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ARTICLES

Test of spin dependence in charm-quark fragmentation to D^*

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We have measured the polarization of D^*, the energy dependence of the polarization, and the spin-density matrix of D^* in e^+e^- annihilation at a center-of-mass energy of 29 GeV using the Time Projection Chamber detector at the SLAC storage ring PEP. In 147 pb^{-1} of data we see no strong evidence for polarization, alignment, or final-state interactions in this fragmentation process.

INTRODUCTION

The main kinematic features of the fragmentation of heavy quarks to hadrons are well described by several fragmentation functions.[1–11] Some of these models are quite successful in describing not only the energy distribution but also the flavor dependence of the fragmentation process. A further development[12] has included the spin state of the hadron in an attempt to introduce dynamics into the description of the fragmentation process. Since spin dependence in fragmentation is not understood, measurement of quantities related to the spin of the final produced hadrons provides a test of this hypothesis, and others, on the nature of dynamical effects in heavy-quark fragmentation. Such quantities are the vector/pseudoscalar production ratio of the heavy mesons, the polarization state of vector meson, and the spin-density matrix of vector mesons decaying into two pseudoscalar mesons. Such a measurement was recently reported by the High Resolution Spectrometer (HRS) Collaboration.[13] Recent theoretical papers[12,14,15] have emphasized the importance of experimental measurements in the decay $D^* \to D\pi$ of the angular distribution of the D in the D^* rest frame. Such measurements give information on coherent fragmentation (or final-state interactions) and on the dynamics of meson formation in quantum chromodynamics.

In this paper we present the results of a study of the

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polarization and the spin-density matrix of the D^* produced in e^+e^- annihilation at the electron-positron collider PEP, located at the Stanford Linear Accelerator Center (SLAC). The data sample reported on here corresponds to an integrated luminosity of 147 pb^{-1} collected by the TPC/2γ facility at an energy of $\sqrt{s}=29$ GeV.

I. DATA SELECTION

The main features of the apparatus, monitoring, calibration, and hadronic event selection have been previously described.[16,17] Here we detail only those aspects important for this analysis. The Time Projection Chamber (TPC) was used to identify particle species by simultaneous measurement of momentum and ionization energy loss dE/dx. The specific ionization of each track was sampled up to 183 times by ionization energy loss in the argon(80%)-methane(20)% gas volume of the TPC. The mean energy loss was estimated from the average of the lower 65% of all available samples, where samples may be lost due to spatial overlap with other tracks, dead channels, or geometrical acceptance. On average 110 samples were available, and by requiring at least 40 samples for each track, the dE/dx resolution was typically 3.3%. From the measured ionization rate and momentum, a 1-constraint mass χ^2 was constructed for each track hypothesis to be an electron, muon, pion, kaon, or proton. For about 12% of the tracks, both the K and π hypotheses met the criterion that the mass χ^2 be less than 6.6, the 1% confidence level. The track-finding efficiency was (97±2)%.

For this analysis, tracks so measured were required to meet the following criteria: (a) the distance of closest approach to the beam-beam interaction point must be smaller than 3 cm in the plane transverse to the beam, and smaller than 5 cm along the beam, (b) the momentum must be greater than 0.4 GeV/c for pions and 1.0 GeV/c for kaons, (c) the curvature error in the orbit fit must be less than 0.26 $(\text{GeV}/c)^{-1}$ for momenta above 1 GeV/c, and the fractional momentum error must be less than 0.26 for momenta below 1 GeV/c, (d) the angle from the beam direction must be greater than 33°, (e) photon candidates were measured by the Geiger-mode hexagonal calorimeter, and were required to have an energy above 0.4 GeV, (f) each track of each decay sequence was required to have a mass χ^2 above the 1% confidence level, and (g) for a kaon below 1.5 GeV/c, the χ^2 of the kaon hypothesis must be less than the χ^2 of the pion and electron hypothesis by at least 1.0 unit. This last criterion was used to reduce the contamination of the kaon sample by pions and electrons at their respective crossover points.

