SPIN ANALYSIS OF CHARMED MESONS PRODUCED IN e⁺e⁻ ANNIHILATION^{*}
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ABSTRACT

We have studied the threshold production and decay angular distribution of neutral charmed mesons produced in e^+e^- annihilation. We find consistency with the expected spin values of 0 and 1 for the ground and excited states D and D* respectively. We rule out the alternative spin assignment of 1 for the D and 0 for the D*.

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We report on a study of the production and decay angular distributions of neutral charmed mesons¹ produced in e^+e^- annihilation at center-of-mass energies near 4.03 GeV. Throughout this Letter, we identify the neutral state decaying into K_R and K_{3R} at 1865 MeV/c² with the D[°] and the charged state decaying into K_{Rπ} at 1875 MeV/c² with the D⁺.² A study³ of the threshold recoil spectrum against the D[°] and D⁺ has provided strong evidence for the existence of excited charmed states: the D^{*°}(2005) and the D^{*+}(2010). Furthermore, this study shows D[°] production near threshold is dominated by two-body reactions such as:

$$e^+e^- \rightarrow D^0\overline{D}^{*0} \text{ or } \overline{D}^0D^{*0}$$
 (1)

$$\rightarrow D^{*O}\overline{D}^{*O}$$
(2)

$$\rightarrow D^{*+}D^{-} \text{ or } D^{*-}D^{+}$$
(3)

where the $D^{*^{O}}$ and $D^{*^{+}}$ decay into D^{O} 's via pion emission⁴ and in the case of the $D^{*^{O}}$, by gamma emission. In this Letter we examine angular distributions in reactions (1) and (2) in order to test the three possible D,D^{*} spin assignments if one assumes that the sum of the spins for the D and the D^{*} is less than two. We show that under this assumption the D is spinless, the D^{*} has spin one and their relative parity is even.⁵

Considerable information on the spin and parity of the D and D^{*} comes from a study of the D^{*} production and decay modes. Our observation of either $D^{*O} \rightarrow D^{O}\gamma$ or $D^{*O} \rightarrow \pi^{O}D^{O}$ produced in $e^+e^- \rightarrow D^{O}\overline{D}^{*O}$ or $\overline{D}^{O}D^{*O}$ implies that the D and D^{*} cannot both be spinless.⁷ Observation of $D^* \rightarrow D\pi$ implies that the D and D^{*} must have even relative parity if one meson has spin zero and the other has spin one. This last observation is quite helpful for it allows unique predictions for the production and decay angular distributions of $D \rightarrow K\pi$ in reaction (1) under the two spin assignments we will further consider, $J_D = 0$, $J_{D*} = 1$ or $J_D = 1$, $J_{D*} = 0$. We express the expected joint D° production and decay distributions in terms of the three angles Θ , θ , φ where Θ is the polar production angle of the D° with respect to the annihilation axis, and (θ, φ) are the spherical angles of the decay kaon in the D° helicity frame.⁸ In the limit of nonrelativistic $D^{*\circ}$'s, one computes from symmetry considerations the distributions below⁹:

$$\frac{d^{3}\sigma}{d\cos\Theta d\cos\theta d\varphi} \propto 1 + \cos^{2}\Theta$$
 (a)

$$\frac{d^{3}\sigma}{d\cos\Theta d\cos\theta d\phi} \propto \sin^{2}\theta(\cos^{2}\phi + \cos^{2}\Theta \sin^{2}\phi)$$
 (b)

where Eq. (a) is for $J_D^P = O^{\overline{+}}$, $J_D^P = 1^{\overline{+}}$, and Eq. (b) is for $J_D^P = 1^{\overline{+}}$, $J_D^P = O^{\overline{+}}$. We shall compare these distributions to the data.

The present analysis is based on about 35,000 hadron events produced in e^+e^- annihilation at center-of-mass energies between 3.9 and 4.15 GeV . The data were taken with the SLAC-LBL magnetic detector at SPEAR. Descriptions of the detector and event selection procedures using time-of-flight information have been published.^{1,10} All neutral two-prong combinations are considered as potential D^o candidates with the track having time-of-flight information most consistent with the kaon hypothesis called the kaon.¹¹ The other track is real D^o called the pion. For approximately 40% of the events this amounts to little more than a random selection. For the production angular distribution this K- π ambiguity is irrelevant; however it could matter in analyzing the decay distribution of the kaon in the D^o helicity frame. Fortunately we find that it does not, since K- π interchange effectively reverses the direction of the kaon in the D^o helicity frame, and the angular distributions we are testing are invariant under this transformation.

