SLAC–PUB–13193
March, 2008

Song of the Electroweak Penguin

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ABSTRACT

This article is a commentary on a new paper by the Belle Collaboration, *Nature* **452**, 332 (2008).

An unexpected imbalance in how particles containing the heaviest quarks decay might reveal exotic influences—and perhaps help to explain why matter, rather than antimatter, dominates the Universe.

to appear as a 'News and Views' commentary article in *Nature*

[1]Work supported by the US Department of Energy, contract DE–AC02–76SF00515.

Recently, the Belle collaboration, based at the electron-positron particle collider of the high-energy accelerator laboratory KEK in Japan, announced their measurement of an anomalous asymmetry in the decay rates of exotic particles known as B mesons [1]. Combined with recent measurements of the same decays from the BaBar collaboration [2], a similar experiment at the Stanford Linear Accelerator Center (SLAC) in California, the new finding provides a tantalizing glimpse of a possible new source for a very fundamental asymmetry: the dominance of matter over antimatter in our Universe.

The two great principles of modern physics, quantum mechanics and Einstein's relativity, together imply that every particle in nature—among them the quarks and the leptons, the elementary particles of matter—has an antimatter counterpart with exactly the same mass, and exactly the opposite electric charge. Over the past 20 years, the theories of the weak and strong nuclear forces that have been built up on this basis have passed numerous rigorous experimental tests. The mathematical form of these theories allows little space for interactions that treat particles and antiparticles differently.

And yet the Universe, as far out as we can see, is made of matter, not of antimatter. We see no signals of the matter-antimatter annihilation that would happen on the edge of our local region if only this region were dominated by matter. So did the initial conditions of the Big Bang perhaps contain more matter than antimatter? It is possible. But in inflationary cosmology, the model that has successfully explained the large-scale distribution of mass in the Universe, any such initial asymmetry would have been erased very early on. We are forced to conclude that the current asymmetry has evolved from a symmetric situation since the end of the cosmic inflation that followed the Big Bang. Nature, it seems, treats matter and antimatter differently [3].

In 1973, Makoto Kobayashi and Toshihide Maskawa pointed out that a term could be added to the theory of the weak interaction (which changes one type of quark to another, for example in radioactive decay) to make this force act asymmetrically on matter and antimatter [4]. This difference would appear only if there were at least six types of quark.

This was a bold prediction, because at the time only three types of quark were known: up (u), down (d) and strange (s). But in the following decades, three more were discovered: charm (c), and the heavy bottom (b) and top (t) quarks. This astounding success led to the proposal [5] that specific experiments on B mesons–quark-antiquark pairings in which one of the particles is a b quark or bmacr antiquark–could test the Kobayashi-Maskawa (KM) theory directly. The idea, proposed by Pier Oddone, that these experiments could be performed by colliding two beams of different energies, one of electrons and one of positrons (the antiparticle of the electron), motivated the construction of new accelerators at KEK and SLAC. In

2002, both BaBar and Belle reported the first observation of a KM asymmetry in a B-meson decay [6].

Since then, evidence accumulated by BaBar and Belle, in a data set of more than 1.2 billion B-meson decays, has been used to fix the two crucial parameters of the KM theory to an accuracy of about 5%. Complementary measurements from other processes involving B mesons [7,8] have confirmed these parameters to accuracies of between 10% and 20%. It would seem that we are well on the way to understanding the basis of particle-antiparticle asymmetry in the early Universe.

In fact, we are not. The KM predictions depend crucially on the masses of the intermediate-mass s and c quarks. But the high temperature of the Universe just after the Big Bang makes these masses irrelevant in calculations of the cosmic-matter excess. The degree of asymmetry predicted by the KM model is ten orders of magnitude too small.

So where does this extra asymmetry come from? If we go beyond the standard picture of particle physics, there are many possible sources. For example, there might be new, heavier types of elementary particles beyond quarks and leptons. The search for these exotic particles is one motivation for building the Large Hadron Collider (LHC) which will soon begin operating at CERN near Geneva, Switzerland. Particle-antiparticle asymmetries are much easier to accommodate in the interactions of very heavy particles.

