MEASUREMENT OF D_S^*–D_S MASS DIFFERENCE

ARGUS Collaboration

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Using the ARGUS detector at DORIS, we observe the production of D_S^{*+} mesons in e^+e^- annihilation through their subsequent decays to a D_S^+ and a photon. Photons which convert in the beam pipe or drift chamber inner wall are used to obtain a high precision measurement of the $D_S^{*+}-D_S^+$ mass difference, while photons detected in the shower counters are used to determine the production cross section, and to provide an independent measurement of the $D_S^{*+}-D_S^+$ mass difference. The observed $D_S^{*+}-D_S^+$ mass difference is $142.5\pm0.8\pm1.5$ MeV/c^2, and $\sigma(e^+e^-\to D_S^{*+}X)\cdot BR(D_S^{*+}\to D_S^+\gamma)(\cdot BR(D_S^+\to\phi\pi^+)$ is $4.4\pm1.1\pm1.0$ pb at 10.2 GeV. The width of the D_S^{*+} is less than 4.5 MeV/c^2 at 90% confidence level.

The D_S^{*+} meson [#1], $J^P=1^-$, $I=0$ (formerly known as F^{*+}) predicted by the quark model [1], has been observed by a number of experiments, including ARGUS [2], TPC [3], and, more recently, MARK III [4]. Isospin conservation forbids the strong decay to $D_S^+\pi^0$, leaving the electromagnetic decay $D_S^{*+}\to D_S^+\gamma$ as the dominant mode. Hitherto the $D_S^{*+}-D_S^+$ mass difference has been measured with an accuracy of order 10 MeV/c^2. In order to confront the theoretical calculations [5], a much higher precision is necessary. In this letter we report on the results of such a high precision measurement, the combined statistical and systematic uncertainty being reduced to 2 MeV/c^2. The analysis uses only the $D_S^+\to\phi\pi^+$ decay channel of the D_S^+, in order to obtain a D_S^+ signal with low background.

The data presented here were collected using the ARGUS detector at the DORIS II e^+e^- storage ring at DESY. The centre-of-mass energy covered a range from 9.4 to 10.6 GeV, with a weighted mean of 10.2 GeV. Data used in this analysis are derived from a 255.5 pb^{-1} sample, comprising 45.0 pb^{-1} on $\Upsilon(1S)$, 36.8 pb^{-1} on $\Upsilon(2S)$, 103.1 pb^{-1} on $\Upsilon(4S)$ and 70.5 pb^{-1} in the continuum and resonance scanning. This corresponds to approximately two million multihadron events. A brief description of the detector, trigger, and multihadron selection criteria may be found in ref. [6].

For charged particle identification, the specific ionization (dE/dx) in the drift chamber, the time-of-flight (TOF), muon counter and shower counter information are used to form an overall χ^2 for each particle species hypothesis. The likelihood for each particle hypothesis is determined for every charged track in an event; details of the procedure may be found in ref. [7]. Most tracks with momentum below 800 MeV/c are uniquely identified, thus reducing combinatorial background.

All K^+K^- combinations which have a χ^2 of less than 16 for the ϕ mass hypothesis, and which fall within 12 MeV/c^2 of the nominal ϕ mass, are considered as ϕ candidates. Subsequently, D_S^+ candidates are formed by adding a π^+ to the ϕ candidates. Since the D_S^+ has zero spin, the angular distribution of its decay products in its rest frame is uniform. A major background to the D_S^+ signal arises from combinations of ϕ's with unassociated pions [8]. The angular distribution, $\cos\theta_\phi$, of the ϕ with respect to the D_S^+ in the D_S^+ rest frame, of this background is peaked towards $\cos\theta_\phi=1$; the signal, however, is uniformly distributed. By selecting $\phi\pi$ combinations where $\cos\theta_\phi<0.8$, almost half of this background is eliminated, while retaining 90% of the signal. Similarly, since the ϕ has spin one, conservation of angular momentum requires that the ϕ and the π be in an $l=1$ state, and that the ϕ has zero helicity in the D_S^+ rest frame. This results in K mesons from the D_S^+ signal having a $\cos^2\theta_{K^+}$ distribution, where θ_{K^+} is the angle

