^+ state as lowest mass states.

State($^{2S+1}L_J$)	Ref [7]	Ref [8]	Ref [9]	Ref [3]	Ref [10]
3P_2	2.294	2.41	2.511	2.50	2.407
3P_1	2.246	2.35	2.503 [†]	2.49 [†]	2.380
1P_1	2.205	2.43	2.364 [†]	2.44 [†]	2.347
3P_0	2.125	2.29	2.354	2.40	2.252

Table 2.1: Some predictions for masses of P-wave charmed mesons from references [3, 7, 8, 9, 10] in GeV/c^2 . [†]: Mass prediction of mixed states.

2.2 Decay Width of a Charmed Meson

Although the measurement of decay width is less accurate than the measurement of mass, decay width investigation could provide us with valuable information for a spin-parity analysis of the particle. One of the decay models we want to discuss is the single pion emission model because it may provide us with some insight on the decay width. The width is given by [6]

$$\Gamma(M^* \rightarrow M\pi) = \frac{p_\pi^3}{M^*} C^2 \sqrt{E_\pi E_M} A^2 \quad (2.16)$$

where M^* is a vector meson, M is a pseudoscalar meson, and E_π and E_M are the energies of the π and M in the M^* center of mass system. C is a Clebsch-Gordan coefficient and A is an amplitude taken common to $D^* \rightarrow D\pi$ and $K^* \rightarrow K\pi$ decay. p_π is the momentum of the π in the M^* rest frame.

This is further simplified for the case of $M^* \simeq E_M$:

$$\Gamma(M^* \rightarrow M\pi) \propto E_\pi p_\pi^3. \quad (2.17)$$

One can test this single pion emission model by comparing the widths for

$\Gamma(K^*(890) \rightarrow K\pi)$ and $\Gamma(D^*(2010) \rightarrow D\pi)$ with the experimental inputs:

$$m(K^0) = 498 \text{ MeV}$$

$$m(K^{*-}) = 892 \text{ MeV}$$

$$\Gamma(K^{*-}) \sim 51 \text{ MeV}$$

$$m(D^0) = 1865 \text{ MeV}$$

$$m(D^{*-}) = 2010 \text{ MeV}$$

We find $\Gamma(D^*(2010)) \sim 0.1 \text{ MeV}$ by comparing with the strange meson system, where for the $D^*(2010)$ case $p_\pi \ll m_\pi$. This is roughly consistent with experimental data.

Formula 2.17 is not exactly the same for P wave meson decays, where the meson emitting a pion can either change its orbital angular momentum projection L_z along the π direction by ± 1 unit or leave it unchanged. The early description of pion emission in the quark model only made use of this latter $\Delta L_z = 0$ term through an effective operator of the form $\sigma \cdot \mathbf{p}_\pi$. Thus in decays of

$$(Q\bar{q})_{L=1} \rightarrow (Q\bar{q})_{L=0} + \pi \quad (2.18)$$

the π and final $L=0$ $Q\bar{q}$ meson can be in a relative S wave or a relative D wave state. The resulting decay amplitudes for P-wave mesons containing one heavy quark are expressed in Table 2.2 in terms of two free parameters, S and D , corresponding to S- and D- wave decays where S and D means that the angular momentum between $Q\bar{q}$ meson and π are 0 and 2, respectively. A theoretical prediction from reference [11] for the case of $D^*(2420) \rightarrow D^*(2010)\pi$ is that

$$D \simeq 0.25 (GeV^{1/2})$$

$$S \simeq 0.7 \text{ (GeV}^{1/2}\text{)}.$$

From Table 2.2, the ratio of decay widths of $D(^3P_2)$ to $D^*\pi$ and $D\pi$, neglecting kinematic factors, is given by:

$$\frac{\hat{\Gamma}(^3P_2 \rightarrow D\pi)}{\hat{\Gamma}(^3P_2 \rightarrow D^*\pi)} = \frac{2}{3} \quad (2.19)$$

Kinematic factors are calculated by 11 and 16 with observed mass (2420 MeV/c²). Decay widths are shown in Table 2.3 and the ratio becomes about 1.5 ~ 3.5 when including kinematic factors.

Decay Mode	Decay Width
$\hat{\Gamma}(^3P_2 \rightarrow ^3S_1 + \pi) =$	$\frac{3}{10}D^2$
$\hat{\Gamma}(^3P_2 \rightarrow ^1S_0 + \pi) =$	$\frac{1}{5}D^2$
$\hat{\Gamma}(^1P_1 \rightarrow ^3S_1 + \pi) =$	$\frac{1}{6}(S^2 - 2D^2)$
$\hat{\Gamma}(^3P_1 \rightarrow ^3S_1 + \pi) =$	$\frac{1}{6}(2S^2 - D^2)$
$\hat{\Gamma}(^3P_0 \rightarrow ^1S_0 + \pi) =$	$\frac{1}{2}S^2$

Table 2.2: Decay width prediction in terms of angular momentum. From 6.

Some predictions on the width of P-wave mesons are in Table 2.3. The result of reference [11] is from the pseudoscalar emission model and it shows the width for a mixture of two 1^- states.

In this chapter we reviewed the theoretical predictions on charmed meson properties, with emphasis on the L=1 meson. Predictions on the mass and width for L=1 charmed meson states still vary largely with the theoretical models.

Decay mode	Decay width from 11 (MeV c ²)	Decay width from 6 (MeV/c ²)
$D^*(^3P_2) \rightarrow D^*\pi$	12	14.6
$\rightarrow D\pi$	43	22.3
$D^*(^3P_1) \rightarrow (D^*\pi)_D$	-	24.3
$D^*(\alpha) \rightarrow (D^*\pi)_S$	250	-
$(D^*\pi)_D$	0.18	-
$D^*(\beta) \rightarrow (D^*\pi)_S$	2.3	-
$\rightarrow (D^*\pi)_D$	19	-

Table 2.3: Decay width prediction from 11 and 6.

Chapter 3

Experimental Procedure

The ARGUS detector is a device for investigating high energy particle physics reactions. It is situated at one of two interaction regions of the DORIS II storage ring where e^+e^- beams interact at about 10 GeV center of mass energy. By measuring the properties of secondary particles which are produced from an e^+e^- interaction, it is possible to reconstruct the underlying physics.

To select events of interest ARGUS employs two levels of trigger. If an event passes both levels, the data is then transferred to an IBM computer and stored on magnetic tape. Multi-hadronic events are selected by requiring at least three charged tracks from the interaction point. Reconstructed events are stored on magnetic tape in compact form for physics analysis.

3.1 Experimental Apparatus

In the presence of the 0.8 Tesla magnetic field which was provided by the magnetic coil, particles move along helical paths. A measurement of the track parameters from the vertex chamber and main drift chamber allows the momentum of the particle to be calculated in event reconstruction.

Charged particles are identified by energy loss measurement (dE/dX) in the main drift chamber and by velocity measurement from TOF counters in conjunction with the momentum measurement in the main drift chamber.

The ARGUS electromagnetic shower counters identify photons and help identify electrons and muons. Electrons are identified by measuring shower shape. Muons are identified by requiring minimum ionization energy loss in the shower counters and hit in the muon chambers which is possible only after the particle passes through a large amount of material.

3.1.1 DORIS II Storage Ring

The ARGUS experiment uses the DORIS II storage ring [12] to provide 5 GeV e^+e^- beams. Originally the DORIS storage ring was designed for a maximum beam energy of 3.5 GeV and was built in the form of two concentric superimposed rings during the late 1960's. In the summer of 1977, shortly after the discovery of the Υ meson at FNAL (Fermi National Accelerator Laboratory) [13], a proposal was made to increase the C.M. (Center of Mass) energy to study the Υ meson. During modification the two upper

Figure 3.1: A schematic diagram of the DORIS II storage ring.

half rings had to be combined into a single ring facility operating with only one bunch in head-on collision. Currently it provides typically $1. pb^{-1}$ of integrated luminosity per day. The beam current starts with around $40 \mu A$ for each beam and the beam decay time is about 1 hour. Figure 3.1 shows a schematic diagram for the DORIS II storage ring.

3.1.2 Drift Chamber

The main drift chamber [14] is one of most important components in this experiment. It provides momentum and dE/dX [15] information for charged particle tracks. It is also used in the trigger processing sequence to reduce background.

There are 5940 identical drift cells arranged in one volume to minimize multiple scattering and to provide many measurements of position along

Figure 3.2: Cross-section of the ARGUS Detector. (1) Muon chambers, (2) Shower counters, (3) Time-of-flight counters, (4) Drift chamber, (5) Vertex chamber, (6) Iron yoke, (7) Magnetic coils, (8) Compensation coils, (9) Mini-beta quadrupoles, (10) Beam pipe. N.B. All components are cylindrically symmetric around the beam pipe except for the iron yoke and muon chambers.

Figure 3.3: A drift cell of the drift chamber.

the track of the particle. The drift cells are designed to produce isochrons as circular as possible so as to minimize software corrections for angled tracks. The pattern of drift cells is shown in Figure 3.3. There are about 10 neighbouring potential wires for each sense wire and the shape of a drift cell is approximately square (18.8 x 18 mm).

The drift cells are organized in 36 layers, 18 of which provide stereo views for axial coordinate measurement. The stereo angle sequence is 0° , $+\alpha^\circ$, 0° , $-\alpha^\circ$ and so on. The stereo angle (α) increases gradually from 40 mrad inside to 80 mrad outside. This method gives substantially better resolution for the z coordinate than the charge division method, demands less electronics and does not require high gas amplification, which might disturb the dE/dX measurement because of the saturation effect.

The chamber cross-section is shown in Figure 3.2. The mechanical structure of the chamber consists of a 3.3 mm thick carbon-fibre epoxy composite inner cylindrical wall and 6 mm aluminium outer cylindrical wall fixed to the 30 mm thick aluminium end-plates. Inner and outer wall diameters are 30 cm and 172 cm and the length is 2 m. The 5940 sense wires of 30 μm diameter gold plated tungsten are strung through plastic feed-throughs inserted in precisely drilled holes in the end plate and crimped. The 24588 potential wires are made of 76 μm diameter beryllium-copper wire and fixed directly on the end plates. The amount of material in the chamber is only 0.55 % of a radiation length. The sense and potential wires are strung with tensions of 70 and 110 grams, respectively.

The chamber was operated with a 97 % propane and 3 % methylal gas mixture. Propane has a very long radiation length and small diffusion thus providing a good momentum resolution. Also propane has a very narrow Landau distribution and hence much better dE/dX resolution than the usually used argon. Methylal was added to reduce the ageing effect by a charge exchange mechanism. The chamber was operated with a slight over-pressure to ensure minimum gas contamination and good gas circulation.

The high voltage distribution is highly segmented to prevent any kind of catastrophic event. There are 157 groups of wires with separate H.V. systems equipped with over-current protection devices.

Preamplifiers are mounted directly on the chamber to minimize noise. Lecroy 4290, 9 bit TDC and Lecroy 2280 ADC systems are used in the read-out electronics. The electronics are calibrated with test pulses delivered to

Figure 3.4: A 12 prong event with a back-scattered particle.

each preamplifier. The gas amplification is monitored by 4 movable Fe^{55} radioactive sources.

Figure 3.4 shows a typical event display. This shows that the chamber works well for a high multiplicity event. The diameter of the circles represent the drift distances from the sense wire. Only axial wires hits are displayed here.

