tineutrino events at small y, will require good-statistics distributions normalized to independently measured incident flux. Since we have recently taken such data, results should be forthcoming soon.

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[10]We have previously reported total ν and $\bar{\nu}$ cross sections based on a small sample of data normalized to the ν and $\bar{\nu}$ flux. This measurement (based on eleven $\bar{\nu}$ events at $E_{\bar{\nu}} = 108$ GeV) showed no indication of a rising $\sigma_{\bar{\nu}}/\sigma_{\nu}$ ratio. See B. C. Barish *et al.*, Phys. Rev. Lett. 35, 1316 (1975).

[11]It should be noted that the hadron energy, E_h, is measured by using calorimetry techniques and calibrated with charged hadrons of known energy. If the final hadronic state in neutrino collisions contained a substantially larger fraction of its energy in π^0's than the interaction of charged hadrons of the same energy, the calorimetry calibration would be systematically different by up to 20%. See e.g., F. J. Sciulli, in Proceedings of the Calorimetry Workshop, Fermi National Accelerator Laboratory, May 1975 (unpublished), p. 79.

Molecular Charmonium: A New Spectroscopy?*

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Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

Properties of recently discovered charmed particles,[1] D^0, D^+, D^{*0}, and D^{*+}, are in good agreement with a simple picture of hadrons as bound states of quarks in a color gauge theory.[2] The model of mesons as quark-antiquark bound states (and baryons as three-quark bound states) with long-range spin-independent binding and short-range spin-dependent color gluon exchange adequately describes many features of normal hadron spectroscopy.[2,3] Moreover, it has correctly predicted the qualitative behavior of the charmonium states and of charmed hadrons themselves.[2] This Letter is focused on one remaining striking and generally unexpected feature of charmed-meson production in e^-e^+ annihilation. Much data in which D mesons are seen are taken at a peak in the annihilation cross section, at $\sqrt{s} = 4.028$ GeV, where the yield of charmed mesons was expected to be, and indeed is, high. Analysis of the recoil-mass spectrum against detected D^0's indicates that $\sigma(\bar{D}^0D^0)$, $\sigma(\bar{D}^0D^{*0}+\bar{D}^{*0}D^0)$, and $\sigma(\bar{D}^{*0}D^{*0})$ are in the ratios 1: ~8: ~11 at this energy.[4,5] Estimates of charmed-meson masses reveal that the available decay energies are ~300, ~160, and ~18 MeV, respectively. It is remarkable that the $\bar{D}^{*0}D^{*0}$ mode, with so little phase space, nonetheless dominates the data.

More precisely, we define reduced coupling strengths to the three channels according to

$$g^2(DD) = \sigma(D\bar{D})(1 - 4m_D{}^2/s)^{-3/2},$$

$$4g^2(DD^*) = \sigma(D\bar{D}^* + D^*\bar{D})[1 - (m_D + m_{D^*})^2/s]^{-3/2},$$

$$7g^2(D^*D^*) = \sigma(\bar{D}^*D^*)(1 - 4m_{D^*}{}^2/s)^{-3/2},$$

where p-wave phase-space factors as well as the spin-counting factors 1:4:7 have been included.[5] Data at $\sqrt{s} = 4.028$ GeV yield $g^2(DD) : g^2(DD^*) : g^2(D^*D^*) \sim 1{:}5{:}100$. The anomalously strong coupling to $D^*\bar{D}^*$ may seem inexplicable until we recall that the energy 4.028 GeV was chosen because the cross section peaks there. What is seen at this special energy is evidently the decay of a resonance. The large coupling strength to $D^*\bar{D}^*$ indicates that this resonance is essentially made up of a D^* and $\bar{D}^*$. We envisage that the 4.028-GeV state can be regarded as a short-lived four-quark "molecule" in which the D^* and $\bar{D}^*$ maintain their "atomic" integrity. Our paper depends upon this frankly speculative hypothesis. If our explanation of this anomaly is correct, then studies at other energies should not yield reduced coupling strengths which are wildly different from unity. Okun and Voloshin,[6] from an analysis of the meson-exchange forces through which two charmed mesons may interact, anticipated the possible existence of molecular states involving charmed quarks. A rich spectroscopy of such states was suggested by several authors.[7] The possible importance of states of four light quarks in normal hadron spectroscopy has been pointed out by Jaffe.[8] In particular, he argues that $S^*(993)$ and $\delta(970)$ are essentially $\bar{K}K$ molecules. D's should interact among themselves much as K's do. Because D's are much heavier than K's it is even more likely that there should exist molecules made up of two oppositely charmed mesons.

