

because one can't tell where the electron is. The collective state is then a condensate of these excitons, which behaves as a superfluid.

A third picture, which further develops the excitonic description, is that of the DC Josephson effect. As presented by one pair of theorists, the excitonic condensate of the quantum Hall bilayer is governed by the same equations as the Josephson junction, with ϕ playing the role of the phase difference between superconductors.⁵ In the views of these theorists, the excitonic condensate embodies the essence of the Josephson effect: It's a coherent system with an indeterminate number of excitations carrying charge in each layer.

Nagging questions

As tempting as it is to make a complete analogy with the Josephson effect, the Caltech–Bell Labs experiment does not yet fit in all regards. In particular, at zero voltage the experimenters observe zero current, not the finite supercurrent one expects from a Josephson junction (see figure 1b). According to Eisenstein, it is not yet clear whether the zero current is intrinsic to the way tunneling works at $\nu = 1$, or is caused by some unknown extrinsic experimental effect. The slope of the I - V curve near $V = 0$ keeps getting steeper (and the associated conductance peak taller and sharper) as he and his team improve the experiment. So, Eisenstein be-

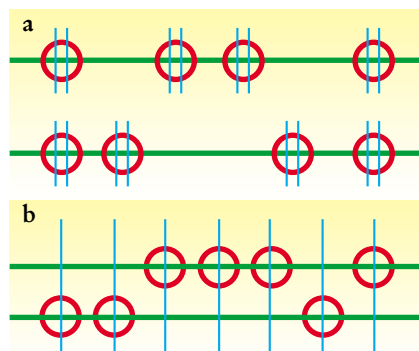


FIGURE 2. QUANTUM HALL BILAYERS are depicted by electrons (red circles) associated with magnetic flux quanta (blue lines). (a) At large separation, each electron is associated with two flux quanta and is little influenced by electrons in the other layer. (b) At small separations, the electrons move in a collective state, each associated with a single flux quantum and each keeping its distance from the others.

lieves, the jury is still out on whether they have a Josephson junction.

Sankar Das Sarma of the University of Maryland, College Park, believes the evidence for a collective mode in the quantum Hall bilayer, but does not think we can claim a full understanding of it until we can reproduce its quantitative as well as qualitative features. To that end, two groups recently tried to understand in detail the observed height and width of the zero-conductance peak in the

Caltech–Bell Labs experiment.^{3,4} They examined the role of disorder in this system. At the same time, Das Sarma and two colleagues explored the possible ground states of the quantum Hall bilayer and found a large number of them, including some that exhibit only a quantum Hall effect or coherent electrons.⁷ In yet other work, a group from Indiana University examined the evolution of the bilayer system between the extremes of large and small separation.⁶

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Novel B Factories Close in on the Violation of CP Symmetry

It's been two years since PEP-II and KEKB, two "asymmetric B factories," one on either side of the Pacific, began their competing assaults on the important problem of CP symmetry violation in particle physics. And now we have the first substantial results.^{1,2}

Both PEP-II at SLAC and KEKB at KEK, the high-energy accelerator laboratory in Tsukuba, Japan, are electron-positron storage-ring colliders. Their novel asymmetric feature is that the two countercirculating beams in each machine don't have the same energy: An 8- or 9-GeV electron beam collides with a lower-energy positron beam to produce B-meson pairs in abundance, in a configuration that greatly facilitates the examination of CP violation in the decays of neutral B mesons. The charged and neutral B mesons, about five times more massive than the proton, carry the heavy

How well does CP violation obey standard particle theory? Electron-positron colliders of a new kind were built in the US and Japan to find out.

third-generation bottom quark (b) or its antiquark ($\bar{b}$).

Though both machines are performing brilliantly at this early stage, neither has as yet produced conclusive evidence for CP violation in B decay. The only clear evidence we have for the violation of CP symmetry in nature—aside from the cosmic preponderance of matter over antimatter—comes from the decay of neutral K mesons. CP denotes the combined operation of charge conjugation (C), the replacement of particles by their antiparticles, and parity inversion (P). After the rude overthrow of parity conservation in 1957, CP offered a refuge for believers

in mirror symmetry, but only until 1964, when CP violation was discovered in a small fraction of K^0 decays.

