Two Experiments Observe Explicit Violation of Time-Reversal Symmetry

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> For 35 years we've believed that some elementary processes can't quite run backward. Now, at last, we have direct evidence.

It is hard to imagine that nature might violate the *CPT* theorem. Its proof invokes only rock-bottom assumptions of quantum field theory, and many of its consequences have been tested to very high precision. The theorem, independently discovered in the mid-1950s by Gerhardt Lüders, Wolfgang Pauli and John Bell, asserts that any local field theory that is invariant under the "proper" Lorentz transformations must also be invariant under the *combined* operation of the three discrete (improper) transformations: time reversal (T), parity inversion (P) and charge conjugation (C).

We have known since 1964 that the weak interactions of neutral K mesons exhibit a small violation of *CP* symmetry.[1] So it comes as no great surprise that two recent kaon-decay experiments[2,3] have given us, for the first time, direct evidence of the violation of time-reversal symmetry in elementary-particle phenomena. Indeed the T asymmetry observed in these experiments is of just the right magnitude required by the *CPT* theorem, given the well-known magnitude of the *CP*-symmetry violation.

At CERN

In the 17 December 1998 issue of *Physics Letters B*, the CPLEAR collaboration's report[2] of its experiment at CERN's Low-Energy Antiproton Ring (LEAR) carries the title "First Direct Observation of Time-Reversal Non-Invariance in the Neutral-Kaon System." The neutral-kaon system is, of course, the one place where the *CPT* theorem absolutely demands T-symmetry violation, because no other system has, as yet, given clear evidence of *CP*-symmetry violation. (See PHYSICS TODAY, January, page 22.)

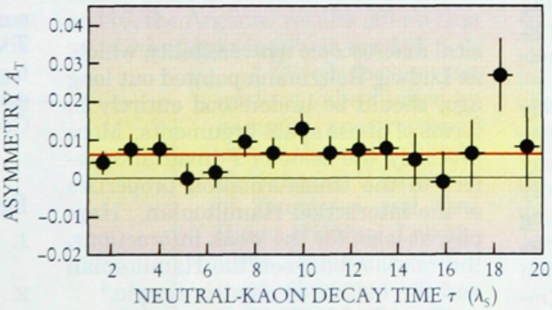
The CPLEAR collaboration, headed by Panagiotis Pavlopoulos (University of Basel), looked for and found a significant difference between the time-dependent rates for the strangeness-oscillation process $K^0 \to \overline{K}^0$ and its inverse, $\overline{K}^0 \to K^0$. The weak interactions, which do not conserve strangeness, permit this well-known oscillatory particle–antiparticle metamorphosis as a neutral kaon travels through the vacuum. If time-reversal symmetry were strictly preserved, the two processes would proceed at precisely identical rates. "Our new result is the first direct measurement of a difference between the rate of an elementary process and its inverse," Pavlopoulos told us.

The LEAR storage ring was built in the 1980s as an ancillary facility at CERN's high-energy SPS proton–antiproton collider. In this experiment, low-energy antiprotons from LEAR came to rest and annihilated with the protons in a hydrogen target surrounded by the CPLEAR detector. The group looked for the annihilation reactions

$$p\bar{p} \to K^- \pi^+ K^0 \text{ or } K^+ \pi^- \overline{K}^0.$$

Because these strong annihilation reactions do conserve strangeness, the sign of the charged kaon tells us whether its neutral companion is a K^0 (strangeness +1) or a $\overline{K}^0$ (strangeness −1) at the moment of its birth.

One wants events in which the strangeness of the neutral kaon has switched sign between its birth and decay. To that end, the group sought out events with a $K^{\pm}$ at the $p\bar{p}$ annihilation vertex followed by the eventual decay of the *neutral* kaon to $e^{\pm} \nu \pi^{\mp}$. In these semileptonic decays, the sign of the lepton's charge equals the sign of the parent neutral kaon's strangeness at the moment of decay. So events in which the charge of the decay lepton equals that of the initial companion charged kaon are precisely those in which the neutral kaon has metamorphosed into its antiparticle.



