Elimination of Charmed Mesons as Source of Anomalous Lepton Events in e^+e^- Annihilations*

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An analysis of the Maryland-Pavia-Princeton experiment on inclusive muon production in e^-e^+ annihilations yields an upper limit for the ratio of charged-multiplicity events from the particle U, charge conjugate to the particle $\bar{U}$ that produced the muon, of $[U \to (n_{\rm ch} \geq 3)]/[U \to (n_{\rm ch}=1)] < 0.33$. If U were a charmed meson, this ratio would be >2, a prediction incompatible with the data. The predicted ratio for U a heavy lepton is ~ 0.18, in good agreement with experiment.

The Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory group has found evidence for new particle production in e^-e^+ annihilation reactions through the observation of events in which a muon and an electron are the only two charged particles in the final state.[1] They deduce that the most likely explanation for these events consists of the production and decay of a pair of heavy leptons L^+ and L^-, of mass $\lesssim 2$ GeV/c^2, i.e.,

$$e^+e^- \to L^+L^-; \quad L^+ \to \mu^+\nu_\mu\nu_L, \quad L^- \to e^-\bar{\nu}_e\nu_L. \qquad (1)$$

A rival, though experimentally less favored, explanation assumes the existence of charmed mesons,[2] such as $D^\pm$ and $F^\pm$, with masses $M \sim 1.8$–2.0 GeV/c^2, which are produced copiously in e^+e^- collisions at c.m. energies above about 4 GeV, and which then decay semileptonically, e.g.,

$$e^+e^- \to D^+D^-; \quad D^+ \to K^0e^+\nu_e, \quad D^- \to \bar{K}^0\mu^-\bar{\nu}_\mu. \qquad (2)$$

It has been conjectured[2,3] for some time that charmed particles will decay frequently via semileptonic modes. In fact the Harvard-Pennsylvania-Wisconsin neutrino-induced dimuon experiment[4] at Fermilab indicates the existence of a charmlike hadron via its muonic decay. Other possible explanations for the anomalous dilepton events produced in e^-e^+ collisions exist, including for example the production and leptonic decays of pairs of quarks and/or vector gluons.[5] It is clearly important to seek further information about the final states into which the new particles that are causing the observed anomaly decay.

The Maryland-Pavia-Princeton experiment (MPP) at SPEAR has recently reported[6] an anomalous signal in the channel $e^+e^- \to \mu^\pm X^\mp$ at 4.8 GeV. It is plausible to assume that these inclusive muon events are secondaries from the same particles that produce the anomalous $\mu^\pm e^\mp$ signal of the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory group at SPEAR. The apparatus in the MPP experiment covers 99% of the solid angle about the interaction region and is triggered by a single charged particle traversing the spectrometers at 90° to the beam direction. Very good muon-hadron separation is possible for charged particles with momenta $p_\mu \gtrsim 1.05$ GeV/c. As a result, information can be obtained about the inclusive muon cross section and the associated charged-particle multiplicity for events with an identified muon with $p_\mu \geq 1.05$ GeV/c. The experimental results are summarized in Table I for a run at 4.8 GeV. [All two-prong events with a noncoplanarity angle $<20°$ have been removed from the sample, thus eliminating almost all $e^+e^- \to \mu^+\mu^-$ (γ) events.] This data sample corresponds to an integrated luminosity of 3.84 ± 0.31 pb^{-1}. From this data sample the authors[6] deduce a real anomalous muon signal with $p_\mu \gtrsim 1.05$ GeV/c, and only two coplanar charged particles ($\varphi > 20°$), of magnitude $(d\sigma/d\Omega)|_{90°} = 23^{+12}_{-9}$ pb/sr. They also deduce a null signal for the inclusive muon cross sections in reactions containing three or more charged particles, with an upper limit $(d\sigma/d\Omega)|_{90°} < 7.5$ pb/sr.