Resolution depends on various factors such as gas mixture stability and background. Relative amplification variation is found to be around 5 %. Spatial resolution(σ) for the chamber is found to be about 170 μm . The typical momentum resolution is

$$\frac{\Delta p}{p} = \sqrt{(0.01 \cdot p)^2 + (0.01)^2}, \quad p \text{ in GeV}/c \quad (3.1)$$

The second term comes from multiple scattering and it is important for lower momentum tracks.

3.1.3 Muon Chamber

The muon chambers [16] are designed to detect muons which penetrate the absorbers comprised of shower counters, copper coils and the iron flux return yoke of the magnet. Almost all other particles are absorbed by these materials because of higher interaction strength. The ARGUS detector is equipped with three layers of muon chambers(Figure 3.2). One layer of muon chambers is inside of the iron yoke and provided with absorption materials of 3.3 absorption lengths from the interaction point and covers 43% of the solid-angle. The two layers of the chambers which are laid

outside of iron yoke (1.8 absorption lengths) are placed orthogonal to each other and cover 87% of the full solid angle.

There are 218 muon chambers (1744 counters) of different sizes. A single chamber consists of eight proportional counters glued together and welded to aluminium plates at both ends. Inside the end-plate there is a high voltage power supply board, a preamplifier connector, and a gas inlet and outlet. Chamber size was determined by the location of the chamber. The length varies from 1 to 4 meters.

Each counter was made of extruded square aluminium tubing with an inner dimension of $56 \times 56 \text{ mm}^2$ and wall thickness of 2 mm. A $50 \mu\text{m}$ gold plated tungsten wire stretched with a tension of about 150 grams was positioned at the center of the tube with an accuracy of $\pm 0.3 \text{ mm}$. The wire was crimped into a thin brass tube which was glued with epoxy in the center of a plastic end-cap with a gas inlet. These caps were glued into the aluminium tubes with silicon rubber thus providing gas-tight volumes for each counter.

To minimize the background it is preferable to use a gas with a high drift velocity. The nonflammable gas mixture (92% Ar - 8% CH_4) was chosen primarily for safety reasons. The muon chambers operate at atmospheric pressure and at high voltage of 2.35 kV.

3.1.4 Shower Counters

The ARGUS electromagnetic shower counters [17] measure the total energy of the shower initiated by electrons and photons. It also acts as a hadron absorber of 0.8 absorption length. This information is used in the fast trigger.

The shower counter system consists of three components (Figure 3.2-2): a cylindrical portion and two end-caps. The shower counters which surround the outer cylindrical shell of the main drift chamber are called barrel shower counters. There is a total of 1280 barrel shower counters. The counters which cover the end plates of main drift chamber are called end-cap shower counters. There is a total of 240 shower counters per end-cap.

The ARGUS shower counters are of the lead scintillator sandwich type with 5 mm thick scintillator plates. The thickness of the lead plates is 1 mm in the barrel, and 1.5 mm in the end cap region. The overall length of each counter corresponds to $12\frac{1}{2}$ radiation lengths for electrons and photons and 0.8 nuclear absorption lengths for hadrons. The lead and scintillator plates are separated by aluminized mylar foils. The lead scintillator sandwich is read-out by a 3 mm thick wavelength shifter coupled to an 1 inch photomultiplier tube.

The shower counters are mounted inside of the magnetic coil. This provides a great advantage in resolution compared to other experiments which usually have shower counters outside of the coil.

Barrel counters consist of 64 plates of each material with 10.9 cm x 10.3 cm lateral cross section. The end cap counters contain 45 plates of each material of trapezoidal shape with maximum lateral dimensions of 11.6 cm and 10.4 cm.

The cylindrical arrangement of the barrel counters (Figure 3.2) results in a variation of the angle of incidence between 0° and 45° for particles coming from the interaction point. The end cap counters are arranged in a plane perpendicular to the beam direction. Incident angle between counters and the particle direction varies between 20° and 45° .

Energy resolution for photons of energy E is on average

$$\frac{\sigma_E}{E} = \sqrt{\frac{(0.065)^2}{E(\text{GeV})} + (0.072)^2} \approx 10\% \text{ at } 1\text{GeV} \quad (3.2)$$

where E is measured in GeV. The angular resolution is 0.7° for electrons with momenta greater than 1 GeV/c. Further details concerning the construction and properties of shower counters are described in reference [17].

3.1.5 Time-of-Flight Counters

The time-of-flight (TOF) system [18] measures the velocity of particles and together with drift chamber information is used in particle identification. In addition, the time-of-flight information is used in trigger processing. The ARGUS time-of-flight system consist of 64 scintillation counters forming a barrel around the outer cylindrical shell of the main drift chamber, plus 2 x 48 end cap counters covering the forward/backward region. The cross-section of TOF counters is shown in Figure 3.2

The counter system covers 92% of 4π (75% for the barrel region and 17% for the end-cap region). The 64 barrel counters are viewed by a photomultiplier tube at each end of each counter. The end-cap counters are viewed by only one photomultiplier tube because of their shape. Measurements at both ends of the barrel counters provide a substantial improvement in resolution compared to measurement at only one end. The signals from the photomultipliers are split up in the following way: 80% of the signal is used to trigger a discriminator where a logical pulse serves as the time reference, while 20% of the pulse is fed into an ADC. This information is used to correct for time-walk fluctuation, which is caused by pulse height fluctuation into fixed threshold electronics. The resolution achieved is 230 psec for barrel counters.

3.1.6 Vertex Chamber

The major role of the vertex chamber [19] is to provide a good vertex position and improve the overall momentum resolution for charged tracks in conjunction with main drift chamber. No attempt is made to provide dE dX measurement or z coordinate information.

It covers almost all of the solid angle (95%) and is about 1 m in length. The two cylindrical shells (inner and outer) are glued to the end plates where specially made feed throughs are accurately positioned. The inner and outer shells have diameters of 8 cm and 28 cm, respectively. To minimize multiple scattering the cylindrical shells are made of carbon fiber epoxy composite. Thickness of inner and outer shells are only 0.9 mm and 1.5

Figure 3.5: Wire pattern of 1/12 of the vertex chamber.

mm, respectively.

The vertex chamber has 594 sense wires made of gold plated tungsten wire a $20\mu\text{m}$ in diameter. Each drift cell has a hexagonal geometry with 6 field wires around a sense wire. The pattern of drift cells is shown in Figure 3.5. The 1412 field wires are made of $127\mu\text{m}$ diameter beryllium copper. The vertex chamber started taking useful data in September 1984. It operates with pure CO_2 gas with a small amount of water vapor which is believed to reduce ageing effects. For the ARGUS vertex chamber the more common argon gas mixtures were not used due to the large synchrotron radiation background. We also tried to avoid hydrocarbon gas mixtures because they are susceptible to radiation damage. To improve spatial resolution the chamber operates at 1.5 atmospheric pressure (absolute) at a high voltage of 3.5 kV. Spatial resolution was about $50\mu\text{m}$ for about a third of the drift region for Bhabha electrons. It has substantially

improved the momentum resolution for high momentum tracks. It has also improved vertex resolution and made life time measurements of the τ meson and charmed mesons possible. Furthermore detection efficiency is improved for long lived particles (K_S^0 , Λ) with the same signal to background ratio by allowing a loose vertex cut.

3.1.7 Other Components

There are other components which perform rather simple tasks as follows.

- There is 1 mm thick aluminum beam pipe with diameter of 8 cm. It must withstand a very high vacuum (pressure $\approx 10^{-11}$ bar).
- The magnetic coil provides 0.8 Tesla magnetic field [20].
- The compensation coils compensate the magnetic field generated by the main magnetic coil so that $\int \mathbf{B} \cdot d\mathbf{l}$ is zero for each e^+e^- beam.
- The iron yoke returns the magnetic flux and also provides 1.8 absorption lengths of material as a muon filter.
- The mini-beta quadrupoles act to focus the beam size down to typically $500 \mu\text{m}$ (horizontal) $\times$ $100 \mu\text{m}$ (vertical) at the interaction point.

For an overall view of the design criteria for the ARGUS detector, see reference [21].

3.2 Data Acquisition

3.2.1 Trigger

To increase the fraction of interesting events recorded, we need a trigger to select events. ARGUS has two levels of triggers [22]. The first one is a very fast trigger (Pre-trigger) using information from TOF, shower counters and the beam crossing signal and it takes about 300 nsec. Digitization of data starts with a fast trigger. The second level (Little-Track-Finder [23]) reduces the trigger rate further by using particle track information from the drift chamber. It takes about 100 μ sec and decides whether to record or throw out an event.

There are 3 different kinds of pre-trigger elements from which 4 pre-triggers are formed. These are defined by:

1. ETOT (Total Energy) - element;

The sum of deposited energy in each of the two shower counter sub-groups should be greater than 750 MeV. The two sub-groups are defined by barrel and end-cap counters for each $+z$ and $-z$ hemisphere.

2. HESH (High Energy Shower) - element:

The sum of deposited energy for any shower counter sub-groups should be greater than 1 GeV. There are 16 subgroups, 2 (in z) $\times$ 8 (in ϕ), for barrel counters. Only barrel counters are used for this trigger.

3. CPPT (Charged Particle Pre-trigger) - element;

The sum of deposited energy for any shower counter sub-groups should be greater than 80 MeV. There are 32 subgroups, $2(\text{in } z) \times 16(\text{in } \phi)$, for barrel counters. Only barrel counters are used for this trigger. Later this information must coincide with an adjacent T-O-F counter which gives a signal for a charged track.

Logical connections of these elements form the following four pre-triggers.

1. ETOT ; two ETOT elements from each of $+z$ and $-z$.
2. HESH ; one HESH element.
3. CPPT ; two CPPT elements from each of $+z$ and $-z$.
4. CMT (Coincidence Matrix Trigger) ; two CPPT elements with minimum angular difference of $5/16 \times 2\pi$ between them in azimuthal angle ϕ .

A pre-trigger signal triggers the digitization process with the beam crossing signal from DORIS II.

The Little-Track-Finder is a fixed cable parallel processor, with programmed masks which are compared with the hit pattern of charged particle tracks in the main drift chamber. If the number of masks (or tracks) found are more than some specified threshold, digitization continues and the event is read-out. This threshold value is dependent on the pre-trigger class and background.

3.2.2 Data Transfer

The whole CAMAC system is controlled by a PDP-11/45. The data is then transferred to a VAX/11/780 which packs the data and sends it to an IBM at the DESY computer center to store on magnetic tape. The VAX does the very first filtering of data and provides online monitoring of data and detector components.

3.3 Event Reconstruction

3.3.1 Track Reconstruction

Event reconstruction starts with pattern recognition in the main drift chamber. This is based on z-wire hits in the r - ϕ plane. According to the calibration of the time-to-distance relation, the drift distance around the corresponding hit wire is calculated. The track finding process starts from the outer part of the chamber and proceeds inward. Each track candidate provides 3 track parameters: curvature and direction in r - ϕ plane. Track candidates with too few wire hits or too large curvature are thrown out. Using α wire (stereo wire) hits for the track, the z coordinate is found later.

A χ^2 fit is made on tracks to provide the basic track parameters and errors. In the fit, the following points were taken into account:

- Probable errors of wire hits
- Magnetic field map

Figure 3.6: Geometrical conventions for charged tracks.