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[#1] References in this paper to a specific charged state are to be interpreted as implying the charge conjugate state also.

of the K^+ with respect to the π^+, in the ϕ rest frame. Uncorrelated background results in a uniform distribution in $\cos\theta_{K^+}$; 50% of the background, and only 12.5% of the signal are removed by requiring that $|\cos\theta_{K^+}| > 0.5$. These two angular cuts are used in the D_S^* analysis. In fig. 1, we invoke the fact that D_S^+ mesons are produced with high momentum due to the hard fragmentation function associated with primary charmed meson production [9], and require that the reduced momentum of the D_S^+, $x_p = p_{D_S}/p_{max}$, be greater than 0.5.

The $\phi\pi^+$ invariant mass spectrum obtained after the two angular cuts, plus the cut on reduced momentum, is shown in fig. 1. There is a clear enhancement at a mass of $1968.8 \pm 1.4 \pm 3.0$ MeV/c^2, with an RMS width of 13.8 ± 1.3 MeV/c^2. The width is consistent with that expected from the experimental resolution. A smaller enhancement at a mass near 1870 MeV/c^2 corresponds to the Cabibbo suppressed decay of the D^+ meson, seen in the $D^+ \to \phi\pi^+$ decay mode. The $\sigma(e^+e^- \to D_S^+ X) \cdot BR(D_S^+ \to \phi\pi^+)$ is $7.8 \pm 0.8 \pm 1.3$ pb at 10.2 GeV, extrapolated over the entire x_p range [7].

To obtain our best result for the mass of the D_S^+, we consider the mass of the D^0 to be 1864.1 ± 1.4 MeV/c^2, as measured by ARGUS [10], which is 0.5 MeV/c^2 lower than the world average [11]. Correcting the D_S^+ mass by this systematic shift yields a mass measurement of $1969.3 \pm 1.4 \pm 1.4$ MeV/c^2.

To search for a D_S^{*+} signal we have combined photons with all $\phi\pi^+$ combinations within 20 MeV/c^2 of the D_S^+ mass, and which have a χ^2 for the D_S^+ mass hypothesis of less than 16.

The photons are detected by two very different methods. Firstly, photon energies are measured using the array of shower counters. These showering photons we denote by γ_s; they are measured with high efficiency in the energy range used in this analysis, and an energy resolution of approximately 12% at 0.5 GeV [12]. Fig. 2a shows the $\gamma_s\gamma_s$ invariant mass distribution. The π^0 is clearly seen at a mass of

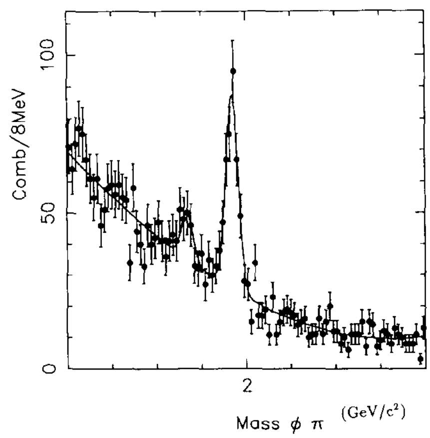

Fig. 1. $\phi\pi^+$ mass spectrum, with $x_p > 0.5$, and angular cuts $\cos\theta_\phi < 0.8$, and $|\cos\theta_K| > 0.5$.