The D^* candidates were selected through the decay mode $D^{*+}\to D^0\pi^+$, with the D^0 decaying through any one of the modes (a) $K^-\pi^+$, (b) $K^-\pi^+\pi^0$, $\pi^0\to\gamma\gamma$, (c) $K^-\pi^+\pi^-\pi^+$, or (d) $\bar{K}^0\pi^+\pi^-$, $K_S^0\to\pi^+\pi^-$. All charge-conjugate states were also included in this analysis.

The decay products of each D^0 candidate were constrained to the D^0 mass using the full measurement error matrix of each track, and in addition, the decay products of intermediate stable particles (π^0 and K_S^0) were also constrained to their respective masses. In addition, K_S^0 was further identified by reconstruction of its decay vertex. Thus, reactions (a) and (c) were 1-constraint fits, whereas reactions (b) and (d) were 2-constraint fits. All decay hypotheses with a kinematic-fit confidence level above 1% were kept. Overall reconstruction efficiency was 87.5%. The resulting mass difference $M(D^0\pi^+)-M(D^0)$ distribution of all the combined decay modes is shown in Fig. 1. The observed width of the D^* peak in Fig. 1 is consistent with the calculated width using a Monte Carlo simulation which generates multihadronic events with initial-state radiation, and an analysis procedure identical to that used for the data. The physics event generator used was the Lund Monte Carlo program. The detector simulation included the geometrical acceptance of the apparatus, particle energy loss, multiple scattering and nuclear interactions in the materials of the detector, and decay loss of pions and kaons. In addition the analysis of the simulated data included charged-track pattern recognition, the loss of dE/dx wire samples due to overlap of nearby tracks, and its effect on the dE/dx resolution. For photons, it included pair production and subsequent bremsstrahlung in the materials before the TPC volume and before the lead mass of the calorimeter, and the pattern-recognition efficiency and energy resolution of the hexagonal calorimeter.

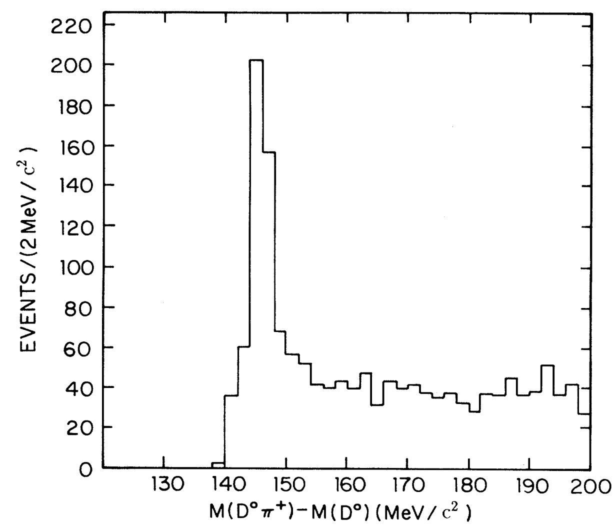

FIG. 1. The mass-difference distribution $M(D^0\pi^+)-M(D^0)$ of all D^0 decay modes.

II. THE DECAY-ANGULAR DISTRIBUTION OF THE D^*

The amplitude for the decay $D^*\to D^0\pi$ in the rest frame of the spin-1 D^* has the form

$$A_m(\cos\theta,\phi)=\left[\frac{3}{4\pi}\right]^{1/2} d^1_{m0}(\theta)e^{im\phi}\ , \tag{2.1}$$

where $d^1_{m0}(\theta)$ is the reduced rotation matrix, in which m

labels the D^* spin state. In our coordinate system θ and ϕ are the polar and azimuthal angles of the D^0 in the D^* helicity frame, where the zero in ϕ is referenced to the production plane formed by the D^* and the incoming electron. The probability of decay in the direction (θ,ϕ) in the D^* rest frame can be written in terms of the spin-density matrix ρ as