- Energy loss of the particle in material
- Multiple scattering in material

Output parameters and errors are listed below:

- ρ : radius
- $\cot\theta_0$: cotangent of polar angle (θ_0 is the angle between track direction and nominal drift chamber axis along the e^+ beam direction)
- ϕ_0 : azimuthal angle of the track (ϕ_0 is the angle between track direction and the x-axis, where the x-axis is in the horizontal plane which includes the z-axis and is normal to the z-axis)

- D, z : track position at closest approach to z-axis. ¹

The complete covariance matrix is determined and stored. Average track reconstruction efficiency is typically 98% within the geometrical acceptance.

3.3.2 Particle Identification

Particle identification with dE/dX

The energy loss is measured using the analog to digital converters (ADC's) connected to each sense wire in the main drift chamber. For each track the ADC values are arranged in increasing order. A mean of all ADC values, except for the lower 10 % and upper 30 %, is calculated. This is called a 'truncated mean' and is a close approximation of the peak of the energy loss distribution.

The mean value is compared to the theoretical value for each e, μ, π, K and p hypothesis and the results are stored in the form of χ^2 .

$$\chi_i^2 = \frac{(dE/dX_i^{trunc} - dE/dX_i^{theo})^2}{\sigma^2} \quad (3.3)$$

where $i=e, \mu, \pi, K$ and p and the value of σ is found from dE/dX distributions of data and depends on the experimental conditions. The relative resolution σ_{rel} is found to be around 5 %. A scatter plot of dE/dX versus momentum is shown in Figure 3.7.

¹D is distance from the z-axis to the track at the closest approach (x_0, y_0) to origin in x-y plane. z is z-value at the (x_0, y_0) on the track. Figure 3.6 shows the schematic diagram for the geometric conventions.

Figure 3.7: A scatter plot of dE/dX versus $\log(p)$ in the ARGUS drift chamber. The bands attributed to e , π , K and p are indicated.

Figure 3.8: A scatter plot of $(\text{mass})^2$ versus $\log(p)$ obtained using the ARGUS TOF system. The bands for e , π , K and p are indicated.

Particle Identification with TOF Counter

Particle identification from the TOF counters is achieved by measuring the velocity of the charged particle which passes through the TOF counters. The track length L and measured flight time T are used to calculate the velocity β of the charged particle.

$$\beta = L/cT$$

$$p = m\beta\gamma$$

and then

$$m^2 = p^2 (T^2 c^2 / L^2) - 1$$

where p is determined from the track curvature in the drift chamber. The square of the mass is calculated and compared with theoretical values for each e, μ, π, K and p hypothesis and the results are stored in the form of a χ^2 .

The scatter plot of square of mass vs. logarithm of momentum of particles is shown in Figure 3.8. In the figure, low momentum π 's, K 's and p 's are well separated.

Particle separation with both dE/dX and TOF measurement

For particle identification, we have used both the specific ionisation measurements in the drift chamber (dE/dX) and time-of-flight (TOF) information. For each track in an event, the probability for each mass hypothesis is:

$$P_i = \frac{f_i (e^{-\chi_i^2/2})_{dE/dX} (e^{-\chi_i^2/2})_{TOF}}{\sum_j f_j (e^{-\chi_j^2/2})_{dE/dX} (e^{-\chi_j^2/2})_{TOF}} \quad (3.4)$$

$$(3.5)$$

$$i, j = e, \mu, \pi, K, p, \quad f_e = 5, \quad f_e + f_\mu + f_K + f_p = 1$$

where the f_i are relative production abundances.

Combining the dE/dX and TOF measurements, a particle separation of 3 standard deviations is possible for

- e/π separation for $p < 180 \text{ MeV}/c$
- π/K separation for $p < 750 \text{ MeV}/c$
- K/p separation for $p < 1150 \text{ MeV}/c$

for the charged particles with $p_T > 110 \text{ MeV}/c$.

Muon Identification

For muon identification, shower counter analysis is necessary. The shower energy deposited in the shower counters should be consistent with a minimum ionizing particle. Also the influence of multiple scattering on the track is calculated. For a hit in the muon chamber plane, the closest distance to the extrapolated drift chamber track is calculated and stored in the form of χ^2 using the calculated errors.

Muons are well identified for a track with momentum above $700 \text{ MeV}/c$ in the inner muon chamber and $1100 \text{ MeV}/c$ in the outer muon chamber.

Shower Counter Analysis

The shower counters require frequent calibration during data taking. This was done with electrons from Bhabha interactions ($e^+e^- \rightarrow e^+e^-$) for long term variation. For short term variation it was done with a laser monitoring system. In reconstruction, ADC-values are calibrated and the hit clusters of nearby counters are sorted. Then a correlation between a cluster and a track in the main drift chamber is sought. If a correlation is not found, then the cluster is assumed to be caused by a photon.

Some shower energy loss occurs in the lead slabs and from longitudinal leakage (12.5 Radiation length in the shower counter). Corrections are made on the output value according to complex local geometry and other corrections such as θ dependence and longitudinal leakage.

Information of cluster size, counter number, energy loss and energy deposited for a shower are stored. Cluster size measurement helps in distinguishing electrons from other charged particles because incident hadrons produce a much larger cluster size than electrons with the same momentum.

3.3.3 Vertex Fit

Tracks found are extrapolated backward to the interaction point. At the same time recalculation is done on the track parameters and the covariance matrix to correct for energy loss using the most probable particle-hypothesis from dE/dX information.

A secondary vertex is found by requiring a combination of tracks whose

combined momentum points towards the main vertex. Also the tracks used in this combination must have a very small probability of coming from the main vertex. Candidates for $K_S^0 \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p \pi^-$ and $\gamma \rightarrow e^+ e^-$ vertices are specially searched for and stored in the data bank.

3.3.4 Data Bank Structure

Raw data and reconstructed data results for each event are stored in a data bank. These include basic general information about the event which is stored in the Header. These contents of the Header are:

1. length of bank structure and pointer
2. experiment, run and event number
3. CMS energy
4. trigger information
5. number of tracks
6. number of photons
7. number of secondary vertices.

These vertices are provided with fit results (coordinates, a covariance matrix, etc.) and information about the charged tracks which belong to the vertex.

For charged tracks, the track bank includes:

1. At the point which is closest to main vertex:

D, z, $1/p_T$, $\cos\theta$, ϕ and their covariance matrix and the probability that the track belongs to the main vertex in terms of χ^2 .

2

2. For the beginning and end points of the track in the drift chamber:

x, y, z, $1/p_T$, $\cos\theta$, ϕ and their covariance matrix and χ^2 probability of track fits.

3. Shower energy information:

4. Time of flight information:

Track length up to counter, flight time and variance of flight time, counter number and χ^2 for each particle hypothesis.

5. dE/dX information:

Number of wires hit, average energy loss, standard deviation of average and χ^2 for each charged particle hypothesis.

6. Muon chamber information:

Position, track length in material and χ^2 for the position.

For photons the shower direction and energy deposited and its error are stored. For neutral secondary vertex candidates the vertex fit information and likelihood for different hypothesis (K_S^0 , Λ , γ) are provided.

² p_T is a transverse momentum of the track

3.4 Data Reduction

In raw data reconstruction, events which are not interesting are rejected. The criteria for the quick process of reconstruction requires a minimum of 2 charged tracks from interaction point. This removes almost all beam-wall (an e^- or an e^+ hits the wall of the beam pipe) interactions which are not possible to remove with trigger selection. Beam-wall interaction is the major background for ARGUS raw data. Also, events with very high energy deposition in shower counters are saved. With these cuts the number of events recorded is reduced by large factor.

For the selection of multi-hadronic event candidates three charged tracks from the interaction point are required. This yields an additional large reduction factor. In this way almost all Bhabha events are rejected. These multihadronic event candidates still contain 20 to 30 % background events. This background consist of:

1. radiative Bhabha events with converted photons
2. events from τ -pair production
3. events from photon-photon interaction with hadronic final states
4. beam-gas interaction
5. beam-wall interaction
6. cosmic ray events.

3.5 Luminosity Determination

In the ARGUS experiment luminosity is determined from Bhabha scattering [24]. This reaction is theoretically calculable and the luminosity is determined by a Monte-Carlo simulation of detector. Luminosity is determined through Bhabha events in an angular range of shower counters in the barrel region only. Here also there are small uncertainties in the detector Monte-Carlo simulation. The visible effective cross section for Bhabha interaction is 11.8 nb near 10 GeV CMS energy. The systematic error in integrated luminosity is estimated to be 5%.

3.6 Monte-Carlo Simulation of Detector

The ARGUS experiment has a detector simulation program, SIMARG (SIMulation of the ARGUS detector) [25], which is based on the general CERN program GEANT (Generation of Events AND Tracks) [26]. SIMARG performs the following tasks:

1. Reads or generates the kinematics of an event.
2. Tracks particles through the detector until they stop or leave the detector fiducial limits and records the energy deposited in the shower counters and TOF as well as coordinates along the track.
3. Uses the track coordinates to intersect tracks with the various detectors and stores the resulting points.

4. Calculates wire hits in the vertex chamber, main drift chamber and muon chambers and their respective TDC values. For the main drift chamber ADC values are also found.
5. Creates an event record with the same format as a real data record.

The output event records are processed by the reconstruction program in the same way as real data are processed and are packed into a dense event record. The same analysis program is used in the analysis of Monte-Carlo events as in real events.

In this chapter, we described the ARGUS detector in detail. Generally speaking, ARGUS is very efficient and accurate detector for high energy e^+e^- experiment. For the excited charmed meson search, its excellent particle identification capability was very important in reducing combinatorial background. Also the large solid angle coverage of the drift chambers provided high efficiency in tracking charged particles. With highly developed software support, ARGUS has produced numerous high quality physics results.

Chapter 4

Observation and Analysis of the $D^*(2420)$ Meson

The subject of this thesis is the study of excited charmed mesons in a 10 GeV e^+e^- experiment. In chapter 2, theoretical predictions for excited charmed mesons were described. In chapter 3, the ARGUS detector and the data handling process for this experiment were described.

Excited charmed mesons ($c\bar{u}$, $c\bar{d}$) are expected to be produced with non-zero angular momentum or the radial quantum number of the two quarks in the meson. The excited state charmed mesons decay hadronically to lower state charmed mesons (D, D^*) by emitting π 's.

This chapter describes the search for excited charmed mesons which decay to $D\pi$ and $D^*\pi$. We observed strong evidence of a new charmed meson in the $D^{*+}\pi^-$ decay mode. The fragmentation function is found to be hard, as expected for a state containing a leading charmed quark. To determine the spin and parity of the object we studied decay angular

distributions.

Direct decay modes ($D\pi$) were searched for in order to constrain the spin-parity of the object. The charged partner of the object was searched for in a less efficient decay mode ($D^{*-}\pi^0$).

4.1 Inclusive D meson production from continuum

To study the excited charmed ($c\bar{u}$, $c\bar{d}$) meson system, the well established $L=0$ charmed mesons (D , D^*) are exploited. Excited charmed mesons will primarily decay strongly to lower level (in this analysis, $L=0$) charmed mesons because the c quark decays only weakly.

The most effective decay channels for D mesons are chosen for this analysis on the basis of branching ratio and detection efficiency.

