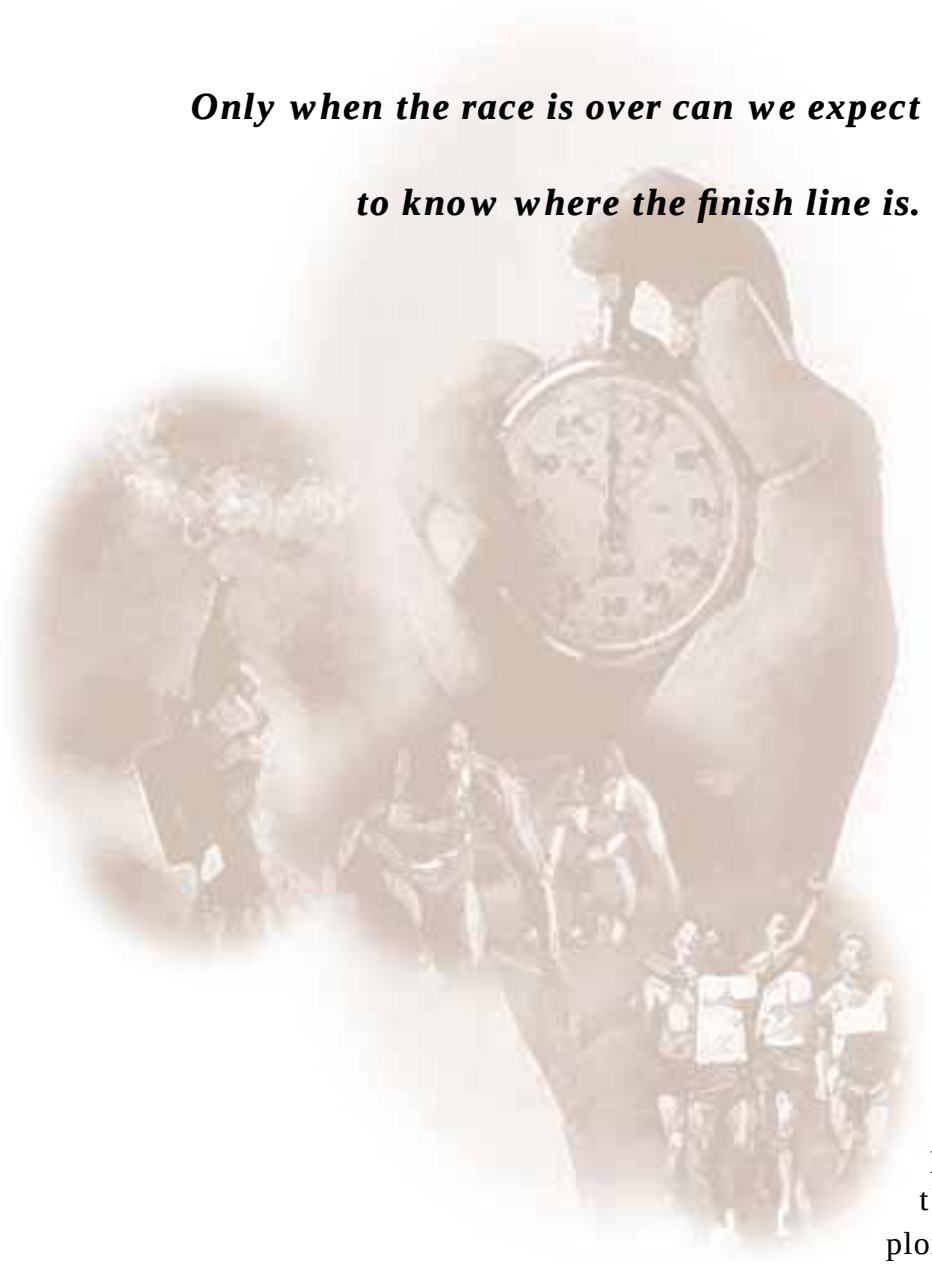
TAKE YOUR MARKS

by ROBERT N. CAHN

Only when the race is over can we expect to know where the finish line is.



IT'S A RACE with no starting point, no fixed course, and really no rules at all: walk, run, ride, do anything you want. Form a team, as big as you like. Build any sort of machine you wish with whatever money you can get your hands on. Just get to the finish line first.