A molecular interpretation of the 4.028-GeV structure suggests the existence of a horde of analogous molecular systems with various spins and isospins. Some of these states may be detected and studied in e^-e^+ annihilation.

The simplest interpretation of the 4.028-GeV peak is that it is a p-wave $D^*\bar{D}^*$ resonance just above elastic threshold with $J^P = 1^-$ and $I^G = 0^-$ or 1^+. There are two isotopic possibilities for the resonance, because D^* is an isodoublet. Whether the 4.028-GeV state is $I=0$ or $I=1$, or a mixture of the two, is unclear theoretically and must be determined experimentally.

P-wave $\bar{D}D^*$ and $\bar{D}D$ states with $J^P = 1^-$ and $I^G = 0^-$ or 1^+ are expected to exist near the appropriate thresholds and may be directly observed in e^-e^+ annihilation.

When two particles almost bind in a p-wave state, it is virtually certain that they do form an s-wave bound state. We are led to anticipate the existence of s-wave molecular states of two D's (with $J^P = 2^+$, 1^+, and 0^+, $I^G = 0^+$ and 1^-; as well as $J^P = 1^+$, $I^G = 0^-$ and 1^+), with masses below those of corresponding p-wave states. At least one of these states may be *truly bound*, i.e., unable to decay into two charmed mesons.

Consider the various mechanisms whereby the 4.028-GeV molecule could decay: (1) *simple dissociation*, the presumably dominant decay into its constituents, $\bar{D}^* + D^*$ [see Fig. 1(a)]. (2) *Dissociation with spin rearrangement*, which can result in the suppressed decay modes $D\bar{D}$ and $D^*\bar{D}$ [see Fig. 1(b)]. (3) *Quark rearrangement:* The constituent quarks of D^* and $\bar{D}^*$ can recombine to form a p-wave state of two mesons, i.e., $J/\psi + \eta$ or $X(2.85) + \omega$. This is unlikely to be a principal decay mode of a p-wave molecule, where the charmed quarks are effectively separated and prevented from combining with one another by the centrifugal barrier but this kind of decay scheme may well be dominant for s-wave molecules [see Fig. 1(c)]. (4) *Molecular transitions:* There should exist a p-wave $D\bar{D}$ molecule with $J^PI^G = 1^-1^+$ with a mass near the $D\bar{D}$ threshold. We may expect an observable branching ratio for the decay of the 4.028-GeV state into the lighter molecule via p-wave pion emission. The fate of the $D\bar{D}$ molecule depends on whether it

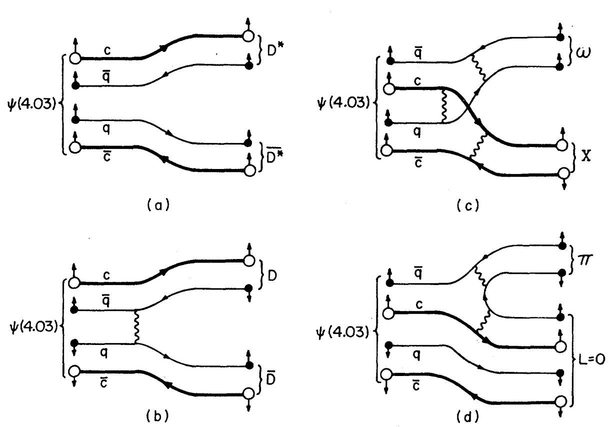

FIG. 1. Some quark diagrams representing decays of molecular charmonium: (a) Simple dissociation, (b) dissociation with spin rearrangement, (c) quark rearrangement, (d) molecular transition.

lies above or below threshold. In the latter case, it decays by a Zweig-forbidden process into normal hadrons, or via quark rearrangement into $J/\psi+\pi$ or $X+\rho$ [see Fig. 1(d)].