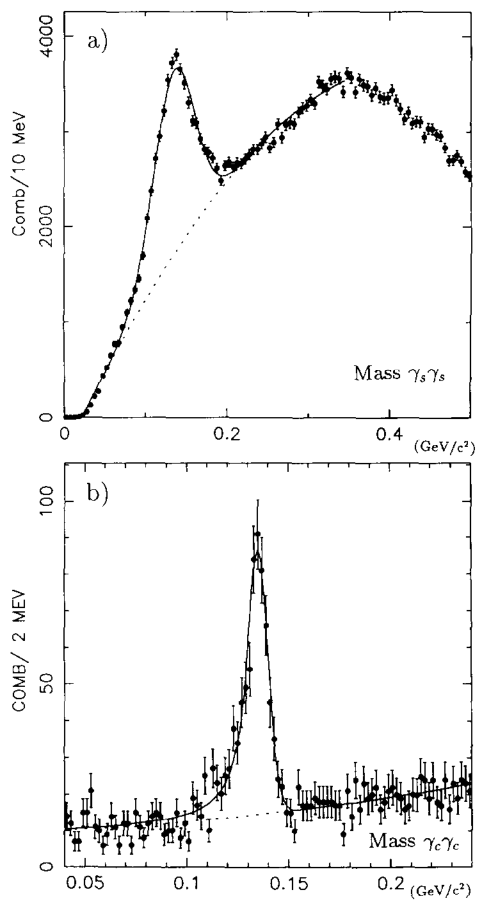

Fig. 2. (a) Mass spectrum $\gamma_s\gamma_s$, showing the neutral pion decaying to two showering photons. The photons are in the energy range of interest in decays of continuum produced D_S^{*+}, $E_\gamma > 0.15$ GeV. The distribution is fitted with a gaussian, plus a radiative tail. (b) Mass spectrum $\gamma_c\gamma_c$, showing neutral pion decaying to two converting photons. The photons are in the energy range relevant in decays of D_S^{*+}, with good reconstruction efficiency, $0.1 < E_\gamma < 0.6$ GeV.

$135.3 \pm 0.3 \pm 4.0$ MeV/c^2, with a width of 23.4 ± 0.4 MeV/c^2. This gives confidence in both the overall calibration of the shower counter system and also the resolution. The high efficiency of this method of photon detection allows us to perform a statistically significant measurement of the production cross section of the D_S^{*+} multiplied by the branching ratio to the $\phi\pi^+$ final state of the D_S^+.

The resolution of the D_S^{*+}–D_S^+ mass difference is dramatically improved by using the second method of photon detection. This method exploits the fact that there is about a 3% probability of photons converting to e^+e^- pairs in the beam pipe, or inner wall of the main drift chamber; these converting photons we denote by γ_c. The resolution with which the energy of these photons is measured is governed by the precise momentum resolution of the ARGUS drift chamber:

$$\sigma_p/p = \sqrt{(0.014p)^2 + (0.01)^2}\,, \qquad (1)$$

where p is in GeV/c. The reconstruction of the γ_c proceeds by finding a secondary vertex formed by an e^+e^- pair. Requiring the invariant mass of each conversion pair to be less than 10 MeV/c^2 results in the $\gamma_c\gamma_c$ invariant mass distribution shown in fig. 2b. The π^0 signal is fitted with a gaussian plus radiative tail. The resulting mass and RMS width are $134.8 \pm 0.4 \pm 1.0$ MeV/c^2 and 5.2 ± 0.4 MeV/c^2, a considerable improvement on the π^0 signal obtained using the γ_s.