A relatively clean sample of D° 's produced against $\overline{D}^{*\circ}$'s in reaction (1) can be selected by cutting on the invariant mass of the K_{π} system and the corresponding recoil mass. We have obtained a sample of 153 D° candidates

by cutting on invariant mass from 1820 to 1920 MeV/c² and on recoil mass, computed with a fixed D^o mass of 1865 MeV/c², from 1970 to 2030 MeV/c². About 70% of these D^o candidates were obtained at the fixed center-of-mass energy of 4.028 GeV. We estimate that approximately 15% of the D^o candidates satisfying these cuts are not D^o's but are background two-prong combinations. Furthermore, we estimate that $(64 \pm 4)\%$ of the real D^o's within this cut are primary D^o's recoiling against $\overline{D}^{*\circ}$'s. The remaining D^o's come from either pion or gamma decays of the D^{*o}'s produced via reaction (1), or pion decays of the D^{*+} produced in reaction (3). The primary fraction exceeds 50% because direct D^o's are partially resolvable from secondary D^o's on the basis of recoil mass. The conservative 4% error on the primary fraction is mainly due to uncertainties in the number of D^o's arising from D^{*+} decays.

Figures 1a and 1b show the observed $\cos \Theta$ and $\cos \theta$ distributions for D° candidates satisfying the above mass and recoil mass cuts. The normalized distributions expected for our two spin assignments are also shown. In both figures the solid curve is computed from Eq. (a) and the dashed curve is computed from Eq. (b). Both curves are calculated by a Monte-Carlo program incorporating the acceptance and resolution appropriate to the SPEAR Magnetic Detector. The theoretical distributions have been corrected for the presence of the 15% background ¹² and the presence of secondary D° 's.¹³ The difference between the solid and dashed curves of Fig. 1a is entirely due to the effects of geometrical acceptance for the different $D \rightarrow K_{\pi}$ decay distributions of Eqs. (a) and (b).

Both the solid and dashed curves are acceptable fits to the data of Fig. la with the solid curve having a χ^2 of 5.6 for 9 degrees of freedom (CL = 76%) and the dashed curve having a χ^2 of 11 for 9 degrees of freedom (CL = 28%). The dashed and dotted curve of Fig. la is the $\sin^2 \Theta$ distribution appropriate for the case of spinless D's and D^{*}'s, corrected for acceptance background,

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and the presence of secondaries. This spin assignment is clearly ruled out by the data of Fig. 1a with a χ^2 of 74 for 9 degrees of freedom. The main discrimination between Eqs. (a) and (b) comes from the kaon polar helicity distribution shown in Fig. 1b. The solid curve of Fig. 1b is consistent with the data with a χ^2 of 8.2 for 9 degrees of freedom (CL = 51%) while the dashed curve is inconsistent with a χ^2 of 23 for 9 degrees of freedom (CL = 6×10^{-3}).¹⁴ On the basis of this analysis the expected spin assignment 0 and 1 for D and D^{*} respectively is preferred over the alternative assignment 1 and 0.

We have devised an alternative method for comparing the data to the distribution of Eqs. (a) and (b) which makes use of all three angular variables and handles backgrounds differently. The technique displays the invariant mass plot for events satisfying the recoil mass cut and having variables within one of two angular regions chosen to insure discrimination between Eqs. (a) and (b) by dividing the space of angular variables by a surface of constant $I = \sin^2 \theta (\cos^2 \varphi + \cos^2 \Theta \sin^2 \varphi)$. Figures 2a and 2b show the $\kappa^{\mp} \pi^{\pm}$ invariant mass distribution for events satisfying I < 0.32 and I > 0.32 respectively. The fit of Figs. 2a and 2b, consisting of a Gaussian signal over an exponentially falling background, gives 58 ± 8 and 73 ± 10 signal events respectively.¹⁵ Defining an asymmetry variable A equal to the difference in the number of signal events over their sum, we obtain $A_{c} = 0.11 \pm 0.10$ which is in good agreement with 0.11 ±0.01, the value expected for spin 0 D's and spin 1 D*'s, but inconsistent with 0.41 \pm 0.03, the value obtained for spin 1 D's and spin 0 D^* 's $(x^2 = 8.3 \text{ for one degree of freedom, } CL = 3.5 \times 10^{-3})$. The errors on the mainly expected asymmetries under the two hypotheses reflect, the errors on the fraction of primary D^o's from reaction (1).

In Fig. 1c we present the production polar distribution for D° 's from the reaction $e^+e^- \rightarrow D^{*\circ}D^{*\circ}$ chosen by selecting an appropriate range in D° momentum. About 75% of D° 's selected come from the fixed center-of-mass energy of 4.028 GeV. We estimate 15% of the D° candidates satisfying this selection are back-

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ground with 75% of the real D° 's arising from $D^{*\circ} \rightarrow D^{\circ}\pi^{\circ}$ and 25% arising from radiative $D^{*\circ}$ decays. A D° background sample taken from sidebands in the πK invariant mass plot is consistent with isotropy.

