OBSERVATION OF CHARMED MESONS IN PHOTON–PHOTON COLLISIONS

JADE Collaboration

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Received 10 October 1986

The inclusive production of $D^{*\pm}$ mesons in single tagged photon–photon collisions is investigated using the JADE detector at PETRA. $D^{*\pm}$ mesons are reconstructed through their decay into $D^0+\pi^\pm$ where the D^0 decays via $D^0\to K\pi\pi^0$. The event rate and topology are compared to the expectations of c quark production in the quark–parton model: $\gamma\gamma\to c\bar{c}$.

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Recent experiments at electron–positron colliding beam facilities have confirmed the existence of jets [†1] at high momentum, transverse to the e^+e^- beam axis, in gamma–gamma collisions [2–4]. When the detected hadronic invariant mass, W_{vis}, is greater than 3 GeV, the total cross section is dominated by jet-like events produced at low p_T^{jet} as described by generalized vector-meson dominance (GVDM) [5] and for $p_T^{jet} > 3$ GeV, by the quark–parton model (QPM). Because the coupling of two photons to two partons, via the box diagram, is proportional to the fourth power of the parton charge, a large contribution to the high-p_T^{jet} cross section is expected to come from charmed quarks. On the other hand, less than 1% of the GVDM cross section is expected to contain charm, based on observations made with real and virtual photon collisions on proton targets [6]. Since annihilation experiments suggest that charmed quarks fragment preferentially to the vector D*(2010) mesons [7], the isolation of a D* signal, particularly in high p_T^{jet} events, provides a method of studying the QPM interaction and its QCD modifications.

In this experiment, multihadronic two-photon collisions were isolated by requiring a single "tagged" electron in one of the two small-angle electron–photon detectors ($37.5 \leqslant \theta_{tag} \leqslant 75$ mrad). A complete description of the JADE detector and its particle measurement and identification properties is given elsewhere [8]. The essential components for the present analysis are the central jet chamber, providing not only tracking information but also up to 48 samples of the ionization energy loss, dE/dx, per track, and the lead-glass electromagnetic calorimeter surrounding the jet chamber. Rather severe cuts were placed on the selection of hadronic events in order to produce a sample free from annihilation background and suitable for particle identification in the D* analysis. Here we can summarize the important cuts in the data selection:

Charged- and neutral-particle momentum:

$|p_i| \geqslant 100$ MeV/c.

Number of charged hadrons:

$n_{ch} \geqslant 4$.

Visible total hadronic mass:

$4\ \text{GeV} \leqslant W_{vis} \leqslant E_{beam}$.

Total longitudinal momentum including the tagged electron:

$$\left|\sum_i p_{z_i}\right| \geqslant 12\ \text{GeV}.$$

Energy of the tagged electron:

$E_{tag} \geqslant 0.6\ E_{beam}$.

The majority of annihilation events were removed by the W_{vis} and single-tag constraints. Those annihilation events where one of the incoming leptons radiates a hard photon into the tagging system were further supressed by the longitudinal momentum cut. Monte Carlo studies using the Berends and Kleiss simulation [9] indicate that the remaining annihilation background was only 1% of the total event sample. The total integrated luminosity was 90 pb^{-1} with an average beam energy of 19 GeV.

Our analysis follows the usual mass difference technique which exploits the low-Q value of the decay $D^* \to D^0\pi$ [10]. The D^0 decay channel with the largest branching ratio is $D^0 \to K^-\pi^+\pi^0$ ($\bar{D}^0 \to K^+\pi^-\pi^0$) and since JADE has good π^0 identification, this mode was chosen as the most likely in which to see a charged D* signal. First, possible π^0 candidates were searched for by pairing all photons detected in the barrel and end-cap lead-glass arrays with energies greater than 100 MeV and selecting those pairs whose invariant mass lay in the region $50 \leqslant M_{\gamma\gamma} \leqslant 200$ MeV. The probability that a particular pair was from a π^0 decay, P_{π^0}, was determined from a 1C kinematical fit, in which the invariant mass of the photons was constrained to the π^0 mass. A good π^0 was defined to be a photon pair with $P_{\pi^0} > 0.01$. All pairs of oppositely charged tracks were then combined with the π^0's to make D^0 candidates. Each track was considered in turn to be either a kaon or a pion, with an additional constraint that the probability of the kaon candidate being a real kaon, as calculated from the dE/dx measurement, was greater than 0.01. From this sample the combination was accepted as a possible D^0 if the $K\pi\pi^0$ invariant mass lay in the range $1.45 \leqslant M_{K\pi\pi^0} \leqslant 2.20$ GeV.

