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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 $O$ and I for the ground and excited states $D$ and $D^{*}$ respectively. We rule out the alternative spin assignment of 1 for the $D$ and $O$ for the $D^{*}$.

[^0]We report on a study of the production and decay angular distributions of neutral charmed mesons ${ }^{l}$ produced in $e^{+} e^{-}$annihilation at center-of-mass energies near 4.03 GeV . Throughout this Letter, we identify the neutral state decaying into $K \pi$ and $K 3 \pi$ at $1865 \mathrm{MeV} / \mathrm{C}^{2}$ with the $\mathrm{D}^{\circ}$ and the charged state decaying into $K \pi \pi$ at $1875 \mathrm{MeV} / \mathrm{c}^{2}$ with the $\mathrm{D}^{+} .^{2}$ A study ${ }^{3}$ of the threshold recoil spectrum against the $D^{\circ}$ and $D^{+}$has provided strong evidence for the existence of excited charmed states: the $D^{* 0}(2005)$ and the $D^{*+}(2010)$. Furthermore, this study shows $D^{\circ}$ production near threshold is dominated by two-body reactions such as:

$$
\begin{align*}
e^{+} e^{-} & \rightarrow D^{\circ} D^{* O} \text { or } D^{-} D^{* O}  \tag{1}\\
& \rightarrow D^{* O} D^{* O}  \tag{2}\\
& \rightarrow D^{*+} D^{-} \text {or } D^{*-} D^{+} \tag{3}
\end{align*}
$$

where the $D^{* O}$ and $D^{*+}$ decay into $D^{\circ}$ s via pion emission ${ }^{4}$ and in the case of the $D^{* 0}$, 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 $D^{* O} \rightarrow D^{\circ} \gamma$ or $D^{* O} \rightarrow \pi^{\circ} D^{\circ}$ produced in $e^{+} e^{-} \rightarrow D^{\circ} D^{* O}$ or $D^{-O} D^{* O}$ 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 $J_{D}=1, J_{D^{*}}=0$. express the expected joint $D^{\circ}$ production and decay distributions in terms of the three angles $\Theta, \theta, \varphi$ where $\Theta$ is the polar production angle of the $D^{\circ}$ with respect to the annihilation axis, and $(\theta, \varphi)$ are the spherical angles of the decay kaon in the $D^{0}$ helicity frame. ${ }^{8}$ In the limit of nonrelativistic $\mathrm{D}^{* O}$ 's, one computes from symmetry considerations the distributions below ${ }^{9}$ :

$$
\begin{align*}
& \frac{d^{3} \sigma}{d \cos \Theta d \cos \theta d \varphi} \propto 1+\cos ^{2} \Theta  \tag{a}\\
& \frac{d^{3} \sigma}{d \cos \Theta d \cos \theta d \varphi} \propto \sin ^{2} \theta\left(\cos ^{2} \varphi+\cos ^{2} \Theta \sin ^{2} \varphi\right) \tag{b}
\end{align*}
$$

where Eq. (a) is for $J_{D}^{P}=O^{\mp}, J_{D^{*}}^{P}=I^{\mp}$, and Eq. (b) is for $J_{D}^{P}=I^{\mp}, J_{D^{*}}^{P}=O^{\mp}$. 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 $D^{\circ}$ candidates with the track having time-of-flight information most consistent with the kaon hypothesis called the kaon. ${ }^{11}$ The other track is real $D^{0}$ called the pion. For approximately $40 \%$ of thenevents this amounts to little more than a random selection. For the production angular distribution this $K-\pi$ ambiguity is irrelevant; however it could matter in analyzing the decay distribution of the kaon in the $D^{\circ}$ helicity frame. Fortunately we find that it does not, since $K-\pi$ interchange effectively reverses the direction of the kaon in the $D^{\circ}$ helicity frame, and the angular distributions we are testing are invariant under this transformation.

A relatively clean sample of $\mathrm{D}^{\circ}$ 's produced against $\overline{\mathrm{D}}^{* O}$, s in reaction (I) can be selected by cutting on the invariant mass of the $K \pi$ system and the corresponding recoil mass. We have obtained a sample of $153 \mathrm{D}^{\circ}$ candidates
by cutting on invariant mass from 1820 to $1920 \mathrm{MeV} / \mathrm{c}^{2}$ and on recoil mass, computed with a fixed $D^{\circ}$ mass of $1865 \mathrm{MeV} / \mathrm{c}^{2}$, from 1970 to $2030 \mathrm{MeV} / \mathrm{c}^{2}$. About $70 \%$ of these $D^{\circ}$ candidates were obtained at the fixed center-of-mass energy of 4.028 GeV . We estimate that approximately $15 \%$ of the $\mathrm{D}^{\circ}$ candidates satisfying these cuts are not $D^{\circ}$ 's but are background two-prong combinations. Furthermore, we estimate that ( $64 \pm 4$ ) \% of the real $D^{\circ}$ 's within this cut are primary $D^{\circ}$ 's recoiling against $\bar{D}^{* O}$ 's. The remaining $D^{\circ}$ '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 $D^{\circ}$ 's are partially resolvable from secondary $D^{\circ}$ 's on the basis of recoil mass. The conservative $4 \%$ error on the primary fraction is mainly due to uncertainties in the number of $D^{\circ}$ 's arising from $D^{*+}$ decays.

