Spin tests for charmed mesons produced in e^+e^- annihilation at $\sqrt{s} = 4.028$ GeV

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Spin tests for particles produced in e^+e^- annihilation at $\sqrt{s} = 4.028$ GeV in the state labeled $\bar{D}^*D^*$ are presented. These particles are currently believed to be spin-1 particles with negative parity. However, their extraordinarily large production rate just above their production threshold—despite the p-wave nature of the production process—leads us to speculate that one of these might, in fact, be a spinless, positive-parity D meson with a mass approximately the same as the D^*. This possibility is considered and tested in detail, along with the usual hypothesis that the particles are spin-1 particles.

One of the most striking features in the e^+e^- annihilation data above the charm threshold is the complex enhancement in

$$R = \frac{e^+e^- \to \text{“hadrons”}}{e^+e^- \to \mu^+\mu^-}$$

in the $\sqrt{s} = 4.0$ GeV region.[1,2] The value of R at $\sqrt{s} \sim 4.0$ GeV is seen to rise from ~4.0 to above 6, reaching a peak at 4.028 GeV. A study of the energy spectrum of the detected D^0's (ESDD), at this center-of-mass energy, indicates copious production of charm, manifesting itself in the $\bar{D}^0D^0$, $\bar{D}^0D^{*0} + D^0\bar{D}^{*0}$, $\bar{D}^{*0}D^{*0}$ channels.[2,3] Quantitative analyses further reveal that the production of these states takes place in the ratio 1:~8:~8. Considering that there is already an "extra" 1 to 1.5 units of R at $\sqrt{s} \sim 4.0$ GeV, presumably mainly due to $\bar{D}D^* + D\bar{D}^*$ production, it then appears that most of the subsequent rise arises from the production of $\bar{D}^{*0}D^{*0}$. Its production threshold of ~4.012 GeV implies a kinetic energy of about only 16 MeV at the peak in contrast to ~160 MeV for the $\bar{D}^0D^{*0} + D^0\bar{D}^{*0}$ channel and ~300 MeV for the $\bar{D}^0D^0$. Since all these processes take place in a p wave $[J^P(D^0) = 0^-, J^P(D^{*0}) = 1^-]$, it becomes clear that the $\bar{D}^{*0}D^{*0}$ production is extraordinarily enhanced; its relative contribution to the peak exceeds, by at least an order of magnitude, that predicted by De Rújula *et al.*[4] on the basis of the simple spin-counting method. In an effort to explain this anomalously large production of $\bar{D}^{*0}D^{*0}$, the authors of Ref. 4 have suggested[5] that the peak at $\sqrt{s} = 4.028$ GeV be interpreted as a molecular charmonium, i.e., a p-wave bound state of $\bar{D}^*D^*$. The contention is that the $\bar{D}^{*0}D^{*0}$ is copious simply because the molecule dissociates easily to appear as a free $\bar{D}^{*0}D^{*0}$ state. On the other hand, its transformation into other states is suppressed owing to the requirement of quark-spin rearrangement.

Because of this unusually large production rate of the state labeled $\bar{D}^*D^*$, we believe it is important to test whether it really involves two spin-1 particles as is usually assumed. Can it be, for example, that one of these is actually a positive-parity D meson (approximately as massive as the D^*) which is copiously produced in conjunction with the D^* in an s wave?[6] The nature of the rise in R at ~4.0 GeV, in fact, motivates us further to consider this possibility somewhat seriously. With the assumption of spin 0 for this positive-parity D meson, which we henceforth denote by D^{**}, we find that the part of the ESDD which we generally ascribe to the $\bar{D}^*D^*$ state can be easily explained in terms of this hypothesis. For example, the first prominent peak in ESDD which is usually attributed to the following sequence of processes,

$$e^+e^- \to \bar{D}^{*0}D^{*0}, \tag{1}$$

$$D^{*0} \to D^0 + \pi^0, \tag{1a}$$

can now be regarded to arise in the following manner:

$$e^+e^- \to \bar{D}^{**0}D^{*0} + D^{**0}\bar{D}^{*0}, \tag{2}$$

$$D^{**0} \to D^0 + \pi^0, \tag{2a}$$

$$D^{*0} \to D^0 + \pi^0. \tag{2b}$$

The presence of significant structure, pertaining to electromagnetic decays[7] in the neighborhood of this peak, is also accounted for by simply requiring that the D^{*0} decays be predominantly electromagnetic in nature. This requirement, it should be noted, is necessary since the electromagnetic decay mode of D^{**0} does not exist. An obvious consequence of it is that the contribution of process (2b) to the peak is relatively small. In what follows, we label Eqs. (1) and (2) as hypotheses A and B respectively, and discuss how these may be tested.

