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TPC/Two-Gamma Collaboration

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The TPC/Two-Gamma Collaboration has measured the inclusive cross section for production of charmed $D^{*\pm}$ mesons in photon–photon collisions. The reaction utilized was $e^+e^- \to e^+e^- D^{*\pm} X$, with $D^{*\pm} \to D^0\pi^\pm$, $D^0 \to K^\mp\pi^\pm$, and either zero or one outgoing $e^\pm$ detected. The result, $\sigma(e^+e^- \to e^+e^- D^{*\pm} X) = 74 \pm 26 \pm 19$ pb, is in agreement with the quark parton model prediction for $e^+e^- \to e^+e^- c\bar{c}$, combined with a Lund model for the hadronization of the charmed quarks.

The two-photon production of a pair of charmed quarks in the $e^+e^- \to e^+e^- c\bar{c}$ reaction is of interest as a test of the quark parton model (QPM). The charmed quarks may either form a charmonium resonance or fragment into charmed particles. Exclusive two-photon production of the η_c meson has been observed with measured rates ranging from agreement [1] with the QPM prediction to levels several times above it [2]. Inclusive production of the charmed D^{*+} meson using the $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^0$ decay mode has been reported [3] at a rate higher than the QPM prediction. In this letter we describe a measurement of inclusive D^{*+} meson pro-

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duction using the $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decay channel [4] [#1].

The data were collected at 29 GeV center-of-mass energy with the TPC/Two-Gamma facility [5] at the SLAC e^+e^- storage ring PEP. The ability to identify kaons, together with the kinematic properties of the cascade decay $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, permit the identification of the D^{*+} in this all-charged decay channel. The time projection chamber (TPC), in conjunction with a 13.25 kG magnetic field, was used to identify kaons and pions by simultaneous measurements of momentum (p) and energy loss (dE/dx). The momentum resolution at polar angles near $\frac{1}{2}\pi$ is given by $(\sigma_p/p)^2 \approx (1.5\%)^2 + (0.65\% \times p)^2$ (p in GeV). Energy loss was measured with a typical resolution of 3.5%. Two proportional-mode pole-tip calorimeters (PTC) and a hexagonal Geiger-mode calorimeter (HEX) provided electromagnetic shower detection at polar angles above 260 mrad. Scattered electrons and positrons (used to tag two-photon interactions, and to determine the four-momentum q of one of the virtual photons) as well as photons were detected in two arrays of NaI crystals (NAI) in the polar angular range 26–90 mrad, and in two lead-scintillator shower counters (SHW) from 100–180 mrad. The charge associated with an energy deposit was measured using two arrays of fifteen drift chamber planes each, positioned in front of these calorimeters.

We used two different triggers. Open trigger, based on information from the TPC, required at least two charged tracks, each with polar angle $\theta \gtrsim 26°$, projecting back to the interaction point within ≈ 20 cm along the beam axis. Tracks with $\theta \gtrsim 45°$ were required to have coincident hits in a drift chamber just outside the solenoid coil. The data sample collected with this trigger will be referred to as the "untagged" sample [#2]; it has an integrated luminosity of 69 pb^{-1}. The other trigger required an energy cluster in either an NAI or SHW calorimeter, together with at least one track in the TPC. This data sample will be referred to as the "single-tagged" sample; it has an integrated luminosity of 67 pb^{-1}, with $0.1 < -q^2 < 6.8$ GeV^2.

Tracks used in the D^{*+} reconstruction were required to have a distance of closest approach to the interaction point of less than 5 cm in the plane transverse to the beam and less than 10 cm along the beam. To find D^0 candidates, the effective mass of each combination of oppositely charged kaon and pion tracks was formed. The momentum of a track had to be larger than 100 MeV (300 MeV) for a pion (kaon) candidate, and the fractional error on the momentum had to be less than 30%. For a precise dE/dx measurement the two tracks were required to have at least 30 dE/dx measurements out of a possible maximum of 183. A track was selected as a kaon candidate if the χ^2 for the kaon dE/dx hypothesis was less than that for the pion hypothesis. The confidence level for the combined $K^-\pi^+$ assignment had to be larger than 10%. A maximum of 0.90 was imposed on the cosine of the angle between the K^- direction in the $K^-\pi^+$ rest frame and the direction of the boost needed to reach that frame. (This angle should be isotropic for D^* decays; the cut preferentially removed random particle combinations.)