Let us assume that the anomalous muon events at 4.8 GeV arise from the reaction $e^+e^- \to U^+U^-$ followed by one of the U particles decaying via the mode $U^\pm \to \mu^\pm$ + neutral particles, with no prejudice as to whether the U particle is a heavy lepton, a charmed meson, a quark, or a color gluon. The data in Table I and the preceding paragraph then allow us to deduce an upper limit for the ra-

TABLE I. Summary of events of the types $e^+e^- \to \mu^\pm$ + anything ($p_\mu \geq 1.05$ GeV/c).

	$n_{\rm ch} = 2$	$n_{\rm ch} \geq 3$
No. of events recorded	13	2
Expected background	3.9	5.3
Anomalous muon signal	9.1	$\lesssim 0$

TABLE II. Estimate of branching ratio (BR) into three or more charged particles for a heavy letpon of mass about 1.8 GeV/c^2.

Decay mode	BR	BR($n_{ch} \geq 3$)
$L^- \to \nu_L \bar{\nu}_e e^-$	0.18	0
$\to \nu_L \nu_\mu \mu^-$	0.18	0
$\to \pi^- \nu_L$	0.085	0
$\to K^- \nu_L$	0.007	0
$\to \rho^- \nu_L$	0.272	0.007
$\to K^{*-} \nu_L$	0.018	...
$\to A_1^- \nu_L$	0.095	0.048
$\to \nu_L$ +hadron continuum	0.161	~0.09
Total	1.0	~0.15

tio of the probability that the other U particle decays into three or more charged particles to the probability that it decays into only one charged particle. If we call this ratio $\Gamma(U^\pm \to (n_{ch} \geq 3))/\Gamma(U^\pm \to (n_{ch}=1))$, where n_{ch} is the number of charged prongs in the final state, we find the interesting result

$$\frac{\Gamma(U^\pm \to (n_{ch} \geq 3))}{\Gamma(U^\pm \to (n_{ch}=1))} \leq 0.33. \qquad (3)$$

This result can be compared with the expected multiplicity ratios for the decays of heavy leptons, charmed mesons, etc., which differ markedly. For heavy leptons, Tsai[7] has estimated the transition probabilities into all prominent channels. Taking $M(L^\pm) \sim 1.8$ GeV/c^2, one finds $\Gamma(L^\pm \to (n_{ch} \geq 3))/\Gamma(L^\pm \to (n_{ch}=1)) \approx 0.15/0.85 = 0.18$ (see Table II for details). The fraction of events in which $n_{ch}=1$ is large since most semileptonic decays of $L^\pm$ have $n_{ch}=1$.

On the other hand a detailed study of the expected nonleptonic hadronic decays of $D^\pm$ and $F^\pm$ charmed mesons, following Einhorn and Quigg,[8] conservatively yields a ratio $\Gamma(D^\pm, F^\pm \to (n_{ch} \geq 3))/\Gamma(D^\pm, F^\pm \to (n_{ch}=1)) \gtrsim 2$ (see Table III for details). Since nonleptonic channels are expected to constitute about 90% of all charmed-particle decays, the data of Cavalli-Sforza *et al.*[6] *are not compatible* (probability $\lesssim 0.1\%$) with the assumption that the anomalous muon events arise from the production of charmed meson pairs, followed by semileptonic decay of at least one of them. On the other hand the data of Ref. 6 *are compatible* with the assumption that all the observed anomalous muon events arise from the production of a pair of heavy leptons, followed by the leptonic decay of at least one of them. Attempts to ascribe the anomalous lepton events to other sources such as quarks and vector gluons, e.g., Ref. 3, can only succeed if the charged-particle multiplicities in the final state satisfy Eq. (3).

TABLE III. Estimate of branching ratio into three or more charged prongs for a charmed meson of mass about 2 GeV/c^2 (see Ref.8). Different theoretical assumptions yield ratios in the range $0.6 < (n_{ch} \geq 3)/(\text{all decays}) \lesssim 0.85$. A conservative but reasonable guess is that $(n_{ch} \geq 3)/(\text{all decays}) \simeq 0.7$.