$$W(\cos\theta,\phi)=\frac{3}{4\pi}[\tfrac{1}{2}(1-\rho_{00})+\tfrac{1}{2}(3\rho_{00}-1)\cos^2\theta - \rho_{1-1}\sin^2\theta\cos2\phi - \sqrt{2}\,\mathrm{Re}\rho_{10}2\theta\cos\phi] , \tag{2.2}$$

where the separate projections in $\cos\theta$ and ϕ are

$$W(\cos\theta)=\tfrac{3}{4}[(1-\rho_{00})+(3\rho_{00}-1)\cos^2\theta] , \tag{2.3}$$

$$W(\phi)=\frac{1}{2\pi}[(1+2\rho_{1-1})-4\rho_{1-1}\cos^2\phi] . \tag{2.4}$$

The diagonal elements of the density matrix are the probabilities of populating the respective J_z spin states, and a polarized D^* ensemble would be characterized by an unequal population of these states. Thus, a measurement of ρ_{00} differing from $\frac{1}{3}$ indicates a net polarization of the D^* ensemble.

III. THE POLARIZATION AND SPIN-DENSITY MATRIX OF THE D^*

The energy dependence of the D^* polarization was determined by measuring the $\cos\theta$ distribution in the D^* helicity frame of the reconstructed D^0 from the decay $D^*\to D^0\pi$. For any z, the D^* decay-angular distribution [Eq. (2.3)] can be parameterized by

$$d\Gamma(D^*\to D\pi)/d\Omega \propto 1+\alpha(z)\cos^2\theta , \tag{3.1}$$

where $z\equiv 2E_{D^*}/\sqrt{s}$, and $\alpha(z)=(3\rho_{00}-1)/(1-\rho_{00})$. An unpolarized D^* would be characterized by $\alpha(z)=0$ or, equivalently, $\rho_{00}=\frac{1}{3}$. We used the maximum-likelihood method for fitting the coefficients $\alpha(z)$ in z bins of 0.10, taking into account the event acceptance of each decay mode in $(z,\cos\theta)$, the combinatorial background in $(z,\cos\theta)$, and the contamination of the D^* sample by the semileptonic decay $B\to D^*l\nu$. The event acceptance was calculated from a detailed simulation of the detector; the combinatorial background averages 12.5%, and was estimated from the kinematic background above the D^* peak in Fig. 1 for each decay mode; and finally, the $B\to D^*l\nu$ contamination was estimated from the known branching ratio for this process, a Lund description of the fragmentation function for B-meson production, and the weak decay kinematics. We estimated this contamination to be a 5.2% for $0.3\le z\le 0.4$, 3.1% for $0.4\le z\le 0.5$, 1.9% for $0.5\le z\le 0.6$, and negligible for $0.6\le z\le 1.0$.

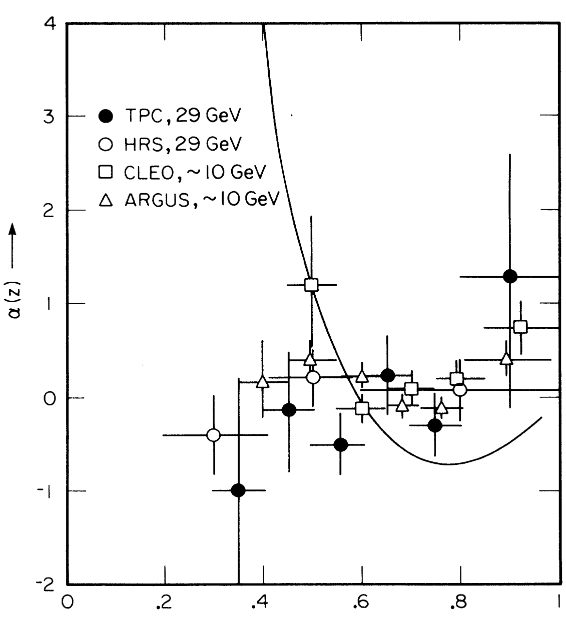

FIG. 2. Measurement of $\alpha(z)$, where $\alpha(z)$ is a measure of the nonisotropy in the decay $D^*\to D^0\pi^+$. The solid curve represents the theoretical prediction of Ref. 12.