The effective mass spectrum of the $K^-\pi^+$ combinations after these cuts is dominated by combinatoric background, and does not show a D^0 signal. However, $D^{*+} \to D^0\pi^+$ candidates can be found by combining the tracks of the D^0 candidate with all tracks of charge *opposite* to the charge of the kaon and computing the mass difference $\Delta M = M_{K^-\pi^+\pi^+} - M_{K^-\pi^+}$. Fig. 1a shows the $K^-\pi^+$ effective mass spectrum for untagged events for values of ΔM within ≈ 2.5 MeV of $M_{D^{*+}} - M_{D^0}$. A narrow peak around the D^0 mass, $M_{K^-\pi^+} = 1.86$ GeV, is seen. There is also a satellite peak around 1.6 GeV; this has been identified as a reflection originating from $D^0 \to K^-\rho^+$, $\rho^+ \to \pi^+\pi^0$ and $D^0 \to K^{*-}\pi^+$, $K^{*-} \to K^-\pi^0$, with the π^0 unobserved [6]. The open data points in fig. 1a show $M_{K^-\pi^+}$ for the "wrong-sign" selection based on the mass difference $\Delta M = M_{K^-\pi^+\pi^-} - M_{K^-\pi^+}$; these contain no excess of events around 1.86 GeV or 1.6 GeV. Alternatively, evidence for D^{*+} production can be found in the ΔM spectrum after requiring the effective $K^-\pi^+$ mass to be compatible with the D^0 mass. By restricting the effective $K^-\pi^+$ mass to the region between 1.78 and 1.94 GeV, we avoid the satellite peak as well as possible contributions from other,

[#1] Throughout this paper, statements regarding a particular state include its charge conjugate state as well; and D^{*+} production cross sections denote an incoherent sum of cross sections for D^{*+} and D^{*-} production.

[#2] In the untagged sample the presence of a tag is allowed, but not required in the trigger.

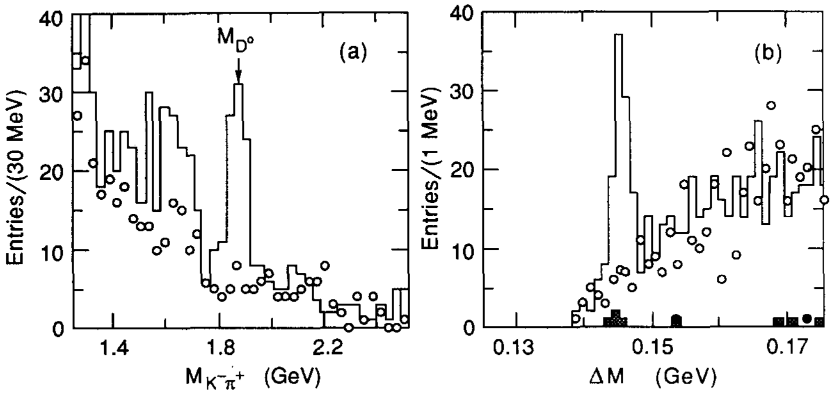

Fig. 1. (a) The histogram shows the $K^-\pi^+$ effective mass distribution for events with $143 < M_{K^-\pi^+\pi^+} - M_{K^-\pi^+} < 148$ MeV. The open data points represent the same distribution for the wrong-sign selection (see text). (b) The open histogram shows the $M_{K^-\pi^+\pi^+} - M_{K^-\pi^+}$ mass difference distribution for events with $1.78 < M_{K^-\pi^+} < 1.94$ GeV. The open data points represent the same distribution for the wrong-sign selection. The shaded histogram and solid data points show the non-zero entries for the single-tagged data and wrong-sign events, respectively.

higher multiplicity D^0 decays. After this mass cut we obtain the ΔM distribution shown in fig. 1b. A clear peak is seen at $\Delta M = 145.5$ MeV, near the nominal value of 145.45 MeV [7]. After a subtraction of the wrong-sign background, shown as the open data points in fig. 1b, and the subsequent ΔM cut, 81 ± 11 inclusive D^{*+} events remain; most of these will be attributed to the e^+e^- annihilation process.