D^0	$\rightarrow K^-\pi^+$	(Br=5.4 %)	—	CHANNEL I
	$\rightarrow K^-\pi^+\pi^+\pi^-$	(Br=10.9 %)	—	CHANNEL II
	$\rightarrow K^-\pi^+(\pi^0)$	(Br=17.3 %)	—	CHANNEL III ¹
D^-	$\rightarrow K^-\pi^+\pi^-$	(Br=11.4 %)	—	CHANNEL IV

A track is considered a candidate for the mass hypothesis which has a probability greater than 5% (details are in section 3.3.2). Candidates with more than one mass hypothesis enter into several mass combinations with equal weight. Loss of efficiency due to the probability cut is negligible, while it significantly reduces the number of fake K's which are actual π 's

¹ π^0 is not measured for this channel.

mimicking as K 's.

There are two major intrinsic inefficiencies due to detector acceptance. Angular acceptance for charged tracks is roughly $|\cos\theta| < 0.92$, where θ is defined by the angle between the beam axis and the track. The p_T cut off due to the pattern recognition limit for high curvature (low momentum) tracks is 50 MeV/c.

Figure 4.1 shows the three invariant mass plots for decay channels I, II and IV, without further cuts. These plots are based on 0.8 million multi-hadronic events (40 % of the full data available at the moment).

Evidence for the decay channels I, II and IV are clear, but they are sitting on top of enormous combinatorial backgrounds. This situation can be improved by applying a momentum cut. The main reason for this improvement of signal to background ratio is understood by the theoretical expectation [4] that the primary quarks (which are those produced first in e^+e^- annihilation) must carry a large fraction of the momentum available. This assumption is verified by experimental results on charmed particle fragmentation (for example, see reference [29]).

For the plots in the Figure 4.2, a relative momentum cut ($x_p > 0.5$) was made for the previous plots, where x_p is defined by

$$x_p = \frac{p}{\sqrt{E_{beam}^2 - M^2}}$$

where p and M are the momentum and mass of the particle combination, and E_{beam} is the energy of e^+ or e^- beam. Mass resolutions (σ_M) are found

Figure 4.1: Invariant mass-distribution for D decays. 1) for $D^0 \rightarrow K^- \pi^+$, 2) for $D^+ \rightarrow K^- \pi^+ \pi^+$, 3) for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$.

Figure 4.2: Invariant mass distribution for D decays. 1) for $D^0 \rightarrow K^- \pi^+$ ($x_p > 0.5$), 2) for $D^+ \rightarrow K^- \pi^+ \pi^+$ ($x_p > 0.5$), 3) for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ ($x_p > 0.5$).

to be about $25 \text{ MeV}/c^2$ for channel I, $15 \text{ MeV}/c^2$ for channel II and $20 \text{ MeV}/c^2$ for channel IV. For the $K^- \pi^+$ (I) and $K^- \pi^+ \pi^-$ (IV) channels, there appear small signals with large background but for $K^- \pi^+ \pi^+ \pi^-$ (II), the signal to background ratio is much worse. A low signal to background ratio hampers the analysis of excited charmed mesons which decay directly to $D \pi$.

4.2 D^{*-} Signal

There is a powerful, well known method of tagging charmed mesons by exploiting the very low Q value of the D^{*-} decay to $D^0 \pi^+$ (5.9 MeV). This provides an excellent resolution for the mass difference ($\Delta = M[D^0 \pi^+] - M[D^0]$), $\sigma_\Delta \simeq 1 \text{ MeV}/c^2$, and hence an excellent signal to background ratio [32]. But this method is only effective for the charged π decay mode. For neutral decay modes, due to poor π^0 and γ momentum resolution, the method is not effective. D^* meson decay branching fractions are (from reference [33]) in table 4.1.

channels	branching ratio (%)
$D^{*-} \rightarrow D^0 \pi^+$	49 ± 8
$D^{*-} \rightarrow D^- \pi^0$	34 ± 7
$D^{*-} \rightarrow D^- \gamma$	17 ± 11
$D^{*0} \rightarrow D^0 \pi^0$	51 ± 8
$D^{*0} \rightarrow D^0 \gamma$	48 ± 8

Table 4.1: Decay branching ratio for the D^* (2010) meson from [33].

Only about 50 % of the D^{*+} decays are in the charged π decay channel that we are interested in. From the table it is clear as to why we can not make use of D^{*0} meson to search for $D^* \pi$ enhancement.

Plots of invariant mass distributions for two D^0 decay modes are shown in Figure 4.3 with mass difference tagging ($\Delta = M(D^0 \pi^+ \pi^-) - M(D^0)$):

For channels I and II: $144 \text{ MeV}/c^2 < \Delta < 147 \text{ MeV}/c^2$

For channel III: $\Delta < 152 \text{ MeV}/c^2$

and with an x_p cut ($x_p > 0.5$).

The peak near $1.6 \text{ GeV}/c^2$ as seen in Figure 4.3-3) is the so-called satellite peak (channel III) [28] which is a kinematic reflection of the decay modes of D^0 . In this analysis the reflected signal is used only to support other decay channels (channel I and II). The decay modes of the D^0 to a vector particle and a pseudo-scalar particle, such as

$$D^0 \rightarrow \rho^+ K^- \quad \dots \quad (\text{BR: } 9.9 \pm 3.5 \%)$$

$$D^0 \rightarrow \begin{array}{l} \longrightarrow \pi^+ \pi^0 \\ K^{*-} \pi^+ \end{array} \quad \dots \quad (\text{BR: } 7.1 \pm 2.5 \%)$$

$$\longrightarrow K^- \pi^0$$

$$\longrightarrow K^0 \pi^-$$

have peculiar characteristics such that a D^0 can be identified without measuring neutral particles (branching ratio from [33]). The vector particles are produced in helicity zero state. It decays into two pseudo-scalars with a $\cos^2 \theta$ distribution where θ is the angle between a decaying pseudo-scalar particle and the decaying vector particle line of flight in the vector particle

Figure 4.3: Invariant mass distribution for D^0 decays with D^{*+} tagging.
 1) for $D^0 \rightarrow K^- \pi^+$ ($x_p > 0.5$, $\Delta M = 145.5 \pm 1.5 \text{ MeV}/c^2$),
 2) for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ ($x_p > 0.5$, $\Delta M = 145.5 \pm 1.5 \text{ MeV}/c^2$),
 3) for $D^0 \rightarrow K^- \pi^+ (\pi^0)$ ($x_p > 0.5$, $\Delta M < 152.0 \text{ MeV}/c^2$).

rest frame. One of two pseudo-scalar particles is likely to be going backward in the vector particle rest frame and it carries away only negligible momentum. The reflected signal could be detected without identifying the backward going neutral π . The mass of the reflected peak is reduced by the missing π mass and negligible momentum it carries away. Of course in this case the chance of finding a signal is reduced by a factor of two. Using the reflected signal is more effective than identifying π^0 's because of the poor resolution, low efficiency and large combinatorial background for π^0 's.

To select D^0 candidates, mass cuts were made according to the detector resolution and kept tight enough to reduce the combinatorial background:

$$\begin{aligned} 1.82 \text{ GeV}/c^2 &< M[K^-\pi^+] < 1.91 \text{ GeV}/c^2 \\ 1.84 \text{ GeV}/c^2 &< M[K^-\pi^+\pi^+\pi^-] < 1.89 \text{ GeV}/c^2. \end{aligned}$$

For the reflected D signal, the mass cut was

$$1.54 \text{ GeV}/c^2 < M[K^-\pi^+] < 1.7 \text{ GeV}/c^2.$$

With these mass cuts for D^0 selection the D^{*+} 's are identified. Figure 4.4 shows mass difference ($\Delta = M[D^0\pi^-] - M[D^0]$) distributions. The resolution of the signal is excellent and σ_Δ is about $1.0 \text{ MeV}/c^2$ for channels I and II and $3.5 \text{ MeV}/c^2$ for channel III.

With an $x_p(D^{*+}) > 0.45$ cut we have an excellent signal to background ratio. Notice that there is almost no background at all in the $D^0 \rightarrow K^-\pi^+$ mode with $x_p > 0.45$. The $x_p > 0.45$ cut used to obtain the plots of Figure 4.4 is not the actual cut made for the subsequent $D^{*+}\pi^-$ analysis. However the x_p cut used for the $D^{*+}\pi^-$ analysis does correspond very closely.

For further analysis, a clean $D^{*+}(2010)$ sample was obtained by requiring, in addition to the cuts on the D^0 mass, that the mass difference, Δ , lie in the interval of 144 to 147 MeV/c^2 for the $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ channels and a looser cut ($\Delta < 152 \text{ MeV}/c^2$) for the $K^-\pi^+(\pi^0)$ channel. With the $x_p > 0.45$ and Δ cuts we have about 3250 D^{*+} 's from channels I and II.

4.3 Observation of an enhancement in the $D^{*+}\pi^-$ channel

We use the mass difference, $\Delta^* = M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$, method for $D^{*+}\pi^-$ combinations to improve resolution. A mass difference distribution was made by combining clean a D^{*+} sample with π^- as shown in Figure 4.5. The following mass selection and the kinematic cuts are applied. For D^0 selection:

$$\text{channel I: } 1.82 \text{ GeV}/c^2 < M[K^-\pi^+] < 1.91 \text{ GeV}/c^2$$

$$\text{channel II: } 1.84 \text{ GeV}/c^2 < M[K^-\pi^+\pi^-\pi^+] < 1.89 \text{ GeV}/c^2$$

$$\text{channel III: } 1.54 \text{ GeV}/c^2 < M[K^-\pi^+] < 1.7 \text{ GeV}/c^2$$

For D^{*+} selection:

$$\text{For channels I and II: } 144 \text{ MeV}/c^2 < \Delta < 147 \text{ MeV}/c^2$$

$$\text{For channel III: } \Delta < 152 \text{ MeV}/c^2$$

Kinematic cuts on $D^{*+}\pi^-$ combination:

$$\cos\theta < 0.0, x_p[D^{*+}\pi^-] > 0.6.$$

Prominent peaks are seen around $410 \text{ MeV}/c^2$ for all three channels.

Figure 4.4: Mass difference distribution ($\Delta = M[D^0\pi^+] - M[D^0]$) for channel I, II and III with $x_p > 0.45$.

1) for $D^0 \rightarrow K^-\pi^+$, $1.82 \text{ GeV}/c^2 < M(K^-\pi^+) < 1.91 \text{ GeV}/c^2$

2) for $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$, $1.84 \text{ GeV}/c^2 < M(K^-\pi^+\pi^-\pi^+) < 1.89 \text{ GeV}/c^2$

3) for $D^0 \rightarrow K^-\pi^+(\pi^0)$, $1.54 \text{ GeV}/c^2 < M(K^-\pi^+) < 1.70 \text{ GeV}/c^2$.

Figure 4.5: Distribution of the mass difference, $\Delta^* = M(D^{*+}(2010) \pi^-) - M(D^{*+}(2010))$, for 3 channels, 1) channel I, 2) channel II, 3) channel III, 4) combined plot of channels I and II. Solid curves are fit results with Breit-Wigner form and 4 parameter background shape.

Figure 4.6: x_p distribution for $D^{*+}\pi^-$ combinations. The solid line is the shape of x_p distribution of other charmed meson (D^{*+}) [29].

This enhancement could be a candidate for an excited state of charmed meson. In the following section we discuss production and decay properties of the object, the applied kinematic cuts and background study.