For the kinematics of the problem, we assume that $M(D^{**0}) = M(D^{*0}) = 2.006$ GeV and $M(D^0) = 1.863$ GeV. Figure 1 shows the schematic representation of the ESDD at $\sqrt{s} = 4.028$ GeV, per-

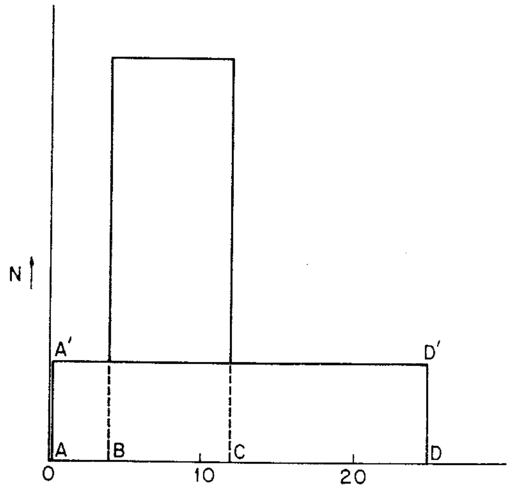

FIG. 1. Schematic representation of ESDD at $\sqrt{s}=4.028$ GeV. T denotes the kinetic energy of D^0 and N the number of events. The rectangular region $AA'D'D$ corresponds to the process $D^{*0}\to D^0+\gamma$, while the peak, superposed on this region, arises from events of the type: "D^{*0}" $\to D^0+\pi^0$, where "D^{*0}" is D^{*0} in case A and either D^{**0} or D^{*0} in case B. In B, it is assumed that $M(D^{**0}) = M(D^{*0})$. See text for other details.

taining to either of the following sources:

case A,

$$e^+e^-\to\bar{D}^{*0}D^{*0}, \tag{3}$$

$$D^{*0}\to D^0+\gamma, \tag{3a}$$

$$D^{*0}\to D^0+\pi^0, \tag{3b}$$

case B,

$$e^+e^-\to\bar{D}^{**0}D^{*0}+D^{**0}\bar{D}^{*0}, \tag{4}$$

$$D^{*0}\to D^0+\gamma, \tag{4a}$$

$$D^{**0}\to D^0+\pi^0, \tag{4b}$$

$$D^{*0}\to D^0+\pi^0. \tag{4c}$$

The events corresponding to the electromagnetic decay of D^{*0} are spread out and occur within the rectangular region $AA'D'D$. The energy distribution is uniform owing to the relation $(dN/dT) = \text{constant}$,[8] where T is the kinetic energy of D^0 in the laboratory. Superposed on this spectrum, in the energy region BC, is the peak due to the pionic decay of either D^{*0} in case A or D^{**0} and D^{*0} in case B. The peak, in general, is narrow due to the low momentum of D^0 in the rest frame of the parent particle. The region AB, and perhaps also a part of BC, is contaminated by D^0's arising from the decay of the charged counterparts of D^{*0} or D^{**0}, produced also in the e^+e^- annihilation process. On the other hand, region CD does not overlap with that corresponding to $e^+e^-\to\bar{D}^0D^{*0}+D^0\bar{D}^{*0}$, $D^{*0}\to D^0+\gamma$, and thus contains events corresponding solely to Eq. (3a) or (4a). For the values of masses assumed, $OA=0.2$ MeV, $AD=24.7$ MeV, $BC=8.0$ MeV, $CD=13.0$ MeV. Our aim is to study the angular distribution of D^0 in the CD region. Since this distribution depends upon the spin polarization of D^{*0} produced in the primary reaction, the annihilation process, its study should enable us to distinguish between cases A and B. The general formalism for obtaining angular correlations is well known.[9] Rather than go into details here, we shall mention only briefly the qualitative features of the matrix elements for the primary reaction and discuss results, whenever possible, with reference to them.