What spoils the symmetry?

Why all this effort to study CP violation by neutral B mesons? In 1973, before there was any hint of the third generation of quarks (the bottom and top, t), Makoto Kobayashi and Toshihide Maskawa made the prescient observation that, within the standard model of particle theory, a third quark generation would provide a natural mechanism for CP violation. But, after decades of painstaking K-decay experiments, we still don't know whether the Kobayashi–Maskawa mechanism is the principal source of CP violation in particle physics (see PHYSICS TODAY, May 1999, page 17). The question is important, because particle physicists are urgently seeking evidence of any

effect beyond the purview of the standard model.

It turns out that the neutral B-meson system is a much better place to look than the kaon system. The B mesons are about 10 times heavier than the K mesons, which carry the much lighter second-generation strange quark (s) or its antiquark. The standard model predicts that the B system should violate CP symmetry much more strongly than the meager parts-per-thousand violation we find in the K system. Furthermore, there are certain “golden” decay modes of the neutral B that allow for particularly clean analysis of CP -violation data, largely free of the theoretical hadronic ambiguities that muddy the neutral-kaon experimental results.

The asymmetric colliders

The beam energies at PEP-II and KEKB are chosen so that the center-of-mass e^+e^- collision energy is precisely 10.58 GeV, the mass of an upsilon meson, the $Y(4S)$, a $b\bar{b}$ bound state that’s just barely massive enough to decay into a $B^0\bar{B}^0$ pair. Therefore the two neutral B’s emerging from an Y decay are almost at rest in the center-of-mass frame. But in the innovative asymmetric collider configuration, both B mesons from each Y decay are flying through the detector, almost together, at about half the speed of light in the direction of the higher-energy beam.

What’s so good about that? The decay lifetime of the B^0 is 1.55 picoseconds. Observing CP violation in the $B^0\bar{B}^0$ system produced by Y decay requires that one measure the time interval between the subsequent decays of the two B mesons. That’s well-nigh impossible if the two B’s are almost at rest. But in the asymmetrical collider configuration, each B travels, on average, about 200 μm before it decays. Thus one can deduce the time interval by measuring the distance between the two decay vertices in the high-spatial-resolution vertex tracking chamber at the heart of the large detector complex that surrounds the collision point.

The KEKB collider’s detector is called Belle. The PEP-II detector is called BaBar. So, naturally, the logo of the SLAC collaboration is Babar, the elephant-king of the celebrated children’s books.

Like the neutral kaon, the neutral B meson continually oscillates between its B^0 and $\bar{B}^0$ “flavor eigenstates,” with a periodicity determined by the tiny mass difference Δm between the mass

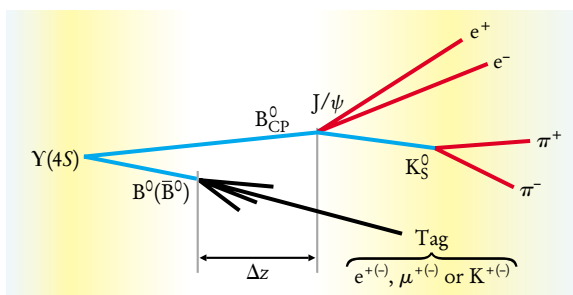


FIGURE 1. A “GOLDEN EVENT” as it might look in the tracking vertex detector of BaBar or Belle. An Y decays to two neutral B’s, each of which travels a few hundred μm before decaying. (Invisible neutral tracks are shown blue.) One B decays into the CP eigenstate $J/\psi K_S^0$, which the detector reconstructs fully, recording the e^+e^- decay of the J/ψ and the $\pi^+\pi^-$ decay of the K_S^0 . The other B decays in one of its flavor eigenstates, revealed by the charge sign of its decay kaon or lepton. The longitudinal distance Δz between decay vertices measures the time difference between the decays.

eigenstates. In most cases, one can tell which state the neutral B was in at the instant of decay by the charge of a lepton or kaon among its decay products. For example, a K^+ signals a B^0 decay, while a K^- reveals a $\bar{B}^0$ decay.

