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ARTICLES

Study of continuum D^{*+} spin alignment

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The spin alignment of D^{*+} mesons produced in e^+e^- annihilation at $\sqrt{s}=10.5$ GeV is obtained from a study of the angular distribution of the decay $D^{*+}\to D^0\pi^+$. The alignment is studied as a function of momentum and compared to theoretical predictions. We find an average value of the spin alignment parameter η of $\langle\eta\rangle=0.04\pm0.02\pm0.01$. We obtain a model-dependent measurement of the probability of producing a vector particle $\langle P_V\rangle=0.77\pm0.02\pm0.01$ for D mesons.

I. INTRODUCTION

The fragmentation of heavy quarks has been intensively studied theoretically. Most of the theoretical models [1] predict a hard fragmentation function for heavy quarks, consistent with experimental data collected in e^+e^- annihilation [2]. D^{*+} mesons produced in nonresonant low-energy e^+e^- annihilation provide a unique place for the study of fragmentation. The probability that charm quarks are produced by mechanisms other than direct pair production via a single virtual photon is small, implying that any produced charmed hadrons must contain the primary quark. The small cross sections for D^{**} production in e^+e^- annihilation [3] suggests that most of the observed D^{*+} mesons are primary first-rank hadrons and that the differential cross section is simply proportional to the fragmentation function.

Spin alignment and its momentum dependence are additional features that may be useful in studying the dynamics of fragmentation. An analysis performed with ρ mesons [4] produced in charged-current $\nu,\bar{\nu}$ interactions shows some evidence of vector-meson alignment. Analogously the D^{*+} meson has spin and can be used to study the role of spin in hadronization. A recent model by Suzuki [5] predicts that the alignment of D^{*+} mesons produced in e^+e^- annihilation at a given energy depends strongly on their momentum.

This paper describes a measurement of the spin-alignment parameter of the D^{*+} meson. We study the dependence of the spin alignment on the fragmentation variable x^+, an experimentally measurable approximation to the light-cone variable, which is defined as

$$x=\frac{E+p}{E_{\max}+p_{\max}} ,$$

where E and p are the D^{*+} energy and momentum, $E_{\max}=E_{\text{beam}}$, and $p_{\max}=\sqrt{E_{\text{beam}}^2-m_{D^{*+}}^2}$. The experimental result is compared to theoretical models.

II. THE SPIN-ALIGNMENT PARAMETER AND THEORETICAL MODELS

A common formalism to describe decay properties of particles with spin is the density matrix $\rho_{\lambda\lambda'}$ [6] where λ and λ' label the vector-meson helicity. We choose to determine the spin-density matrix in a reference system with the quantization axis along the direction of motion of the D^{*+} in the laboratory. For the process $D^{*+}\to D^0\pi^+$ the decay angular distribution can be written

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

where θ is the angle of the D^0 in the D^{*+} rest frame with respect to the D^{*+} direction in the laboratory frame and ρ_{00} is the probability for the vector meson to be in the $J_z=0$ state.

Most of the fragmentation models in the literature [7] introduce spin according to statistical assumptions [8]. The primary quark can combine with antiquarks from the sea to form either a vector or a pseudoscalar meson. If the spins of the two quarks are aligned, the state formed is a vector meson with $J_z=\pm1$ with probability $\frac{1}{2}$. If the quark spins are antiparallel, a pseudoscalar or a vector meson with $J_z=0$ is formed with probabilities f and $1-f$, respectively. In this picture ρ_{00} is given by

$$\rho_{00}=\frac{1-f}{2-f} . \tag{2}$$

This result implies a connection between $P_V=V/(V+P)$, where V and P are the respective probabilities of producing a vector or a pseudoscalar meson, and the spin-density-matrix elements

$$P_V=\frac{2-f}{2}=\frac{1}{2(1-\rho_{00})} . \tag{3}$$

Common choices of P_V are $P_V=0.75$ ($f=\frac{1}{2}$) and $P_V=0.50$ ($f=1$). A simple spin-counting argument gives $P_V=0.75$ while $P_V=0.50$ is supported by the experimental evidence that the ρ^0 and π^0 are produced in approximately equal numbers [9].