[†1] In the JADE analysis, jets are defined using a cluster algorithm [1] and p_T^{jet} is the component of the total jet momentum transverse to the e^-e^- beam axis.

Next, the D^0 candidates were combined with a further charged track, assumed to be a pion, to form possible D*'s. In order to reduce the considerable amount of background from random combinations, a cut was made on the fractional energy of the D*; since the D* was expected to take most of the original quark's momentum, D* candidates were rejected if $x_{D^*} = D_{D^*}/E_{beam}$ was less than 0.5. Further constraints were then applied to the D^0 and lone π candidates. First, the lone pion had to have a momentum of at least 50 MeV/c in the $\gamma\gamma$ centre of mass system, since very low momentum tracks tend to produce low-mass D* candidates simply due to kinematics. Secondly, in order to combine only tracks in approximately the same hemisphere, the D^0–π opening angle, in the $\gamma\gamma$ centre of mass system, was limited to 90°. Finally, the ratio of the lone pion to the D^0 momentum was constrained to be less than 0.3. This comes purely from the decay properties of the D* where, due to the low-Q value, the lone pion obtains most of its momentum from the Lorentz boost into the $\gamma\gamma$ rest frame, rather than from the D* decay itself. Consequently, it should be of only low momentum compared to the D^0, the latter taking away most of the original D*'s momentum. All quantities were evaluated in the $\gamma\gamma$ centre of mass system, as defined by the final state rest frame.

The resulting D*–D^0 mass difference, ΔM, is shown in fig. 1. A clear peak is visible around 145 MeV. To demonstrate that the presumed D* signal is not caused by spurious kinematic effects and to help estimate the background contribution under the peak, the analysis was repeated for two independent control samples. These were:

(i) D^0 combinations with $2.30 \leqslant M_{D^0} \leqslant 3.00$ GeV, and

(ii) D* combinations with the correct D^0 mass, but with all tracks having the same charge, such as $K^+\pi^+\pi^0\pi^+$.

The results are shown in figs. 2 and 3 and no peak is visible.

It was possible to estimate the contribution from background annihilation events, which can trigger the tagging system by hard photon radiation, as a source of the D* events in two ways. First, the analysis was repeated on a large sample of annihilation Monte Carlo events generated using the Lund program [11] with initial state radiation according to Berends and Kleiss [9]. From this it was possible to conclude that there was negligible annihilation background to the observed D* signal. Secondly, the real data were reanalyzed with the longitudinal momentum cut reversed in order to suppress the two-photon signal,

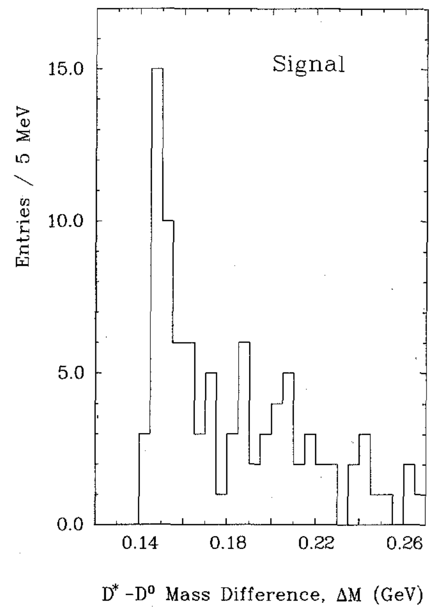

Fig. 1. D*–D^0 mass difference, ΔM, for entries with $1.45 \leqslant M_{K\pi\pi^0} \leqslant 2.20$ GeV.

