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Question of parity violation in e^+e^- annihilation*

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Neutral currents, charmed-hadron decays, and heavy-lepton decays can all yield observable parity-violating effects in e^+e^- annihilation. We discuss how these effects can be detected and disentangled from one another. Their measurement can reveal what new phenomena are taking place, and can serve to distinguish the charm hypothesis from other explanations of the data.

We propose the measurement of pseudoscalar observables in e^+e^- annihilation in order to determine what weak processes, if any, are taking place. Parity-violating phenomena can arise from the electromagnetic production and subsequent weak decay of heavy leptons, or from the electromagnetic production (either directly or via a resonance) of charmed particles, which are also expected to decay weakly. They can also be due to the interference between electromagnetic and weak (neutral-current) e^+e^- annihilations. We discuss several pseudoscalar observables whose measurements can disentangle the effects due to one or more of the conjectured particles or interactions. Conventional sources of parity-violating effects (the weak decays of uncharmed mesons and baryons) will not affect our results.[1]

Heavy leptons are not uncommon in theoretical models and may have been found; evidence for the production of particles decaying into (more-than-two-body) final states containing muons or electrons exists.[2] We expect the decays of heavy leptons into hadrons and/or leptons to violate parity.

Neutral currents have been observed in neutrino scattering at the level predicted by unified theories of the weak and electromagnetic interactions.[3] Should neutral currents not involving neutrinos violate parity (a point which is not settled either experimentally or by theoretical consensus), their interference with the electromagnetic current would also lead to parity violation in e^+e^- annihilation.

Charm, a new hadronic quantum number conserved by all but the weak interactions, plays many roles: It suppresses $\Delta S = 1$ neutral currents and the K_1-K_2 mass difference,[4] restores quark-lepton symmetry, cancels anomalies,[5] and predicts neutrino-induced dilepton and $\Delta S = -\Delta Q$ events (both subsequently reported[6,7]). Charm also offers an explanation for the existence and narrow widths of e^+e^- resonances at 3.1 and 3.7 GeV and predicts other levels of charmonium later seen.[8] Convincing experimental evidence for hadrons with nonzero charm does not exist. But charmed hadrons, which seem to be infrequently produced in hadron collisions,[9] should be abundant in e^+e^- annihilation. The "asymptotic" value $R \sim 5$ for the ratio of e^+e^- annihilation into hadrons to muon pairs suggests[10] four quark flavors and a heavy lepton, with charm produced in ~30% of the events. Broad resonances near 4.2 GeV,[11] which are probably above charm threshold, should decay into states containing charmed hadrons; on resonance ~65% of the events may be charmed. Charmed-hadron decay necessarily proceeds through weak interactions violating parity. This prediction is not shared by other schemes[12] that attempt to explain features of e^+e^- annihilation with the help of new approximately conserved quantum numbers. The observation of a peak or peaks in the invariant mass of a subset of final hadrons would not in itself distinguish charm from these conjectures. The presence of a peak in $K^+\pi^-\pi^-$ and $K_S\pi^-$ at the same invariant mass would be suggestive but not conclusive evidence of parity violation. So far, searches for bumps in two- and three-body invariant-mass plots have not been successful,[13] indicating that if charmed hadrons exist their decays generally involve neutrals or large multiplicities. *The measurements we propose may succeed in establishing the electromagnetic production and subsequent parity-violating decay of short-lived heavy hadrons* not yet seen as peaks in e^+e^- annihilation. Even with the peaks not observed, it may be possible to detect the predicted parity-violating effects in charmed-hadron decay and to distinguish these effects from those due to heavy leptons or neutral currents.

Parity violation is revealed by nonzero expectation values of pseudoscalars built with available observables. We choose pseudoscalars that are not difficult to measure, and ones that are likely, we argue, to have the largest expectation values.

The effects of interference between the electromagnetic current and a parity-violating neutral current are known.[14] Well below the mass of the hypothetical neutral intermediate vector boson, the effects increase linearly with $Q^2 = (E_{e^+} + E_{e^-})^2$. Parity violation is observable as asymmetries with respect to the beam axis in the production of particle-antiparticle pairs. *No such effects are produced by the decays of heavy leptons and/or charmed particles.* In what follows we concentrate on charm and heavy leptons and search for effects that may be expected at the one-photon-exchange level.