A variable commonly used in polarization analysis is the alignment

$$\eta=\tfrac{1}{2}(3\rho_{00}-1) . \tag{4}$$

The statistical picture with $0.50\le P_V\le 0.75$ predicts that $-\frac{1}{2}\le\eta\le 0$.

In the parton shower model [10], the fragmentation is described by iterative use of $q\to qg$, $g\to gg$, and $g\to q\bar{q}$. The iterative process tends to smear out the properties of the primary quarks, so that helicity states are uniformly populated and the resultant angular distribution is isotropic ($\eta=0$). When the hadron has large transverse momentum with respect to the primary quark, axis and $m_{\text{hadron}}/p_{\text{hadron}}\to 0$, a perturbation calculation favors $\eta=-\frac{1}{2}$ [11].

In the Lund string model [12], the ratio P_V is calculated by solving a confining potential problem with a spin-spin force added phenomenologically. The spin-spin interaction term produces a triplet wave function broader than the singlet wave function. Therefore, the model predicts that the probability of producing a vector meson is suppressed and P_V is smaller than the spin-counting result of 0.75 ($\eta<=0$). In this model it is also expected that the vector-meson suppression factor depends on the masses of the particles. The relative suppression is smaller for K^* and K than ρ and π. For D^* and D mesons the suppression is even smaller.

Large values of η are obtained in models [8] in which the vector meson couples to quarks with a vector current. In this case $\eta=1$.

In the Suzuki model [5] the heavy quark Q and the light antiquark $\bar{q}$ are emitted collinearly and only a single gluon is exchanged (see Fig. 1). The spin-dependent fragmentation function can be given in terms of the D^{*+} spin-density matrix $D_{\lambda\lambda'}(z)=D^*(z)\rho_{\lambda\lambda'}$ where $D^*(z)$, the usual spin-averaged fragmentation function, is the trace of the matrix $D_{\lambda\lambda'}(z)$ and z is defined as $z=E_{\text{meson}}/E_{\text{beam}}$. $D_L(z)=D_{00}(z)$ and $D_T(z)=[D_{11}(z)+D_{-1-1}(z)]/2$ are the longitudinal and transverse components of the fragmentation with respect to the polarization axis. The fragmentation functions for the vector $[D^*(z)]$ and the pseudoscalar meson $[D^0(z)]$ are plotted in Fig. 2. The different shapes of $D^*(z)$ and $D^0(z)$ produce a z dependence for $P_V(z)=D^*(z)/[D^*(z)+D^0(z)]$. Furthermore,

$$\alpha(z)=\frac{D_L(z)-D_T(z)}{D_T(z)}=\frac{3\rho_{00}-1}{1-\rho_{00}}=\frac{3\eta}{1-\eta} \tag{5}$$

is a strong function of z. The functions $P_V(z)$ and $\alpha(z)$ are also plotted in Fig. 2. The parameter α is experimen-

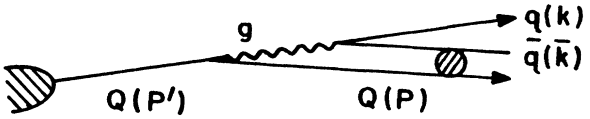

FIG. 1. Possible diagram for the formation of a heavy-flavored $Q\bar{q}$ meson by a single gluon in the model by Suzuki [5].