That finish line isn't a particular place but a new understanding of a symmetry (or rather, an almost symmetry) of the Universe. This rather inchoate race is just now coming into focus. Teams in Tsukuba, Hamburg, Chicago, Ithaca, and Palo Alto have been preparing for the final stretch the last year or two.

No one announced this race. It began spontaneously in the 1980s when physicists realized that they could use the newly discovered *B* mesons to explore the violation of CP symmetry in novel ways. This was welcome because ever since its discovery in 1964, CP violation has been a particularly

enigmatic, if subtle, phenomenon. CP symmetry was salvaged from the wreckage of the separate symmetries parity (P) and charge conjugation (C). For thirty-five years its violation has been a preoccupation of particle physics.

Just as the human eye searches for symmetries, patterns of identical appearance, particle physicists seek symmetries in Nature. Some of these are symmetries of space and time: Nature looks pretty much the same in every direction and in every place, and the same today as yesterday. Other symmetries are less obvious, especially symmetries that assert that one particle is the look-alike partner of another. For example the neutron and proton form such a pair, related by a symmetry called isospin invariance; their masses differ by only 0.13 percent, and their interactions with other neutrons and protons are quite similar. Nonetheless, in matter they behave in dramatically different ways, because one is neutral and the other electrically charged. The isospin symmetry that relates the neutron and proton is not respected by the electromagnetic force: the symmetry is said to be broken by electromagnetism.

The progress in understanding elementary particles is a story of uncovering unsuspected symmetries and then struggling to understand what breaks them. The Standard Model of particle physics is based on a symmetry like the one that connects the neutron and proton, but it makes much more improbable pairs. The electron, the stuff responsible for all chemistry (and thus, life) is appointed the partner of a scarcely observable neutrino. More precisely, the electron that spins clockwise around its direction of motion (a left-handed electron) is the partner of the neutrino whose spin is similarly oriented. The evidence for this bizarre identification is compelling.

Why is a distinction made between left-handed and right-handed particles? Before 1956 physicists thought such a distinction could hardly be fundamental. Surely one could build one laboratory and another that was its mirror image and obtain identical results in the two. To be thorough, you could hire left-handed graduate students to work in one and right-handed ones for the other. Each setup would simply be the mirror image of the other. In 1956, Tsung-Dao Lee and Chen Ning Yang pointed out that there

Madame Chen-Shing Wu and Wolfgang Pauli. In 1930, Pauli proposed that in nuclear beta decay the emitted electron was accompanied by a light neutral particle, the neutrino. In 1957, Madame Wu, with her collaborators, Raymond Hayward, Dale Hoppes, and Ralph Hudson from the National Bureau of Standards, showed that parity is violated in beta decay. (Courtesy AIP Emilio Segrè Visual Archives)

was no evidence, at least for the weak interactions like the beta-decay of radioactive nuclei, that these laboratories would be equivalent. Indeed, in 1957 when Madame Chen-Shing Wu and her collaborators tested the parity symmetry (P) that connects left-handed arrangements to right-handed ones, they found that the weak interactions could tell the difference between them. The two mirror-image laboratories got different results.

One manifestation of this parity violation was that electrons emitted in beta decay were overwhelmingly left-handed (instead of being equally right-handed and left-handed), showing that parity was violated as much as it possibly could be. On the other hand, when positrons were emitted, they emerged predominantly right-handed. This violated another possible symmetry: charge conjugation invariance (C). If C symmetry were respected, the antiparticle of the electron would be emitted left-handed like the electron itself.

Even though both C and P symmetries were lost, if they were combined, the result might still be a true symmetry. CP would change the left-handed electron into the right-handed positron. These were both seen in nuclear decays, so it appeared that the combination CP, though not either C or P separately, was respected by the weak interactions.