TIME-REVERSAL ASYMMETRY A_T, the observed difference between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum, is plotted here as a function of the proper time interval τ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of λ_S = 89.3 ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

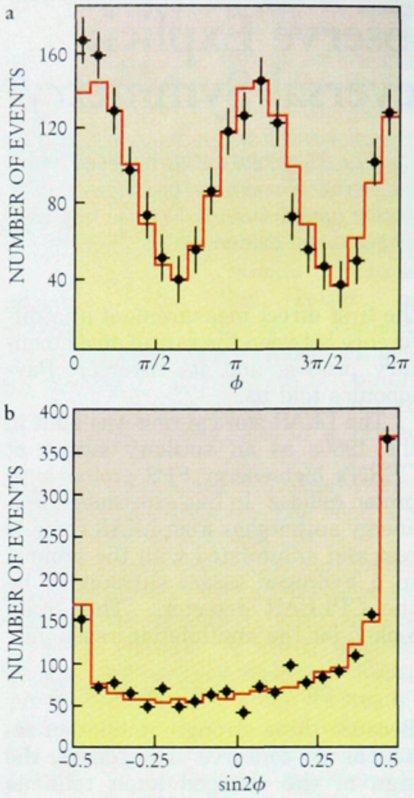
Having harvested more than a million such telltale events, the CPLEAR group calculated the time-reversal asymmetry parameter $A_T(\tau)$ as a function of τ, the proper time interval (in the rest frame of the neutral kaon) between its birth and decay. The asymmetry A_T is defined as the observed *difference* between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum.

If time-reversal symmetry were obeyed, A_T would vanish for all time intervals. In the figure below, in which the measured CPLEAR asymmetry is plotted against τ, we see that A_T certainly does not vanish. Its average value for times out to 1.8 nanoseconds (20 times λ_S, the shorter of the two neutral-kaon lifetimes) is $(6.6 \pm 1.6) \times 10^{-3}$. That's in good agreement with the 6.2×10^{-3} one would expect from *CPT* symmetry in the face of the measured *CP* violation parameters of the neutral-kaon system.

If one wants to invoke the CPLEAR experiment as a verification of the *CPT* theorem, one has to come to grips with an apparent circularity in the argument: The connection between a semileptonic decay mode and the strangeness of the neutral kaon at the moment of its decay—a crucial cog in the experiment—can, in principle, be corrupted by a small violation of the very *CPT* symmetry one is testing. But all seems to be well. A follow-up paper by Pavlopoulis and a group of CERN theorists[4] addresses this issue in detail and concludes that "the [time-reversal] asymmetry measured by CPLEAR is independent of any *CPT* or unitarity assumption," essentially because the experiment looks at only the two semileptonic decay modes.

At Fermilab

The other experiment[3] that reports the observation of explicit T-symmetry violation was carried out by the KTeV collaboration at Fermilab. The KTeV facility, completed in 1996, is a linear array of beam transport, decay volume and particle detectors extending almost 200 meters from a fixed-target source of neutral kaons at the Tevatron. Organized by Bruce Winstein (University of Chi-



ASYMMETRIC DISTRIBUTION of the angle ϕ between the planes of the pion and lepton momenta for almost 2000 rare decay events $K^0_L \to \pi^+ \pi^- e^+ e^-$, recorded by the KTeV detectors at Fermilab. If this decay were symmetric under time reversal, the ϕ distribution (**a**) would be symmetric about 0 (or π, which comes to the same thing), and the sin2ϕ distribution (**b**) would be symmetric about 0. The observed asymmetry of about 14% agrees well with the theoretical expectation indicated by the red lines. (Adapted from ref. 3.).

cago), KTeV is designed to capture an unprecedentedly intense neutral kaon beam and exploit it for two principal purposes: (1) to elucidate the physical mechanisms underlying the one decay in a thousand that manifests *CP* violation, and (2) to look for and study very much rarer neutral-kaon decays that might unearth altogether new physics.

One such decay mode,

$$K^0_L \to \pi^+ \pi^- e^+ e^-$$

is so rare that the Particle Data Group's 1998 compilation[5] gave only an *upper limit* of 4.6×10^{-7} for its branching ratio. (The subscript L denotes the longer lived of the two neutral-kaon mass eigenstates.) Early last year, KTeV reported the first observation of this rare decay mode, and by autumn the collaboration had accumulated almost 2000 such events from among 10^{11} K^0_L decays.