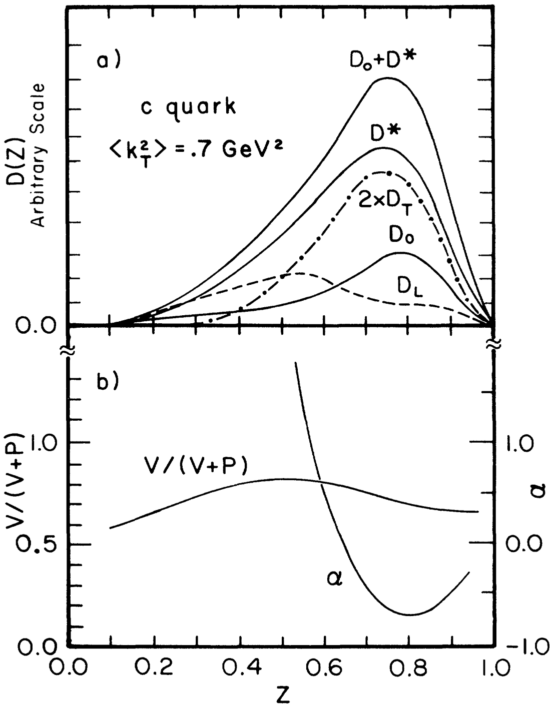

FIG. 2. Results of the Suzuki model: (a) Fragmentation functions of c quarks. $D^0(z)$ is the fragmentation function for the D meson, while $D_{L,T}(z)$ are the longitudinal- and transverse-polarized fragmentation functions of the D^{*+} meson. $D^*(z)=2D_T(z)+D_L(z)$ is the spin-averaged fragmentation function for the D^* meson. (b) Distributions of $\alpha(z)=[D_L(z)-D_T(z)]/D_T(z)$ and P_V as a function of z.

tally determined from the decay angular distribution of $D^{*+}\to D^0\pi^+$:

$$W(\theta)=N(1+\alpha\cos^2\theta) \tag{6}$$

where N is a normalization factor. The parameter α is bounded between -1 and ∞; where $\alpha=-1$ the decay angular distribution is proportional to $\sin^2\theta$ and when $\alpha=\infty$ the decay angular distribution is proportional to $\cos^2\theta$. The values of α and P_V integrated over the whole z range [5] $P_V=0.74$ and $\alpha=-0.05$, are not distinguishable from the spin-counting results. Therefore, a study of α as a function of momentum must be performed if the Suzuki model is to be tested.

III. DETECTOR AND EVENT SELECTION

The data sample used in this study was collected with the upgraded CLEO detector at the Cornell Electron Storage Ring (CESR). It consists of 212 pb^{-1} at the $\Upsilon(4S)$ resonance and 102 pb^{-1} at energies just below the $B\bar{B}$ threshold. The CLEO detector and our selection criteria for hadronic events are described in detail elsewhere [13,14]. Here we will briefly describe the recent modifications to the central-tracking system. Charged-particle tracking is performed inside a superconducting solenoid of radius 1.0 m which produces a 1.0-T magnetic field. Three nested cylindrical drift chambers measure momenta and specific ionization for charged particles. The innermost part of the tracking system is a three-layer straw tube vertex detector which gives position accuracy of 70 μm in the r-ϕ plane. The middle ten-layer vertex chamber measures position with an accuracy of 90 μm in the r-ϕ plane and dE/dx to 14%. The main drift-chamber system [15] contains 51 layers, eleven of which are strung at stereo angles of 1.9° to 3.5° to the z axis, and provides a position accuracy of 110 μm and specific ionization to 6.5%. Measurements of the track coordinates along the beam position (z) are achieved by using the stereo layers and cathode strip readouts in the middle vertex detector and the main drift chamber. The system achieves a momentum resolution given by $(\delta p/p)^2=(0.23\%p)^2+(0.7\%)^2$, where p is in GeV.

Because D^* mesons with momentum up to 2.5 GeV/c can be decay products of B mesons in the data sample taken on the $\Upsilon(4S)$, only continuum data are examined for D^*'s below 2.5 GeV/c. We use the particle-identification capabilities of the detector to reduce background, requiring kaon candidates to have specific ionization within 3σ of the expected value. Reconstructed tracks that do not originate from the event vertex are rejected and momenta are corrected for ionization energy loss in the material before the drift chamber.

We identify D^{*+} in the decay mode $D^0\pi^+$ with the D^0 reconstructed through the decay channels $D^0\to K^-\pi^+$ and $D^0\to K^-\pi^+\pi^-\pi^+$ (inclusion of charge-conjugate modes is implied throughout this paper). Two different procedures are possible.

(1) We can first select $K^-\pi^+(K^-\pi^+\pi^-\pi^+)$ combinations for which $\Delta M=M(D^0\pi^+)-M(D^0)$ is close to the known $D^{*+}-D^0$ mass difference. The number of D^{*+} candidates is then obtained through a fit of the D^0 invariant-mass distribution.