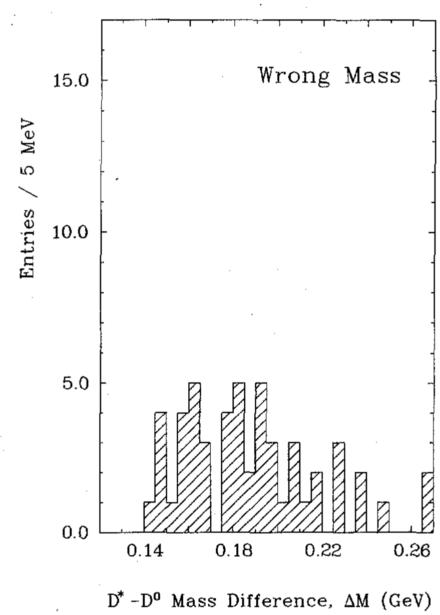

Fig. 2. ΔM, for entries with $2.30 \leqslant M_{K\pi\pi^0} \leqslant 3.00$ GeV.

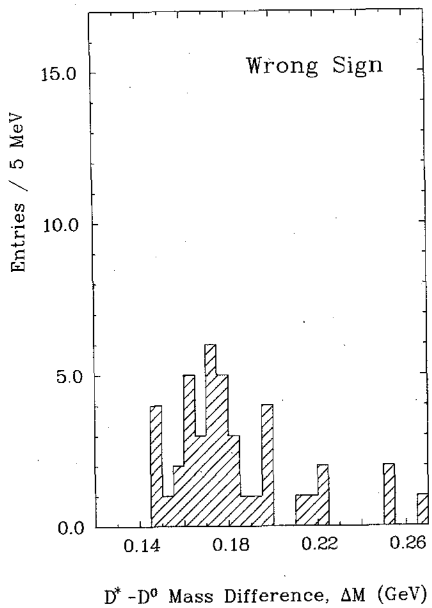

Fig. 3. ΔM, for entries with $1.45 \leqslant M_{K\pi\pi^0} \leqslant 2.20$ GeV, but all charged tracks with same sign.

leaving mainly the annihilation background. Once again, there was negligible annihilation background in the region $\Delta M < 160$ MeV.

A search for D* mesons via the decay $D^0 \to K^- \pi^+$, which has a smaller branching ratio, was also made but no statistically significant signal could be seen. This does not, however, conflict with the number of D*'s observed in the $K\pi\pi^0$ channel.

The number of events observed in the region $\Delta M < 160$ MeV is 32 and, using the "wrong mass" plot of fig. 2, we estimate the background to be 13 events. This was calculated by normalizing the "wrong mass" to the "signal" plot outside the signal region. The number of D* events is therefore 19 with a statistical uncertainty of ± 7. Alternative methods of estimating the background, such as using the "wrong sign" plot, suggest an additional systematic error of ± 3.

In order to investigate the likely source of the charmed mesons, the topology of the 32 events observed was compared with $c\bar{c}$ events generated by QPM Monte Carlo routines and also with GVDM MC events, not containing charm [12] [‡2] The event variables considered were the mean Q^2, the mean jet p_T^2 determined from the sphericity and thrust axes and by the Dorfan cluster algorithm [1], and the mean values of sphericity $\langle S \rangle$ and thrust $\langle T \rangle$. The results are given in table 1. It can be seen that the events are typically jet-like, as one would expect from both QPM and GVDM but the mean Q^2 of the events and the mean jet transverse momentum is much closer to the QPM expectation.

Given as knowledge of the $D^* \to D^0\pi$ and $D^0 \to K^-\pi^+\pi^0$ branching ratios and the efficiency for detecting D*'s, and if additional assumptions are made on the fragmentation of c quarks, it is possible to compare our observed signal with the QPM expectation.

The event detection efficiency was determined from a QPM Monte Carlo using the Vermaseren generator for gamma–gamma to lepton pairs [13] and the Lund fragmentation scheme. Charmed quarks with a mass of 1.5 GeV were produced and forced to fragment to D* mesons, with the D* following the required decay modes. The Monte Carlo events were then passed through a detector simulation program and analyzed in the same way as the real data. The overall detection efficiency for D* events, including the tagging efficiency, was $(0.4 \pm 0.1)\%$ where most of the error is due to systematic uncertainties, and in

‡2 The final state hadrons have a limited p_T according to $d\sigma/dp_T^2 \sim \exp(-2.5 p_T^2)$.

Table 1
Comparison between observed D*, QPM $c\bar{c}$ MC and GVDM MC event topologies. $\langle$jet $p_T^2\rangle$ is given for three cases. Case (a): using the cluster algorithm of ref. [1]. Case (b): as defined by the sphericity axis. Case (c): as defined by the thrust axis.