Consider the annihilation of an e^+e^- pair via one photon into a set of final particles of which the momenta and charges of a subset of n particles are measured. Let these be mesons, possibly unidentified as pions or kaons. The differential cross section will be of the form

$$Q^2 \frac{d\sigma}{dk_1, \ldots, dk_n} = (p_\mu \bar{p}_\nu + p_\nu \bar{p}_\mu - p\cdot\bar{p} g_{\mu\nu}) \times H^{\mu\nu}(Q, k_1, \ldots, k_n) , \tag{1}$$

where $p(\bar{p})$ are $e^-(e^+)$ momenta, $Q = p + \bar{p}$, and $Q_\mu H^{\mu\nu} = 0$. Terms in Eq. (1) that vanish because of current conservation have been omitted. Pseudoscalar observables can only be constructed for $n \geqslant 2$. We study the cases $n = 2, 3$.

Parity-violating effects depending on two measured momenta. In Eq. (1), $H^{\mu\nu}$ may contain terms of the form

$$A^{\mu\nu} = F(k_1, k_2, k_i\, Q, Q^2)\,(Q^2 k_1^\mu - k_1 Q\, Q^\mu) \times \epsilon^{\nu}_{\alpha\beta\gamma} k_1^\alpha k_2^\beta Q^\gamma , \tag{2}$$

which lead to a nonvanishing expectation value for the pseudoscalar $A = \vec{p}\cdot(\vec{k}_1 \times \vec{k}_2)\,(\vec{k}_1 - \vec{k}_2)\cdot\vec{p}$, where the momenta are lab momenta. Even though A is time-reversal (T) odd, $\langle A\rangle$ need not vanish by T invariance when strong interactions are present. However, $\langle A\rangle$ does vanish by CP invariance if the two observed particles have opposite charges and unknown identities or are a particle-antiparticle pair. CP invariance also requires that $\langle A\rangle$ take values equal in magnitude and opposite in sign when the detected particles are both positive or both negative. Moreover, one may prove that *the electromagnetic production and weak decay of either a heavy lepton or a spin-zero charmed meson yields* $\langle A\rangle = 0$.

Contributions to $\langle A\rangle$ can result only from the electromagnetic production and direct weak decay of a charmed hadron of nonzero spin. Although a charmed baryon could make such an effect, we expect production of such particles in e^+e^- annihilation to be quite small, as production of conventional baryons is known to be. If naive ideas[15] are true, charmed pseudoscalar mesons are lighter than any charmed mesons with spin and $\langle A\rangle$ mush vanish. Were it shown that $\langle A\rangle \neq 0$, it would most probably mean that these ideas are wrong,[16] and that charmed vector mesons are lighter than charmed pseudoscalars.

To detect the existence of parity violation it is enough to measure a nonvanishing value of $a = (A_+ - A_-)/(A_+ + A_-)$, where A_+ (A_-) is the number of events in which A is positive (negative). This may be less demanding in momentum resolution, and all we said about $\langle A\rangle$ applies to a as well.

Parity-violating effects depending on three measured momenta. If three momenta are measured, the pseudoscalar $B = \vec{k}_1\cdot(\vec{k}_2 \times \vec{k}_3)$ can be constructed. Define $b = (B_+ - B_-)/(B_+ + B_-)$ in analogy with the definition of a from A. Again $\langle B\rangle \neq 0$ or $b \neq 0$ proves the existence of a parity-violating step in the process. Suppose k_1 is positively charged while k_2 and k_3 are negatively charged mesons of unknown identity. Clearly $\langle B\rangle = b = 0$ unless we canonically order k_2 and k_3. If only charges and momenta are measured, we must require $|\vec{k}_3| > |\vec{k}_2|$. As before, CP conservation requires $b(++-) + b(--+) = 0$. Suppose what is measured is a K_s and two charged mesons. As before, $b(K_S +-) = 0$, while $b(K_S ++) + b(K_S --) = 0$.

A nonzero $\langle B\rangle$ *or* b *may be induced by the production and subsequent weak decay of heavy leptons and/or charmed mesons.* In either case the effect will have an energy threshold. This will not be so if the effect results from neutral currents. The energy dependence of the effect in the region of the conspicuous resonances at 3.9–4.6 GeV may help distinguish effects caused by heavy leptons from those due to charmed mesons. This is simply because the fraction of events involving charmed mesons should increase on resonance, while the fraction involving heavy leptons must decrease.