Our $\alpha(z)$ measurement is shown in Fig. 2 and Table I. As a check we also performed least-squares fits to the $\cos\theta$ distributions. Results of these fits are consistent with the results from the maximum-likelihood method. Our measured values of $\alpha(z)$ are insensitive to contamination by $B\to D^*l\nu$ decays. If we include in the fit a contribution for this process as measured by the ARGUS Collaboration,[18] or even if we allow for strongly longitudinally polarized D^*'s we find in either case only a negligible effect on $\alpha(z)$.

In Ref. 12 Suzuki treats the heavy meson from the fragmentation as a nonrelativistic bound state moving along the heavy-quark-jet direction with negligible Fermi motion. The D^* polarization is calculated in terms of two fragmentation functions of D^*: $D_L(z)$ for a longitudinally polarized D^*, and $D_T(z)$ for a transversely polarized D^*. It is also assumed that light quarks are produced from the spin-one gluon emitted by the heavy quark. This calculation suggests that $D_L(z)$ has a broad enhancement at lower z values, while $D_T(z)$ has a large sharp enhancement at higher z values. These differences in the z dependence would be observed in the $D^*\to D\pi$ decay angular distribution where $\alpha(z)$ in Eq. (3.1) would be expressed as $\alpha(z)=[D_L(z)-D_T(z)]/D_T(z)$, as shown in Fig. 2.

Based on our measurement of $\rho=0.30\pm0.04\pm0.01$,

TABLE I. The measurement of $\alpha(z)$ where the first error is statistical, and the second error is systematic.

z	$\alpha(z)$
0.3–0.4	$-1.00\pm1.28\pm0.27$
0.4–0.5	$-0.14\pm0.61\pm0.21$
0.5–0.6	$-0.50\pm0.25\pm0.09$
0.6–0.7	$0.24\pm0.38\pm0.14$
0.7–0.8	$-0.29\pm0.32\pm0.03$
0.8–1.0	$1.29\pm1.40\pm0.15$
Average	$-0.14\pm0.17\pm0.03$

TABLE II. The measurement of spin-density matrix of D^* where the first error is statistical, and the second error is systematic.

z	ρ_{00}	ρ_{1-1}	Reρ_{10}
0.3–0.4	0.00±0.64±0.14	0.11±0.21±0.01	0.25±0.25±0.02
0.4–0.5	0.30±0.15±0.05	0.00±0.04±0.00	0.05±0.09±0.01
0.5–0.6	0.20±0.08±0.03	0.10±0.08±0.00	0.05±0.06±0.00
0.6–0.7	0.38±0.08±0.03	0.00±0.07±0.00	0.03±0.05±0.08
0.7–0.8	0.26±0.09±0.01	−0.03±0.08±0.00	0.00±0.06±0.07
0.8–1.0	0.53±0.15±0.02	0.04±0.12±0.00	−0.02±0.09±0.02
Average	0.30±0.04±0.01	0.01±0.03±0.00	0.03±0.03±0.00

which corresponds to $\alpha(z) = -0.14 \pm 0.17 \pm 0.03$, we conclude that the D^* is not strongly polarized, and that there is no strong energy dependence to the polarization. There is a slow increase in $\alpha(z)$ with z, but it is about one standard deviation from the $\alpha(z)=0$ hypothesis, and in either case does not agree with the calculation of Ref. 12. We also used the maximum-likelihood method to determine all of the spin-density-matrix elements ρ_{00}, ρ_{1-1}, and Reρ_{10} in Eq. (2.2) averaged over all z. As a check we made a least-squares fit of our data to the $\cos\theta$ and ϕ distribution functions separately, and we used the method of moments to determine Reρ_{10}. We find that the results of these fits are in good agreement with the results of the maximum-likelihood method, shown in Table II. The spin density matrix of D^*, averaged over z, is