Topologies	$\langle Q^2 \rangle$ (GeV²)	$\langle$jet $p_T^2\rangle$ (GeV²)			$\langle S \rangle$	$\langle T \rangle$
		case (a)	case (b)	case (c)		
D* events	0.91±0.10	2.3±0.3	1.9±0.3	2.3±0.4	0.45±0.03	0.74±0.01
QPM $c\bar{c}$	0.86±0.02	3.1±0.1	2.3±0.1	2.6±0.1	0.43±0.01	0.75±0.01
GVDM	0.72±0.02	1.4±0.1	1.2±0.1	1.4±0.1	0.44±0.01	0.74±0.01

particular errors associated with the dE/dx simulation.

The D* and D^0 branching ratios were taken to be (64 ± 11)% for $D^* \to D^0\pi$ [14] and (20.1 ± 3.5)% for $D^0 \to K^-\pi^+\pi^0$ [15]. Following studies of annihilation production of D* mesons [7] it was assumed that charmed quarks materialize as either D or D* mesons in the ratio 1:3, and that charged and neutral D*'s occur with equal probability, which leads to $\sigma_{\gamma\gamma\to D^{*\pm}X}=0.61\ \sigma_{\gamma\gamma\to c\bar{c}}$. Combining these branching ratios with the detection efficiency gives a prediction of 3.4 ± 1.4 events from the QPM, to be compared with our observation of $19\pm7\pm3$ events. Even assuming that charmed quarks invariably manifest themselves as D* mesons, the QPM prediction is only 4.2 ± 1.6 events. As we have seen, the event topology does not favour GVDM processes and indeed a study of the detection efficiency for such processes gives a very low value of (0.06 ± 0.03)%. If the fraction of D* events in all $\gamma\gamma$ collisions via GVDM processes is of the same order as the fraction observed in γp collisions (i.e. $\leqslant 1$%) then we expect essentially zero contribution in this experiment.

From previous studies of jet production in two-photon collisions there is strong evidence that in an intermediate p_T^{jet} region, $2\leqslant p_T^{jet}\leqslant 3$ GeV, the event rate is in excess of that predicted by the sum of GVDM and QPM. This is ascribed to the presence of scale invariant QCD modifications to the basic QPM "box" diagram ($\gamma\gamma\to q\bar{q}$) which produce hard scattering three- ($\gamma\gamma\to q\bar{q}g$) and four-parton ($\gamma\gamma\to q\bar{q}q\bar{q}$) processes. At PETRA energies, these additional processes cannot be directly observed as three- or four-jet events because the $\gamma\gamma$ centre of mass energy is effectively limited to 15 GeV. In the PLUTO analysis [3] they appear as an excess of low thrust events, and in the JADE cluster analysis [2] as events classified as "zero jet" or "one jet". The previously measured excess of events over the QPM expectation, for $x_T=p_T^{jet}/E_{beam}$ between 0.1 and 0.3, is roughly in agreement with the calculations of Stirling [16] and Grayson [17], which suggest a ratio of (two- + three- + four-jet) events to two-jet events of between 2.5 and 1.5. The mean p_T^{jet} of the 32 observed D* events, from table 1, corresponds to an x_T value of 0.1.

To summarize, we have observed charged D* events in photon–photon collisions, with a mean Q^2 of 0.91 GeV^2 and a visible invariant mass $W_{vis}\geqslant 4$ GeV, at a rate higher than that expected from QPM alone. This is consistent with the general observation on jet production, at the same mean x_T value, which exceeds the QPM expectation and has been ascribed to the presence of QCD corrections to the basic diagram.

We are grateful to the PETRA machine group and the DESY computer centre for their excellent service during this experiment. We also acknowledge the effort of all the engineers and technicians who have participated in the construction and maintenance of the apparatus, and in particular, we would like to thank those who installed the tagging systems. This experiment was supported by the Bundesministerium für Forschung und Technologie, by the Japanese Ministry of Education, Science and Culture, by the UK Science and Engineering Research Council through the Rutherford Appleton Laboratory and by the US Department of Energy. The visiting groups wish to thank the DESY directorate for the hospitality extended to them.

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