Using the first method of photon detection, the D_S^+ candidates are combined with shower counter photons. There is a large background from low energy uncorrelated photons. This results in a given D_S^+ candidate combining with several photons to produce more than one D_S^{*+} candidate in the 130–150 MeV/c^2 mass difference region. This double counting effect is rendered negligible, and the general background is substantially reduced, by requiring that the photons have an energy greater than 180 MeV. Since one expects the D_S^{*+} production to be from primary continuum charm particle production, we exploit the hard charm fragmentation by requiring that $x_p > 0.5$ for the $D_S^+\gamma_s$ system. The data sample used includes data from the $\Upsilon(4S)$, and clearly there could be D_S^{*+} production from the decay of B mesons. The x_p cut selects combinations beyond the kinematic limit for D_S^{*+} from B decay, ensuring that only events from continuum production are included. The mass difference spectrum, $\Delta M = m(D_S^+\gamma_s) - m(D_S^+)$, is shown in fig. 3a. A significant peak is seen at ΔM near 140 MeV/c^2, rather close to the threshold in the mass difference distribution. The shape of the background dominates the systematic error on the measured mass difference. It has been determined in two ways. Firstly, by Monte Carlo; secondly, by fitting to the shape of the mass difference distribution resulting when the $\phi\pi^+$ combinations are required to lie outside of the D_S^+— region. This latter distribution is shown in fig. 3b. These two determinations of the background shape give consistent results. In fitting the distributions in figs. 3a and 3b, the background shape is determined using Monte Carlo; it is a third order polynomial with a threshold factor. The signal is fitted with a gaussian with width fixed to the value

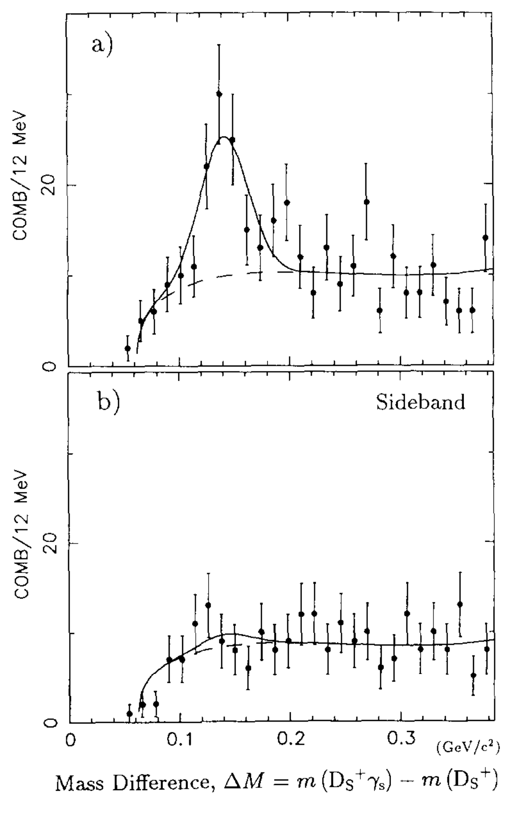

Fig. 3. (a) Mass difference spectrum using showering photons, $\Delta M = m(D_S^+\gamma_s) - m(D_S^+)$. (b) Mass difference spectrum, with the $\phi\pi$ taken from the D_S sideband, within 50 MeV/c^2 of $m(\phi\pi) = 2.16$ GeV/c^2.

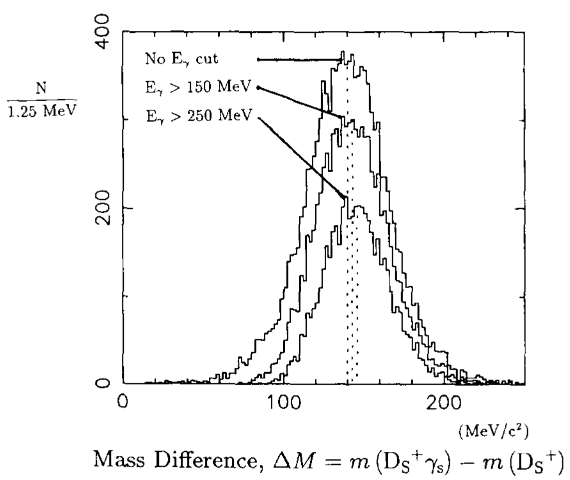

Fig. 4. Shift of ΔM peak as a function of photon energy cut.