If these heavier particles exist, they could imprint themselves on the decays of B mesons: pairs of them might be created as short-lived quantum fluctuations that would contribute to the rate of B-meson decay. The kind of processes in which these particles might pop up are represented by so-called Feynman diagrams (Fig. 1). Two types of diagram are important: 'box' diagrams, involving a straightforward two-way exchange of particles with a resulting swapping of quark types (Fig. 1a); and 'penguin' diagrams, in which a new quark-antiquark pair sprouts from a particle loop via an intermediary particle known as a boson (Fig. 1b). The particles in the exchange or in the loop could be known particles, or heavy exotic ones.

Of the processes that have so far provided evidence for the KM theory, most have involved only the simpler box diagrams. None has tested the contribution from the electroweak penguin process—that is, a penguin process in which the intermediary boson is a Z^0, one of the particles that transmit the weak force. This process is relatively rare, but is potentially the most sensitive to new heavy particles.

This is the crux of the latest finding from the Belle collaboration [1]. They find evidence for an exotic electroweak penguin contribution to decays of B mesons into two lighter mesons: a K-meson and a π-meson. This decay receives contributions both from a direct weak-interaction decay with no loop and from a standard penguin

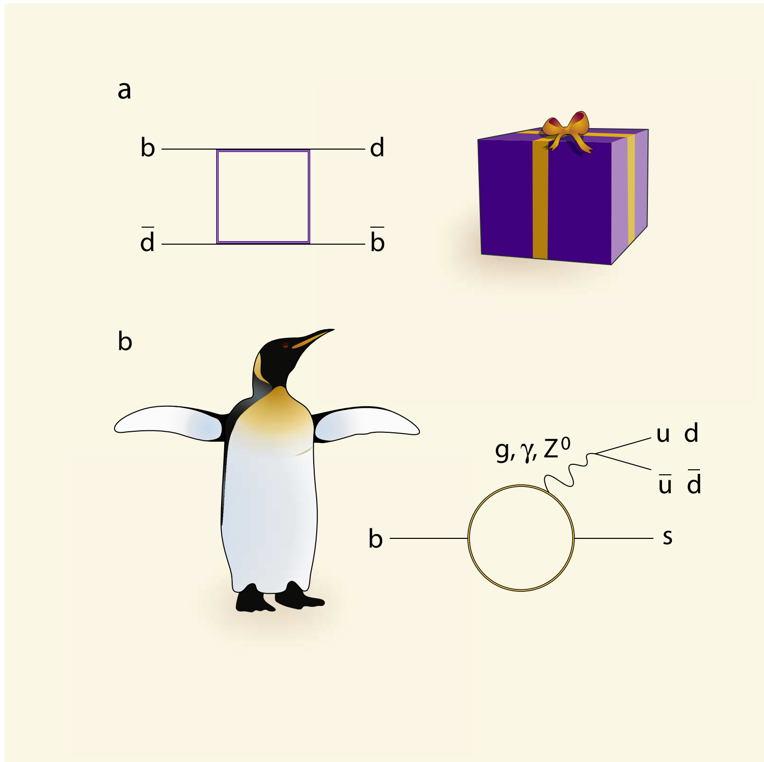

Figure 1: A Feynman diagram represents the time evolution of a particle process (shown here from left to right). (a) In a standard 'box' diagram of weak quark-mixing interactions, quarks change type by exchanging a pair of particles, for example a heavy top (t) quark and a W boson, the intermediary of the weak force. Here, a B^0 meson (quark content $d\overline{b}$) converts into a B^0 ($b\overline{d}$). (b) In a penguin process, the change of quark type occurs via a particle loop, which connects via a boson (wavy line; a gluon, g, gives a 'strong penguin'; a Z^0 an 'electroweak penguin'; gamma is a photon) to a further particle. Here, for example, a $\overline{B}^-$ or $\overline{B}^0$ could be decaying into a K^- ($\overline{u}s$) or $\overline{K}^0$ ($\overline{d}s$), plus an additional u or d quark that combines with the u or d antiquark in the B meson. The other end product is a π^0 particle, which can have quark content $u\overline{u}$ or $d\overline{d}$. In both penguin and box processes, the particles represented by the heavy lines could be as-yet-undiscovered exotic particles. Recent results from the Belle [1] and BaBar [2] collaborations invite the conclusion that penguin processes involving exotic particles are contributing to B-meson decays in their experiments. (The resemblance of the penguin diagram to a penguin is hard to discern. The name originated in a bet between particle physicists John Ellis of CERN and Melissa Franklin of Harvard University over a game of darts in a Geneva bar [9].)