Golden events

Much rarer than these “flavor tagging decays” are decays in which a neutral B decays into an eigenstate of CP . Such

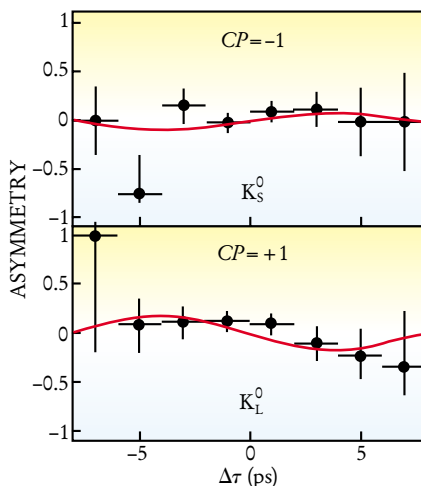


FIGURE 2. ASYMMETRY RATIO A , measured at BaBar as a function of the time interval between the flavor-tagging B decay and the B decay to a CP eigenstate (mostly J/ψ plus K_S^0 or K_L^0). For a total of 529 events, the two panels display the data and best fits for each of the two CP eigenvalues.

decays are crucial to the observation of CP violation in these experiments. The most useful of the CP decay eigenstates has the ungainly designation $J/\psi K_S^0$. The K_S^0 is the shorter-lived of the two neutral-kaon mass eigenstates. And the J/ψ is the first-discovered bound state of the charmed quark (c) and its antiquark. The double-barreled name of this first “charmonium”

meson is a relic of the rivalry that marked its 1974 discovery.

What the experimenters are looking for is any difference in the rates at which the B^0 and $\bar{B}^0$ decay to a common CP eigenstate. Any such difference would violate CP symmetry. To that end, each experiment has already harvested more than 5 million $Y \rightarrow B^0\bar{B}^0$ decays. The few hundred prized events gleaned thus far have one neutral B decaying to a well-measured CP eigenstate, while the other B reveals its flavor in a tagging decay (see figure 1).

The situation is much like the Einstein-Podolsky-Rosen *gedanken* experiment. Before either B decays, the system evolves undisturbed in the coherent state $(B^0\bar{B}^0 - \bar{B}^0B^0)/\sqrt{2}$. But then the tagging decay starts a new clock by measuring the flavor of one B and thus projecting the other B into the opposite flavor state.

The Belle and BaBar experiments measure the time dependent CP -violating asymmetry

$$A(\Delta\tau) \equiv \frac{f_+(\Delta\tau) - f_-(\Delta\tau)}{f_+(\Delta\tau) + f_-(\Delta\tau)},$$

where f_+ and f_- are, respectively, the evolving decay rates of the B^0 and $\bar{B}^0$ to the same CP eigenstate. $\Delta\tau$ is the proper time difference between the two decays (in the Y rest frame). It can be positive or negative, depending on whether the tagging decay comes before or after the CP decay.

The standard model predicts that

$$A(\Delta\tau) = -\eta \sin 2\beta \sin(\Delta m \Delta\tau),$$

where η is the CP eigenvalue of the decay eigenstate. For $J/\psi K_S^0$, $CP = -1$, but for $J/\psi K_L^0$, the other important CP eigenstate in these experiments, it’s $+1$. K_L^0 is the longer-lived mass eigenstate of the neutral kaon system. (See figure 2).

The amplitude of this CP -violating oscillation, $\sin 2\beta$, is the key parameter these experiments set out to measure. If it’s zero, there is no CP violation.