In contrast, by using the single-tagged sample with a minimum tag energy of 7 GeV we select a two-photon signal nearly free of annihilation background. The ΔM spectrum for the resulting events is shown in fig. 1b as the solid histogram; it contains four events in the signal region. The wrong-sign selection is shown by the solid data points in fig. 1b; it has no entries in the signal region.

The best handle for separating two-photon events from annihilation events in the untagged sample is that most of the former have a visible hadronic energy W_{vis} well below $\sqrt{s}$. In fig. 2a we show the W_{vis} spectrum for the events with $143 \leqslant \Delta M \leqslant 148$ MeV for the untagged and single-tagged samples. W_{vis} is calculated from the *charged* particles, excluding the tag (if present). The spectrum has two clusters of events; the one centered at $W_{vis} \approx 16$ GeV comes from e^+e^- annihilation, and the other, at low W_{vis}, predominantly from events produced by two-photon interactions. As expected, the four D^{*+} events in the single-tagged sample cluster at low W_{vis}. For this reason we cannot make the cut on $2E_{D^*}/\sqrt{s}$, the fractional D^{*+} energy, that is customarily made to enhance the D^{*+} signal in e^+e^- annihilation. We also present in fig. 2b the transverse momentum (P_T^2) distribution. Here P_T is the vector sum of the transverse momenta calculated from the *charged* particles only (excluding the tag). All four D^{*+} events in the single-tagged sample have $P_T^2 < 6.25$ GeV^2. On the basis of these observations and of the Monte Carlo calculations described below, we suppress annihilation events from the untagged sample by requiring $W_{vis} < 8$ GeV and $P_T^2 < 6.25$ GeV^2. After these cuts and the wrong-sign background subtraction, 10 ± 3.7 inclusive D^{*+} events remain in the untagged sample.

To obtain a cross section, and also to determine the remaining background from e^+e^- annihilation, we calculate the D^{*+} acceptance using the event generators specified below. The events were processed through a detector simulation (which includes resolution effects, energy loss, multiple scattering, nuclear interactions in the detector materials and a trigger simulation), and then subjected to the same cuts as the data. The resulting W_{vis} and P_T^2 predictions are shown in fig. 2. They are in good agreement with the data, and the W_{vis} curves indicate our ability to separate the two-photon events in the untagged sample.

The Monte Carlo simulation of the e^+e^- annihilation process combined the Berends and Kleiss [8]

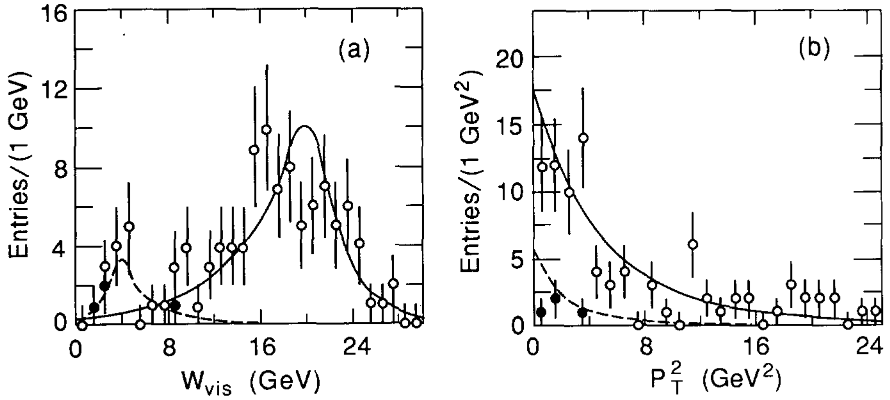

Fig. 2. The open data points show (a) the W_{vis}, and (b) the P_T^2 distributions for the D^{*+} events identified in the untagged sample; the solid data points give the non-zero entries for the four D^{*+} events found in the single-tagged sample. The data still include the background under the peak in fig. 1b. The continuous and dashed curves represent the shapes of the Monte Carlo predictions for the e^+e^- annihilation process and the untagged two-photon process, respectively (see footnote 3).