Consider the annihilation process shown in Fig. 2. Particle 3 is a D^{*0} meson while particle 4 is either $\bar{D}^{*0}$ or $\bar{D}^{**0}$, depending upon the case under consideration. The matrix element for this process may be expressed as

$$M=(e^2/s)j_\mu J^\mu, \tag{5}$$

where j_μ is the familiar leptonic current, $\bar{v}(p_1)\gamma_\mu u(p_2)$ and J_μ, the hadronic current whose form again depends upon the case under consideration. Gauge invariance, which is expressed by the condition $(p_1+p_2)_\mu j^\mu=(p_1+p_2)_\mu J^\mu=0$, immediately gives $j^0=J^0=0$ in the center-of-mass system. In the nonrelativistic limit, the hadronic current is then expressible as

$$\vec{J}_A=a(\vec{\rho}_3\cdot\vec{\rho}_4)\vec{p}+b[\vec{\rho}_3\vec{\rho}_4+\vec{\rho}_4\vec{\rho}_3-\tfrac{2}{3}(\vec{\rho}_3\cdot\vec{\rho}_4)\overleftrightarrow{I}]\cdot\vec{p}, \tag{6a}$$

$$\vec{J}_B=c\vec{\rho}_3 \tag{6b}$$

where the subscript in $\vec{J}$ refers to the hypothesis under consideration, $\vec{p}=\vec{p}_3=-\vec{p}_4$ is the center-of-mass momentum of particle 3, $\vec{\rho}_3$ and $\vec{\rho}_4$ are the polarization vectors of D^{*0} and $\bar{D}^{*0}$, respectively, and $\overleftrightarrow{I}$ is a unit dyadic. The two terms in $\vec{J}_A$ correspond to the $L=1$, $S=0$ and $L=1$, $S=2$ states, respectively. A third term corresponding to the $L=3$, $S=2$ state is neglected. Likewise, in writing $\vec{J}_B$, we have omitted the $L=2$, $S=1$ term; the only term present corresponds to the $L=0$, $S=1$ state of $\bar{D}^{**0}D^{*0}$. Coefficients a and b in Eq. (6a) can,

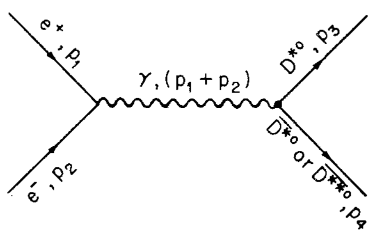

FIG. 2. The e^+e^- annihilation process.

in general, be complex. However, if the $\bar{D}^{*0}D^{*0}$ arises solely from a single resonance, as is believed to be the case in case A, then a and b will have no phase difference. It is also clear that any angular distribution calculated in case A will depend upon the values of a and b. For example, while the angular distribution of the final-state particles in case B is clearly isotropic, that in case A is of the form

$$d\sigma/d(\cos\theta) \sim (1 + P\cos^2\theta), \quad (7)$$

where

$$P = -(9 + 2\alpha^2)/(9 + 14\alpha^2), \quad (8)$$

$$\alpha = |b/a|, \quad (9)$$

and θ is the angle with respect to the e^+e^- beam axis. We have as yet no theoretical knowledge about α; consequently, the distribution in Eq. (7) remains unknown.[10] Nevertheless, from the manner in which P is related to α, we easily see that

$$-1 \leq P \leq -\tfrac{1}{7}, \quad (10)$$

where the lower and upper limits correspond to the extreme cases: $a \neq 0$, $b = 0$ and $a = 0$, $b \neq 0$ respectively.

To obtain the angular correlation of D^0's emerging from $D^{*0} \to D^0 + \gamma$, we must multiply the matrix element M in Eq. (5) by the decay matrix element for this process, and sum over the spins of D^{*0}. Finally, after squaring the resultant matrix element, summing over the spins of the final-state particles and averaging over the initial spins, we get an expression for the energy-angle distribution for D^0 in the laboratory. Symbolically,

$$d\sigma_{D^0} \sim |T(\theta', \omega|^2 d(\cos\theta')d\omega, \quad (11)$$

θ' = angle of D^0 with respect to the initial beam direction and ω = energy of D^0 observed in the laboratory. The extreme limits of ω, namely,

$$\omega_{\min} = \frac{E_3}{M_3}\left(\omega^* - \frac{p_3 q^*}{E_3}\right)$$

and

$$\omega_{\max} = \frac{E_3}{M_3}\left(\omega^* + \frac{p_3 q^*}{E_3}\right),$$

where q^*, ω^* are respectively the momentum, energy of D^0 in the parent's rest frame, are clearly determined by q^* and p_3. Therefore, it is clear that kinematics will play an important role in determining the angular distribution; for example in our problem, for the masses chosen, $p_3 \approx 0.18$ GeV and q^*, in $D^{*0} \to D^0 + \gamma$, ≈ 0.14 GeV, which implies comparable velocities for the D^{*0} in the laboratory and the D^0 in the rest frame of D^{*0}. This situation corresponds to the case which lies intermediate between the following two extreme cases:

(i) The particles in the annihilation process are created almost at rest, i.e., $p_3 \approx 0$.

(ii) The decay products are produced almost at rest in the rest frame of the decaying particle, i.e., $q^* \approx 0$.

In case (ii), the angular distribution is evidently the angular distribution of the primary process. On the other hand, in a situation like case (i), it is governed solely by the spin polarization of the produced-at-rest decaying particle; e.g., for hypothesis B, the distribution is $1 + \cos^2\theta'$. This is due to the fact that when the e^+e^- beam is unpolarized the spin of the produced D^{*0} is aligned half the time forward and half the time backward with respect to the beam axis. However, as soon as a boost is given to D^{*0}, the emitted D^0 tends to go forward with respect to the direction of motion of D^{*0}. As a matter of fact, for the masses in our problem, kinematics shows that any D^0 emitted by D^{*0} is confined within a forward cone of angle ~110°. This naturally has the effect of modifying the angular distribution of the D^0 with respect to the beam axis. In fact, it now seems that, owing to this kinematical constraint of forward confinement, not all the D^{*0} can contribute a D^0 in the direction of the beam axis along which for B, in the case (ii), the emission was a maximum. This apparently results in "dilution." Integration of Eq. (11) over the entire allowed energy interval, yields the distribution $1 + P'_T\cos^2\theta'$ with $P'_T = 0.12$. This is to be compared with the value $P'_T = 0$ for case (ii) and $P'_T = 1$ for case (i). The value $P'_T = 0.12$ is clearly intermediate. In general, the smearing of the ideal case (i) dis-

TABLE I. P'_T in the angular distribution: $1 + P'_T\cos^2\theta'$ for the entire region AD in Fig. 1. θ' is the angle of the detected D^0 with respect to the beam axis.

Hypothesis	Case (i)	Case (ii)	Values obtained for $\sqrt{s}$ = 4.028	4.038	4.048 (GeV)
B	0.0	1.0	0.12	0.06	0.04
A: $a \neq 0$, $b = 0$	−1.0	0.0	−0.5	−0.7	−0.8
$a = 0$, $b \neq 0$	−0.14	0.3	−0.01	−0.06	−0.09

TABLE II. P' in the angular distribution: $1+P'\cos^2\theta'$ for the CD region of Fig. 1. θ' is the angle of the detected D^0 with respect to the beam axis.

Hypothesis	Values obtained for $\sqrt{s}$ = 4.028	4.038	4.048 (GeV)
B	0.46	0.40	0.37
A: $a \neq 0,\ b=0$	−0.76	−0.84	−0.88
$a=0,\ b\neq 0$	0.03	−0.01	−0.03

tribution of D^0, as a result of boost, takes place smoothly such that in the limit $p_3 \gg q^*$, it tends to that for the parent particle. In Table I, we compare these results for both A and B. However, the case of interest is the pure $D^{*0} \to D^0+\gamma$ region, which is CD in Fig. 1. It is approximately half as large as the entire region AD, and thus contains approximately half the total number of events. All these events correspond to the emission of D^0 in the rest frame of D^{*0} within a polar angle of ~90° measured with respect to an axis taken for each D^{*0} to be its direction of motion. Table II gives the results for this region. It is not surprising that here also, with increase in the center-of-mass energy $\sqrt{s}$, the shift in the distribution is towards the production distribution. In A, we must allow for the possibility that the $\bar{D}^{*0}D^{*0}$ state could be an arbitrary mixture of the $L=1$, $S=0$ and the $L=1$, $S=2$ configurations. If we do so, an interference term arises in the distribution. Taking this into account and letting a and b be complex, we find for $\sqrt{s}=4.028$ GeV that

