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A measurement of the charmed quark asymmetry in e^+e^- annihilation

JADE Collaboration

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Abstract. The charmed quark charge asymmetry has been measured at the average centre of mass energy of 35 GeV with the JADE detector at the e^+e^- storage ring PETRA. Charmed quarks were identified by $D^{*\pm}$ tagging using the ΔM technique. $D^{*\pm}$ mesons were reconstructed through their decay into D^0 mesons resulting in $(K\pi)\pi$ and $(K\pi\pi\pi)\pi$ final states. The measured charge asymmetry $A=-0.149\pm0.067$ is in agreement with the expectation from the electroweak interference effect in quantum flavour dynamics (QFD).

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The inclusive production of charged D^* mesons in e^+e^- annihilation has been studied by various experiments [1, 2]. Since the production of $c\bar{c}$ pairs in the fragmentation process is heavily suppressed, most of the charmed hadrons are certain to contain the primary charm quarks from $e^+e^-\to c\bar{c}$. Furthermore, at sufficiently high D^* energies, the reconstructed $D^{*\pm}$ direction reflects that of the charmed quark. The study of the $D^{*\pm}$ angular distribution allows investigation of electroweak interference effects in c-quark pair production and constraints on the weak isospin of the c-quark can be obtained.

In QFD [3, 4], the lowest order differential cross-section for the pair production in e^+e^- annihilation of fermions $f\bar{f}$ (where $f=\mu$, τ or q) is given by:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4s}\cdot(C_1\cdot(1+\cos^2\theta)+C_2\cdot\cos\theta), \tag{1}$$

where

$$C_1=Q_f^2-2\cdot Q_f\,v_e\,v_f\,\chi+(v_e^2+a_e^2)\cdot(v_f^2+a_f^2)\cdot\chi^2 \tag{2}$$

$$C_2=\quad -4\cdot Q_f\,a_e\,a_f\,\chi+8\cdot v_e\,v_f\,a_f\cdot\chi^2 \tag{3}$$

and v_e, v_f, a_e and a_f denote the vector and axial-vector weak couplings of the electron and fermion respectively.

Neglecting the width of the Z^0 vector boson, the propagator term χ is given by:

$$\chi=\frac{\rho G_F(1-\Delta r)}{8\pi\alpha\sqrt{2}}\frac{sM_Z^2}{s-M_Z^2}=\frac{1}{16\sin^2\theta_w\cos^2\theta_w}\frac{s}{s-M_Z^2}, \tag{4}$$

where $\sqrt{s}$ is the centre of mass energy, G_F is the Fermi constant and α the electromagnetic coupling constant. M_Z is the experimentally observable mass of the Z^0 intermediate vector boson:

$$M_Z^2=\frac{\pi\alpha}{\rho\sqrt{2}\,G_F(1-\Delta r)}\frac{1}{\sin^2\theta_w\cos^2\theta_w}. \tag{5}$$

In the following we assume the parameter ρ to be equal to 1. The electroweak mixing angle $\sin^2\theta_w$ is defined by the ratio of the masses of the W and Z bosons:

$$\sin^2\theta_w=1-\frac{M_w^2}{M_Z^2}. \tag{6}$$

The quantity Δr ($\Delta r=0.0711$ [4]) contains the electroweak radiative corrections and makes the two parametrizations of χ in (4) equivalent.

The terms proportional to χ arise from the interference between γ and Z^0 exchange and those proportional to χ^2 from direct Z^0 exchange.

The forward-backward charge asymmetry in the differential cross-section is:

$$A_f=\frac{N_F-N_B}{N_F+N_B}=\frac{3}{8}\cdot\frac{C_2}{C_1}, \tag{7}$$

where N_F is the number of fermions in the forward hemisphere ($\theta\leqq 90°$ with respect to the e^--beam) and N_B the number of fermions in the backward hemisphere ($\theta\geqq 90°$).

Due to the fractional charges of the heavy quarks, $Q_f=+\frac{2}{3}$ for c and $-\frac{1}{3}$ for b, the expected asymmetries are substantially larger than those in the leptonic sector. At 35 GeV and for $\sin^2\theta_w=0.229\pm0.004$ and $M_Z=92.1$ GeV, one predicts [4]: $A_{\mu,\tau}=-0.089\pm0.0016$ whereas $A_c=-0.133\pm0.0024$ and $A_b=-0.255\pm0.0047$*.