formalism to account for initial state photon radiation with the Lund model [9] for the hadronization of the quark pairs [#3], and led to a $D^{*+} \to K^-\pi^+\pi^+$ acceptance of 29%. Using a branching fraction of $(2.1\pm0.4)\%$ [#4], the 81 ± 11 inclusive D^{*+} events identified in the untagged sample yield, for inclusive D^{*+} production by e^+e^- annihilation, $\sigma(e^+e^- \to D^{*+}X) = 178\pm26\pm32$ pb (see footnote 1). This cross section is corrected for the small contamination, 6 events, expected from two-photon production described below. The first error represents the statistical uncertainty and the second the quadratic sum of the systematic uncertainties in the integrated luminosity (10%), in the D^{*+} selection algorithm (10%), and in the D^{*+} reconstruction efficiency (10%). The latter uncertainty was determined by replacing the Lund hadronization scheme by a scheme which always hadronized a $c\bar{c}$ (or $b\bar{b}$) quark pair into a $D^*\bar{D}^*$ meson pair. The measured cross section is in agreement with earlier measurements [11] and also in accord with the simple prediction $\sigma(e^+e^- \to D^{*+}X) = \frac{3}{4}\sigma(e^+e^- \to c\bar{c}) + \frac{3}{4}\sigma(e^+e^- \to b\bar{b}) = 155$ pb (see footnote 1), which follows if one assumes that [#5] (a) the D and D* production alone saturate the total charm cross section in e^+e^- annihilation, (b) the charged and neutral production are equal, and (c) D* production is three times the D production.

Even after the W_{vis} and P_T^2 cuts, there remains in the untagged two-photon sample a background of 2.1 events due to D^{*+} production by radiative annihilation. The radiation of a high energy photon by the incident electron or positron leads to a relatively low e^+e^- center-of-mass energy. A $c\bar{c}$ quark pair produced by subsequent e^+e^- annihilation will, in many respects (W_{vis}, P_T^2, Lorentz boost), be similar to a two-photon produced $c\bar{c}$ state. The annihilation background in the single-tagged sample is negligible even without the W_{vis} and P_T^2 cuts. To verify these Monte Carlo predictions, we searched for D* events in which a radiated photon with energy greater than 10 GeV was detected in one of the calorimeters. The result (3 events) was in accord with the Monte Carlo prediction (1.7 events). A subtraction of the e^+e^- annihilation contamination leaves 7.9 ± 3.8 and

[#3] Quark pairs of all flavors were included. In particular, since a b quark decays predominantly to a c quark it is necessary to include the production of $b\bar{b}$ quark pairs, which contribute $\approx 25\%$ for the e^+e^- annihilation process. In the case of the two-photon process the b quark contribution is negligible because (a) it involves the fourth power of the quark charges and (b) it only contributes if the two-photon invariant mass exceeds twice the mass of the b quark.

[#4] $Br(D^0 \to K^-\pi^+) = (4.2\pm0.6)\%$ was taken from ref. [10], and $Br(D^{*+} \to D^0\pi^+) = (49\pm8)\%$ was taken from ref. [7].

[#5] These assumptions are in reasonable agreement with experimental results at center-of-mass energies from 10–34 GeV and with the Lund hadronization model. See for example ref. [12].

4.0 ± 2.0 two-photon produced D^{*+} events in the untagged and single-tagged samples, respectively. Two of the events are common to the two samples (see footnote 2).