Decay mode		BR	BR($n_{ch}=1$)	BR($n_{ch} \geq 3$)
PP	$\pi^+\eta'$	4/9	0.01	0.44
	$K^+\bar{K}^0$	1/3	0.33	0
	$\pi^+\eta$	2/9	0.16	0.05
Total			0.50	0.49
VV	$\rho^+\omega$	2/3	0.06	0.61
	$K^{*+}\bar{K}^{*0}$	1/3	0.11	0.22
Total			0.17	0.83
PP	$K^+\eta'$	4/9	0.01	0.44
	$K^0\pi^+$	1/3	0.33	0.0
	$K^+\pi^0$	1/6	0.17	0.0
	$K^+\eta$	1/18	0.04	0.02
Total			0.55	0.46
VV	$K^{*+}\psi$	1/3	0.10	0.23
	$K^{*0}\rho^+$	1/3	0.11	0.22
	$K^{*0}\rho^0$	1/6	0.00	0.17
	$K^{*+}\omega$	1/6	0.02	0.15
Total			0.23	0.77
PPP decays	($S=0$)		0.11	0.82
	($S=1$)		0.15	0.84

If the anomalous signal is due to more than one source it is more difficult to make strong statements. The condition $p_\mu \geq 1.05$ GeV/c in the MPP experiment can exempt some leptonic sources from the necessity of satisfying Eq. (3). The charmed-meson-decay leptons are not far from this exemption since for $M_{D,F} \lesssim 2.0$ GeV/c^2, only 10–15% of the muons from the sequence $e^+e^- \rightarrow D^+D^-$, $D^+ \rightarrow K^0{}_\mu{}^+\nu$, would satisfy the condition $p_\mu \geq 1.05$ GeV/c. If in fact the charmed pseudoscalar mesons are mostly produced[9] with extra pions and /or γ rays, then very few if any decay muons will satisfy the condition $p_\mu \geq 1.05$ GeV/c.

In conclusion the source of the anomalous muon signal reported by Cavalli-Sforza *et al.*[6] in e^-e^+ reactions at 4.8 GeV is compatible with heavy leptons but not with charmed mesons. The high muon momentum required in this experiment still leaves some possibility for the presence of undetected charmed mesons and their subsequent semileptonic decays. It is necessary that heavy leptons or some other equivalent source of leptons also be present. Any alternative *sole* source of anomalous leptons must satisfy the condition that the ratio of final states with $n_{ch} \geq 3$ to final states with $n_{ch} = 1$ be less than one third.

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Infrared Finiteness in Yang-Mills Theories

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The infrared divergences of renormalizable theories with coupled massless fields (in particular the Yang-Mills theory) are shown to cancel for transition probabilities corresponding to finite-energy-resolution detectors, just as in quantum electrodynamics. This result is established through lowest nontrivial order in perturbation theory for the detection of massive muons in a quantum electrodynamic theory containing massless electrons or the detection of massive quarks in a Yang-Mills theory.

In quantum electrodynamics (QED), physically sensible transition probabilities are infrared finite to all orders in α. It has been shown by many people[1,2] beginning with Bloch and Nordsieck that the infrared divergences associated with virtual corrections are canceled by corresponding divergences in the emission of undetected photons whose total energy is less than the energy resolution ΔE of the detector. A central question in the study of Yang-Mills theories is whether an analog to the Bloch-Nordsieck program can be carried out. Our work suggests that this is possible for any renormalizable theory containing coupled massless fields along with massive ones. This result should help to sharpen questions about the confinement mechanism in gauge theories. In particular, it has been speculated that confinement is connected to the existence of mass singularities in perturbation theory. However, to lowest nontrivial order we have proven that there are no singularities in experimentally accessible transition probabilities. We