But in 1964 CP symmetry, too, fell in a study of decays of neutral *K* mesons. There are two such particles. One "*K*-short" (K_S) decays in less than a billionth of a second. The "*K*-long" (K_L) lives 500 times as long (see bottom illustration on the next page). This difference could be understood in terms of CP. When CP acts on an object it generally changes it into something quite different: a left-handed electron becomes a right-handed positron. Some systems, though, are turned into themselves and these fall into two categories: CP-even and CP-odd. In 1964 the K_S was thought to be purely even, which would permit it to decay to CP-even states $\pi^+\pi^-$ and $\pi^0\pi^0$, while these decays would be forbidden for the CP-odd K_L. Because the K_L lacks these opportunities to disintegrate, it lives longer. However, a careful experiment by James Christenson, James Cronin, Val Fitch, and Rene Turlay showed that about two K_L's in a thousand decay to $\pi^+\pi^-$, in violation of the supposed CP symmetry.

In the subsequent thirty-five years, CP violation has been the subject of investigation by ever more thorough experiments. Why has such

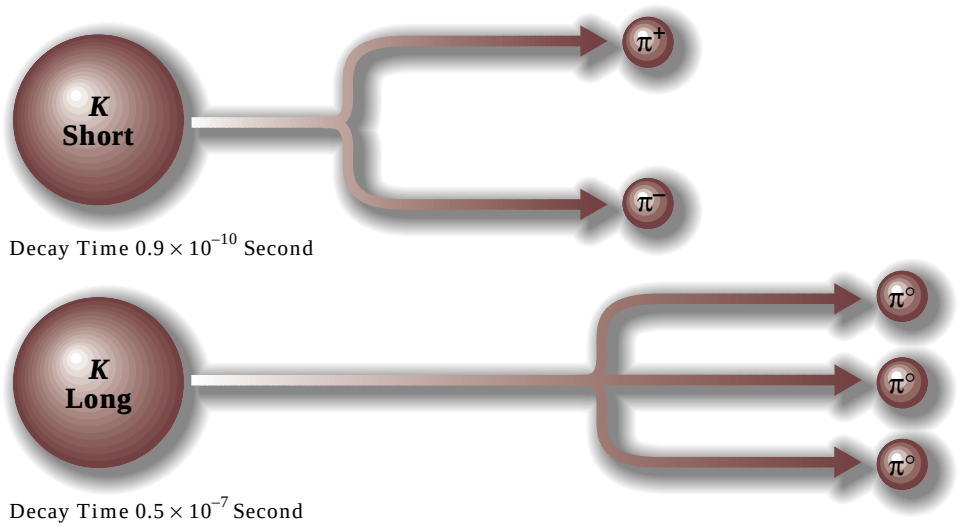
enormous effort been expended? First, CP is clearly a very fundamental symmetry, or rather near symmetry. When combined with time-reversal invariance, it gives the combination CPT, which is believed on very fundamental theoretical grounds to be a true, unbroken, symmetry. Thus if CP fails, T must fail in an exactly compensating way. Second, Andrei Sakharov argued convincingly in 1967 that CP violation is probably essential to the creation of the apparent preponderance of matter over antimatter in the Universe. In other words, without CP violation probably all matter and antimatter would have annihilated leaving nothing tangible behind. Thus CP violation is evidently at the heart of the material world.

If CP symmetry held true, the K_S and K_L would be purely even and odd respectively. One could not be changed into the other. Since CP symmetry is not completely respected, the odd and even states can change back and forth, one into the other. Physicists say they "mix." Is this the only source of CP violation? Very careful study of the decays of the neutral K meson can answer this question, and just such studies have been going on ever since the discovery of CP violation. Experiments at CERN and Fermilab now seem to have convincing evidence that CP violation comes not just from the mixing of the CP-odd and CP-even states of the K.

In 1972, Makoto Kobayashi and Toshihide Maskawa proposed an explanation of CP violation within the Standard Model. They recognized that if there were three generations of quarks, as we now know there are, there could be a misalignment among them. If that misalignment were simply like a spatial rotation, described by three angles, no CP violation would arise. But in general the misalignment needs four angles for its description, and in that case, CP symmetry is violated. The misalignment is often represented by a complex 3×3 matrix, called the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

This dramatic prediction is about to be tested in experiments at SLAC, KEK (in Japan), DESY (in Germany), Fermilab (in Illinois), and at CESR (in New York). The experiments with K mesons are not easily compared with the theory of Kobayashi and Maskawa. The new experiments, which use B mesons instead of K mesons, will confront the theory directly.