4.3.1 $D^{*+}\pi^-$ Signal

Mass combinations of selected $D^{*+}(2010)$'s with all other π^- candidates which are not involved in $D^{*+}(2010)$ decays in the event were then studied.

First, sources of momentum dependent background were studied. Figure 4.6 shows the x_p distribution of $D^{*+}\pi^-$ combinations where the background peaks near $x_p=0.3$ while other charmed meson (D^{*+}) production is shown in solid line which peaks near $x_p=0.65$. A clear difference between

the two distribution shapes is seen. A previous study of the D^{*+} production [29] showed a very hard fragmentation function for charmed mesons. The reason for the hard fragmentation of charmed mesons is that primordial quarks take up a very large portion of the available momentum [4]. By analogy we expect a very hard fragmentation function for any charmed meson and for the excited states of charmed mesons. A higher scaled momentum cut ($x_p > 0.6$) reduces background significantly. According to the plot of Figure 4.6 we lose about 1/2 of the charmed meson signal with the cut of $x_p > 0.6$, but it eliminates about 85% of the combinatorial background. The x_p of the $D^{*+}\pi^-$ combination is quite similar to the x_p of D^{*-} and the major purpose of a high x_p cut on the $D^{*+}\pi^-$ is to provide very clean D^{*+} signals.

A second background study made on the angular distribution of $D^{*+}\pi^-$ combinations is shown where angles are defined in Figure 4.7. In Figure 4.8 the $\cos\theta$ distribution is shown (with $x_p > 0.6$) to have a large background concentrated near $\cos\theta \approx 1$. This is due to a random combination of low momentum π 's with high momentum D^{*+} 's. In the rest frame of the $D^{*+}\pi^-$, randomly combined low momentum π 's are going backward relative to the direction of the line of flight of the $D^{*+}\pi^-$. Only π 's which have a momentum well aligned to the $D^{*+}\pi^-$ line of flight survive this cut. We applied a quite strong cut ($\cos\theta < 0.0$) to remove background.

The mass difference, $\Delta^* = M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$, spectrum for combinations that survived these cuts, is shown in Figure 4.5. A prominent peak is seen around 410 MeV/c². A Breit-Wigner for the signal, plus

Figure 4.7: Definition of Decay Angles.

Figure 4.8: $\cos\theta$ distribution of $D^{*+} \pi^-$ combinations. We expect that the real signal should have a symmetrical distribution about $\cos\theta=0$. Peaking near $\cos\theta=1$ is due to random combinatorial background. N.B. The region of inefficiency which comes from the p_T cut is pointed out by an arrow.

a threshold factor times a second order polynomial for the background, were fitted using the maximum likelihood method to the mass difference distribution, yielding the results listed in Table 4.2.

In producing these plots, multiple entries for D^* candidates per event are weighted so that the sum of the weights is unity. A multiple entry is when there is greater than one reconstructed D^* meson of a given charge state per event. This measure was taken because the exchange of low momentum π 's from D^0 decays with random π 's from background sometimes does not change the mass and momentum of the D^0 very much. As a result, we see more signal with a slightly broader width than the real signal. Only high multiplicity D^0 decays are prone to this effect because they produce more low momentum π 's and the fraction of momentum taken by one π is small compared to the low multiplicity case. A detailed study has shown that this effect is significant in only one of the three channels ($D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$).

The fit results on mass, width and number of events for three D^0 decay chains are shown separately. The mass and width for channel I and channel II are consistent with their being the same object. A Monte-Carlo study shows that although the mass difference shift due to the missing π^0 is negligible, the width for channel III is substantially broader ($\sigma_\Delta \simeq 25 \text{ MeV}/c^2$) due to the intrinsic mass difference resolution. The number of $D^{*0}(2420)$ events from the fit were compared with the number of $D^{*+}(x_p > 0.45)$ for each channel for a consistency check. The number of $D^{*+}(x_p > 0.45)$ events for each channel are:

channel I : 1230 $D^{*+}(2010)$ events

channel II : 2020 $D^{*+}(2010)$ events

channel III : 2090 $D^{*+}(2010)$ events.

The ratio of the number of $D^{*0}(2420)$ events to the number of $D^{*+}(2010)$ events is consistent for each channel implying that the object seen by all the three channels is the same (see Table 4.2).

According to the theoretical mass prediction (see Figure 2.2), the signal is most likely be a P state or mixture of P states. The width of the object is found to be (41 ± 16) MeV/ c^2 . Monte-Carlo studies had shown that the detector resolution ($\sigma_{\Delta\cdot}$) was 8 MeV/ c^2 in channels I and II, whereas the observed width is much larger indicating that the new state decays strongly.

Due to large measurement error and uncertainty of theoretical predictions, it is very hard to constrain the spin-parity states of the object by the measured decay width. The statistical significance of the enhancement is 4.7 standard deviations for the combined signal from channels I and II. Combining with the additional significance from channel III (3.3 standard deviations) in quadrature, this enhancement is about a 5.7 standard deviation effect. In the following we refer this state as $D^{*0}(2420)$.

4.3.2 Background Studies

Two different studies have been made in order to confirm that the enhancement is not an artifact of the kinematic selection criteria employed. These were made using (1) a sideband of the D^{*+} , and (2) wrong charge

Channel	I	II	III	I - II
Mass difference [MeV/c ²]	404±7	412±8	418±10	409±6
M D ⁰ (2420) [MeV/c ²]	2414±7	2422±8	2428±10	2419±6
Full width [MeV/c ²]	28 ⁺²¹ ₋₁₇	54 ⁺⁴⁴ ₋₂₆	80 ⁺³⁵ ₋₂₅	41 ⁺²² ₋₁₄
Number of D ⁰ (2420)	45 ⁺¹⁸ ₋₁₄	97 ⁺⁶³ ₋₂₉	116 ⁺⁴³ ₋₃₅	130 ⁺⁴³ ₋₂₈
Background parameter, A	690.9	1763	850.2	2551
" B	-1825	-5344	-1064	-7572
" C	1292	4359	-344.9	6070
" G	0.3605	0.4985	0.1120	0.4701
χ ² /degrees of freedom	37/36	36/36	40/36	36/36
D ⁰ branching ratio	0.054±0.04	0.109±0.01	0.173±0.017	0.163
D ⁰ (2420) efficiency	0.17±0.05	0.12±0.04	~0.04	0.14±0.04
Number of D ⁺⁺ (2010)	1230	2020	2090	3250
$\frac{\text{Number of D}^0(2420)}{\text{Number of D}^{++}(2010)}$	0.037	0.048	0.055	0.040

Table 4.2: Properties of the D⁰(2420) determined from fits to the distribution of mass difference, Δ^{*} and other information. Errors on mass and width include systematic errors from binning of the histograms. A,B,C and D are fit results of background parameters. Background shape is found by fitting with the form:

$$0.02 \cdot (A + B(x-0.4) + C(x-0.4)^2) \cdot (x-0.13499)^G.$$

Figure 4.9: Distribution of the mass difference, Δ^* , for side-band of D^{*+} is shown by the dotted histogram. For comparison, data presented in Figure 4.5-4) is overlaid.

combinations, that is $D^{*+}\pi^+$.

Background Study with Fake D^{*+}

To study the background from the fake D^{*+} , fake D^{*+} were selected by choosing combinations of $D^0\pi^+$ which fall into side-bands of the D^{*+} region. Mass differences, $\Delta = M[D^0\pi^+] - M[D^0]$, between

$$155 \text{ MeV}/c^2 < \Delta < 170 \text{ MeV}/c^2 \quad \text{for channel I}$$

$$155 \text{ MeV}/c^2 < \Delta < 160 \text{ MeV}/c^2 \quad \text{for channel II}$$

were chosen as side bands of D^{*+} . The mass difference cut was made so that the ratio of the number of $D^{*+}\pi^-$ combinations between these two

Figure 4.10: Distribution of the mass difference, Δ^* , for wrong charge ($D^{*+}\pi^+$) combinations. is shown by the dotted histogram. For comparison, data presented in Figure 4.5-4) is overlayed.

channels on the D^{*+} side-band are the same as the ratio of the number of $D^{*+}\pi^-$ combinations between them on the D^{*-} band.

If we observe a similar bump near the mass region of $D^{*0}(2420)$, the signal we observed with D^{*-} band would be considered as an artificial effect which has arisen due to the kinematic cuts made. Now a π^- was combined with fake D^{*-} candidates and all other cuts were exactly identical to D^{*-} band combinations.

As shown in Figure 4.9 not only was no significant enhancement found in the plot but also the shape of the distribution describes the smooth background of $D^{*+}\pi^-$ combinations reasonably well except in the higher mass region where the background is enhanced.

Background Study with Wrong Charge Combinations

The second method used is a rather simple one. D^{*-} 's are selected as usual and then combined with π^- 's and all other cuts are made as in the real case. No doubly charged particle is expected in this study.

As shown in Figure 4.10, again not only was no significant enhancement found in the plot but also the shape of the distribution describe the smooth background of $D^{*+}\pi^-$ combinations quite well.

From these two types of background tests we conclude that this enhancement is not due to a kinematic effect caused by the cuts employed.

4.3.3 Fragmentation of the $D^{*0}(2420)$

The study of the momentum distributions of primary hadrons from e^+e^- interactions provides us with valuable information on how quarks fragment and emerge as hadrons. Theoretical speculation predicts that the primary hadrons take a large portion of the available momentum. Theoretical models can be tested with an experimental measurement of the momentum distribution of the primary hadrons.

The fragmentation function for the $D^{*0}(2420)$ was extracted by fitting a Breit-Wigner form plus a background polynomial to the mass distributions of the events selected in different x_p [$D^{*0}(2420)$] bins with the same $\cos\theta < 0$ cut. Only channels I and II are used for this purpose because channel III has missing momentum. Also $\Upsilon(4S)$ data are not used in this analysis because they contain secondary charmed mesons produced by B meson decay.

The result, corrected for acceptance, is shown in Figure 4.11. Also shown are the results of fits made with two commonly used theoretical models of scaled cross-section, that of Peterson et al. [5] where:

$$\frac{dN}{dx_p} \approx \frac{1}{x_p \left(1 - \frac{1}{x_p} - \frac{1}{1-x_p}\right)^2} \quad (4.1)$$

and that of Kartvelishvili et al. [30] where:

$$\frac{dN}{dx_p} \approx x_p^\alpha (1 - x_p) \quad (4.2)$$

The fitted values for the parameters of the models were $\epsilon = 0.07 \pm 0.04$ with χ^2 probability of 0.35 (one degree of freedom), and $\alpha = 2.8 \pm 0.9$ with χ^2

Figure 4.11: Number of $D^{*0}(2420)$ events in channels I and II as a function of x_p , corrected for acceptance. The error bars are statistical only. The solid curve is the result of a fit to the data using expression (Peterson), and the dashed curve using expression 4.2 (Kartvelishvili). The plot has been normalized so that the integral of the Peterson fit is unity.

probability of 0.11. No attempt has been made to adjust the results for the effects of photon or gluon initial state radiation. Either form describes the distribution adequately. The $D^{*0}(2420)$ fragmentation function is found to be harder than $D^{*+}(2010)$ fragmentation function ($\alpha = 0.19 \pm 0.03$) [29].

