evaluations of these diagrams have been made; we essentially follow the approach of G. Altarelli, G. Parisi, and R. Petronzio, CERN Report No. Ref. TH-2413, 1977 (to be published). See also K. Kajantie and R. Raitio, University of Helsinki Report No. HU-TFT-77-21, 1977 (to be published). Our evaluation of the QCD diagrams disagrees with the latter results as well as those of Refs. 4 and 5. The Compton diagrams of Fig. 1(c) have also been considered by H. Fritzsch and P. Minkowski, CERN Report No. Ref. TH-2400, 1977 (to be published).

[9]We believe the turnover of $\langle p_T \rangle$ at low mass to be unrelated to constituent dynamics. It represents the observed scaling in transverse mass $m_T = (m^2 + p_T^2)^{1/2}$ of any hadronic process. Scaling the $\langle p_T \rangle$ of π secondaries in pp collisions in transverse mass m_T yields the curve shown in Fig. 4 to support our assertion.

[10]Assuming approximately Gaussian distributions, we simply add the intrinsic and QCD contributions to $\langle k_T^2 \rangle$. Our working assumption is that $\langle k_T^2 \rangle$ of initial quarks and gluons is independent of m and s. Relaxing this assumption strips from QCD any predictive power concerning average transverse momenta.

[11]We used the quark and gluon structure functions from R. D. Field and R. P. Feynman [Caltech Report No. CALT-68-565 (to be published)] for π mesons.

[12]G. R. Farrar, Caltech Report No. CALT-68-576, 1977 (to be published); F. Halzen, Rutherford Report No. RL-77-049/A, 1977 (to be published); H. Fritzsch and P. Minkowski, CERN Report No. TH. 2320, 1977 (to be published); S. J. Brodsky, private communication.

[13]The expansion in α_s is valid in the high-transverse-momentum regime, even for real photons. The assumption is identical to that made in any QCD calculation of high-p_T reaction mechanisms.

Observation of $\mu 3\pi$ Events in e^+e^- Annihilation

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We have observed events of the type $\mu^\pm + (3\pi)^\mp$ in e^+e^- interactions at center-of-mass energies above 6 GeV. The properties of the events are consistent with their coming from the heavy-lepton decays $\tau \to \mu\nu\bar{\nu}$ and $\bar{\tau} \to \bar{\nu}3\pi$ or $\bar{\tau} \to \bar{\nu}4\pi$. The three-charged-pion invariant-mass distribution shows a significant peak at a mass 1.1 GeV/c^2. We find the branching ratio into three charged and any number of neutral pions $B(\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^- n\pi^0) = 0.18 \pm 0.065$.

Evidence for the existence of a new lepton τ with a mass[1] about 1.8 GeV/c^2 has mounted steadily since the original observation of anomalous $e\mu$ events in e^+e^- interactions.[2] Recently several groups have reported the observation of semihadronic τ decays.[1,3,4] In this Letter we report the observation of $\mu^\pm(3\pi)^\mp$ events which we interpret as evidence for τ decays involving three charged pions. One such decay, $\tau \to \nu 3\pi$, is of special interest because the A_1 is expected to appear prominently in this final state.[5] Despite many searches for this axial-vector state predicted by the quark model, it has yet to be conclusively established.[6] More generally, the study of multihadronic decays of the τ probes the nature and strengths of its couplings.