21.7 MeV$/c^2$, as determined by the Monte Carlo. The fit results in $68.8^{+13.0}_{-12.3}$ events in the signal, and an uncorrected mass difference of

$$\Delta M = m(D_S^+\gamma_s) - m(D_S^+) = 141.7 \pm 4.8\ \mathrm{MeV}/c^2\ . \tag{2}$$

Fitting the same background and signal shape to the sideband distribution in fig. 3b does not result in a statistical significant signal: $6.1^{+9.3}_{-8.6}$ events at a mass difference of 141.7 MeV$/c^2$. Due to the finite resolution of the photon energy measurement, the requirement that the photons have an energy greater than 180 MeV introduces an experimental bias to larger mass differences. In fig. 4 we show the result of a Monte Carlo simulation of this bias; as the photon energy cut increases, the D_S^{*+}–D_S^+ mass difference effectively shifts to higher values. In this way we estimate that the cuts applied to the data yield a mass difference shift of 3.1 MeV$/c^2$, resulting in a corrected value of $\Delta M = 138.6 \pm 4.8 \pm 4.0$ MeV$/c^2$. The corrected result is listed in table 1. In extracting the production cross section multiplied by the branching ratio of the D_S^+ to $\phi\pi^+$ we must correct for the effect of the cut on x_p, the reduced momentum. This is done by extrapolating over all x_p, using the Peterson et al. fragmentation function [9] with parameter [7] $\epsilon = 0.04^{+0.03}_{-0.01}$, which results in $\sigma(e^+e^- \to D_S^{*+}X) \cdot BR(D_S^{*+} \to D_S^+\gamma) \cdot BR(D_S^+ \to \phi\pi^+) = 4.4 \pm 1.1 \pm 1.0$ pb for the production of D_S^{*+} from the continuum. The systematic error is dominated by the extrapolation of the fragmentation function. We deduce that $(56 \pm 22 \pm 11)$% of D_S^+ are produced from D_S^{*+}.

In using the converted photons to make a precise measurement of the mass difference, we have relaxed some of the kinematical cuts mentioned above, in order to increase the acceptance. The relaxed cuts are $\cos\theta_\phi < 0.9$ and a mass cut around the D_S^+ of ± 25 MeV$/c^2$. The cut of $\cos\theta_{K^+}| > 0.5$ is unchanged. Converted photons are combined with D_S^+ candidates; the resulting mass difference spectrum, $\Delta M = m(D_S^+\gamma_c) - m(D_S^+)$, is shown in fig. 5a. The narrow peak at a mass difference near 140 MeV$/c^2$ is fitted with a gaussian of fixed width 2.0 MeV$/c^2$, allowing for the radiative tail, while the background is

Table 1

	Mass (MeV$/c^2$)	Width (MeV$/c^2$)	Number events
$D_S^+\gamma_s$	$138.6 \pm 4.8 \pm 4.0$	21.7	$68.8^{+13.0}_{-12.3}$
$D_S^+\gamma_c$	$142.9 \pm 0.8 \pm 1.6$	2.0	$9.9^{+3.8}_{-3.0}$
combined	$142.5 \pm 0.8 \pm 1.5$		

