

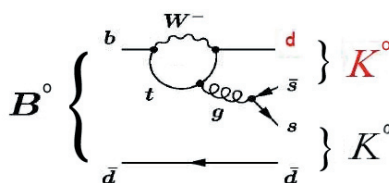
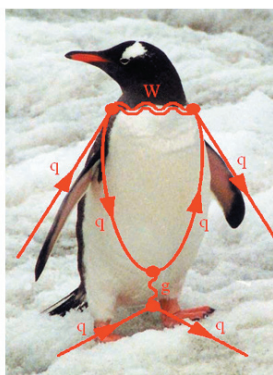
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March of the Penguins

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Every year the American Physical Society awards the Mitsuyoshi Tanaka Award to the author of the best dissertation in experimental particle physics. The 2008 award went to Jędrzej (Jed) Biesiada, a Chamberlain Fellow in the Physics Division at Berkeley Lab, who earned his doctorate from Princeton University with a thesis on penguins.

Penguin decays, that is ... a form of particle interaction represented by Feynman diagrams which—according to John Ellis, the physicist who first used them while investigating charge-parity violation—“look like penguins.” (Well, not much.)



At left, a generalized diagram in which one quark (q) changes to another by way of a loop diagram involving a virtual W boson and yet another quark, meanwhile emitting a gluon (g), which decays to still other quarks; after a bit of pushing and shoving, such diagrams can be made to resemble penguins. The top part of the diagram at right shows a b-to-d penguin decay in which a b quark changes into a d quark by way of a loop involving a W boson and a top quark, while emitting a gluon which decays to a strange/ anti-strange quark pair. (Undistorted penguin diagrams like this don't look much like penguins.) In rare B-meson decays of the kind studied by Jed Biesiada, the s quarks from such a decay combine with the d and the neutral B meson's original anti-b to form a pair of neutral kaons.

(Generalized diagram and penguin photo from Wikipedia)

For his dissertation, Biesiada did experimental work at the BaBar experiment at SLAC, the Stanford Linear Accelerator Center, where he sought to observe rare b-to-d penguin decays, events he hoped might point to new kinds of charge-parity (CP) violation. In this he succeeded, opening a new path of investigation into one of the most fundamental problems in physics—namely, why there is matter in the universe.

“The universe began in a hot big bang that created equal amounts of matter and antimatter,” Biesiada explains. “Then, as it cooled, all the particles and antiparticles should have recombined and annihilated one another, with nothing left over except energy. Instead, for every 10 billion mutual particle-antiparticle annihilations, one particle was left over—enough matter to make all the stars and galaxies, and eventually humans as well. How did that happen?”

In 1967 Russian physicist Andrei Sakharov listed three conditions necessary to explain the slight excess of matter over antimatter that followed upon their initial symmetry. Two of these conditions were related to the instability of the proton and a phase of rapid universal expansion.

“But one of Sakharov's conditions,” says Biesiada—and perhaps the most intriguing—“was the necessity for a certain amount of CP violation.”

Charge-conjugation symmetry, C, proposes that the universe or any isolated process within it should behave the same if all its particles are replaced by their antiparticles—that is, if the charges and other quantum numbers of all the particles are reversed. (Some neutral particles are their own antiparticles.) Parity symmetry, P, says that physical processes behave the same when left and right are reversed, as in a mirror.

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Beginning in the 1950s, several kinds of interactions that proceed via the weak force were found that violate either P symmetry or C and P together. The latter was first observed in 1963 by James Cronin and Val Fitch, who won the Nobel Prize for it: they found decays of long-lived neutral K mesons (kaons) to two charged pi mesons, a decay mode forbidden by strict CP symmetry. At the turn of the century, SLAC's BaBar experiment and the Belle experiment in Japan discovered, as they had been designed to do, CP violation in processes involving B mesons.

Mesons are short-lived particles pairing a quark and an antiquark; B mesons consist of an up or down quark, u or d , paired with an antibottom quark. An antibottom quark has a charge of $+1/3$; paired with a d quark of charge $-1/3$, it forms a neutral B meson of charge 0; paired with a u quark of charge $+2/3$, it forms a B meson with charge 1.