Our evidence comes from a study of e^+e^- interactions at center-of-mass energies above 6 GeV. The data were taken with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at SPEAR. We select events with four charged particles, total charge zero, which include a muon; these could result from the process $e^+e^- \to \tau^+\tau^-$ followed by the decays $\tau^- \to \nu\bar{\nu}\mu^-$ and $\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^- n\pi^0$. The muon is identified with a system which has been described previously.[7] Briefly, it consists of several layers of spark chambers located behind steel and concrete absorbers outside the main detector. The original system subtended a solid angle of 1.1 sr; for part of these data on additional 0.6 sr was covered with a 30-cm iron absorber followed by a spark chamber. To penetrate to the second or third levels of muon chambers, a particle must on the average traverse the equivalent of 65 or 92 cm of iron, respectively. We call any particle a *candidate* if it has a direction and momentum such that it would be detected by the second and/or third level of muon chambers if it were a muon. A *muon* is a candidate which was detected in every chamber through which it was projected within 3 standard deviations of the expected multiple scattering. A hadron may be misidentified as a muon because of punchthrough or decay in flight. We calculate the punchthrough probability by doing Monte Carlo simulations with the high-energy nucleon-meson transport code HETC,[8] and we evaluate the decay probability analytically. The total misidentification probability is constant to within 25% for all candidate momenta greater than 1 GeV/c; averaged over the candidate momentum spectrum, it is found to be 0.038 ± 0.009. To identify events with one or more neutral particles which decay into photons, we use information from the 24 lead-scintillator shower counters which surround the solenoid. These counters are greater than 90% efficient for photons of energies above 200 MeV/c^2 and have a spatial resolution of about ±30 cm. For the purposes of this Letter, the number of detected photons, n_γ, is the number of shower counters which have more than 10 MeV deposited and which have not been traversed by a charged particle. We exclude shower counters adjacent to a counter hit by a charged particle if the shower position is within 0.3 m of the projected position of that particle; this minimizes the effect of hadronic interactions in one counter simulating a photon in an adjoining counter.

The invariant mass of the three charged particles (assumed to be pions) which accompany a muon is shown in Fig. 1 for events with 0, 1 or 2, and more than two detected photons. The distributions have been corrected for the misidentification of hadrons as muons; this correction is about 5% at the peak of the $n_\gamma = 0$ distribution. The fact that much of the $n_\gamma = 1$ or 2 distribution and nearly all of the $n_\gamma > 2$ distribution are consistent with having no signal assures us that we have estimated the hadron misidentification probability conservatively. Events in which at least one of the particles has been identified as a kaon with a time-of-flight measurement or in which a neutral two-pion combination is consistent with coming from a K_s^0 have been eliminated.[9] The peak in the $n_\gamma = 0$ category is clear evidence that there are events with a muon and three charged particles. There is an indication of a similar signal in the $n_\gamma > 0$ categories.

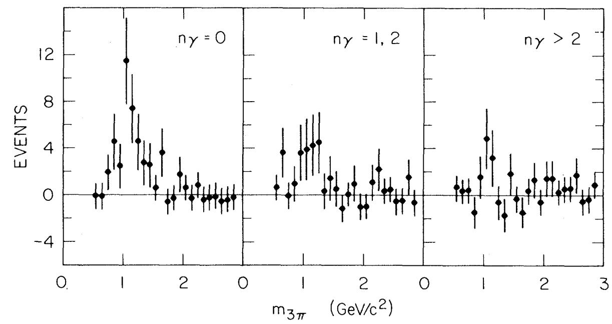

FIG. 1. Invariant-mass distribution of the three particles opposite a muon in events with four particles and zero, one or two, or more than two detected photons. The distributions have been corrected for hadron misidentification.