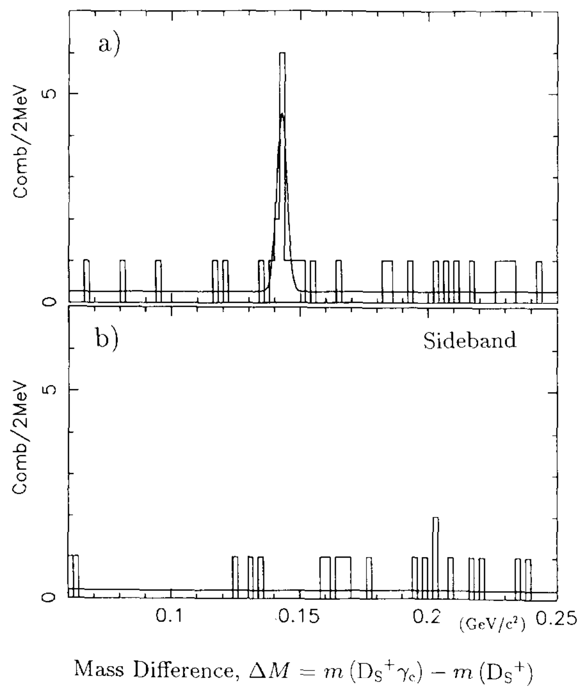

Fig. 5. (a) Mass difference spectrum using converted photons, $\Delta M = m(D_S^+\gamma_c) - m(D_S^+)$. (b) Mass difference spectrum, with $\phi\pi$ taken from sideband, within 25 MeV$/c^2$ of $m(\phi\pi) = 2.15$ GeV$/c^2$.

flat. Fitting to this distribution results in a signal of $9.9^{+3.7}_{-3.0}$ events, at a mass difference of

$$\Delta M = m(D_S^+\gamma_c) - m(D_S^+) = 142.9 \pm 0.8 \text{ MeV}/c^2 . \quad (3)$$

Allowing the width of the signal to vary yields $\Gamma(D_S^{*+}) < 4.5$ MeV/c^2 at 90% CL. No signal is evident when the D_S^+ is taken from the sideband region, as seen in fig. 5b.

We verify the mass scale by using the measured value of the D^{*0}–D^0 mass difference. We have measured this mass difference using the process,

$$D^{*0} \to D^0\gamma_c$$
$$\text{where} \quad D^0 \to K^-\pi^+, D^0 \to K^-\pi^+\pi^+\pi^- , \quad (4)$$

which has very similar systematics to the process under study, although it has a much larger background, due to the many photons correlated with D^0 mesons, through the decay $D^{*0} \to D^0\pi^0$. The mass difference spectrum $\Delta M = m(D^0\gamma_c) - m(D^0)$, is shown in fig. 6. The D^{*0}–D^0 mass difference is 142.2 ± 0.9 MeV/c^2, in good agreement with the Particle Data Group value [11] of 142.5 ± 1.3 MeV/c^2. The quoted systematic error on the D_S^{*+}–D_S^+ mass difference is dominated by the Particle Data Group's statistical error on the D^{*0}–D^0 mass difference.

In conclusion, the production cross section from continuum at $\langle E_{CM} \rangle = 10.2$ GeV is

$$\sigma(D_S^{*+}) \cdot BR(D_S^{*+} \to D_S^+\gamma) \cdot BR(D_s^+ \to \phi\pi^+)$$
$$= 4.4 \pm 1.1 \pm 1.0 \text{ pb} \quad (5)$$

or

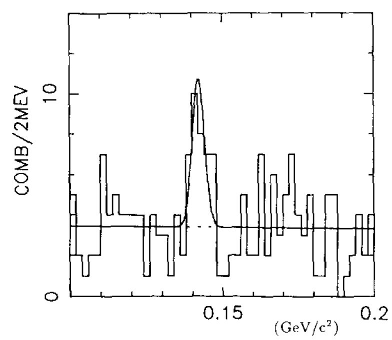

Fig. 6. Mass difference spectrum, $\Delta M = m(D^0\gamma_c) - m(D^0)$.

$$R_{D_S^{*+}} \cdot BR(D_S^+ \to \phi\pi^+) = (5.3 \pm 1.3 \pm 1.2) \times 10^{-3} , \quad (6)$$

where $R_{D_S^{*+}}$ is the production cross section relative to $\sigma_{\mu\mu}$, the muon pair production cross section. The two independent D_S^{*+}–D_S^+ mass difference measurements are combined to give

$$\Delta M = 142.5 \pm 0.8 \pm 1.5 \text{ MeV}/c^2 . \quad (7)$$

The mass of the D_S^+ has been measured using the decay $D_S^+ \to \phi\pi$ with the result

$$M_{D_S^+} = 1969.3 \pm 1.4 \pm 1.4 \text{ MeV}/c^2 . \quad (8)$$

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