Extreme rarity is not the sole attraction of the $\pi^+ \pi^- e^+ e^-$ decay mode. After theorists had predicted that this mode should exhibit particularly strong *CP* violation,[6] Winstein pointed out that the proposed *CP* test should also manifest explicit *T* violation. The search for *T*-symmetry violation in this sample was spearheaded by the KTeV collaboration's University of Virginia contingent, headed by Bradley Cox. Their result was first reported at the Heavy Quark '98 workshop, held at Fermilab in October.

The time-reversal operator reverses the direction of a particle's momentum. (So does the parity operator; but *T*, unlike *P*, also reverses the particle's spin.) What Cox and company did was to measure, for each observed decay, an angular variable ϕ that changes sign when all the final-state momenta have their directions reversed. Time-reversal symmetry would require that the observed ϕ distribution be symmetrical about zero.

The argument is not entirely straightforward, because, strictly speaking, time reversal turns a decay with four daughters into an absurdly simultaneous collision of four incoming particles to make just one. Of course, the phase space for such a collision vanishes, requiring, as it does, an impossibly exact energy–momentum balance. The justification for simply inverting the outgoing momenta through the vertex is that the probability of a decay (or collision) process is taken to be the product of a transition matrix element squared and a phase-space factor. It's the latter that makes the four-to-one collision process impossible, while it's only the former whose behavior under time reversal we're interested in. The situation is reminiscent of classical macroscopic irreversibility, which, as Ludwig Boltzmann pointed out long ago, should be understood entirely in terms of phase space arguments. More precisely, the issue of *T* invariance refers to the transformation properties of the interaction Hamiltonian. Happily, at least for the weak interactions, the relation between the Hamiltonian and the matrix element is simple.[4]

The "*T*-odd" dynamical variable ϕ is the angle between the normals to two planes in the rest frame of the decaying K^0_L: the plane of the pion momenta and the plane of the lepton momenta. To give the angle an unambiguous sign, one defines

$$\sin\phi \cos\phi \equiv (\mathbf{n}_e \times \mathbf{n}_\pi) \cdot \mathbf{z}\, (\mathbf{n}_e \cdot \mathbf{n}_\pi),$$

where $\mathbf{n}_e$ and $\mathbf{n}_\pi$ are unit vectors in the directions $\mathbf{p}_{e^+} \times \mathbf{p}_{e^-}$ and $\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-}$, respectively, and $\mathbf{z}$ is the unit vector in the direction of the sum of the pion momenta.

The $K^0_L \to \pi^+ \pi^- e^+ e^-$ decay was expected to proceed by way of a competition between *CP*-conserving and *CP*-violating mechanisms, yielding a ϕ distribution of the form

$$dN/d\phi = A \cos^2\phi + B \sin^2\phi + C \sin\phi \cos\phi,$$

where only the interference term $C \sin\phi \cos\phi$ changes sign under time reversal and spoils the symmetry of the distribution with respect to $\phi = 0$. Sin ϕ (and therefore the angle itself) changes sign under time reversal because it is a product of an odd number of momentum vectors.

Nuclear physicists have spent much effort in looking for tiny *T*-violating effects with such *T*-odd dynamical vector products, thus far without success. "Our good fortune," Winstein told us, "was to find, in effect, an amplifier for *T* violation." For the portion of the decay phase space sampled by the KTeV detector's fiducial volume, the theoretical expression predicts an asymmetry of 14% about $\phi = 0$. That's an enormous signal, considering that *CP* violation usually involves only parts per thousand. But that, indeed, is what the KTeV collaboration found. The figure at left compares the ϕ and sin 2ϕ distributions measured by KTeV with the theoretical expectation. The group's preliminary value for the measured asymmetry is $13.5 \pm 4\%$. Once again, the *CPT* theorem would seem to be vindicated.

One might argue, however, that final-state Coulomb interaction could explain away much of the observed asymmetry. "But we've convinced ourselves," Cox told us, "that such effects would be very small, and that we've really seen explicit *T* violation at the predicted level. That, together with the CPLEAR result, is very gratifying, 35 years after the Fitch–Cronin experiment."

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