An estimate of the acceptance for the two-photon process was obtained from a QPM calculation for the $e^+e^- \to e^+e^- c\bar{c}$ process combined with the Lund model for the hadronization of the $c\bar{c}$ quark pair. The calculated D^{*+} reconstruction efficiency is more sensitive to the details of hadronization than is the case for the e^+e^- annihilation process. This is largely due to model-dependence of the predicted fraction of events in the W region just above threshold, where the two-photon flux is largest and the acceptance is rapidly varying. The $e^+e^- \to e^+e^- c\bar{c}$ cross section was obtained from the exact $[O(\alpha^4)]$ $e^+e^- \to e^+e^- \mu^+\mu^-$ cross section [13], including the contributions from transverse and longitudinal photons, by a substitution of the charmed quark mass for the muon mass and a multiplication by $3(\frac{2}{3})^4$ to account for color and the charge of the charmed quark. Our acceptance calculation is based on a charmed quark mass of $m_c = 1.6$ GeV and only admits $c\bar{c}$ quark pair masses above the threshold for $D^*\bar{D}^*$ meson pair production (4.02 GeV). This gives an acceptance of 9.3% for the untagged sample, while for the tagged sample the product of tagging probability and final state acceptance is 2.8%. In the QPM calculation the c-quarks are pointlike; if a J/ψ form factor were introduced to allow for non-pointlike q^2-dependence, the tagging probability would change by $\approx 10\%$.

The 7.9 ± 3.8 events in the untagged sample yield $\sigma(e^+e^- \to e^+e^- D^{*+}X) = 59 \pm 28 \pm 15$ pb, and the 4.0 ± 2.0 events in the single-tagged sample yield $\sigma(e^+e^- \to e^+e^- D^{*+}X) = 102 \pm 51 \pm 27$ pb for the cross section of inclusive D^{*+} production via the two-photon mechanism [#6]. In both cross sections the first error represents the statistical uncertainty and the second the quadratic sum of the systematic uncertainties in the integrated luminosity (10%), the tagging efficiency (10%), the D^{*+} selection algorithm (10%) and the D^{*+} reconstruction efficiency (20%). The 20% branching fraction uncertainty is not included. The average of the two methods, using Poisson distributions to describe the low statistics results and taking into account the correlation between the untagged and single-tagged results, gives $\sigma(e^+e^- \to e^+e^- D^{*+}X) = 74 \pm 26 \pm 19$ pb [#7] (see also footnote 1). This can be compared to the simple prediction $\sigma(e^+e^- \to e^+e^- D^{*+}X) = \frac{3}{4}\sigma(e^+e^- \to e^+e^- c\bar{c}) = 43$ pb. The ratio of the data to our QPM prediction does not support JADE's conclusion [3] of excess D^{*+} production [#8].

To summarize, we have observed inclusive D^{*+} production in photon–photon collisions at a rate compatible with the QPM prediction for $e^+e^- \to e^+e^- c\bar{c}$ combined with a conventional model for the hadronization of the charmed quarks.

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[#6] The $|q|^2$ distribution of the data is compatible with the Monte Carlo simulation. The mean and RMS $|q|^2$ values for tagged data are 2.0 and 1.6 GeV^2, compared to the Monte Carlo values of 1.5 and 1.6 GeV^2.

[#7] We also studied the channel used by JADE [3], $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$. Due to a large combinatoric background, the analysis of the untagged sample could only be performed for energetic D^{*+} mesons ($2E_{D^*}/\sqrt{s} > 0.4$) and was therefore only sensitive to the e^+e^- annihilation process. Only one single-tagged two-photon event was identified, resulting in a cross section of $18 \pm 18 \pm 4$ pb. That value and the measured annihilation cross section, $185 \pm 28 \pm 22$ pb, are consistent with the results from the $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decay mode of the D^{*+} reported in this letter. The details can be found in ref. [4].

[#8] There is an unavoidable model-dependence to such comparisons. The predicted e^+e^- cross section is sensitive to the value of m_c used in computing $\sigma(\gamma\gamma \to c\bar{c})$, and to the assumed value and threshold dependence of the ratio $\sigma(\gamma\gamma \to D^{*+}D^{*-}) / \sigma(\gamma\gamma \to c\bar{c})$. We have assumed a constant ratio above a minimum W of 4.02 GeV, and not included any lower-mass $c\bar{c}$ pairs in the calculation. JADE, on the other hand, did not make this W cut, and used $m_c = 1.5$ GeV as compared to our 1.6 GeV. Our ratio of data to QPM prediction would decrease if we were to follow JADE's prescription.

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