# Time-reversal asymmetry in particle physics has finally been clearly seen

**Bedrock theory has insisted since 1964 that the weak interactions should look slightly different when the movie is run backwards.**

When it was discovered in 1957 that the weak interactions of elementary particles are not symmetric under the parity operation *P*, theorists retreated to the seemingly safe presumption that the combined operation *CP* remained an inviolate symmetry. (The charge-conjugation operation *C* replaces all particles by their antiparticles.) But seven years later came a second rude awakening: The decay of neutral K mesons revealed a minuscule but undeniable violation of *CP* symmetry. So particles viewed in a mirror don't behave *exactly* like their antiparticles.

The violation of *CP* symmetry strongly implies that the weak interactions must also be asymmetric under time reversal *T*. That's because violate *CPT* symmetry was, and still remains, a bedrock theorem of particle theory. In 1999 experimenters thought they had found the first direct evidence of *T* violation in the observed difference in the forward and backward rates for the oscillatory metamorphosis $K^0 \leftrightarrow \overline{K}^0$ (see PHYSICS TODAY, February 1999, page 19).

But theorist Lincoln Wolfenstein soon pointed out that because $K^0$ and $\overline{K}^0$ are antiparticles, such rate comparisons can't disentangle the contributions of *T* and *CP* violation.[1] He suggested instead that less ambiguous evidence of *T* violation be sought in decay cascades of the much heavier neutral B mesons soon to be produced in great profusion at the "B factories," small, special-purpose electron–positron colliders just then starting up at SLAC and at KEK in Japan. "Though accepted theory insisted on the *CPT* theorem," Wolfenstein recalls, "testing it has long been a goal."

From 1999 to its final shutdown in 2008, SLAC's B factory produced several hundred million pairs of neutral B mesons quantum-entangled in such a way that, sometimes, the decay of one instantaneously fixes the state of its partner, perhaps a millimeter away. Having combed through all those B pairs, the international collaboration that ran the B factory's BaBar detector now reports the first clear, direct evidence of *T*-symmetry violation.[2] In transitions between neutral-B states not connected by *CP*, they find transition rates that depend on temporal direction in a way that can only be attributed to *T* violation. And the observed level of *T* asymmetry is consistent with what's expected from the known violation of *CP* symmetry. To no one's surprise, then, the *CPT* theorem emerges unscathed.

## B factories

B mesons are bound states of the heavy b quark (or its antiquark $\overline{\text{b}}$) and one of the ordinary light antiquarks (or quarks). Therefore, the B meson's mass (5.28 GeV) is about five times that of the proton. To create B pairs at the highest possible rate, the countercirculating $e^-$ and $e^+$ beams in the SLAC collider were tuned so that their center-of-mass collision energy was 10.58 GeV, the mass of an upsilon meson [the *s*-wave $b\overline{b}$ bound state $\Upsilon(4s)$] that immediately decays, with roughly equal

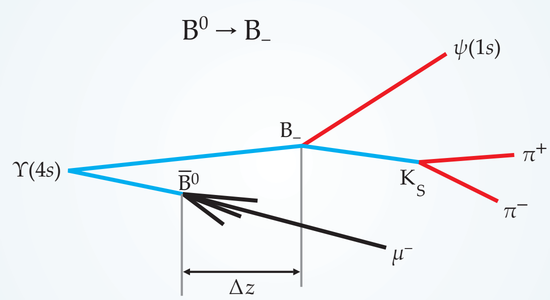


**Figure 1. Two neutral B mesons**, entangled by the internal quantum numbers of their rapidly moving parent $\Upsilon(4s)$ meson, decay a few picoseconds apart in the BaBar detector at SLAC. The $\mu^-$ emerging from the first decay reveals that the other B was, at that instant, in the quark-flavor eigenstate $B^0$. But then the survivor's decay mode, after a time interval measured by the longitudinal separation $\Delta z$, reveals that the $B^0$ had become the *CP* eigenstate $B\_$ .