process in which the boson is a gluon, the particle responsible for the strong force. The interplay of these two processes leads to a small difference in the rates of particle and antiparticle processes: the rate of the decay $B^0 \to K^+\pi^-$ is 20% larger than that of the equivalent antiparticle decay $\overline{B}^0 \to K^-\pi^+$.

The B^0 meson is composed of a d and a $\bar{b}$; the $\overline{B}^0$ contains a $\bar{d}$ and a b. In both of the above processes, the decay is essentially a decay of the b quark or its antiparticle. The lighter d or $\bar{d}$ does not participate. Given this fact, one would expect that replacing the d or d macr in the B meson by the similarly light u or u macr would produce the same asymmetry. But Belle observes that the equivalent decays of the mesons corresponding to those quark compositions, $B^+ \to K^+\pi^0$ and $\overline{B}^- \to K^-\pi^0$, have an asymmetry of the opposite sign. Together with the same asymmetries recently announced by BaBar [2], the effect has a statistical significance greater than five standard deviations—the 'gold standard' of particle physicists for proof that an effect is real.

Unlike the decays of the neutral B mesons B^0 and $\overline{B}^0$, the decays of the charged B mesons B^+ and $\overline{B}^-$ produce two u quarks or antiquarks. This means that other processes that preferentially produce u quarks rather than d quarks might affect the asymmetry. The electroweak penguin is just such an effect—but to alter the asymmetry, this process must differ from the standard electroweak penguin, which affects the decay rates symmetrically. A contribution from an exotic loop is required. There are admittedly other possibilities that might explain the anomaly in the asymmetry: a direct weak-interaction decay process, the so-called 'colour-suppressed' contribution, also has the required properties. The size of this contribution depends on the quarks involved. In decays of mesons containing the c quark, it is substantial. For the heavier B mesons, however, it is indeed expected to be suppressed.

The new results [1,2] are not conclusive, but they are tantalizing. They might be due to properties of standard b-quark weak interactions that we cannot quite yet estimate precisely, but it is equally possible that this is the first hint of an entirely new mechanism for particle-antiparticle asymmetry. In the next few years, these ideas will be tested, both through the analysis of the huge Belle and BaBar data set, and from the hunt for exotic particles at the LHC. We do not yet know whether it is penguins or even more unusual creatures that produce our Universe made of matter and not antimatter.

References

[1] S.-W. Lin *et al.*, [Belle Collaboration] *Nature* **452**, 332 (2008).

[2] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **99**, 021603 (2007) [arXiv:hep-ex/0703016]; B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **76**, 091102 (2007) [arXiv:0707.2798 [hep-ex]].

[3] A. Riotto and M. Trodden, Ann. Rev. Nucl. Part. Sci. **49**, 35 (1999) [arXiv:hep-ph/9901362].

[4] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[5] A. B. Carter and A. I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); I. I. Y. Bigi and A. I. Sanda, Nucl. Phys. B **193**, 85 (1981);

[6] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **89**, 201802 (2002) [arXiv:hep-ex/0207042]; K. Abe *et al.* [Belle Collaboration], Phys. Rev. D **66**, 071102 (2002) [arXiv:hep-ex/0208025].

[7] A summary of the experimental constraints on the KM theory as of spring 2006 (too early for ref. 5) is given in A. Hocker and Z. Ligeti, Ann. Rev. Nucl. Part. Sci. **56**, 501 (2006) [arXiv:hep-ph/0605217].

[8] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **97**, 021802 (2006) [arXiv:hep-ex/0603029]; A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 242003 (2006) [arXiv:hep-ex/0609040].

[9] For an etymology, see K. Lingel, T. Skwarnicki and J. G. Smith, Ann. Rev. Nucl. Part. Sci. **48**, 253 (1998) [arXiv:hep-ex/9804015].