The data used in this study were taken with the JADE detector at the DESY e^+e^- storage ring PETRA, at centre of mass energies in the range between 30 GeV and 38 GeV. In a previous publication [2] we presented results on charged D^* production using an integrated luminosity of $\int L dt \sim 75\ \mathrm{pb}^{-1}$. In the present investigation we extend our earlier work, also analysing the data taken in 1985 at 38 GeV ($\int L dt \sim 10\ \mathrm{pb}^{-1}$) and in 1986 at 35 GeV ($\int L dt \sim 93\ \mathrm{pb}^{-1}$). In total 79398 multi-hadronic events were recorded at an average centre of mass energy of 35 GeV.

A detailed description of the JADE detector, the trigger conditions and the selection of hadronic events is given in [6].

In this analysis only charged particles coming from the primary vertex were used. In order to improve the momentum resolution, the average e^+e^- interaction vertex was included in a constrained track fit. Each track was required to have:

– at least 30 reconstructed hits in the jet chamber (at least 35 hits for the 1986 data taken with the vertex chamber)
– at least 5 hits (out of 16 possible hits) per ring in the jet chamber
– a momentum $p<0.75\,E_{\mathrm{beam}}$
– a distance to the vertex in the $R\phi$-plane, which is the plane perpendicular to the beam axis, $R_{\min}<10$ mm.

The D^{*+} signal was reconstructed through the decay mode

$$D^{*+}\to D^0\pi^+ \tag{8}$$

and its charge conjugate.

Tagging of the D^{*+} is possible even without kaon identification due to the very tight kinematical constraints on the decay (8), where the lone pion has a kinetic energy of 5.8 MeV in the D^{*+} rest frame. Consequently, the mass difference

$$\Delta M=M(D^0\pi^+)-M(D^0) \tag{9}$$

can be measured more accurately than the D^{*+} mass itself [7].

The following decay modes of the D^0 were used to reconstruct charged D^* mesons*:

$$D^0\to K^-\pi^+ \tag{10}$$

$$D^0\to K^-\pi^+\pi^-\pi^+ \tag{11}$$

$$D^0\to K^-\pi^+(\pi^0). \tag{12}$$

The last decay mode, where the π^0 is not reconstructed, corresponds to the so-called "satellite enhancement" S^0 which mainly proceeds via the intermediate states

$$D^0\to K^-\rho^+\ \to K^-(\pi^+\pi^0) \tag{13}$$

$$D^0\to K^{*-}\pi^+\to(K^-\pi^0)\,\pi^+ \tag{14}$$

$$D^0\to K^{*0}\pi^0\ \to(K^-\pi^+)\,\pi^0. \tag{15}$$

* Including reasonable assumptions concerning the mixing in the $B^0\bar{B}^0$ system [5], the predicted B-asymmetry becomes: $A_b'\sim 0.75\,A_b$

* Due to the deterioration of the z-resolution (z is the coordinate along the wire) during the last period of running, only the data taken before 1986 were used for the channel $D^0\to K^-\pi^+\pi^-\pi^+$ [2]

In addition to the D^0 peak at $M \sim 1.86$ GeV, the $K^-\pi^+$ mass distribution has a second peak ($M \sim 1.62$ GeV), much broader, corresponding to the S^0. The $K^-\pi^+$ mass interval [1.48–1.68 GeV) contains ~90% of the enhancement S^0[8].

In reconstructing the D^0 through the $K^-\pi^+$ decay mode, charged tracks with momenta $p > 1.0$ GeV/c were combined. No particle identification was used and each track was considered in turn to be a kaon or a pion. The momentum cut was set to $p > 1.4$ GeV/c for kaons. The combination was accepted as a possible candidate D^0 if the $K^-\pi^+$ invariant mass lay in the range

$$1.70 < M(K^-\pi^+) < 2.02 \text{ GeV}. \tag{16}$$

To form a D^{*+}, these D^0 candidates were combined with an additional charged track, assumed to be a pion, with a momentum cut $0.3 < p_\pi < 1.5$ GeV/c. The kaon and the additional pion were required to have opposite charges.