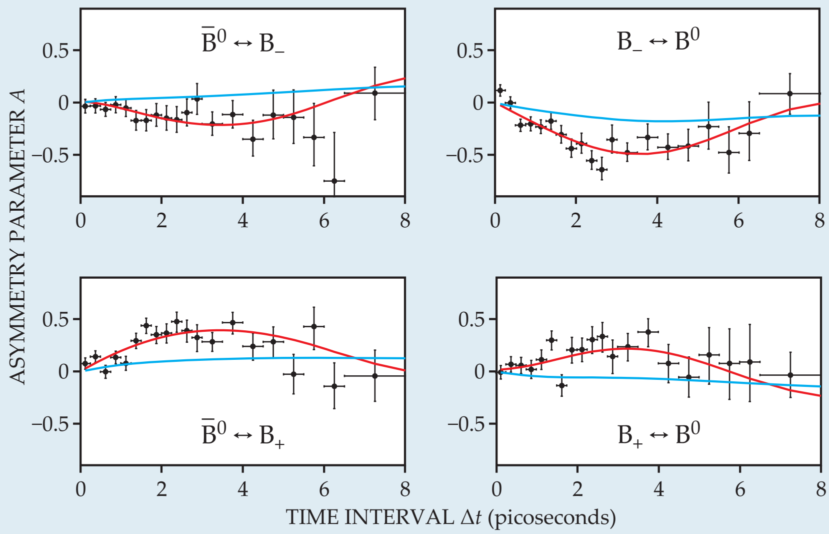


**Figure 2. Violation of symmetry** under time reversal *T* is evident in these plots of the measured asymmetry parameter *A* (defined in the text) for various transformations of neutral B-meson states versus the time interval between state-identifying decays. The blue curves estimate departures of measured *A* from zero due to instrumental effects even in the absence of *T* asymmetry. The best global fit (red curves) to all the data indicates a 14-standard-deviation signal of *T*-symmetry violation. (Adapted from ref. 2.)

probability, into a pair of neutral or oppositely charged B mesons.

The B mesons then decay with a half-life of about a picosecond. Much like its Japanese rival, the SLAC collider employed a trick to better observe the individual B decays: The beam electrons are accelerated to three times the momentum of the positrons that run into them. In a conventional collider with equal and opposite beam momenta, the B mesons would be born almost at rest. But the asymmetric SLAC collider imparts a hefty 6-GeV net momentum to the B pair. Thus a measurable distance between the two B-decay vertices in the BaBar detector reveals the time interval between them (see PHYSICS TODAY, May 2001, page 17).

## Looking for violation

Symmetry under time reversal would require the transition rate between two different neutral-B states to be independent of the time order. The internal quantum state of a neutral B meson can be described in terms of either the quark-flavor eigenstates $B^0$ and $\bar{B}^0$ (depending on whether the heavy quark is a b or $\bar{b}$) or the even and odd *CP* eigenstates $B_+$ and $B_-$, which are orthogonal superpositions of the flavor states:

$$B_\pm = (B^0 \pm \bar{B}^0)/\sqrt{2}\,.$$

Like neutral kaons and neutrinos, neutral B mesons exhibit flavor oscillation as they travel. Born, say, as a pure $\bar{B}^0$, a neutral B can later show itself in a revealing decay as a $B^0$, or even as one of the *CP* eigenstates.

The entanglement imposed on the neutral-B pair by the parent $\Upsilon(4s)$ dictates that if the first decay of a daughter reveals it to have been in a specific flavor or *CP* eigenstate, her still undecayed sister must—at that instant—be in the opposite state. "That's the kind of Einstein-Podolsky-Rosen quantum weirdness we exploited in search of *T* violation," says BaBar spokesman Michael Roney.

To that end, a BaBar analysis team led by Fernando Martinez-Vidal (University of Valencia, Spain) sought the rare neutral-B pairs in which the decay of one B clearly revealed a *CP* eigenstate and the decay of the other, a flavor eigenstate. Decays that reveal a neutral B's quark flavor are not rare. The charge of an energetic lepton among the decay products can serve as a flavor tag. If it's an $e^-$ or a $\mu^-$, the progenitor was a $\bar{B}^0$; but if it's an $e^+$ or a $\mu^+$, the decay began with a $B^0$.

Much rarer are the decays that unambiguously reveal a *CP* eigenstate. The gold standard is

$$B_{+/-} \rightarrow \psi(1s) + K_{L/S}\,.$$

The $\psi(1s)$ meson is the first discovered bound state of the charmed quark and its antiquark. The B meson's *CP* state is revealed by the subsequent decay of the neutral K. Its subscripts L and S, for *long* and *short*, denote the very disparate half-lives of the neutral kaon's two mass eigenstates.

In the example sketched in figure 1, at the moment of the first tagged B decay, the survivor must have been a $B^0$. Its subsequent tagged demise, then, shows the transformation of a $B^0$ into a $B_-$ after a time interval $\Delta t$ of a few picoseconds, measured by $\Delta z$, the beam-direction component of the displacement between the two decay vertices in the detector.

If time-reversal symmetry holds, the transition rate, as a function of $\Delta t$, must precisely equal the rate for its time reverse, $B_- \rightarrow B^0$. Figure 2 shows the results of the team's tests of that symmetry for four different neutral-B transformations. The data were gleaned from a few thousand appropriately tagged decays of neutral-B pairs.