Semileptonic decays of charmed particles and decays of heavy leptons are the only known sources of anomalous muons in e^+e^- interactions. We first consider the possibility that the μ"3π" events are produced in charm decays. In particular, if we assume that the events originated in D decays, we expect each event to be associated with two kaons, one or both of which may have escaped detection. There are 42 μ"3π" events with three-pion masses in the peak ($0.95 < m_{3\pi} < 1.25$ GeV/c^2), $n_\gamma \leq 2$, and no well-identified kaons. We estimate that 1.2 ± 1.7 of these include a kaon with sufficiently high momentum that it could not be well identified by time of flight. If the other events are from D decays, two kaons must have escaped detection. As a consequence, there must be other classes of events in which a kaon is detected. We have searched for these and found eight $K^\pm$ μ"3π" and one K_s^0 μ"3π" events. After accounting for the relative efficiencies to detect or miss K^0 and $K^\pm$ mesons and the expected background from pions being misidentified as kaons, we estimate that 8.2 ± 4.6 of the μ"3π" events are associated with kaons that have escaped detection. Thus 9.4 ± 4.9 of the observed events are associated with kaons. Since this number is small compared to the 42 events actually observed, it is very unlikely that all the μ"3π" events result from D decays. Decays of F mesons or charmed baryons are other potential sources. If the μ"3π" events originate from F decays, we expect the events to be associated either with kaons or with high photon multiplicities. Neither is the case. If charmed-baryon decays are the source of the μ"3π" events, we expect to see protons in the final state. Only one of the 42 events has a particle identified as a proton by time of flight. In summary, it appears unlikely that the bulk of the μ"3π" events are produced in charmed-particle decays. This conclusion is borne out by the momentum spectrum of muons opposite the three-pion enhancement, which is shown in Fig. 2(a) along with a Monte Carlo calculation of the spectrum expected from the decay of a heavy lepton of mass 1.85 GeV/c^2 having $V-A$ coupling and a massless neutrino. Also indicated is an estimate of the muon spectrum due to charmed-particle decays.[10] Both curves have been normalized to the observed number of events. A heavy-lepton origin for the events is clearly preferred. The "3π" momentum spectrum provides another check of the hypothesis that the events originate in heavy-lepton decays. The data, shown in Fig. 2(b), are consistent with Monte Carlo predictions for $\tau \to \nu 3\pi$ or $\tau \to \nu 4\pi$, which are also shown in the figure.

Heavy-lepton decays into three, four, or more

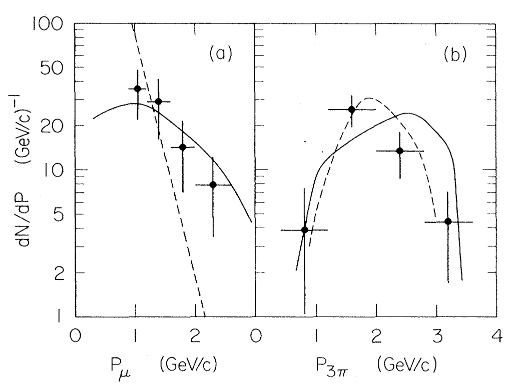

FIG. 2. (a) Momentum distribution of muons in events with $0.95 < m_{3\pi} < 1.25$ GeV/c^2 and $n_\gamma \leq 2$, corrected for hadron misidentification. The solid and dashed curves are the expected spectra from heavy-lepton decays and charmed-particle decays, respectively. (b) Momentum distribution of the three-pion system is events with $0.95 < m_{3\pi} < 1.25$ GeV/c^2 and $n_\gamma \leq 2$. The solid and dashed curves are the spectra expected for the decays $\tau \to \nu 3\pi$ and $\tau \to \nu 4\pi$, respectively.

pions could lead to a $\mu 3\pi$ signal in the $n_\gamma = 0$ category; decays into four or more pions can feed down into this category because our detector covers a limited solid angle and because it is insensitive to photons that have converted in shower counters hit by charged particles. We have used Monte Carlo techniques to calculate the three-pion mass distributions and the feeddown probabilities from various initial states. The three-pion mass distribution from $\tau \to \nu 5\pi$ is broad and peaked 0.2–0.3 GeV/c^2 below the observed enhancement (depending on the five-pion mass we assume) and so cannot account for it. We have estimated the mass distribution from $\tau \to \nu 4\pi$ by taking the four-pion mass distribution from Gilman and Miller[11] and assuming that $\pi\pi\rho$ dominates the decay. The resultant three-pion mass distribution, when normalized to the $n_\gamma = 0$ data, gives an adequate fit ($\chi^2/N = 19.3/10$). The $n_\gamma = 0$ distribution can also be fitted if we assume $\tau \to \nu A_1$,[12] where we have assumed the A_1 has mass 1.1 GeV/c^2 and width 0.2 GeV/c^2 ($\chi^2/N = 6.3/7$); or $\tau \to \nu \pi \rho$, where we have assumed that the π and ρ are nonresonant[13] ($\chi^2/N = \frac{21}{10}$). In summary, the shape of the mass distribution for the $n_\gamma = 0$ events is consistent with that expected from the decays $\tau \to \nu 4\pi$ or $\tau \to \nu 3\pi$, but not from decays involving more pions.