In order to reduce the considerable amount of background from random combinations, an additional cut in x_{D*}, the fractional energy of the D^*,

$$x_{D*} = \frac{E_{D*}}{E_{\text{beam}}}, \tag{17}$$

was introduced. Since the energy spectrum of the D^{*+} is harder than that of the combinatorial background, D^{*+} candidates were required to have $x_{D*} > 0.45$.

Figure 1a shows the resulting distribution of the mass difference $\Delta M = M(K^-\pi^+\pi^-) - M(K^-\pi^+)$. A clear enhancement around $\Delta M = 145$ MeV is seen, corresponding to the decay of the D^{*+} meson into $D^0\pi^+$. The width is consistent with the experimental mass resolution obtained from model calculations as described below.

The peak structure in ΔM disappears if instead of (16), the mass interval

$$2.10 < M(K^-\pi^+) < 2.50 \text{ GeV} \tag{18}$$

is used (Fig. 1b).

The "signal" event sample, defined by $\Delta M < 156$ MeV, contains 152 events. Note that the number of entries in Fig. 1 corresponds roughly to the number of events.

The Lund Monte Carlo program [9] was used to generate events containing a charged D^* including initial state radiation effects. The D^{*+} and D^0 were forced to follow the required decay modes. The generated events were processed by routines which followed the trajectory of each particle through the JADE detector and taking into account the energy loss and resolution of the apparatus. The simulated events were then subjected to the same analysis as the real data so that the acceptance and mass resolution could be determined.

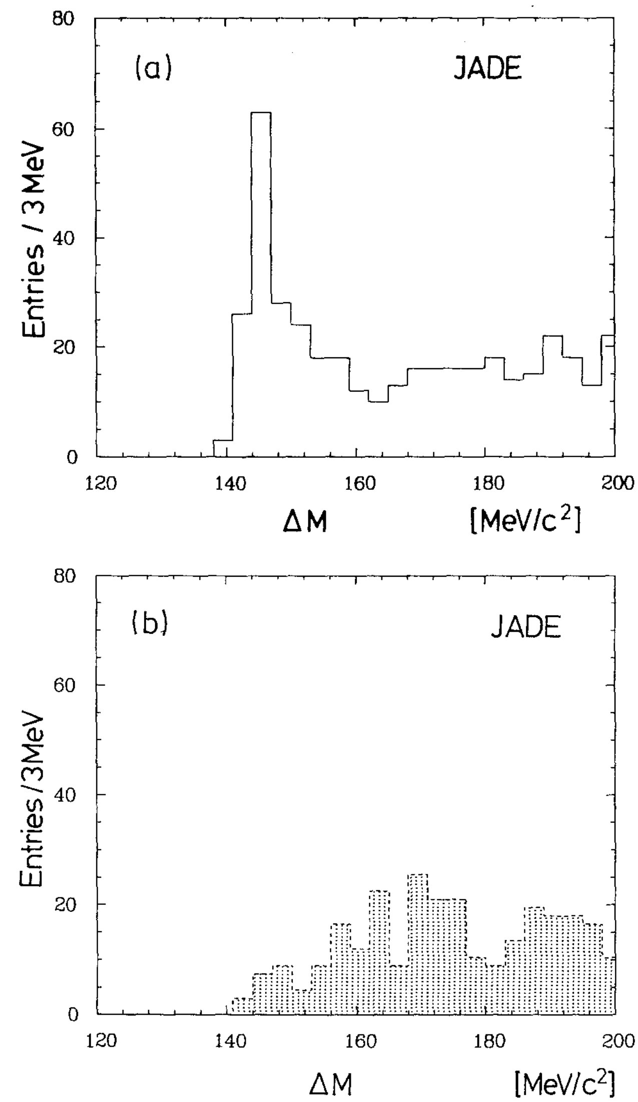

Fig. 1. The $\Delta M = M(K^-\pi^+\pi^-) = M(K^-\pi^+)$ mass difference for **a** $1.70 \leq M(K^-\pi^+) \leq 2.02$ GeV and for **b** the wrong mass $K^-\pi^+$ combinations $2.10 \leq M(K^-\pi^+) \leq 2.50$ GeV

Using the "wrong mass" distribution shown in Fig. 1b, the number of background events was estimated to be of the order of 17%. This was confirmed using Monte Carlo data in which only u, d and s events were generated.

Other sources of background are D^* from bottom-hadrons and from D^* with D^0 decaying according to (11) and (12)*.