These quarks and their antiquarks result in antimemesons as well. For example, a b quark teamed with an anti- d quark also produces a particle of neutral charge, this time a B antimeson, or B-bar—thus the name BaBar. (Besides up, down, and bottom, the other quark "flavors" are strange, charm, and top, or s , c , and t .)

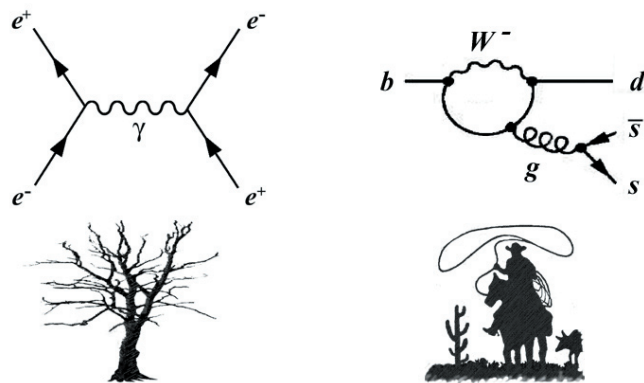
What BaBar and Belle found was that B mesons and B antimesons decay to certain combinations of particles at different rates, the kind of CP violation predicted by the Standard Model. The only problem was, says Biesiada, "that all the different processes of CP violation yet observed were not enough to account for that one-in-10-billion asymmetry of matter over antimatter in the early universe. There must be still-undiscovered forms of CP violation, attributable to new physics."

The Standard Model permits two classes of decays, those called tree level, whose Feynman diagrams are connected simply like the junctures of tree branches, and loop decays, with connections involving the invisibly brief exchange of virtual particles that recombine into new components—and thus can change the flavor of quarks, for example from b to s or b to d . Most processes can proceed by various pathways, both tree level and loop, but tree-level decays are usually favored.

"For some processes, including the flavor-changing, neutral-current transitions that can violate the CP symmetry, there are no tree-level diagrams," says Biesiada. "These can only proceed through loop processes, which makes them extremely rare. But it also opens the possibility that there are supersymmetry particles in the loop—way too massive to be created, but which could appear as virtual particles—or other kinds of new physics effects in the loop."

One class of decays studied at BaBar involved flavor-changing processes in which a b quark changed to an s quark— b -to- s penguin decays which, like all penguin decay processes, are "suppressed" (rare) in the Standard Model of physics, occurring only once in every 50,000 B-meson decays. By their nature, b -to- s penguin decays are sensitive to possible deviations from what the Standard Model predicts for CP-violating measurements.

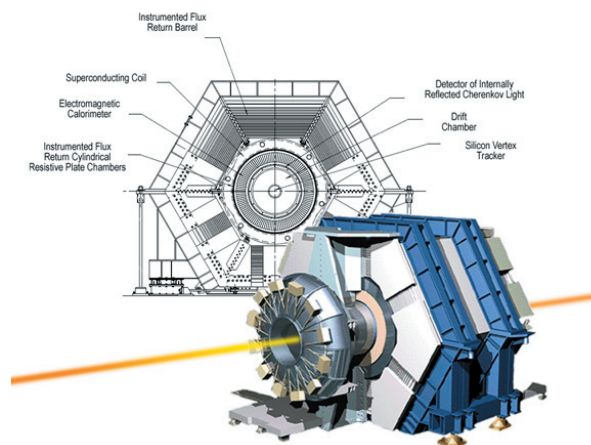
In other words, they hint at new physics, such as supersymmetric (SUSY) particles or extra dimensions of space, concepts beyond the Standard Model by which new pathways for CP violation might occur.



Feynman diagrams may be classified as tree level (left), in which particle interactions are connected simply like branches, or as loop diagrams (right), involving pairs of short-lived virtual particles. Although tree-level processes are favored most of the time, all possible decay paths occur at some calculable frequency, however rarely. But for some decays there are no tree-level diagrams, and decays can only proceed via loop processes.