4.3.4 Inclusive Production Rate of the $D^{*0}(2420)$

The production cross section for the $D^{*0}(2420)$ meson decaying to $D^{*+}(2010) \pi^-$ has been estimated by comparison with the rate observed for $D^{*+}(2010)$ production. We observed 130^{+43}_{-28} $D^{*0}(2420)$ events. The efficiency for the

decay $D^{*0}(2420) \rightarrow D^{*+}(2010) \pi^-$, where $D^{*+}(2010)$ decays through channels I and II. and with the requirement that $\cos\theta < 0$ and $x_p[D^{*0}(2420)] > 0.6$, was found to be 0.14 ± 0.04 , using a detector Monte Carlo study. The error is dominated by the uncertainty in extrapolating the observed cross section to $x_p[D^{*0}(2420)] = 0$. The efficiency corrected number of $D^{*0}(2420) \rightarrow D^{*+}(2010) \pi^-$ is $930_{-200}^{+310} \pm 270$, where the first error is statistical and the second systematic.

The total number of observed $D^{*+}(2010)$ decays to the same channels with $x_p[D^{*+}(2010)] > 0.45$ is 3250 ± 100 events. Corrections are made for the unseen low $x_p[D^{*+}(2010)]$ portion of the fragmentation distribution and for acceptance. The efficiency corrected number of $D^{*+}(2010)$ is found to be $10250 \pm 320 \pm 1040$, where the first error is statistical and the second systematic.

By comparing these numbers, we conclude that

$$\frac{\sigma(D^{*0}(2420)) \cdot BR(D^{*0}(2420) \rightarrow D^{*+}(2010) \pi^-)}{\sigma(D^{*+}(2010))} = 9_{-2}^{+3} \pm 3(\%)$$

where the first error is statistical and the second systematic.

The production cross section, $\sigma[D^{*0}(2420)]$, is estimated by correcting for the neutral decay channel $D^{*0}(2420) \rightarrow D^{*0}(2010) \pi^0$ using isospin symmetry and using the results quoted in Albrecht et al. [29], Baltrusaitis et al. [31], and Particle Data Group [33],

$$\sigma[D^{*0}(2420)] \cdot BR(D^{*0}(2420) \rightarrow D^{*+}(2010) \pi^-) = 0.09 \cdot \sigma[D^{*+}(2010)] \cdot \frac{3}{2}.$$

Based on the results quoted in references [29], [31] and [33] we calculate that

$$\sigma[D^{*+}(2010)] = (940 \pm 150 \pm 270) \text{ pb at } \sqrt{s} \simeq 10 \text{ GeV}.$$

we find that $\sigma[D^*(2420)] \cdot \text{BR}[D^*(2420) \rightarrow D^*(2010) \pi] = (130^{+50}_{-35} \pm 55) \text{ pb}$

4.3.5 Decay Angular Distribution of the $D^{*0}(2420)$

Due to quantum effects there is a specific angular orientation of the wave function of a meson for each state. When the meson decays a unique angular distribution can be measured from its decay products for a given production mechanism. This distribution then identifies the spin and parity of the meson.

Two decay angles θ and θ_1 (defined in Figure 4.7) are examined. In the absence of an interfering background, the angular distributions should be symmetric if this is a pure resonance. An angular distribution was extracted by making five slices on the $\cos\theta$ range and fitting the mass distribution with fixed mass and width plus background. The decay angular distribution (with acceptance correction) of θ is shown in Figure 4.12 where the angular distribution has a flat distribution shape with slight enhancement near $\cos\theta = \pm 1.0$ and is quite symmetrical. On the plot, the first half of the bin near $\cos\theta=1.0$ is not used due to very low efficiency. The background under the $D^{*0}(2420)$, obtained from the fit is also shown in Figure 4.12 for each angular bin.

The angular distribution of θ_1 is very useful for spin parity analysis. There is a very simple method of spin-parity analysis [35] which is independent of the production mechanism for a particle which decays sequentially.

With a cascade decay mode of the form

$\frac{\lambda}{0.4 \text{ in } \cos\theta}$

Figure 4.12: $\cos\theta$ distribution of $D^{*0}(2420)$. Half of the bin near $\cos\theta=1$ was not measured due to very low efficiency. The background shape, as determined in $D^{*0}(2420)$ region, is presented as a hatched histogram (arbitrary scale).

$$J^P(D^{*0}(2420)) \rightarrow 1^-(D^{*+}(2010)) \quad 0^-(\pi^-)$$

$$\rightarrow 0^-(D^0) + 0^-(\pi^+).$$

decay angular distribution of θ_1 should be proportional to (for P states)

$$1) \quad 1^- : \quad a + b(1 - 3\cos^2\theta_1),$$

$$2) \quad 2^- : \quad \sin^2\theta_1$$

where a, b are positive values and are related to S and D wave production rates, respectively [34]. The 0^+ state is excluded because it is not allowed to decay to $D^* \pi$ due to parity conservation.

In a way similar to the $\cos\theta$ distribution analysis, a method was applied to extract the acceptance corrected $\cos\theta_1$ distribution. Figure 4.13 shows the angular distribution of $\cos\theta_1$. The background under the $D^{*0}(2420)$ obtained from the fit is also shown in Figure 4.13 for each angular bin.

Assuming that this object is a P state, the discrimination between 1) and 2) is most interesting. A fit was made according to the shape of 1) (with $b=0$, because it does not show any significant b contribution) and 2) on the distribution to acquire a χ^2 probability (4 degrees of freedom). The results are

$$\text{For 1) : } 0.70$$

$$\text{For 2) : } 0.03$$

Thus the distribution prefers the case of 1) over 2) without conclusive discrimination due to low statistics.

Figure 4.13: $\cos \theta_1$ distribution of $D^{*0}(2420)$. The overlaid curves are fitted according to theoretical predictions. 1) Solid line: flat distribution. 2) dotted line: $\sin^2 \theta$ distribution. The background shape, as determined in $D^{*0}(2420)$ region, is presented as a hatched histogram (arbitrary scale).

4.3.6 Moment Analysis for a Sequential Decay

In a sequential decay there are four decay angles $(\theta, \phi, \theta_1, \phi_1)$ which can be measured. If we exploit all four decay angles, then the spin-parity determination could be more accurate than when using information from one or two angles. There is a method [34] using all four angles, namely the so called 'double moment method'. In this subsection we explain the basic theory of this method and apply it to data.

In this analysis we follow Chung's original work [35]. More generally, in a sequential decay, where a particle J is produced which decays into two particles, S and a π , and S decays into two particles, S_1 and a π ,

$$\begin{array}{c}
 a + b \rightarrow J + X \\
 \quad \quad \quad \downarrow \\
 \quad \quad \quad S + \pi \\
 \quad \quad \quad \downarrow \\
 \quad \quad \quad S_1 + \pi
 \end{array}$$

the production matrix element has the form

$$m \sim \langle \Omega_1 S_1 \lambda_1 | m_S S \lambda \rangle \langle \Omega S \lambda | m_J J \Lambda \rangle \langle p_f \lambda_X \Lambda | T | p_i \lambda_a \lambda_b \rangle. \quad (4.3)$$

Here the first term represents the decay property of S, the second term represents the decay of J and the third term represents the production of J. The symbols are defined as,

Λ : helicity state of J,

λ_X : helicity state of X,

λ : helicity state of S,

λ_1 : helicity state of S_1 ,

Ω : angles(θ, ϕ) in the J rest frame,

Ω_1 : angles(θ_1, ϕ_1) in the S rest frame,

p_f, p_i : four momentum of out-going and in-coming particles, respectively.

The matrix element can be written in terms of helicity decay amplitudes as follows

$$m \sim F_{\lambda_1}^S D_{\lambda\lambda_1}^{S*}(\theta_1, \phi_1) \cdot F_{\lambda}^J D_{\lambda\lambda}^{J*}(\theta, \phi) \cdot \rho_{\lambda\lambda'},$$

where the F's are helicity decay amplitudes, the D's are standard D functions, and the ρ is the density matrix which is related to the production of J. The angles are defined in Figure 4.7. We can express the angular distribution in the form,

$$\begin{aligned} I(\Omega, \Omega_1) &\propto \sum_{\lambda\lambda'} |\hat{m}|^2 \\ &= \left(\frac{2J+1}{4\pi}\right) \left(\frac{2S+1}{4\pi}\right) \sum_{\substack{\lambda\lambda' \\ \lambda\lambda'\lambda_1}} \rho_{\lambda\lambda'}^J F_{\lambda}^J F_{\lambda'}^{J*} |F_{\lambda_1}^S|^2 D_{\lambda\lambda}^J(\Omega) D_{\lambda'\lambda'}^{J*}(\Omega) D_{\lambda\lambda_1}^S(\Omega_1) D_{\lambda'\lambda_1}^{S*}(\Omega_1). \end{aligned}$$

We can define a double moment in terms of the standard cartesian formalism rather than the helicity formalism,

$$\begin{aligned} H(LM|m) &= \langle D_{Mm}^L(\Omega) D_{m0}^L(\Omega_1) \rangle \\ &= \int d\Omega d\Omega_1 I(\Omega, \Omega_1) D_{Mm}^L(\Omega) D_{m0}^L(\Omega_1). \end{aligned} \quad (4.4)$$

Using standard D function properties,

$$\int d\Omega D_{M_1 N_1}^{L_1} D_{M_2 N_2}^{L_2} D_{M_3 N_3}^{L_3} = \frac{4\pi^2}{2L_3+1} (L_1 M_1 L_2 M_2 | L_3 M_3) (L_1 N_1 L_2 N_2 | L_3 N_3),$$

where the three D functions are reduced to 2 Clebsch-Gordan coefficients.

Substituting $I(\Omega, \Omega_1)$ into this equation and integrating, we find

$$H(LMlm) = i_{LM}^{J*} f_{lm}^{JL} f_l^S \quad (4.5)$$

where we have used the definitions.

$$i_{LM}^{J*} = \sum_{\Lambda\Lambda'} \rho_{\Lambda\Lambda'} (J\Lambda'LM J\Lambda) \quad (4.6)$$

$$f_{lm}^{JL} = \sum_{\lambda\lambda'} F_{\lambda}^J F_{\lambda'}^{J*} (J\lambda' Lm J\lambda) (S\lambda' lm S\lambda) \quad (4.7)$$

$$f_l^S = (S0l0 S0). \quad (4.8)$$

Here the first term represents the production properties of J, the second term represents the decay of J, and the third term represents the decay of S.

Some assumptions have been made in the above. These are 1) there is no energy dependence in the helicity amplitude, and 2) there is no interference between spin-parity states.

Symmetry relations and the parity conservation rule provide very useful constraints such that f_{lm}^{JL} vanishes when $L+l$ is odd and f_l^S vanishes when l is odd. As a result, the double moment $H(LMlm)$ vanishes when L is odd or l is odd.

From parity conservation, $F_{\lambda} = \eta(-1)^{J-1} F_{-\lambda}$.

If $F_0 \neq 0$, then $\eta(-1)^{J-1} = +1$ or unnatural parity. Or, in other words, if B_{00} is consistently non-zero, the state must be an unnatural parity state ($1^+, 2^-, 3^+, \dots$).