Molecular transitions of the 4.028-GeV state can also reveal the existence of various s-wave molecules. For example, the 4.028-GeV state could emit an s-wave pion to become a 1^+1^+ s-wave $\bar{D}D^*$ molecule, or an s-wave (off-mass-shell) ρ to become a 0^+1^- $\bar{D}D$ molecule. These intermediate states could be detected by the observation of peaks in the momentum distribution of low-energy $\pi^\pm$ or "ρ^0" $=\pi^+\pi^-$, or photons.

The s-wave molecules should lie close to threshold, some being too light to decay into charmed mesons. However, they are all subject to decay via quark rearrangement, for which there is considerable phase space and no centrifugal-barrier suppression. They should have significant branching ratios for decay into a charmonium state plus a normal meson. Ultimately, the 4.028-GeV state may decay measurably, via an s-wave molecule, into J/ψ together with a "dichromatic" charged pion pair, one very soft, the other quite hard.

The more interesting decay schemes of the 4.028-GeV molecule from its $I=0$ component are shown in Fig. 2(a); those from its $I=1$ component in Fig. 2(b). How these molecular transitions compete with dissociative decay, we dare not predict. Since charmed particles are seen to be copiously produced, it seems clear that the molecular transitions are not predominant. Many levels of charmonium are ultimately produced either by single-meson emission (ρ^0, ω, π^0, η, ϵ) or by double emission via an intermediate molecular state. A careful measurement of the J/ψ yield at 4.028 GeV is necessary to establish the strength of the molecular transitions. Omitted from Fig. 2 is the expected $J^P=1^-$ $D^*\bar{D}$ molecule, which should appear as a peak in R between 3.7 and 4 GeV.

There is a conspicuous peak in R at $\sqrt{s}=4.4$ GeV. Perhaps this state is also a four-quark molecule. The obvious candidate is an s-wave bound state of a D or D^* and a p-wave $\bar{D}^{**}$. (By $\bar{D}^{**}$ we mean a bound state of a charmed quark with a light antiquark in a p-wave state. In this case, the unit of orbital angular momentum is carried by the light quark in $\bar{D}^{**}$, rather than by the $c\bar{c}$ pair as in the case of the 4.028-GeV state.) Dissociative decays include $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$, $D\bar{D}^{**}$, and $D^*\bar{D}^{**}$.[9] Because this is an s-wave molecule, the atomic integrity of the charmed

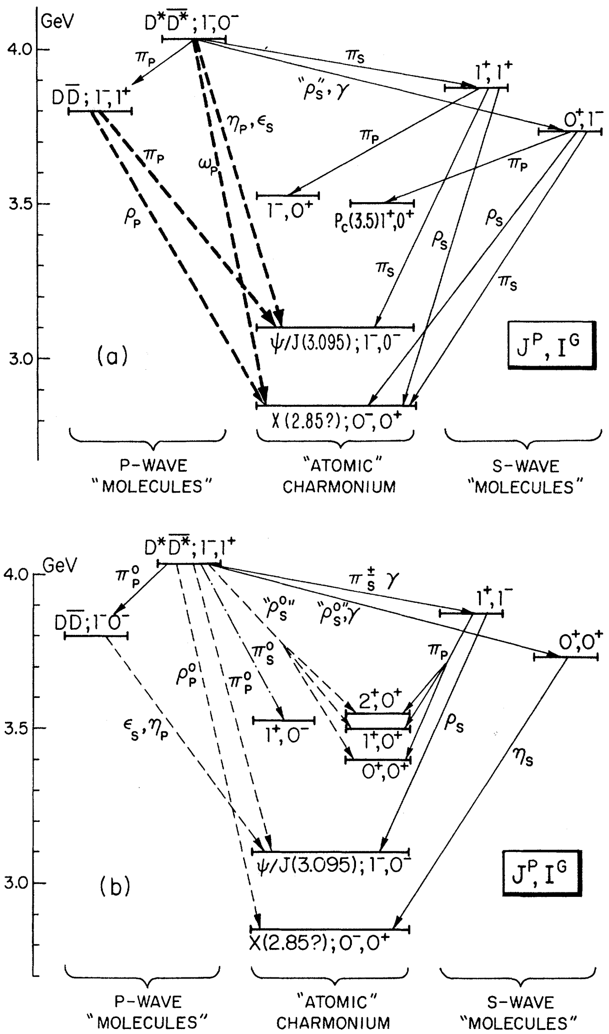

FIG. 2. Transitions from the (a) isoscalar and (b) isovector $\psi(4.028)$. Dashed transitions are suppressed by a heavy-quark angular-momentum barrier. Subscripts S and P, respectively, refer to $l=0$ and 1 transitions. Except for the fact that s-wave molecules are expected to lie below corresponding p-wave states, the masses indicated in this figure and the next are merely guesses.