To estimate the number of D^* mesons coming from bottom hadrons,

* These events, which contain primary charm quarks as well, can however be used for the asymmetry measurement. Using Monte Carlo calculations, the contribution from (12) is found to be ~6%

$B^- \to D^{*+}\pi^-\pi^-$ (19)

$\overline{B}^0 \to D^{*+}\pi^-,$ (20)

the distributions of the masses $M(D^{*+}\pi^-)$ and $M(D^{*+}\pi^-\pi^-)$ were analysed by adding one or two charged π to the reconstructed D^* candidate. At most 5% of D^* events were found to come from $\overline{B}^0$ and B^- mesons. As a consistency check, Monte Carlo B-events, generated according to (19) and (20), were subjected to the same analysis as the D^{*+} candidates. The branching ratios used in the Monte Carlo were

$$B(B^- \to D^{*+}\pi^-\pi^-) = 0.25^{+0.15}_{-0.13}\%$$
$$B(\overline{B}^0 \to D^{*+}\pi^-) \quad = 0.33^{+0.12}_{-0.10}\%.$$

The resulting B-contamination was found to be compatible with that obtained with the method described above.

The number of charged D^* observed is, after background subtraction, $N_{D^{*\pm}} = 126 \pm 14$. The error is due to the statistics and to the uncertainty in determining the background.

The overall acceptance, calculated using the Lund Monte-Carlo program, varies between 20% and 35% for the decay mode (10), depending on the D^* energy and on the data taking period. Using the branching ratios [10]

$$B(D^{*+} \to D^0\pi^+) \; = 0.57 \pm 0.04 \pm 0.04$$
$$B(D^0 \;\; \to K^-\pi^+) = 0.042 \pm 0.004 \pm 0.004$$

and the integrated luminosity of $\int L\,dt \sim 180\ \text{pb}^{-1}$, we expect to observe ~ 130 events, in good agreement with the observed number.

For the determination of the D^{*+} angular distribution, S^0 events corresponding to the decay channel (12), which contain primary charm quarks as well, were included by enlarging the $M(K^-\pi^+)$ mass interval to

$$1.50 < M(K^-\pi^+) < 2.02\ \text{GeV}. \quad (21)$$

We also took into account the decay mode (11) using the data taken before 1986.

The total number of events observed, after requiring $-0.8 \leq \cos\theta_{D^*} \leq 0.8$ ⋆ and after background subtraction, is $N_{D^{*\pm}} = 253 \pm 19$ for the 3 decay channels (10), (11) and (12).

The resulting $D^{*\pm}$ production angular distribution is given in Fig. 2. The background (not subtracted in the figure) was assumed to be forward-backward symmetric (this was checked with Monte Carlo Events without c and b quarks).

⋆ We checked that within this cut, the acceptance is uniform in $\cos\theta$

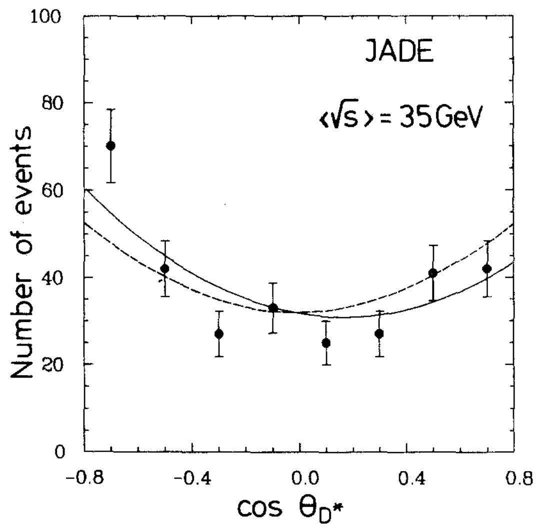

Fig. 2. The measured $D^{*\pm}$ angular distribution. The full curve is a fit to the data with an asymmetry of -0.149. The dashed curve is a fit with the asymmetry set to zero. The background was assumed to be forward-backward symmetric

To extract the charge asymmetry the expression (1), modified in order to allow for the combinatorial background and the D^* mesons from bottom hadrons, were fitted to our data. The total number of signal and background events were set to the estimated values and were allowed to vary within the errors. The B asymmetry was fixed to its predicted value. No other corrections were applied to the data (luminosity, acceptance, radiative effects, etc. ...) and the overall normalization was taken as a second free parameter. The fit yields (for the full $\cos\theta_{D^*}$ range)

$$A_c = -0.149 \pm 0.067,$$

which is in good agreement with the lowest order QFD expectation of $A_c = 0.133$. Note that the error quoted takes into account the background. The result has not been corrected for radiative effects. Higher order QED effects introduce a forward-backward asymmetry of the order of -0.005.