$$-0.79 \leq P' \leq 0.07\,. \tag{12}$$

On the other hand, we note from Table II that P' is 0.46 for B. Thus, a study of the region CD should enable one to conclude whether the events are due to $\bar{D}^{*0}D^{*0}$ or $\bar{D}^{**0}D^{*0}+D^{**0}\bar{D}^{*0}$ in the primary process. As a double check, it is probably worthwhile to examine some other energy region, and see whether the angular distribution for that region is indeed consistent with the hypothesis determined from the region CD. For purpose of illustration, we chose the region BC which is almost the pure D^{*0} or $D^{**0} \to D^0+\pi^0$ region. Since D^0 is produced almost at rest in this decay mode ($q^* \approx 0.045$ GeV), its distribution in this region is very nearly the production distribution of the decaying particle. The presence of $D^{*0}\to D^0+\gamma$ events actually causes some deviation which, although small, is taken into account. If we now write the distribution of D^0 in this region as $1+P''\cos^2\theta'$, we find that P'', while being a function of a and b for A, is nearly zero for B. In Fig. 3, we give a plot of P'' vs P'. The point for B is situated far away from the closed region corresponding to A. Unless the errors in the

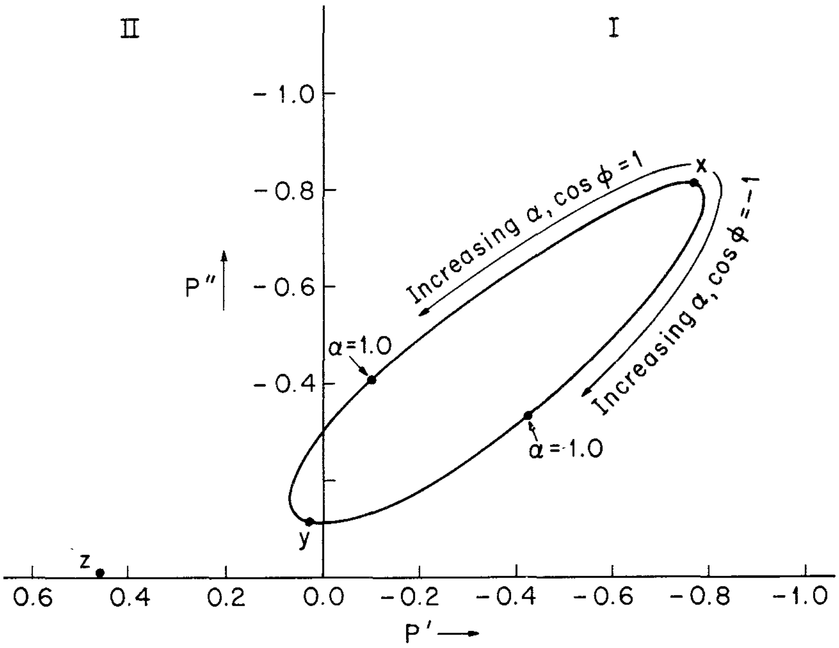

FIG. 3. The plot P'' vs P'. The point Z, which corresponds to case B, lies in quadrant II. The point for case A, on the other hand, can lie anywhere in the region enclosed by the closed curve. Its exact location is determined by the value $\alpha=|b/a|$, where a and b are coefficients in $\vec{J}_A$ [see Eq. (6a)] and ϕ, which is the relative phase between them. Points X and Y correspond to $\alpha=0$ and $\alpha=\infty$ respectively. The top portion of the curve is the locus of points with $\cos\phi=1$, while the lower part corresponds to those for which $\cos\phi=-1$.

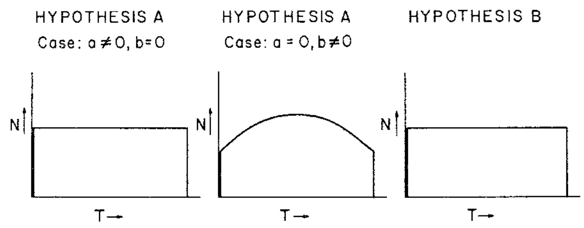

FIG. 4. Energy distribution of D^0 arising from $D^{*0} \to D^0 + \gamma$ for various cases.