$$\rho_{mm'} = \begin{bmatrix} 0.35\pm0.02 & 0.03\pm0.03 & 0.01\pm0.03 \\ 0.03\pm0.03 & 0.30\pm0.04 & -0.03\pm0.03 \\ 0.01\pm0.03 & -0.03\pm0.03 & 0.35\pm0.02 \end{bmatrix}, \tag{3.2}$$

which is consistent with $\frac{1}{3}$ times the unit matrix. Since we have no way of determining the imaginary part of ρ_{10}, the matrix element for ρ_{10} is only the real part of ρ_{10}. The errors on ρ_{00}, ρ_{1-1}, and Reρ_{10} are independent, and the rest of the errors are derived using the trace condition and parity conservation.

IV. ALIGNMENT, THE VECTOR-TO-PSEUDOSCALAR RATIO, AND FINAL-STATE INTERACTIONS

The alignment of the D^*, the vector/pseudoscalar (V/P) ratio, and the possibility of final-state interactions can be related to our measurements of the density matrix. The alignment η, defined as $\eta = \frac{1}{2}(2\rho_{00} - \rho_{11} - \rho_{-1-1}) = (3\rho_{00} - 1)/2$ with physical limits of $-\frac{1}{2} \le \eta \le 1$, measures the relative probabilities of the helicity 0 and ± 1 states of the D^*. Our measured value of $\eta = -0.05 \pm 0.06$ shows no alignment of the D^* and that both the helicity ± 1 states and the helicity 0 state are equally populated (see Table III).

TABLE III. The alignment η of the D^* and the inferred ratio of V to P.

z	η	V/P
0.3–0.4	−0.50±0.96	1.00±1.28
0.4–0.5	−0.05±0.23	2.50±1.88
0.5–0.6	−0.20±0.12	1.67±0.44
0.6–0.7	0.07±0.14	4.17±3.13
0.7–0.8	−0.11±0.14	2.08±0.78
0.8–1.0	0.30±0.23	−16.7 ±83.3
Average	−0.05±0.06	2.50±0.50

The matrix element ρ_{00} may also be treated to the ratio of vector-to-pseudoscalar mesons, as pointed out by Donoghue,[19] if the spin states are assumed to be equally populated (statistical models). When a quark combines with an antiquark, it forms either a vector meson or a pseudoscalar meson. If the quarks' spins are antiparallel it is assumed they form a pseudoscalar with probability F, and a vector with probability $1-F$. If the spins of the two quarks are parallel they form a vector meson with $J_z = \pm 1$. The physical limits on F and $0 < F \le 1$. By simply counting possible spin states we have $\rho_{00} = (1-F)/(2-F)$ and $V/P = (2-F)/F$. Some models[1] favor $F=1$ and $V/P=1$. Direct experimental measurement of the V/P ratio for the charmed mesons has large statistical and systematic errors.[20] From our ρ_{00} measurement we infer that F and the V/P ratio are consistent with $\frac{1}{2}$ and 3, respectively, the values expected in some statistical models, as opposed to other models[1] (see Table III).

Off-diagonal terms of the spin-density matrix are consistent with zero. It has been suggested by Anselmino[14] that the measurement of the vector-meson spin-density matrix can test the strength of final-state interactions in the hadronization process since final-state coherent interactions could make ρ_{1-1} nonvanishing. Our measurement of the spin-density matrix of D^*, although of limited statistical precision, shows no significant strength of final-state interactions.

V. SUMMARY AND CONCLUSIONS

In summary, our measurement of $\alpha(z)$ shows that the D^* is not strongly polarized in this fragmentation process and that there is no strong energy dependence to the polarization. The spin-density-matrix analysis shows that there is negligible alignment of D^* helicity states in this data sample. Finally, no measurable indication of final-state interactions is observed.

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