The measured asymmetry is consistent with other PETRA and PEP measurements [11], as is shown in Table 1.

From the asymmetry the product of the axial-vector couplings of the electron and the charm quark was obtained using relation (7):

$$a_e\, a_c = 1.09 \pm 0.49.$$

QFD predicts $a_e\, a_c = -1$.

In summary, the charge asymmetry of the process $e^+e^- \to c\bar{c}$ was measured with the JADE detector at an average centre of mass energy of 35 GeV. The charm quark was tagged by D^*-identification using the decay $D^{*\pm} \to D^0\pi^\pm$. For sufficiently high D^* en-

Table 1. Measured asymmetries for $e^+e^- \to c\bar{c}$ using the D^* technique

Experiment	$\sqrt{s}$ (GeV)	Method	A_c (%)	A_{QFD} (%)
JADE	35	D^*	-14.9 ± 6.7	-13.3
TASSO (Prel.)	35.8	D^*	-16.6 ± 7.5	-13.8
HRS	29	D^*	-9.9 ± 2.7	-8.7
TPC	29	D^*	-16.0 ± 16.0	-8.7

ergies, the reconstructed $D^{*\pm}$ direction coincides with that of the charm quark.

The measured charm quark charge asymmetry $A_c = -0.149 \pm 0.067$ is in agreement with the lowest order QFD expectation of $A_c = -0.133$. The product of the axial-vector couplings of the electron and the charm quark obtained was $a_e a_c = -1.09 \pm 0.49$, whereas QFD predicts $a_e a_c = -1$.

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References

1. J.M. Yelton et al.: Phys. Rev. Lett. 49 (1982) 430; C. Bebek et al.: Phys. Rev. Lett. 49 (1982) 610; P. Avery et al.: Phys. Rev. Lett. 51 (1983) 1139; DELCO Coll. H. Yamamoto et al.: Phys. Rev. Lett. 54 (1985) 522; HRS Coll. S. Ahlen et al.: Phys. Rev. Lett. 51 (1983) 1147; M. Derrick et al.: Phys. Lett. 146B (1984) 261; P. Baringer et al.: Phys. Lett. 206B (1988) 551; TPC Coll. H. Aihara et al.: Phys. Rev. D31 (1985) 2719; Z. Phys. C27 (1985) 39; Phys. Rev. D34 (1986) 1945; TASSO Coll. M. Althoff et al.: Phys. Lett. 126B (1983) 493; Phys. Lett. 135B (1984) 243
2. JADE Coll. W. Bartel et al.: Phys. Lett. 146B (1984) 121
3. S.L. Glashow: Nucl. Phys. 22 (1961) 579; A. Salam: Phys. Rev. 127 (1962) 331; S. Weinberg: Phys. Rev. Lett. 19 (1967) 1264
4. D. Haidt, H. Pietschmann: Landolt-Boernstein, New Series 1/10, Berlin, Heidelberg, New York: Springer 1988
5. ARGUS Coll. H. Albrecht et al.: Phys. Lett. 192B (1987) 245; CLEO Coll. A. Jawahery, Proc. 24th Intern. Conf. on High Energy Physics, Munich (1988)
6. JADE Coll. W. Bartel et al.: Phys. Lett. 88B (1979) 171; Phys. Lett. 129B (1983) 145
7. G.J. Feldman et al.: Phys. Rev. Lett. 38 (1977) 1313
8. G. Goldhaber: Proc. 18th rencontre de Moriond, La Plagne-Savoie-France (1983)
9. B. Anderson, G. Gustafson, G. Ingelman, T. Sjöstrand: Phys. Rep. 97 (1983) 33; T. Sjöstrand: Comput. Phys. Commun. 27 (1982) 243; 28 (1983) 229
10. J. Adler et al.: Phys. Rev. Lett. 60 (1988) 89
11. F. Ould Saada: DESY Report 88/177