The asymmetry parameter $A$, plotted as a function of $\Delta t$ in each of the figure 2 panels, is defined as the difference between the rates of the transition and its time reverse, divided by their sum. Even in the absence of any *T*-symmetry violation, instrumental effects would cause the small departures of the measured $A$ from zero indicated by the blue curves. But the best global fit to the actual data (red curves) constitutes a 14-standard-deviation departure from the null hypothesis that *T* symmetry is not violated.

The level of *T* violation indicated by that fit agrees well with what one expects from inviolate *CPT* symmetry, given the well-characterized violation of *CP* symmetry in the neutral-B system. Indeed, the BaBar data also yield several direct tests of *CPT* symmetry. And none of them shows any evidence of its violation.

**Bertram Schwarzschild**

## References

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2. J. P. Lees et al. (BaBar collaboration), *Phys. Rev. Lett.* (in press), available at http://arxiv.org/abs/1207.5832.

# A new 3D microscopy tool in the geologist's kit

**Coherent Raman scattering can be exploited to image a rock's interior with molecular contrast.**

In 1999 Sunney Xie and coworkers at Pacific Northwest National Laboratory published an article containing an image of three cervical cancer cells, in which each cell's mitochondria appear as bright yellow splotches in a sea of red cytoplasm.[1] The researchers used no fluorescent labels or stains to generate the color contrast; rather, they used a technique known as coherent anti-Stokes Raman scattering (CARS) microscopy.

The technique was developed in the early 1980s at the US Naval Research Laboratory, but it went virtually unnoticed until Xie and colleagues rediscovered and refined it. In the past decade, CARS has stirred considerable interest among biologists, and now work by Robert Burruss (US Geological Survey), Aaron Slepkov (Trent University, Peterborough, Ontario), Albert Stolow, and Adrian Pegoraro (both at National Research Council Canada) suggests the technique could also prove useful to geoscientists.[2] Applied to translucent samples of sedimentary rock, CARS microscopy produced richly informative three-dimensional maps that could shed new light on geochemical and geophysical processes.

## Coherent Raman scattering

In CARS microscopy, chemical contrast is generated with a pair of laser pulses—a pump pulse and a Stokes pulse—whose frequencies $\omega_p$ and $\omega_S$ differ by the frequency $\omega_v$ of a molecular vibration of interest. As depicted in figure 1a, a pump photon excites the molecule to a virtual state and a Stokes photon stimulates an emission that leaves the molecule in a vibrationally excited state. When a second pump photon scatters off the vibrating molecule, it can emerge as a so-called anti-Stokes photon, which has blueshifted frequency $\omega_{aS} = \omega_p + \omega_v$. By mapping the intensity of the blueshifted signal as a function of location in the sample, one can construct a 3D map of the molecule's spatial distribution.

Raman scattering is notoriously inefficient; it typically occurs just once in every million or so scattering events. Thus conventional, spontaneous Raman scattering techniques yield a frequency-shifted signal that can be difficult to distinguish from noise. However, if Raman scattering is stimulated with lasers, as it is in CARS, it yields a coherent, and therefore much more intense, signal.

## Speedy CARS

To implement CARS using Xie and colleagues' method, one has to synchronize a pair of picosecond pulsed lasers. Then, to scan a spectrum of vibrational resonances, one must repeatedly retune the lasers' frequencies. Three years ago, Stolow and coworkers at the National Research Council Canada devised a simpler, quicker strategy that involves just a single, femtosecond pulsed laser.[3]

As sketched in figure 1b, they split a laser beam into two arms, one of which is then redshifted—by way of a photonic crystal fiber and bandpass filter—for use as the lower-frequency Stokes beam. As with any laser, however, a decrease in pulse duration comes at the cost of an increase in bandwidth. So the femtosecond pulses should be thought of not as having specific frequencies $\omega_p$ and $\omega_S$ but as containing broad distributions of frequencies that are centered on those values. In fact, the pulse bandwidths can be tens of times broader than the spectral lines they are meant to detect. That presents a seeming conundrum: How does one tune the difference frequency of two pulses to achieve a spectral resolution exceeding that of the pulses themselves?

The trick was to use what are commonly known as chirped pulses. Using blocks of dispersive glass, each pulse is stretched in a way that temporally sorts its light according to frequency: A miniature observer who watches the chirped pulse go by would see its frequency grow linearly with time. Stolow likens it to a "piano run" in which every note is played in sequence, from low to high. To understand how the chirp facilitates fine-tuning of two pulses' difference frequency, imagine someone playing two piano runs, one with each hand. As long as each hand progresses at the