(2) Otherwise, we can select $K^-\pi^+(K^-\pi^+\pi^-\pi^+)$ combinations which are close to the D^0 mass and then determine the number of D^{*+} candidates through a fit of ΔM.

We choose to follow the first method because the exchange of the K^- and π^- interpretations in the decay $D^0\to K^-\pi^+\pi^-\pi^+$ results in a broad peak in the D^0 candidate mass distribution which is easily incorporated in the random background, whereas in the second method the interchanged mass interpretation will contribute a peak in the ΔM distribution of the same width as the real D^0 signal and therefore will be indistinguishable from it.

Because the D^0 is spinless, the decay angular distribution of the kaon in the D^0 rest frame is isotropic for the decay $D^0\to K^-\pi^+$. Choosing the direction of the D^0 laboratory momentum as the reference axis, the cosine of the decay angle of the kaon, θ_k, in the D^0 rest frame should be uniformly distributed. However, background combinations tend to be peaked in the forward and backward direction because of the jetlike nature of continuum events and the preponderance of low-momentum tracks. To increase the signal-to-background ratio, we require

$\cos\theta_K \geq -0.80$ for D^{*+} candidates with $x^+ \leq 0.80$.

Charged-track combinations are selected such that the absolute value of the mass difference ΔM is within 1.5 MeV of the known value of 145 MeV. The distributions of the invariant mass of the $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ combinations satisfying the mass difference cut are shown in Fig. 3 where combinations with $x^+ > 0.55$ and $x^+ < 0.55$ are plotted separately.

The D^0 mass distribution is binned in $\cos\theta$ and x^+, with $\cos\theta$ intervals of 0.4 and six x^+ ranges, for $x^+ \geq 0.25$. The angle θ, defined in Sec. II, is the D^{*+} decay angle. The mass distribution of the resulting $K^-\pi^+(K^-\pi^+\pi^-\pi^+)$ combinations is then fit to a Gaussian signal plus background. We exclude from the fit of the $K^-\pi^+$ invariant mass the region between 1.55 and 1.70 due to the presence of structure from the decay $D^0 \rightarrow K^+\pi^+\pi^0$ [16]. The mean and the width of the Gaussian are fixed to the value determined by a Monte Carlo simulation.

The efficiencies are determined from a Monte Carlo study. The acceptance is approximately flat over the full $\cos\theta$ and x^+ range but it drops near $\cos\theta \approx 1$ in the first and second x^+ bins due to inefficiency in detecting the slow pion [17].

IV. DISCUSSION OF THE RESULTS

In the first x^+ bin $0.25 < x^+ < 0.45$ we use only the $K^-\pi^+$ decay mode of the D^0 because of the high level of background present in the $K^-\pi^+\pi^-\pi^+$ channel. Over the rest of the x^+ range we have combined the data from the two D^0 decay modes by taking the weighted average of the $\cos\theta$ distributions appropriately corrected for efficiencies and branching ratios [18]. The number of D^{*+} mesons found in each decay mode is given in Table I. The combined result is plotted in Fig. 4. The values of α and χ^2 in each x^+ bin are also given in Table I. Using the formalism outlined in Sec. II, we can extract from the measurement of α other spin-related quantities and compare them to predictions from various theoretical models. In Table II the results of the spin-related quantities that we have measured are listed. The first error is statistical while the second is systematic. In the study of the systematic error we have taken into account the uncertainties in the Monte Carlo efficiencies and the fitting procedure.

In Fig. 5 we plot the fitted values of α as a function of x^+. The error on each point is obtained from the statistical and systematic errors, quoted in Table II, summed in