Define,

$$B_{\lambda\lambda'}(LM) = \sum_{l: l+l'=L} \frac{(2l+1)(S\lambda'lm S\lambda)}{(S0l0 S0)} H(LMlm). \quad (4.9)$$

Then using 4.5,

$$B_{\lambda\lambda'}(LM) = (2S+1)t_{LM}^{J\lambda} \frac{1}{2} (F_{\lambda}^J F_{\lambda'}^{J*} - (-1)^L F_{\lambda}^{J*} F_{\lambda'}^J) (J\lambda' Lm J\lambda). \quad (4.10)$$

Some useful relations up to $\Lambda=1$ (because our interest is mainly in the D meson and $S=1$ for this case) derived from equation 4.9 are:

$$B_{00}(LM) = H(LM00) + 5H(LM20)$$

$$B_{11}(LM) = H(LM00) - \frac{5}{2}H(LM20)$$

$$B_{10}(LM) = \frac{\sqrt{3}}{2}5H(LM21)$$

$$B_{1-1}(LM) = -\sqrt{\frac{3}{2}}5H(LM22).$$

Another set of relations from 4.10 are:

$$B_{00}(LM) = 3\text{Re}(t_{LM}^J) F_0^2 (J0L0 J0)$$

$$B_{11}(LM) = 3\text{Re}(t_{LM}^J) F_1^2 (J0L0 J0) (1 - \frac{L(L+1)}{2J(J+1)})$$

$$B_{10}(LM) = 3\text{Re}(t_{LM}^J) \text{Re}(F_1 F_0^*) (J0L0 J0)^{\frac{1}{2}} (\frac{L(L+1)}{J(J+1)})^{\frac{1}{2}}$$

$$B_{1-1}(LM) = 3\text{Re}(t_{LM}^J) (-\eta(-1)^{J-1}) F_1^2 (J0L0 J0) (\frac{L(L+1)}{(L-1)(L+2)})^{\frac{1}{2}}$$

where η is the intrinsic parity of the particle J. From these relations we can deduce the useful constraints:

If $|F_1|^2 \neq 0$ ($B_{11} \neq 0$), the $\lambda=1$ component exists and $J \neq 0$.

From $B_{11}(LM)/B_{1-1}(LM)$,

$$\Delta^{JP} \begin{pmatrix} L & M \end{pmatrix} = \left(\frac{2(L+1)}{3(L-1)(L+2)} \right)^{\frac{1}{2}} \left(H(LM00) - \frac{5}{2}H(LM20) \right) - \eta(-1)^{J-1} \left(1 - \frac{L(L+1)}{2J(J+1)} \right) 5H(LM22) \dots (L \geq 2). \quad (4.11)$$

This implies that if J^P is correct, then $\Delta J^P \simeq 0$ and if J^P is not correct $\Delta J^P \neq 0$. However there is no discrimination between 1^- and 2^- , or 1^+ and 2^+ due to the characteristics of the equation.

Due to lack of statistics we have tried a simple spin parity analysis with this method and no attempt was made for the higher moments ($L \leq 2$, $1 < 2$). Only 5 double moments are necessary for this purpose. These moments are shown below in terms of decay angles.

- 1) $H(0000) \propto \langle \text{isotropic} \rangle$
- 2) $H(0020) \propto \langle \frac{3}{2} \cos^2 \theta_1 - \frac{1}{2} \rangle$
- 3) $H(2000) \propto \langle \frac{3}{2} \cos^2 \theta - \frac{1}{2} \rangle$
- 4) $H(2020) \propto \langle (\frac{3}{2} \cos^2 \theta - \frac{1}{2})(\frac{3}{2} \cos^2 \theta_1 - \frac{1}{2}) \rangle$
- 5) $H(2022) \propto \langle (\sin^2 \theta) \sin^2 \theta_1 e^{-i2\phi_1} \rangle$

As all of the double moments shown are symmetric in θ , the cut $\cos \theta = 0$ does not distort any of the moments.

Double moments and their errors are estimated according to the expressions above for each entry. Because of the orthogonality properties of the moments, if there are no components of the double moment in the decay angular distribution, then the value of that specific double moment approaches zero. If the estimated value of any double moment deviates from zero, it is understood that there is a component of that double moment in the decay angular distribution.

Acceptance Calculation

Monte-Carlo events were generated and processed through the detector simulation to obtain the acceptance corrected moments. First, particles were generated according to.

1) $1 + \cos^2 \theta_{LAB}$ distributions. This is based on the known fermion anti-fermion production cross-section for the e^+e^- annihilation process.

2) Momentum distribution with $\alpha=1.5$ for the Kartvelishvili Model 30 fragmentation.²

3) Events of decay channels I and II have been generated separately with more than 10 times the statistics of the corresponding data mass bin. All unstable particles were made to decay isotropically in the Monte-Carlo.

The decay angular distribution for Monte-Carlo data after detector simulation is shown in Figure 4.14.

An acceptance for each moment can be calculated by the integral [36].

$$A_{\alpha\alpha'} = \frac{(2L' + 1)}{4\pi} \frac{(2l' + 1)}{4\pi} \int \int D_{Mm}^L(\Omega) D_{m0}^{l'}(\Omega_1) \cdot a(\Omega, \Omega_1) \cdot D_{M'm'}^{L'}(\Omega) D_{m'0}^{l'}(\Omega_1) d\Omega_1 d\Omega \quad (4.12)$$

where $a(\Omega, \Omega_1)$ is the detector acceptance at angles Ω and Ω_1 . Experimentally observed moments are related to the acceptance corrected moments via

$$H_{\alpha}^{obs} = \sum_{\alpha'} A_{\alpha\alpha'} H_{\alpha'} \quad (4.13)$$

² Although fragmentation of $D^{*0}(2420)$ is harder ($\alpha=2.8$) than those of M.C. data, the efficiency is found to be not sensitive above $x_p > 0.6$ which is the cut made in this analysis.

Figure 4.14: Decay angular distribution for the Monte-Carlo data (channel I) only $\cos \theta < 0.0$ cut was made on the Monte-Carlo data to match the real data. 1) $\cos \theta$, 2) ϕ , 3) $\cos \theta_1$, 4) ϕ_1 .

2

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2

or alternatively,

$$H = A^{-1} [H^{obs}] \quad (4.14)$$

The corrected error for each moment is calculated from the acceptance and the observed error of moment [37]

$$E = [A^T (E^{obs})^{-1} A]^{-1} \quad (4.15)$$

From the definition, the double moment for each experimental event is

$$\begin{aligned} H_i(LMlm) &\equiv \int \int \delta(\Omega_i) \delta(\Omega_1) D_{Mm}^L(\Omega) D_{m0}^l(\Omega_1) d\Omega_1 d\Omega \\ &= D_{Mm}^L(\theta_1, \phi_1) D_{m0}^l(\theta_1, \phi_1). \end{aligned} \quad (4.16)$$

For the data set, it is just the sum over all events:

$$\sum_i H_i(LMlm) = \sum_i D_{Mm}^L(\theta_1, \phi_1) D_{m0}^l(\theta_1, \phi_1). \quad (4.17)$$

The acceptance of each moment was calculated for each of the 14 mass bins (60 MeV/c²). The starting value of each bin was adjusted so as to have the mass of the D^{*0}(2420) ($\Delta^* = 410$ MeV/c²) right at the middle of the bin so it is easy to see the significance. Figure 4.15 shows the double moments of the real data. The first plot shows the double moment H(0000), which for real data is just an acceptance corrected plot of the distribution of the observed mass difference, Δ^* . No significant moment is seen in the D^{*0}(2420) mass region ($\Delta^* = 410$ MeV/c²), with the exception of the H(0000) moment.

In Figure 4.16 we show the moment B₀₀(00) which exhibits some enhancement at the D^{*0}(2420) mass. As explained earlier, the deviation of

Figure 4.15: Acceptance corrected double moments for real data.

Figure 4.16: $B_{00}(00) = H(0000) - 5H(0020)$: for channel I and channel II.

the bin at the $D^{*0}(2420)$ mass bin means that the $D^{*0}(2420)$ might be an unnatural parity meson. Some deviation is visible in channel I but nothing in channel II. Discrimination with our statistics does not seem possible.

In Figure 4.17 we show the moment $B_{11}^*(00)$ which should vanish for a spin zero object. A small enhancement is seen in the $D^{*0}(2420)$ mass region. In terms of χ^2 , the probability of spin zero for the $D^{*0}(2420)$ is about 10 %. Again the statistics are too low to discriminate other possibilities.

In Figure 4.18 we show plots of Δ^{JP} for two parity states according to equation 4.11 with $L=2$ and $M=0$. Significant deviation from background means that the parity assignment is not correct. No significant deviation is seen near $\Delta^*=410 \text{ MeV}/c^2$ for both cases of parity. Discrimination with

Figure 4.17: $B_{11}(00) = H(0000) - \frac{5}{2}H(0020)$: for channel I and channel II.

our statistics does not seem possible.

4.4 $D^{*+}(2420)$ Analysis

The charged partner of the $D^{*0}(2420)$ is expected to exist as a (cd) -meson. In this section we search for the $D^{*-}(2420)$, by combining π^0 's with well defined D^{*-} candidates. According to an isospin argument its production rate is suppressed by a factor of 2 assuming the same production rate for the two different charged states of $D^*(2420)$ in an e^+e^- experiment. On top of this, the efficiency for π^0 identification drops quite significantly relative to charged π 's. For the photon energy cut of 100 MeV the efficiency for the π^0 's from $D^{*+}(2420)$ decay is around 40% with the other cuts which are

Figure 4.18: Δ^{JP} for two parity states. Significant deviation from background means that the parity assignments are not correct.

made later on.

The π^0 was identified by two photons having energies greater than 100 MeV deposited in the shower counters. A plot of the invariant mass distribution of two gamma's is shown in Figure 4.19. A mass cut was made on the $\gamma\gamma$ system requiring $M(\gamma\gamma)$ to be within ± 30 MeV/c² of the π^0 mass. To improve the overall mass resolution we applied a kinematic fit (1C) which constrains the mass of the two photons to be 0.1396 GeV/c².

The π^0 's are combined with $D^{*-}(2010)$ candidates to produce an invariant mass difference distribution which is shown in Figure 4.20 (only the decay channels I and II are used here). The reason for excluding channel III was that the unidentified π^0 's from D^0 decay can produce large background. Also two cuts were made on the $D^{*-}(2010)\pi^0$ system in same way as in the $D^{*-}(2010)\pi^-$ system. The cuts were $x_F > 0.6$ and $\cos\theta < 0.0$.

There is an enhancement near the $D^{*0}(2420)$ mass region ($\Delta^* = 410$ MeV/c²). The fit was made with Gaussian signal of a fixed mass ($\Delta^* = 410$ MeV/c²) and a fixed width ($\sigma_{\Delta^*} = 35$ MeV/c²) combined with a second order polynomial background. Width broadening was calculated by Monte-Carlo study and found to be $\sigma_{\Delta^*} = 35$ MeV/c².

The number of events and error obtained from the fit is 36 ± 12 (3 standard deviations). Although the significance of the signal is not so convincing by itself, it is a good check on the production of the charged partner of $D^{*0}(2420)$. The fit results provide the cross-section of production of the $D^{*-}(2420)$ with the acceptance corrections of π^0 from Monte Carlo calcu-

Figure 4.19: Invariant mass distribution of $\gamma\gamma$ with $p(\gamma\gamma) > 0.5$ GeV/c.

lation. The detection efficiency ratio for $(D^{*+}(2420) \rightarrow D^{*+}\pi^0)$ relative to $(D^{*0}(2420) \rightarrow D^{*+}\pi^-)$ is found to be 0.46. The cross-section for $D^{*+}(2420)$ was calculated according to this efficiency ratio and isospin factor in a similar manner to the $D^{*0}(2420)$ case. The cross-section was found to be $\sigma[D^{*+}(2420)] \cdot \text{BR}[D^{*+}(2420) \rightarrow D^*(2010)\pi] = (155 \pm 100)$ pb.