First results

By the end of last year’s running, BaBar had harvested about 500 flavor-tagged $J/\psi K^0$ events and a handful of

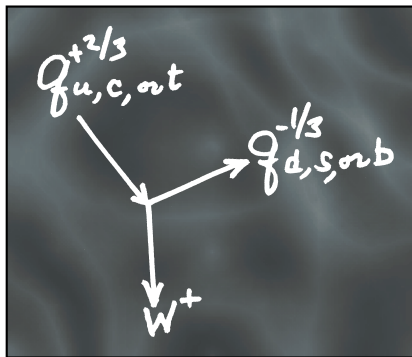


FIGURE 3. THE CKM MATRIX elements are the relative amplitudes for the nine weak-interaction couplings represented by this Feynman vertex. In each case, a charge $+2/3$ quark (up, charmed, or top) couples to a charge $-1/3$ quark (down, strange, or bottom) and the charged W boson that mediates these weak interactions. Ordinary beta decay, for example, would involve primarily the first-generation diagonal CKM matrix element V_{ud} .

additional events sporting a heavier charmonium state in place of the J/ψ . From this first sample, the collaboration extracts $\sin 2\beta = 0.34 \pm 0.21$. The Belle collaboration, with about half as many events analyzed at year's end, reports $\sin 2\beta = 0.58 \pm 0.34$.

The first order of business was to see whether the B system exhibits any CP violation at all. That's obviously still up in the air, given that both experiments have measured a $\sin 2\beta$ that, so far, is only about 1.7 standard deviations from zero. In fact, at this point the asymmetric-collider results are only slightly better than the recent result from the Fermilab Tevatron,³ a high-energy hadron collider not ideally suited to this task.

If the measured $\sin 2\beta$ does not vanish, the next thing is to see how well it agrees with the standard model. To explain the standard-model prediction for the CP decay eigenstates recorded in these experiments, we must refer to the so-called Cabbibo-Kobayashi-Maskawa matrix. Simply put, the CKM matrix is an empirical 3×3 unitary matrix whose elements V_{ij} are the relative amplitudes for the nine different quark-quark couplings to W, the heavy fundamental boson that mediates the charge-changing weak interactions, as shown in figure 3.

The CKM matrix is 3×3 because there are three quark generations. What Kobayashi and Maskawa pointed out in 1973 was that a third generation would endow the matrix with

one irreducible complex phase that would cause CP violation—unless that phase turns out to vanish. If that phase did indeed vanish, one would have to look beyond the standard model for the explanation of any observed CP violation.

In the appropriate phase convention, the angle β is simply the phase of the product $V_{td}V_{tb}^*$ in the complex plane. (The designation d refers to the first-generation down quark that inhabits the proton and neutron.) Extracting the various CKM matrix elements from a great variety of experiments is a difficult experimental and theoretical business. At present, a conservative estimate⁴ of $\sin 2\beta$ from the CKM matrix would be 0.7 ± 0.2 .

That, for the moment, is the standard-model prediction for the amplitude of the $A(\Delta\tau)$ oscillation in the BaBar and Belle experiments. The error bars in both experiments are still too large for a meaningful comparison with the standard-model prediction from the CKM matrix elements. But by the end of 2005, both Belle and BaBar hope to have measured $\sin 2\beta$ with an uncertainty of less than 0.02. By then, there should also be a much narrower estimate of $\sin 2\beta$ from the improved determinations of the CKM matrix elements.

The two asymmetric B factories will, in fact, play important roles in this latter task. In addition to measuring CP -violating asymmetries, BaBar and Belle are designed to examine a broad range of other phenomena relevant to the direct determination of CKM matrix elements. Their excellent vertex detection, calorimetry, and particle identification make them particularly well suited, for example, to the study of rare decay modes of charged as well as neutral B mesons.

As the measurements of the CP -violating asymmetries on the one hand, and the direct determinations of the relevant CKM matrix elements on the other, become increasingly precise, a persistent discrepancy between these two approaches would be evidence for new physics beyond the standard model.

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