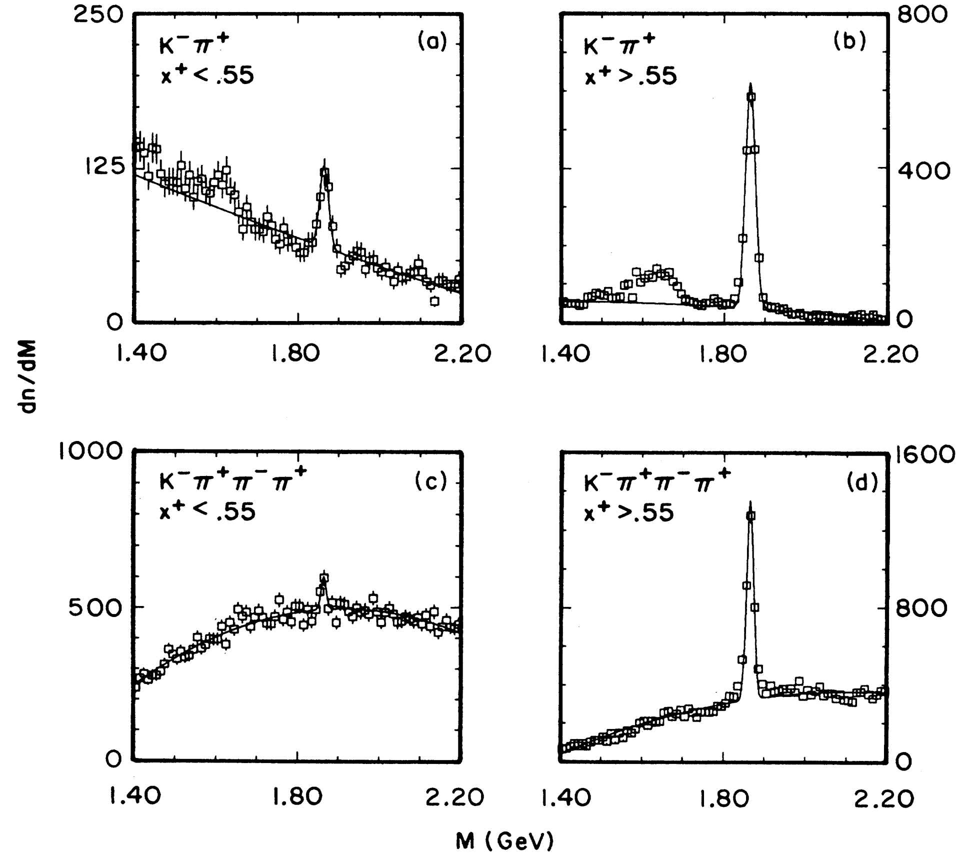

FIG. 3. D^0 invariant-mass distributions: (a) $D^0 \rightarrow K^-\pi^+$ for $x^+ < 0.55$; (b) $D^0 \rightarrow K^-\pi^+$ for $x^+ > 0.55$; (c) $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ for $x^+ < 0.55$; (d) $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ for $x^+ > 0.55$.

TABLE I. Number of reconstructed D^{*+} and fit results for three degrees of freedom.

	$K^-\pi^+$		$K^-\pi^+\pi^-\pi^+$		Combined	
x^+	Events	α	Events	α	α	C.L. (%)
0.25–0.45	47±14	−0.99±0.50			−0.99±0.50	32
0.45–0.55	129±12	0.72±0.59	137±22	0.04±0.56	0.30±0.45	54
0.55–0.645	544±25	−0.09±0.18	674±37	0.08±0.22	−0.12±0.14	4
0.65–0.75	547±25	0.02±0.18	730±33	0.06±0.22	0.06±0.14	98
0.75–0.85	418±21	0.39±0.25	649±28	0.26±0.22	0.31±0.16	16
0.85–1.0	270±17	0.08±0.35	237±16	0.42±0.26	0.42±0.25	21

quadrature. The solid curve in the plot is the prediction of the Suzuki model [5] and the horizontal line at $\alpha=0$ corresponds to the statistical model [8] for $P_V=0.75$. It is clear from the plot that the data are not well described by either model; the Suzuki model gives a χ^2 of 141 for six degrees of freedom, while the statistical model gives a χ^2 of 12 for six degrees of freedom.

Similar analyses have also been performed by the HRS [19], the TPC [20], and the ARGUS [21] Collaborations. Their results are included in Fig. 5 and are in good agreement with our data; note that the error bars on the ARGUS and HRS data points are statistical only [22]. The overall fit to the data points of the four experiments yields a χ^2 of 53.1 for 21 degrees of freedom for the statistical model.