The D^{*} polar distribution for the reaction $e^+e^- \rightarrow D^{*-}D^*$ is of the form

$$(d\sigma)/(d\cos\theta) \propto 1 + \alpha\cos^2\theta$$
, (c)

where unique predictions for α cannot be made by symmetry arguments except for spin 0 for which $\alpha = -1$.

The production polar distribution of D° from $D^{*\circ} \rightarrow D^{\circ}\pi^{\circ}$ closely follows Eq. (c) owing to the low $D^{*\circ}$, D° relative momentum, whereas that of D° 's arising from radiative $D^{*\circ}$ decays is a broad convolution over Eq. (c) owing to the larger D, D^{*} relative momentum. We estimate that $\alpha = -0.30 \pm 0.33$ by fitting the data of Fig. lc to a linear combination of Eq. (c) for pionic decays, the convoluted form of Eq. (c) for radiative decays, and an isotropic background. The curve superimposed on Fig. lc represents the above fit. This result is 2.1 standard deviations from the value expected for spinless D^{*} 's.

In summary, we have shown that the production and decay angular distributions for D⁰'s produced near threshold via the reaction $e^+e^- \rightarrow D^0\bar{D}^{*0}$ or \bar{D}^0D^{*0} are incompatible with D⁰, D^{*} spin-parity assignments of 1[‡], 0[‡] and compatible with 0[‡], 1[‡]. In addition the angular distribution of D^{*0}'s produced in reaction $e^+e^- \rightarrow D^{*0}\bar{D}^{*0}$ is incompatible with spinless D^{*} on the 2 standard deviation level. In the conventional quark model, one constructs the light neutral charmed mesons from an S-wave combination of a c and \bar{u} quark. In light of experience with the conventional, uncharmed mesons, one expects the ${}^{1}S_{0}$ pesudoscalar charmed state to lie lower in mass than the ${}^{3}S_{1}$ vector state. In this model the D⁰ is a pseudoscalar and the D^{*0} is a vector. 16 Our data are consistent with this assignment. Several theorists, however, have contemplated the alternative possibility that the D⁰ is a vector and the D^{*0} is a pseudoscalar. 17 We wish to thank J. D. Jackson and F. Gilman for useful discussions.

FOOTNOTES AND REFERENCES

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- 8. The helicity frame is oriented with its z axis (polar axis) along the direction of the D momentum in the overall c.m. and its y axis along the production plane normal.
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- 11. Neutral two-body combinations with both tracks lacking time-of-flight are dropped from the analysis. This occurs for about 10% of the combinations.
- 12. Background effects were included by the addition of a 15% isotropic background in both production and decay angular distributions. The assumption of background isotropy was checked by background events from 50 MeV/ c^2 sidebands in the K_A invariant mass distribution.

- 13. The presence of secondary D° 's only slightly distorts the $\cos \Theta$ distribution of Fig. la owing to the small momentum of the D° 's in the $D^{*\circ}$ rest frame for D^* pion decays. We estimate the direction of D° 's from $D^{*\circ} \rightarrow D^{\circ}\pi^{\circ}$ lies within 5° of the D-D^{*} axis. The largest effect of secondary D° 's is the addition of a nearly isotropic contribution to the $\cos \theta$ distribution of Fig. lb for the curve appropriate to Eq. (b).
- 14. Errors in the calculation of the expected curves are not included in these χ^2 calculations.
- 15. We note that there is a 1.5 standard deviation inconsistency in the widths of the peaks of Fig. 2.
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FIGURE CAPTIONS

Fig. 1. (a) Production polar distribution of D^{O} in reaction (1). Solid curve corresponds to $J_{D}^{P} = O^{\pm}$ and $J_{D^{*}}^{P} = 1^{\pm}$. Dashed curve corresponds to $J_{D} = 1^{\pm}$ and $J_{D^{*}}^{P} = O^{\pm}$. Dashed and dotted curve corresponds to spinless D and D^{*}; here "theta" = Θ (see text). (b) Helicity polar distribution for D^O in reaction (1). Solid curve corresponds to $J_{D}^{P} = O^{\pm}$ and $J_{D^{*}}^{P} = 1^{\pm}$. Dashed curve corresponds to $J_{D}^{P} = 1^{\pm}$ and $J_{D^{*}}^{P} = O^{\pm}$; here "theta" = θ . (c) Production polar distribution for D^O in reaction (2). Solid curve is deduced from fit; here "theta" = Θ .

Fig. 2. Invariant mass spectra of $K_{\pi}^{\pm \mp}$ system for I < 0.32 and I > 0.32.

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Fig. 1