mesons is likely to be less well preserved than for P-wave molecules. The different dissociative decays may compete on equal footing and, contrary to the $\psi(4.028)$ case, we do not expect one of them to dominate. Possible molecular transitions into s-wave molecules are shown in Fig. 3.

However, one must expect that the 4.4-GeV state, if it is truly a molecule, will decay readily through quark rearrangement into a charmonium state and a normal meson, also shown in Fig. 3.

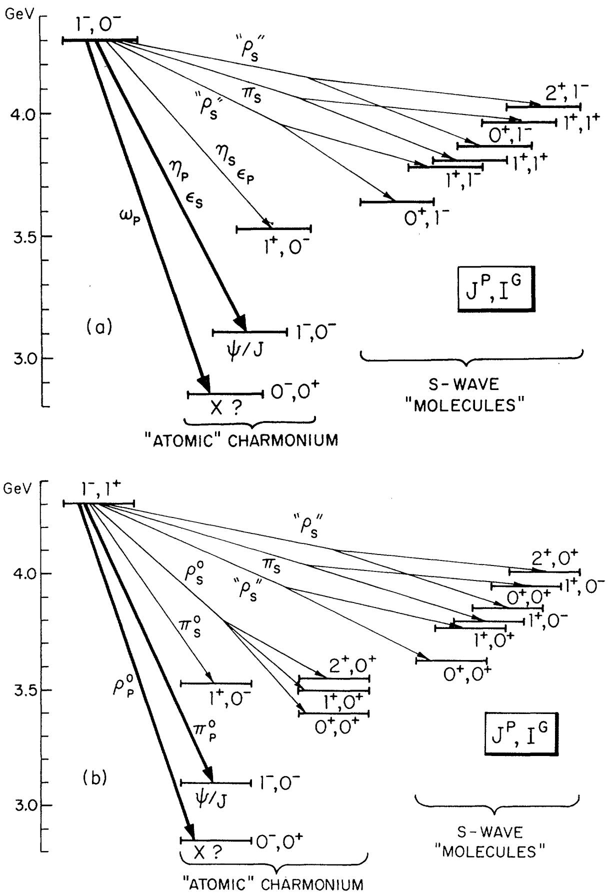

FIG. 3. Transitions from the (a) isoscalar and (b) isovector ψ (4.4).

An s-wave configuration of two charmed mesons (unlike a p-wave configuration such as the 4.028-GeV state), involves no centrifugal barrier between the charmed mesons (and hence, between the charmed quarks) which would suppress these decay modes. Indeed these transitions may be more important than dissociative or molecular transitions. If this is so, then the yield of charmed mesons at 4.4 GeV should be substantially smaller than at 4.028 GeV, despite the fact that R is roughly the same at those two peaks. Indeed, preliminary data[10] suggest that the charm yield at 4.4 GeV is $\sim\frac{1}{3}$ that at 4.028 GeV. Thus, the molecular interpretation of the 4.4-GeV peak provides a mechanism of "charm-burning" at this energy.[6] But, this burning probably produces J/ψ as an end product. For our interpretation to be self-consistent, at least ~10% of the events at 4.4 GeV must be of the form $J/\psi+(2\pi$ or $4\pi)$ (or, for some unknown reason, the decays of s-wave molecules into atomic charmonium are suppressed).[11] The naive notion that the yield of charmed particles should parallel "the new physics" (i.e., R, from which light-quark and heavy-lepton contributions are subtracted) may be grossly inaccurate.[12]

Molecular states of $F\bar{F}$, $F\bar{F}^*$, etc., may also exist with $J^P=1^-$ and be produced in e^+e^- annihilation. They are not expected to display molecular transitions, but may dissociate into two charmed mesons or undergo quark-rearrangement decay into $\eta+J$ or $\varphi+X$.