The results depend on the assumption that the D^{*+} meson is not produced polarized in decays of higher D^{**} resonances. CLEO [3] finds two D^{**} states decaying into $D^{*+}\pi^-$ which are consistent with the following assignments of spin and parity quantum numbers: $D^{**}(2428)$ with $J^P=1^+$, and $D^{**}(2461)$ with $J^P=2^+$.

An analysis of the angular distribution of D^{*+} from a D^{**} was performed by CLEO [3]. The data are consistent with the D^{*+} from the decay of $D^{**}(2461)$ being

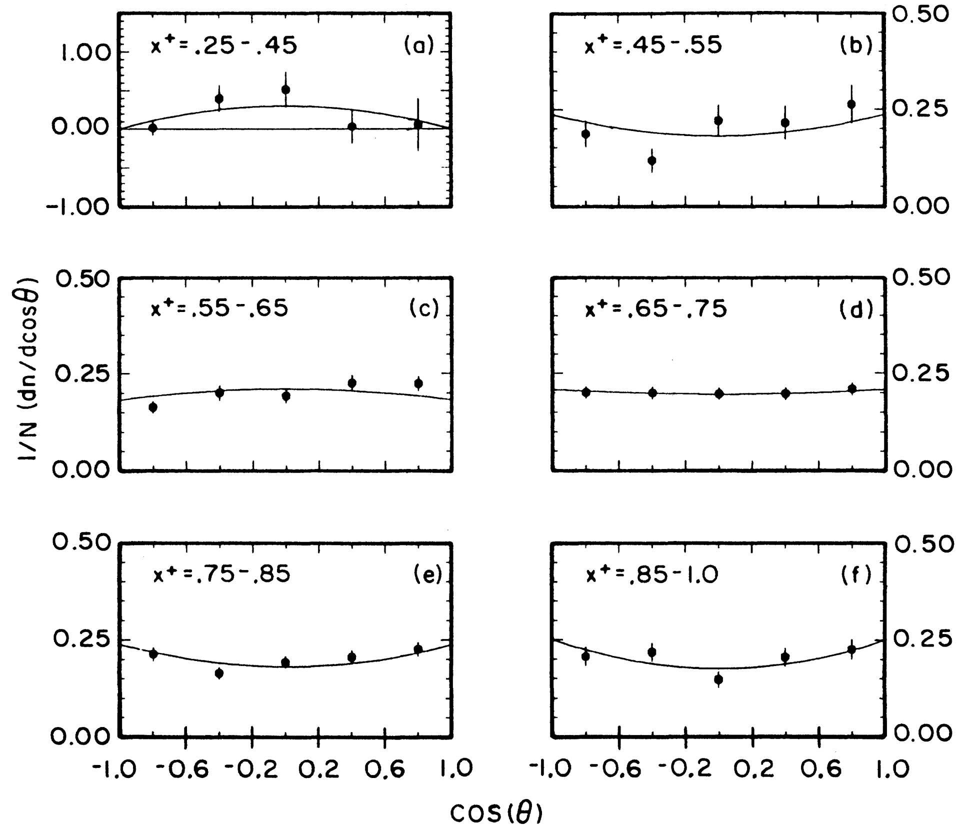

FIG. 4. Distributions of $(1/N)(dn/d\cos\theta)$ fit to $[3/(6+2\alpha)](1+\alpha\cos^2\theta)$ for the following ranges of x^+: (a) $0.45\le x^+\le 0.55$; (b) $0.55\le x^+\le 0.65$; (c) $0.65\le x^+\le 0.75$; (d) $0.75\le x^+\le 0.85$; (e) $0.85\le x^+\le 1.0$. The data are obtained by an average of the two D^0 decay modes: $D^0\to K^-\pi^+$ and $D^0\to K^-\pi^+\pi^-\pi^+$.

