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Viewpoint

Particle Decays Point to an Arrow of Time

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An experiment studying B meson decays makes a direct observation of time-reversal violation without relying on assumed relationships with other fundamental symmetries.

Subject Areas: **Particles and Fields**

A Viewpoint on:
Observation of Time-Reversal Violation in the B0 Meson System
J. P. Lees emet al./em
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Time moves irrevocably in one direction. Things get old, decay, and fall apart, but they rarely ever reassemble and grow young. But at the particle level, time's arrow is not so clearly defined. Most collisions and other particle interactions look the same whether run forwards or backwards. Physicists have, however, identified a few reactions that appear to change when time is reversed, but the reasoning has assumed certain relations between fundamental symmetries of particle physics. The BaBar collaboration has now observed time-reversal violation directly and unambiguously in decays of B mesons. The measured asymmetry, reported in *Physical Review Letters*[1], is statistically significant and consistent with indirect observations.

In trying to understand the nature of particle interactions, observing the behavior of those interactions under different symmetry transformations has proven invaluable in formulating and verifying the fundamental theory. It is well known, and has been experimentally shown, that the strong and electromagnetic interactions are unchanged when viewed in a mirror world, in which particle positions are reflected ($\vec{r}$ to $-\vec{r}$). In contrast, experiments in 1956 [2] demonstrated that the weak interaction is not invariant under such parity inversion (P). A decade later, researchers found evidence in K meson decays [3] that weak interactions may also violate a combination of parity inversion with charge conjugation (C), where particles are interchanged for antiparticles. Physicists continue to study CP violation, in part to explore whether it can explain the dominance of matter over antimatter in the universe. But a related symmetry, time inversion (T), has been more elusive. It involves running an experiment backwards (t to $-t$) and converting initial states to final states. Weak interactions may violate time-reversal symmetry, but observing this directly with high enough precision proves difficult.

It is, however, possible to infer time-reversal violation (TRV) through observations of CP violation in K and B meson decays using the CPT theorem. The CPT theorem states that all local Lorentz invariant quantum field theories are invariant under the simultaneous operation of charge conjugation, parity reversal, and time reversal. Thus an experiment that measures a violation of CP might infer a corresponding lack of invariance under time reversal in order to maintain CPT invariance. Attempts to measure TRV without reference to CP violation have been controversial. Experiments at CPLEAR (measuring the difference in rates between K^0 transitions to $\overline{K}^0$ and $\overline{K}^0$ transitions to K^0[4]) and at Fermilab (observing an asymmetry seen in the decay $K_L^0 \rightarrow \pi^+\pi^-e^+e^-$[5]) claim to detect TRV directly, but some researchers have doubted this interpretation because of complicating factors in the K meson decays.

Using a method suggested previously [6], Lees *et al.* of the BaBar collaboration have now observed an explicit time-reversal violation in the decay of B mesons [1]. The experiment, performed at the Stanford Linear Accelerator Center (SLAC) in California, takes advantage of entangled B^0 and $\overline{B}^0$ mesons in the $\Upsilon(4s)$ resonance produced in positron-electron (e^+e^-) collisions at SLAC. This allows measurement of an asymmetry that can only come about through a T inversion, and not by a CP transformation.

Each of the entangled B^0 and $\overline{B}^0$ mesons resulting from the $\Upsilon(4s)$ can decay into either a CP eigenstate (e.g., $J/\psi K_L$, called B_+ for CP even, and $J/\psi K_s$, called B_- for CP odd), or a state that identifies the flavor of the meson (e.g., l^-X for $\overline{B}^0$ and l^+X for B^0, where $l^\pm$ is a lepton and X represents the other particles in the decay). To study T inversion, the experimenters selected events where one meson decayed into a flavor state and the other decayed into a CP eigenstate. The time between these two decays was measured, and the rate of decay of the second with respect to the first was determined. As an example, let's consider events in which