It seems very likely to us that four-quark molecules involving a $c\bar{c}$ pair do exist, and have a rich spectroscopy. Our conjecture that the 4.028-GeV and perhaps the 4.4-GeV peaks in e^-e^+ annihilation are indeed due to the production of these molecules is more speculative. If it is true, then nature has provided us with a spigot to a fascinating but otherwise almost inaccessible new "molecular" spectroscopy full of experimental and theoretical challenges.

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[11]If we assume that charm burning is negligible at $\sqrt{s} = 4.028$ GeV, then we expect that ~ 40% of the events at that energy involve charmed-meson production. Were there no charm-burning operative at $\sqrt{s} = 4.4$ GeV, a similar fraction of the events there would be charmed. But, data indicate a charm yield at 4.4 GeV of ~ $\frac{1}{3}$ that at 4.028 GeV, so that "charm burning" must account for ~ 27% of the events at 4.4 GeV. More than $\frac{1}{3}$ of the charm-burning processes should yield J/ψ.

[12]The concept of charm burning was first discussed by Okun' and Voloshin, Ref. 6.

Second-Class Currents

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We show that *effective* nuclear second-class axial-vector currents provide a consistent description of the available β-decay data and probe the fundamental structure of weak currents.

The recent correlation experiments[1] in nuclear β decay, if taken at their face value, would suggest the presence of an alarmingly large G-parity irregular component[2] (second-class currents, hereafter denoted by SCC) in weak interaction Hamiltonian. This appears to be at variance with the conclusion reached from the ensemble of data on ft asymmetries in mirror Gamow-Teller transitions.[3] To dramatize the seemingly conflicting nature of the two results, we state the present situation in terms of the naive impulse approximation: The correlation data imply a SCC form factor g_T as large as or even larger than the first-class weak magnetism form factor whereas careful analyses of mirror asymmetries, in particular in the mass-8 system,[4] would suggest $g_T \approx 0$ within large uncertainties in the nuclear-induced effects. In view of the enormous difficulties in accomodating second-class currents in modern gauge theories,[5] a vital question for a viable theory of anomalous currents to face is whether the contradictory observations can be reconciled in a natural and consistent way. The ensuing discussion is based on the assumption that the correlation data are not in error and therefore the effects are genuine.

In this Letter, we show that the model of *effective nuclear* second-class axial-vector currents proposed by us several years ago[6] which incorporates mesonic effects properly can indeed reconcile most, if not all, of the conflicting observations, and we suggest that nuclear many-body effects through which this occurs can play a unique and crucial role in providing information on the basic structure of the current. In particular it is shown that the class of models involving solely Fermion fields with derivative couplings is completely ruled out.

We start by briefly describing the ingredients that enter into the KDR model. In analogy with the description of the electromagnetic nuclear current[7] which has been found to be extremely successful,[8] we construct a nuclear SCC with an impulse-approximation term and a two-body meson-exchange current. As in Ref. 6, we shall confine ourselves to the simplest nontrivial account of possible off-shell effects by taking the second-class current coupling to off-shell nucleons in the form

$$i(g_T\sigma_{\mu\lambda}q_\lambda\gamma_5 + ig_T'P_\mu\gamma_5) \tag{1}$$

with q_μ and P_μ the difference and the sum, respectively, of the initial and final nucleon momenta. The meson-exchange currents are given by the "pair" term and the "$\omega\pi$" term of Ref. 6. The matrix element for $\omega \to \pi e\nu$ contributing to the latter can be written in the limit of low-pion momentum q in the form

$$iF_\omega S_\lambda + O(q). \tag{2}$$

Here S_λ is the polarization four-vector of the ω meson and F_ω a form factor, real if time-reversal invariance holds. Just as in the case of the electromagnetic current, we have used the notion that the exchanged pion is soft,[7] so that the expression (2) provides the relevant amplitude.

It was shown in Ref. 6 that all the observables can be described entirely by the two constants

$$\zeta \equiv g_T + g_T',$$
$$\lambda \equiv \frac{m_\pi^3 g_{\pi NN}^2}{24\pi m_N^2}\left(g_T' - \frac{g_{\omega NN}F_\omega}{g_{\pi NN}m_\omega^2}\right). \tag{3}$$

Equation (1) tells us that the constant ζ governs neutron β decay, reflecting directly the strength of the *basic* SCC. The quantity λ, however, is a