TABLE II. Spin-related quantities.

x^+	α	ρ_{00}	η
0.25–0.45	$-0.99\pm0.50\pm0.15$	$0.005\pm0.25\pm0.03$	$-0.49\pm0.37\pm0.04$
0.45–0.55	$0.30\pm0.45\pm0.15$	$0.39\pm0.08\pm0.03$	$0.09\pm0.11\pm0.04$
0.55–0.65	$-0.12\pm0.14\pm0.05$	$0.31\pm0.03\pm0.01$	$-0.04\pm0.05\pm0.02$
0.65–0.75	$0.06\pm0.14\pm0.03$	$0.35\pm0.03\pm0.01$	$0.02\pm0.04\pm0.01$
0.75–0.85	$0.31\pm0.16\pm0.04$	$0.40\pm0.03\pm0.01$	$0.09\pm0.04\pm0.01$
0.85–0.10	$0.04\pm0.25\pm0.07$	$0.42\pm0.04\pm0.01$	$0.12\pm0.06\pm0.02$

transversely polarized. However the D^{*+} decay angular distribution should be isotropic from the $D^{**}(2428)$ decay. Because of the small production rate $D^{**}(2461)\to D^{*+}\pi^-/D^{*+}=3.6\pm1.0^{+0.4}_{-0.8}\%$ we conclude that the effect of the transverse polarization is small.

To obtain a result averaged over x^+ we take each $\cos\theta$ distribution corrected only for detection efficiency and sum over x^+ in the observed range $x^+>0.25$. We combine the two D^0 decay modes with a weighted average of the distributions corrected by the respective branching ratios. A fit to the resulting distribution yields $\langle\alpha\rangle=0.08\ \pm0.07\pm0.04$ corresponding to $\langle\eta\rangle=0.04\ \pm0.02\pm0.01$ with a χ^2 of 6.2 for three degrees of freedom. In Table III we compare the measured value of $\langle\eta\rangle$ with model predictions. The values of $\langle\eta\rangle$ from the various experiments suggest a positive value of the alignment and hence that vector mesons are produced preferentially in the helicity 0 state.

In the statistical model the above value of $\langle\alpha\rangle$ implies $\langle P_V\rangle=0.77\pm0.02\pm0.01$. The result is in agreement with the value of $\langle P_V\rangle$ for the charm sector measured by the CLEO Collaboration $\langle P_V\rangle=0.85\pm0.11\pm0.17$ [2] and with an average of various experimental measurements at the SLAC and DESY storage rings PEP and PETRA which yields $\langle P_V\rangle=0.81\pm0.09$ [23]. We emphasize that our result is valid only in the limit of the statis- tical model but is independent of the value $B(D^{*+}\to D^0\pi^+)B(D^0\to K^-\pi^+)$. On the contrary the value of P_V found in Ref. [23] is inversely proportional to $B(D^{*+}\to D^0\pi^+)\,B(D^0\to K^-\pi^+)$.

The value of $\langle P_V\rangle$ we find in charm decays agrees with the theoretical hypothesis that the production ratio of vector and pseudoscalar particle depends on the masses of the particles [12]. We use the average value of P_V found in the K^*/K and ρ/π systems [23] together with our measurement for the charm sector to verify this hypothesis. The data are fit to the functions

$$\frac{P}{V}=\frac{1}{3}\left[\frac{M_V}{M_P}\right]^{\beta}$$

were M_V and M_P are the masses of the appropriate pseudoscalar and vector states. The fit, shown in Fig. 6, yields $\beta=0.53\pm0.09$.

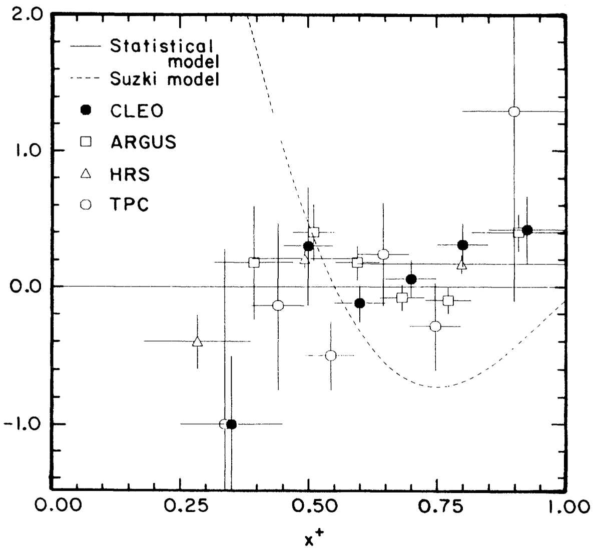

FIG. 5. Distributions of α vs x^+: CLEO data (solid circles); TPC data (empty circles); HRS data (triangles); ARGUS data (squares); Suzuki model (dashed line) and statistical model for $f=\frac{1}{2}$ (solid line).