How large an effect can be expected? In our estimates we maintain our naive prejudice that the lightest charmed particles are pseudoscalar. Both for the heavy lepton and for the charmed meson, only weak decays into four or more decay products of which at least three are observed can contribute. If charmed particles and heavy leptons have only two-body and three-body decays, $b = 0$; but then invariant mass peaks should probably have been seen. Let us consider another extreme possibility: Suppose charmed mesons decay via $D \to \bar{K}^*\rho$, so that there are *no* two- or three-body decays. In a naive but more realistic picture wherein D is equally coupled to two members of the meson 36-plet, we might expect (2 : 3 : 4)-body decays of D to be in the ratio 1 : 6 : 9. In our model we predict a mean charge multiplicity for charmed events of ~4.8, which is close to what is seen.

Assuming that the final-state phase shifts and the ratio between parity-conserving and parity-violating amplitudes conspire to maximize b, we find that for a pure $D\bar{D}$ sample yielding four prongs (where K and π are not distinguished, and all combinations of momenta are counted), $|b(++-)| = |b(-++)| \sim 0.05$. With uncharmed background taken into account, a minimum of 2000 four-prong events on the 4.1 GeV resonance (or 8000 off resonance) are needed to establish a three-standard-deviation effect. One-sixth as many events may suffice with charged kaons identified and $b(K^+\pi^-\pi^-) - b(K^-\pi^+\pi^+)$ measured.

These are optimistic estimates, and it is likely that the value of b will be smaller. On the other hand, larger values of b could be found once bumps are discovered in the invariant masses of four charged particles. In such bumps, where the meson identities are known and a common parentage is ensured, values of b up to $\frac{1}{2}$ are conceivable. Incidentally, the chance of finding peaks in the invariant mass of a $(K^\pm\pi^\mp\pi^+\pi^-)$ system seems good. For example, a sample of a few thousand events with five observed prongs of total charge ±1 taken on resonance at 4.1 GeV should suffice to obtain a three-standard-deviation peak. Indeed, since the reaction $e^+e^- \to D\bar{D}$ (or possibly $e^+e^- \to D^*\bar{D}$) should be significant at this energy, one might even anticipate a peak (or peaks) in the *total momentum* of any four prongs with total charge zero. This kind of search lacks the artificial background of the invariant-mass hunt, since one need not try four different assignments of meson identity. Moreover, we estimate the experimental resolution of the charmed mass (or masses) to be superior in this method. Finally, it may permit the simultaneous determination of the masses of both pseudoscalar and vector charmed mesons. Once the peaks are found the search for parity-violating effects becomes obligatory if it is to be established that they result from the weak decays of charmed hadrons.

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[1] Early studies of possible parity- violation in e^-e^+ collisions were done by A. Pais and S. B. Treiman, Phys. Lett. 29B, 308 (1969); Phys. Rev. 187, 2076 (1969).

[2] M. L. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975).

[3] See, for example, D. C. Cundy, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974,* edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. IV–131.

[4] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[5] C. Bouchiat, J. Iliopoulos, and Ph. Meyer, Phys. Lett. B38, 519 (1972).

[6] A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1203 (1975).

[7] E. G. Cazzoli *et al.*, Phys. Rev. Lett. 34, 1125 (1975).

[8] See, for instance, the review by A. De Rújula, in Proceedings of the 1975 Summer Institute at DESY, Hamburg, Germany (unpublished).

[9] J. J. Aubert *et al.*, Phys. Rev. Lett. 35, 416 (1975).

[10] J. Kogut and L. Susskind, Phys. Rev. Lett. 34, 767 (1975).

[11] A. M. Boyarski *et al.*, Phys. Rev. Lett. 34, 1357 (1975).

[12] For a review of schemes involving color see, for instance, O. W. Greenberg, in *New Pathways in High-Energy Physics I,* edited by B. Kurşunoğlu (Plenum, New York, 1975). For an early example of a theory with the new quantum number of SU(4) broken by strong interactions, see D. Amati *et al.*, Nuovo Cimento 34, 1732 (1964) and Phys. Lett. 11, 190 (1964). Yet another way to explain the new resonances in terms of new approximate symmetries was proposed by H. T. Nieh *et al.*, Phys. Rev. Lett. 34, 49 (1975).

[13] A. M. Boyarski *et al.*, Phys. Rev. Lett. 35, 195 (1975).

[14] A recent review is given by R. Gatto and G. Preparata, Nuovo Cimento 4, 445 (1974).

[15] A. De Rújula, Howard Georgi, and S. L. Glashow, Phys. Rev. D 12, 147 (1975).

[16] G. Altarelli, N. Cabibbo, and L. Maiani, Phys. Rev. Lett. 35, 635 (1975).