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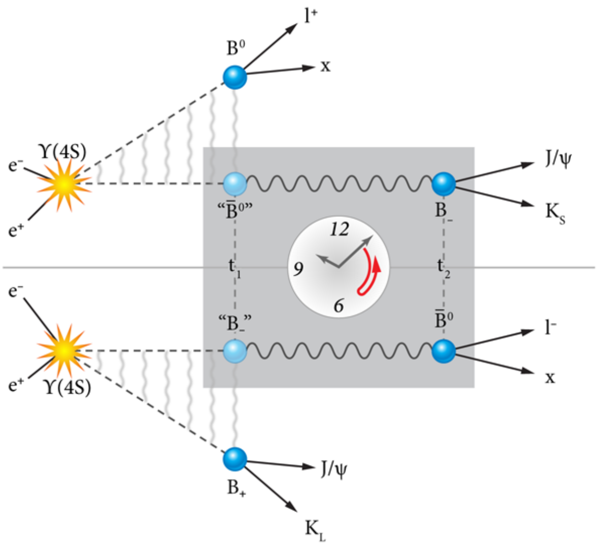

FIG. 1: Electron-positron collisions at SLAC produce a $\Upsilon(4s)$ resonance that results in an entangled pair of B mesons. When one meson decays at time t_1 , the identity of the other is “tagged” but not measured specifically. In the top panel, the tagged meson is a “$\overline{B}^0$”. This surviving meson decays later at t_2 , encapsulating a time-ordered event, which in this case corresponds to “$\overline{B}^0$” $\rightarrow B_-$. To study time reversal, the BaBar collaboration compared the rates of decay in one set of events to the rates in the time-reversed pair. In the present case, these would be the “B_-” $\rightarrow \overline{B}^0$ events, shown in the bottom panel. (APS/Alan Stonebraker)

the first meson decays at time t_1 into l^+X for B^0. Due to entanglement, the surviving meson is tagged as “$\overline{B}^0$” without being measured. At a later time t_2 , this second meson decays into $J/\psi K_s$, implying a B_- (see Fig. 1). The researchers compared these “$\overline{B}^0$” $\rightarrow B_-$ events to the time-reversed pair: “B_-” $\rightarrow \overline{B}^0$, which are those events identified by both reversing the order of decays and exchanging initial and final states. In this example, the time-reversed events are the ones with a $J/\psi K_L$ decay followed by a l^-X decay.

One of the keys to identifying the various B meson combinations is the energetic, asymmetric e^+e^- collider of the PEP-II at SLAC. In the asymmetric collider, the beams are tuned to a center-of-mass energy of 10.58 GeV, corresponding to the $\Upsilon(4s)$ mass. At that setting, 9 GeV electrons collide with positrons at 3.1 GeV, giving a boost to the resulting $\Upsilon(4s)$ and thus to its B and $\overline{B}$ decay products. This extra momentum makes it possible for the BaBar detector to determine the species of each final state meson. The detector—built inside the flux return of a superconducting solenoid magnet—surrounds the e^+e^- collision point with cylindrical trackers followed by cylindrical calorimeters [7]. Those detectors both track the outgoing trajectories and identify the particle species of the collision products, with reconstruction of that information yielding the identities of the B mesons. The flavor identity of neutral B mesons was made on the basis of the charges of prompt leptons, kaons, pions from $D*$ mesons, and high-momentum charged particles, while the B_- states were reconstructed from several CP-odd states in addition to the $J/\psi K_s$ mode. K_L^0 mesons passed through the trackers undetected, so $J/\psi K_L^0$ states were reconstructed with information from the decay product appearances in the outer detectors and the information from the other particles in the B decay.

After detecting and identifying the mesons, the experimenters determined the proper time difference between the decay of the two B states by determining the energy of each meson and measuring the separation of the two meson decay vertices along the e^+e^- beam axis. When time-reversed pairs were compared, the BaBar collaboration found discrepancies in the decay rates. The asymmetry, which could only come from a T transformation and not a CP violation, was significant, being fourteen standard deviations away from time invariance. Thus the long wait for an unequivocal time-reversal violation in particle physics is finally over.

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Michael Zeller is an experimental elementary particle physicist concentrating on weak interactions employing K mesons. His experimental work has been mostly at Brookhaven's Alternating Gradient Synchrotron, although he has also performed experiments at SLAC, Fermilab, and CERN. He has been Chairman of the Division of Particles and Fields of the American Physical Society, was a member of the C-11 commission representing the U.S. to the International Union of Pure and Applied Physics. He has served on many national planning and advisory committees, including HEPAP and several laboratory advisory committees. He is a fellow of the American Physical Society. As a professor and educator he has received both teaching prizes awarded to Yale faculty. He frequently has been invited to give popular lectures to high school and elementary teachers in the New Haven area. He recently retired from the Yale faculty and spends his time reading, studying, and doing those things he has meant to do for many years.

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