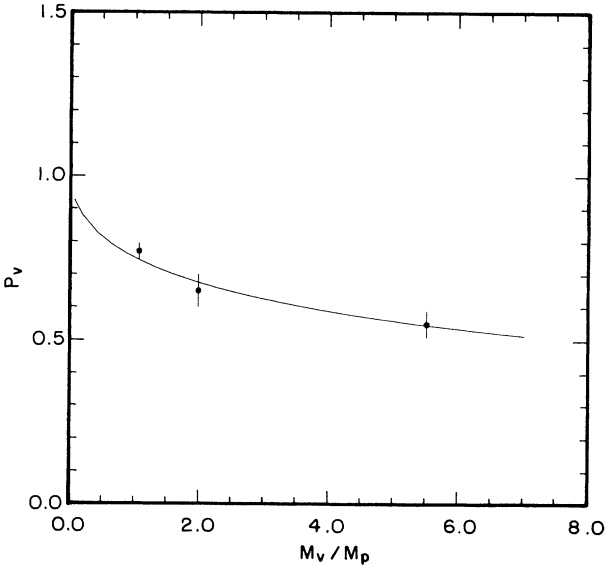

FIG. 6. P_V vs M_V/M_P. The point for D^* and D at $M_V/M_P\approx1$ is given by our analysis. The other two points are the weighted average of the results presented in the review paper by Mättig [23].

TABLE III. Measurements and model predictions of $\langle \eta \rangle$.

Case		Reference	$\langle \eta \rangle$
Experiment	$e^+e^-[\sqrt{s}=10.5\ \text{GeV}]$	This experiment	$0.04\pm0.02(\text{stat})\pm0.01(\text{syst})$
	$e^+e^-[\sqrt{(s)}=29\ \text{GeV}]$	[19]	0.05 ± 0.01
	$e^+e^-[\sqrt{(s)}=29\ \text{GeV}]$	[20]	-0.05 ± 0.06
	$e^+e^-[\sqrt{(s)}=10\ \text{GeV}]$	α values from [21]	0.04 ± 0.02
	$\bar{\nu}Ne \rightarrow \rho X$	[4]	$0.48\pm0.27(\text{stat})\pm0.15(\text{syst})$
	$\nu Ne \rightarrow \rho X$	[4]	$0.12\pm0.20(\text{stat})\pm0.10(\text{syst})$
Theory	Statistical model $V/P=1$	[8]	$-\frac{1}{2}$
	Statistical model $V/P=3$	[8]	0
	Lund model	[12]	≤ 0
	Parton shower picture	[10,11]	$-1/2<\langle \eta \rangle <0$
	Vector currents	[8]	1
	Suzuki model	[5]	-0.016

V. SUMMARY

We have measured the spin alignment with respect to the helicity axis of D^{*+} mesons produced in e^+e^- annihilation at $\sqrt{s}=10.5$ GeV. Our data are in good agreement with results from other experiments. The polarization is observed to vary with x^+; this behavior is not well described by model predictions. Disregarding this dependence, the overall polarization is marginally consistent with zero as expected in the statistical model. The experimental data available from the study of D^{*+} and ρ mesons suggest a positive value for the spin alignment while most of the theoretical models predict $-\frac{1}{2} \leq \eta \leq 0$.

Our results depend on the assumption that the D^{*+} meson is not produced polarized in decays of higher D^{**} resonances. This assumption is supported by the experimental evidence [3] that only $\approx 12\%$ of D^{*+} mesons are the products of D^{**} decays. Furthermore only $\approx 4\%$ of the D^{*+} produced from D^{**} decays are polarized [3].

In the framework of the statistical approach we have determined $P_V=0.77\pm0.02\pm0.01$ independently of $B(D^{*+}\rightarrow D^0\pi)B(D^0\rightarrow K^-\pi^+)$. The result supports the hypothesis that P_V depends on the masses of the particles and that it is bigger in the case of charm than in the light-quark system.

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