We evaluate the branching ratio for τ decays into three charged and any number of neutral pions using all the $\mu 3\pi$ events with $m_{3\pi} < 1.8$ GeV/c^2 and subtracting the number of events (about 25%) which we have calculated are associated with kaons.[14] We find $B(\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^- n\pi^0) = 0.18 \pm 0.065$. In principle, we can separate the $\tau \to \nu 4\pi$ and $\tau \to \nu 3\pi$ contributions by comparing the $n_\gamma = 0$ and $n_\gamma = 1$ or 2 signals since 40% of the $\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^-\pi^0$ decays should appear in the $n_\gamma = 1$ or 2 category. In practice our accuracy in doing so is limited by our uncertainty in calculating the background from charm decays and low statistics. Assuming that only the decays $\tau \to \nu 4\pi$ and $\tau \to \nu 3\pi$ contribute to the $n_\gamma \leq 2$ distributions, we find the branching ratios $B(\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^-) = 0.07 \pm 0.05$ and $B(\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^-\pi^0) = 0.11 \pm 0.07$. The presence of a small number of $\tau \to \nu 5\pi$ decays would lower $B(\tau \to \nu 4\pi)$ without much affecting $B(\tau \to \nu 3\pi)$. These results are consistent with the predicted[5,11] branching ratios $B(\tau^+ \to \bar{\nu}A_1^+ \to \nu\pi^+\pi^+\pi^-) \approx 0.05$ and $B(\tau^+ \to \bar{\nu}\pi^+\pi^+\pi^-\pi^0) \approx 0.08$, where we have assumed that the A_1 decays via $\pi\rho$. Our determination of $B(\tau \to \nu 3\pi)$ is in agreement with that of Alexander *et al.*[4] who report $B(\tau^+ \to \bar{\nu}\pi^+\rho^0) = 0.05 \pm 0.02$.

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[10]We estimate the muon-momentum spectrum from charm decays by correcting the muon spectrum observed in multiparticle events from Ref. 7 for contamination from τ decays.

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[13]We assume $d\Gamma/dm \propto m(m_\tau^2 - m^2)^2(m_\tau^2 + 2m^2)$ modified by a threshold factor.

[14]To evaluate the branching ratios, we have used the calculated cross section for the production of a pointlike, spin-$\frac{1}{2}$ particle; the branching ratio $B(\tau \to \mu\nu\bar{\nu}) = 0.18$, the integrated luminosity (20 pb^{-1}), and the experimental acceptance as determined with Monte Carlo techniques.

Heavy-Ion Fusion Based on the Proximity Potential and One-Body Friction

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A simple dynamical model is shown to reproduce heavy-ion fusion excitation functions over a wide mass and energy range. The trajectory calculations employ the proximity nuclear potential and the proximity one-body nuclear friction. The importance of tangential friction in determining the magnitude and shape of the fusion excitation functions at higher energies is discussed.

The measurement of heavy-ion fusion excitation functions offers the possibility of insight into the form of the internuclear conservative force, the magnitude and mechanisms of nuclear friction, and the limits of rotational stability of heavy nuclei. Analyses of experimental fusion excitation functions on the basis of simple friction-free models have already been reported.[1,2] These friction-free models assume that a sufficient condition for the fusion of target and pro-