This result is consistent with the assumption that the production rate of charged and non charged $D^*(2420)$ is the same.

4.5 $D\pi$ Analysis

In determining the spin-parity of this object, one major task is to search for the direct decay mode $(X \rightarrow D\pi)$. A 2^+ state is allowed to decay to $D\pi$ while a 1^+ state is forbidden to do so due to parity conservation. So if

Figure 4.20: Distribution of mass difference $M D^{*-}(2010)\pi^0 - M D^{*-}(2010)$. 1) D^* band. 2) side band of D^* . Solid curves are fit results with Breit-Wigner form and 4 parameter background shape.

we find a signal at the same mass with the same width as $D^{*0}(2420)$ with a $D\pi$ decay mode, the $D^{*0}(2420)$ might be a 2^+ state. If we find a signal at a different mass with a different width and no signal at the $D^{*0}(2420)$ mass it would mean that the $D^{*0}(2420)$ might be an 1^+ state. The possibility of a 0^+ state is excluded because it can not decay to $D^{*+}\pi^-$ mode due to parity conservation.

The following decay modes were studied for this purpose:

$$X \rightarrow D^0\pi^+; D^0 \rightarrow K^-\pi^+$$

$$X \rightarrow D^-\pi^-; D^+ \rightarrow K^-\pi^+\pi^-$$

D^0 's were selected with a mass cut of $1.82 \text{ GeV}/c^2 < M[K^-\pi^+] < 1.91 \text{ GeV}/c^2$. Only the $K^-\pi^+$ decay mode of the D^0 was used for this analysis. The $K^-\pi^-\pi^+\pi^+$ decay mode of the D^0 was excluded because of large combinatorial background near the D^0 mass (see Figure 4.1).

D^+ 's were selected with mass cut of $1.83 \text{ GeV}/c^2 < M[K^-\pi^+\pi^-] < 1.90 \text{ GeV}/c^2$. Other decay modes of the D^+ are not so effective because of their small branching ratio, low efficiency or large background and are not attempted in this analysis.

A mass difference distribution was made with $x_p > 0.5$. This cut was motivated by the same reason as in the case of the $D^{*0}(2420) \rightarrow D^{*+}(2010)\pi^-$ decay. There is no significant signal near the $D^{*0}(2420)$ region ($\Delta, M[D\pi]$ $\{ M[D] = 540 \text{ MeV}/c^2$) in Figure 4.21. In order to extract $\sigma \cdot BR$, many fits were made to the mass difference (Δ^*) region between $300 \text{ MeV}/c^2$ and $800 \text{ MeV}/c^2$ varying M_0 but with a fixed width of $65 \text{ MeV}/c^2$ in the Breit-Wigner form and using a third order polynomial background. The width of

Figure 0.1: Distribution of mass difference, $\Delta = M[D\pi] - M[D]$, 1) $D^0\pi^-$, 2) $D^-\pi^-$.

65 MeV/c^2 represents the upper range of possible values. An upper limit calculation was made using a Monte-Carlo acceptance calculation and with the fit result as shown in Figure 4.22.

The theoretical predictions of the branching ratio between the direct decay mode ($D^*(2420) \rightarrow D\pi$) and the sequential decay mode ($D^*(2420) \rightarrow D^*\pi$) for a 2^+ state lie between 1.5 and 3.5 (section 2.2). A χ^2 probability calculation was made by comparing the fit result with a sequential decay production rate. The probability of the object being a 2^+ state is about 2% assuming that the production rate of both charged states is the same and the ratio of the decay width, $\Gamma(D\pi)/\Gamma(D^*\pi)$, is 1.5, the least favourable value for this search.

$$\frac{\sigma(X)BR(X \rightarrow D\pi)}{\sigma(D^{*0}(2420) \rightarrow D^{*0}(2420) \rightarrow D^{*+}(2010) \pi^-)}$$

Figure 4.22: Upper limit of $\frac{\sigma(X)BR(X \rightarrow D\pi)}{\sigma(D^{*0}(2420) \rightarrow D^{*0}(2420) \rightarrow D^{*+}(2010) \pi^-)}$ for direct decay: 1) $D^0 \pi^+$, 2) $D^+ \pi^-$.

4.6 Summary and discussion of the analysis

In this chapter we described the excited charmed meson which we searched for. Very strong evidence for a new resonance has been observed near $2420 \text{ MeV}/c^2$, which we call the $D^{*0}(2420)$, which decays to $D^{*+}\pi^-$. The observed mass and width are $(2419 \pm 6) \text{ MeV}/c^2$ and $(41_{-14}^{+22}) \text{ MeV}/c^2$ respectively.

The fragmentation function is found to be hard, as expected for a state containing a leading charm quark produced by non-resonant e^+e^- annihilation. The fragmentation function for the $D^{*0}(2420)$ was extracted by fitting a Breit-Wigner plus a background polynomial to the mass distributions. The fitted values for the parameters of the Peterson and Kartvelishvili models were $\epsilon = 0.07 \pm 0.04$ with χ^2 probability of 0.35 (1 degree of freedom) and $\alpha = 2.8 \pm 0.9$ with χ^2 probability of 0.11. Both of the forms describe the data adequately.

A background study was made in order to confirm that the enhancement is not an artifact of the kinematic selection criteria employed. This study used (1) a side-band of the $D^{*+}(2010)$ and (2) wrong charge combinations, that is $D^{*+}(2010)\pi^-$. No significant enhancement was found in either approach.

The production rate for the object was found to be consistent within three D^0 decay chains by comparing the ratio between the number of $D^{*0}(2420)$ to the number of $D^{*+}(2010)$ for each decay chain. About $9_{-2}^{+3} \pm 3\%$ of $D^{*+}(2010)$ are found to be decay products of the $D^{*0}(2420)$.

The production cross section was calculated to be
 $\sigma D^{*0}(2420) \cdot \text{BR}[D^{*0}(2420) \rightarrow D^*(2010) \pi] = (130^{+50}_{-35} \pm 55) \text{ pb}.$

Assuming the object to be in a P state, a study of decay angular distribution was made using a simple method [35]. The result slightly favours the 1^+ state hypothesis over the 2^- state hypothesis (χ^2 probability of 70 % vs. 3 %). No clear discrimination is possible with our statistics.

The decay angular distribution was studied in order to constrain the quantum numbers of the object by exploiting the theoretical work of S.U. Chung. Exploiting the sequential characteristics of the decay chain, the double moment method [35] was applied to the decay angular distribution. No significant moment was found at the mass region of the object. The discrimination between an unnatural spin parity ($0^-, 1^+, 2^-, \dots$) and a natural spin parity ($0^+, 1^-, 2^+, \dots$) series was also not possible. In general, the angular distribution study was not conclusive due to lack of statistics.

Direct decay modes ($D\pi$) were studied to constrain the spin parity. Upper limits were obtained on production of the direct decay mode for the object and in a $500 \text{ MeV}/c^2$ mass range near the object. Based on theoretical predictions of the branching ratio between the direct decay mode ($D\pi$) and the sequential decay mode ($D^{*-} \pi^-$) of a 2^- state, a χ^2 probability of the object being a 2^- was calculated. The probability was found to be 2% assuming that the production rate for both charged states of the $D^{*0}(2420)$ is the same. From these χ^2 probabilities (3% from angular distribution analysis and 2% from direct decay mode search) we may conclude that this

object is unlikely to be a 2^+ state.

Assuming that this object is one of the 1^+ states, we can compare the measured width to theoretical width predictions [11]. The observed decay width ($41 \pm_{14}^{22} \text{ MeV } c^2$) is much closer to a β (lower, $\Gamma=19 \text{ MeV}/c^2$) state width than an α (higher, $\Gamma=250 \text{ MeV } c^2$) state (Table 2.3).

Finally, for a consistency check, the charged partners of the object were searched for using the less efficient decay mode ($D^{*-} \pi^0$) and the production rate was calculated. The results are consistent with each other if one assumes the production rate of both charged states of the $D^*(2420)$ are the same.

Chapter 5

Conclusions

In this thesis the production of excited charmed mesons at a 10 GeV e^+e^- experiment was investigated. Very strong evidence (about 6 standard deviations) for a new resonance has been observed near 2420 MeV/c², which we call the $D^{*0}(2420)$, which decays to $D^{*+}\pi^-$. The observed mass and width are (2419 ± 6) MeV/c² and $(41 \pm_{14}^{22})$ MeV/c², respectively. A similar object was seen in another experiment in 1977. The MARK II experiment [38] at the SPEAR storage ring observed an enhancement near 2.44 GeV/c² in the recoil spectrum to $D^0 \rightarrow K^-\pi^-$. It is now clear that at least part of the enhancement seen by MARK II is due to the $D^*(2420)$.

The resonance reported here is most likely one of the P states of c and $\bar{u}$ quarks, according to theoretical mass predictions. Also the P states are expected to be the lowest lying of the orbitally excited charmed states and would be more easily produced than the higher angular momentum states in e^+e^- annihilation.

The possible assignments are $^3P_J(0^+, 1^+, 2^-)$ and $^1P_1(1^+)$. As in the case of excited strange mesons, the 3P_1 and 1P_1 states can and probably do mix, complicating predictions of mass and widths. Almost all theoretical model calculations (section 2.1) have predicted P states lying within 150 MeV/c² of our observed value. Because the 0^- state cannot decay strongly to a vector and a pseudoscalar meson owing to parity conservation, this assignment can be excluded. Of course the possibility exists that more than one resonance contributes to the observed signal because the mass splittings of some of these states are less than their natural width.

The decay angular distribution was studied to constrain the quantum number of the object by exploiting the original work of S.U. Chung. The result of angular distribution analysis weakly favours the 1^+ state over the 2^- state. In general, the angular distribution study was not conclusive due to a lack of statistics.

In this analysis we could not observe any object decaying to $D\pi$ near the 2420 MeV/c² region. Because the theoretical predictions of the decay width of a 2^+ state via a direct decay mode ($D\pi$) is a factor of 1.5~3.5 larger than the decay width in the sequential decay mode ($D^{*-}\pi^-$), it seems unlikely that this object is a 2^- state, assuming that the production rates for both charged states of the $D^{*0}(2420)$ are not very different.

These two facts, namely the results of angular distribution and decay mode analysis, lead us to conclude that for the spin and parity of this object to be a 1^+ state is slightly favoured if this object is an L=1 charmed meson.

Very recently (after the draft of this thesis was written) the CLEO group announced the observation of similar object [39] via the same decay mode ($D^{*+}\pi^-$) with mass of $(2414 \pm 6) \text{ MeV}/c^2$, width of $(53^{+30}_{-20}) \text{ MeV}/c^2$ and the relative $D^{*0}(2420)$ $D^{*-}(2010)$ production rate of $(12 \pm 4 \pm 3) \%$. Because their results are very close to the results of this analysis we may say that both experiments observe the same object.

To constrain theoretical physics parameters we need more statistics to determine spin and parity and measure the mass and width of the object more accurately. Further studies on the direct decay mode ($D\pi$) would be most valuable on determining the spin parity of this object and could possibly lead to the observation of other states.

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