Figures la and lb show the observed $\cos \Theta$ and $\cos \theta$ distributions for $D^{\circ}$ 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 $D^{0},{ }^{13}$ The difference between the solid and dashed curves of Fig. la 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 $X^{2}$ of 5.6 for 9 degrees of freedom (CL $=76 \%$ ) and the dashed curve having a $x^{2}$ 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 $D^{\prime} s$ and $D^{*}$, $s$, corrected for acceptance, background,
and the presence of secondaries. This spin assignment is clearly ruled out by the data of Fig. la with $a x^{2}$ 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. lb. The solid curve of Fig. lb is consistent with the data with a $x^{2}$ of 8.2 for 9 degrees of freedom ( $C L=51 \%$ ) while the dashed curve is inconsistent with a $\chi^{2}$ of 23 for 9 degrees of freedom ( $C L=6 \times 10^{-3}$ ). ${ }^{14}$ on the basis of this analysis the expected spin assignment $O$ 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 $I=\sin ^{2} \theta\left(\cos ^{2} \varphi+\cos ^{2} \Theta \sin ^{2} \varphi\right)$. Figures $2 a$ and $2 b$ show the $K^{\mp} \pi^{ \pm}$invariant mass distribution for events satisfying $I<0.32$ and $I>0.32$ respectively. The fit of Figs. 2 a and 2 b , consisting of a Gaussian signal over an exponentially falling background, gives $58 \pm 8$ and $73 \pm 10$ signal events respectively. 15 Defining an asymmetry variable $A_{s}$ equal to the difference in the number of signal events over their sum, we obtain $A_{s}=0.11 \pm 0.10$ which is in good agreement with $0.11 \pm 0.01$, the value expected for $\operatorname{spin} O D^{\prime} s$ and $\operatorname{spin} 1 D^{*} s$, but inconsistent with $0.41 \pm 0.03$, the value obtained for $\operatorname{spin} 1 D^{\prime} s$ and $\operatorname{spin} O D^{*} s$ $\left(x^{2}=8.3\right.$ for one degree of freedom, $\left.C L=3.5 \times 10^{-3}\right)$. The errors on the expected asymmetries under the two hypotheses reflect ${ }_{\wedge}$ the errors on the fraction of primary $D^{\circ}$,s from reaction (1).

In Fig. lc we present the production polar distribution for $D^{\circ}$ 's from the reaction $e^{+} e^{-} \rightarrow D^{* O} D^{* O}$ chosen by selecting an appropriate range in $D^{\circ}$ momentum. About $75 \%$ of $\mathrm{D}^{\circ}$ 's selected come from the fixed center-of-mass energy of 4.028 GeV. We estimate $15 \%$ of the $\mathrm{D}^{\circ}$ candidates satisfying this selection are back-
ground with $75 \%$ of the real $D^{\circ}$ 's arising from $D^{* O} \rightarrow D^{\circ} \pi^{\circ}$ and $25 \%$ arising from radiative $D^{* O}$ decays. $A D^{\circ}$ background sample taken from sidebands in the $\pi K$ invariant mass plot is consistent with isotropy.

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

$$
\begin{equation*}
(d \sigma) /(d \cos \theta) \propto 1+\alpha \cos ^{2} \theta \tag{c}
\end{equation*}
$$

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

The production polar distribution of $D^{\circ}$ from $D^{* O} \rightarrow D^{\circ} \pi^{\circ}$ closely follows Eq. (c) owing to the low $D^{* O}, D^{\circ}$ relative momentum, whereas that of $D^{\circ}$ 's arising from radiative $D^{* O}$ 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 $D^{\circ}$ 's produced near threshold via the reaction $e^{+} e^{-} \rightarrow D^{\circ} \bar{D}^{* O}$ or $\vec{D}^{\circ} D^{* O}$ are incompatible with $D^{\circ}, D^{*}$ spin-parity assignments of $I^{\mp}, O^{\mp}$ and compatible with $O^{\mp}, 1^{\mp}$. In addition the angular distribution of $D^{* O}$, s produced in reaction $e^{+} e^{-} \rightarrow D^{* O} \bar{D}^{* O}$ 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 $\overline{\mathrm{u}}$ quark. In light of experience with the conventional, uncharmed mesons, one expects the ${ }^{1}{ }_{S}$ pesudoscalar charmed state to lie lower in mass than the ${ }^{3} S_{1}$ vector state. In this model the $D^{\circ}$ is a pseudoscalar and the $D^{* O}$ is a vector. ${ }^{16}$ our data are consistent with this assignment. Several theorists, however, have contemplated the alternative possibility that the $D^{\circ}$ is a vector and the $D^{* O}$ is a pseudoscalar. ${ }^{17}$ This possibility has now been ruled out.

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## 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 $50 \mathrm{MeV} / \mathrm{c}^{2}$ sidebands in the $K \pi$ invariant mass distribution.
13. The presence of secondary $D^{\circ}$ 's only slightly distorts the cos $\Theta$ distribution of Fig. la owing to the small momentum of the $D^{\circ}$ 's in the $D^{* O}$ rest frame for $D^{*}$ pion decays. We estimate the direction of $D^{\circ}$ s from $D^{* O} \rightarrow$ $D^{\circ} \pi^{\circ} \quad$ lies within $5^{\circ}$ of the $D-D^{*}$ axis. The largest effect of secondary $D^{\circ}$ 's is the addition of a nearly isotropic contribution to the cos $\theta$ distribution of Fig. 1 l for the curve appropriate to Eq. (b).
14. Errors in the calculation of the expected curves are not included in these $x^{2}$ calculations.
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## FIGURE CAPTIONS

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

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


Fig. 1


Fig. 2


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