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Biesiada thought that an even rarer form of flavor-changing process, the *b-to-d* penguin decays—predicted to occur only once in every million B-meson decays—might also produce a sign of CP violation due to new physics. He set out to see whether he could find them.



Jed Biesiada analyzed 350 million events captured by the BaBar experiment at SLAC to find less than three dozen *b-to-d* penguin decays of neutral B mesons to neutral K-meson pairs, expanding the search for CP violation from sources beyond the Standard Model.

SLAC's B factory and the BaBar experiment, says Biesiada, have an advantage. "The kinds of decay processes we observe at BaBar are the product of relatively low-energy particle collisions, but we get lots and lots of them, which allows us to examine interactions of interest with very high precision. To find *b-to-d* decays I did an analysis of about 350 million events in which an Upsilon particle decayed into B and B-bar pairs, looking for instances where the B mesons subsequently decayed into a pair of kaons."

He found 32 such events where a neutral B meson decayed to a neutral kaon and a neutral antikaon—only about eight percent of the one-in-a-million possibilities, due to experimental limitations, but "just enough to claim a discovery," he says. He also found events where a charged B meson decayed to a neutral antikaon and a charged kaon. In both processes, *b* quarks changed to *d* quarks via virtual loops and the emission of a gluon, which in turn yielded strange quarks; a neutral kaon combines a down and a strange quark (one of which is an antiquark).

"With 23 of these 32 events we could study the time evolution of this quantum-mechanically entangled system of particle and antiparticle and distinguish between the different decay patterns of B mesons and antimmesons, which is one way to measure CP violation in B decays," Biesiada says. "Although the 23-event dataset was small and the error bars were large, we were able to make a nontrivial statement regarding the possibility of CP violation via non-Standard-Model physics." The paper Biesiada wrote with his BaBar colleagues on these results for Physical Review Letters, "Observation of $B^+ \rightarrow K^0\text{-bar}/K^+$ and $B^0 \rightarrow K^0/K^0\text{-bar}$," has often been cited.

But what happens next is in doubt. "CP violation connects the largest cosmic issues with the smallest scales of subatomic particles and the most fundamental laws of physics, with *b-to-d* decays opening an exciting new avenue for exploring CP violation at the B factories," Biesiada says. "But this first crack at measuring CP violation via new physics in these decays was based on 350 million B-meson events measured at BaBar. I had hoped that the continuation of BaBar's operation would soon double that number of events, allowing us to reduce our estimate of errors by the square root of 2. Unfortunately, the science budget passed by Congress for fiscal year 2008 is going to shut BaBar down before the additional data can be collected."

Biesiada notes that he is Berkeley Lab's second Chamberlain Fellow in a row to win the Mitsuyoshi Tanaka Award, which last year went to his colleague Jean-Francois Arguin for a dissertation on studies of top-quark mass done at Fermilab.



Jed Biesiada
(Photo by Stu Loken)

"Jean-Francois's work represents what can be done at high-energy machines, while my dissertation research is the kind that needs low-energy but high-precision machines," Biesiada says. "These are complementary approaches, and both are essential as we advance into the coming era of new physics."

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Additional information

To read “Measurement of branching fractions and CP-violating asymmetries in B^0 to $K^0/K^0\text{-bar}$ and B^+ to $K^0\text{-bar}/K^+$ decays at the BaBar experiment,” a doctoral dissertation by Jędrzej Biesiada, go to <http://www.slac.stanford.edu/pubs/slacreports/slac-r-869.html>.

For more about Feynman diagrams (including penguin diagrams), visit Wikipedia at http://en.wikipedia.org/wiki/Feynman_diagram.

More about particle physics and the Standard Model of fundamental particles and interactions is at <http://particleadventure.org/>.

More about CP violation in the decay of B mesons is at http://www.physics.uc.edu/~kayk/cpviol/CP_A0.html.

More about BaBar and SLAC is at <http://www-public.slac.stanford.edu/babar/>.

More about the Mitsuyoshi Tanaka Dissertation Award in Experimental Particle Physics is at <http://www.aps.org/programs/honors/dissertation/tanaka.cfm>.