experimental determination of P' and P'' are large and the experimental point turns out to be close to the origin, the distinction should be clear. If the point is found located in quadrant I far from the origin, then not only is A correct but also the $L=1$, $S=0$ state is the predominant one. On the other hand, a point close to the origin would imply the dominance of the $L=1$, $S=2$ configuration in the $\bar{D}^{*0}D^{*0}$ state. It may be mentioned here that in obtaining P'', we ignored the contribution of D^0 coming from the charged counterparts of D^{*0}, etc. Except for the effects arising from mass differences between the neutral particles and their charged counterparts, the distribution of all such D^0's, from isospin consideration, is the same as the one for D^0's originating in $D^{*0} \to D^0 + \pi^0$. Their inclusion under the peak, therefore, should not alter the results significantly. It is also important to remark that hypothesis B is an extreme assumption which neglects completely the production of $\bar{D}^{*0}D^{*0}$. This state, in fact, is also present, though in a relatively small amount. Its presence, when taken into account, will cause some smearing of the results; the point Z on the plot, for instance, will be slightly displaced towards the A region.

In Fig. 1, we gave the energy spectrum of D^0 without incorporating dynamics. It is instructive to find out how it exactly looks for the different cases we have considered in this paper. From Eq. (11), one notes one can deduce it by integrating over the angles. In Fig. 4, we give the forms, for the various cases, for D^0 originating in the decay mode $D^{*0} \to D^0 + \gamma$. Their symmetry about the center of the energy range is simply a consequence of the fact that as many D^0 go in the forward direction as in the backward direction with respect to the direction of motion of D^{*0}. For A, in the case $a \neq 0$, $b=0$, one obtains a distribution uniform in energy. This is because the D^{*0} is unpolarized and thus has isotropic distribution of D^0 in its rest frame. On the other hand, the energy spectrum in the case $a=0$, $b \neq 0$ has a maximum at the center, i.e., the number of D^0 emitted perpendicular to the direction of motion of D^{*0} is more than that along either the forward or the backward direction. This can be roughly understood if one notes that the angular distribution of D^{*0} in the primary process is $1-\frac{1}{7}\cos^2\theta$. This is a result of the tendency of D^{*0} to align its spin along the beam axis as a result of which the emission of D^0 is favored more in the direction of the beam axis. Thus, this requires that the D^{*0} which step out perpendicular to the beam axis emit more D^0 perpendicular to their direction of motion in their respective rest frames. In B, the uniform distribution is due to the s-wave production of D^{*0}. For each D^{*0}, the energy distribution of the emitted D^0 is different due to the different spin alignment of D^{*0} with respect to its motion. Since the primary distribution is uniform, the cumulative effect is that of an energy distribution corresponding to the case of unpolarized D^{*0}. It is clear from Fig. 4 that, from a study of the energy distribution of detected D^0 in experiments, it is not possible to conclude about the nature of the primary process.

In short, although it is generally believed that the particles produced in e^+e^- annihilation at $\sqrt{s}=4.028$ GeV in the state $\bar{D}^{*0}D^{*0}$ are spin-1 particles (case A), we have considered an alternative possibility that one of these may be a positive-parity spin-0 D meson (case B). We were led to the consideration of case B owing to the s-wave nature of the production of the particles involved in it; with production taking place in an s-wave, it seemed easier to understand the rapid rise in R at $\sqrt{s} \sim 4.0$ GeV and, thus, the presence of a large amount of the state usually labeled $\bar{D}^*D^*$ at $\sqrt{s}=4.028$ GeV, just above its production threshold. The tests, we have provided for the two cases A and B, involve the study of the angular distribution of the detected D^0 in various energy regions of ESDD. Our results show that, unless the experimental errors are too large, it should be possible to distinguish between the two cases.

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[7] An overall fit to the entire ESDD, in fact, gives for the branching fraction for $D^{*0} \to D^0 + \gamma$ the value 0.45 ± 0.15 (see Ref. 2).
[8] This does not take into account the dynamics. The exact shapes may be different; these are discussed in detail later in the paper.
[9] See, e.g., N. Cabbibo and R. Gatto, Phys. Rev. 124, 1577 (1961); Yung-Su Tsai, *ibid.* 4, 2821 (1971).
[10] A preliminary analysis of the current experimental data by H. K. Nguyen *et al.* [Phys. Rev. Lett. 39, 262 (1977)], yields the value $P = -0.30 \pm 0.33$. Perhaps, with the accumulation of more data especially at $\sqrt{s} = 4.028$ GeV and a larger solid angle of the magnetic detector at SLAC, it may be possible to reduce the uncertainty in P.