B mesons are a lot like K mesons. Every meson is made of a quark and an antiquark. In a K^0 meson there is a d quark and an s antiquark. The meson with a d antiquark and an s quark is called a $\overline{K}^0$ ("kay-zero-bar"). The K_S and K_L are combinations of K^0



K mesons have two different life spans. One type of kaon, the K-short, decays quickly into two pions, whereas the other decays slowly into three pions. The difference in behavior comes from the two kaons having opposite CP symmetry. Only rarely however, the K-long can also decay into two pions, proving that CP can be violated.

Toshihide Maskawa, left, currently Director of the Yukawa Institute at Kyoto University, Kyoto, Japan, and Makoto Kobayashi, professor at the Institute of Particle and Nuclear Studies at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan. For a photograph of the pair when they were students, see page 24.

and $\overline{K}^0$. The B mesons are exactly analogous, except that they have a very heavy b quark in place of the much lighter s quark. Although the b quark itself became known in 1977, B mesons were discovered only in 1982.

The B meson is a master of disguises. It disappears in dozens of ways, using each no more than a few percent of the time. An especially nice decay is $B^0 \rightarrow J/\psi K_S$. It is attractive because the J/ψ is an extraordinary particle. Called J by Samuel Ting and his collaborators who found it at Brookhaven and psi (ψ) by Burton Richter and his collaborators, who found it simultaneously at SLAC, this particle decays into the stunningly simply states e^+e^- and $\mu^+\mu^-$—pairs of charged particles that are easily identified. Unfortunately, only one B meson in 2000 decays to $J/\psi K_S$, and only 12 percent of these have the wonderful e^+e^- or $\mu^+\mu^-$ signature.

How can we test CP symmetry with B mesons? The simplest way is to ask whether the decays $B^0 \rightarrow J/\psi K_S$ and $\overline{B}^0 \rightarrow J/\psi K_S$ happen in exactly the same way. CP symmetry would require them to be identical since the action of CP on a B^0 makes a $\overline{B}^0$ while it turns $J/\psi K_S$ into itself.

But if we observe $J/\psi K_S$ in a detector, how can we determine whether it came from a B^0 or a $\overline{B}^0$? This requires a physicist-detective to examine telltale clues in the remainder of the event. The b quark is always produced together with an anti-b quark. If evidence can be found for a b quark elsewhere in the event, then it must have been an anti b quark (and thus a B^0 meson) that decayed into the $J/\psi K_s$. This detective work is called "tagging."

Actually, neutral B mesons are more cunning than this. They change into their antiparticles and back on a regular basis, seventy billion times a second. This makes tagging somewhat harder. When the b and anti-b are produced so that they act independently, we can forget about all these oscillations and simply take an average. This is what happens when B's are produced in high-energy collisions of protons, as they will be at Fermilab and at the HERA accelerator at DESY.

At the electron-positron colliders coming on line at SLAC and KEK, the situation is totally different. There the machine energies are fixed so that the electron and positron combine with just the right energy to make exactly one B^0 and one $\overline{B}^0$. Each oscillates back and forth between particle and antiparticle, but with their oscillations synchronized so that if one decays as a B^0 then the

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other must be a $\overline{B}^0$ at that very instant. To test CP violation in this case, we need to tag one B and measure the time until the other decays, for during that time it continues to oscillate. A typical B makes only about a quarter of an oscillation before decaying, but some live much longer.

At SLAC and KEK physicists study the behavior of B mesons as a function of the time interval between the decays of the two mesons produced in a single event. To do this, their electron-positron colliders are operated in a novel way: the energies of the electrons are raised to about 9 GeV while the positrons have only 3 GeV. When the two collide, the resulting resonant state, $\Upsilon(4S)$, is moving at more than half the speed of light in the direction of the electron beam. The $\Upsilon(4S)$ itself decays nearly instantaneously into a B^0 and $\overline{B}^0$. These mesons themselves decay, first one then the other, after traveling typically about a quarter of a millimeter. By carefully tracing the paths of the decay products, the locations of the two decays can be determined. The distance between these points is a measure of the time that elapsed between the two decays.

The "gold-plated" decay $B^0 \rightarrow J/\psi K_S$ will be the immediate goal of every CP violation experiment using B mesons because it occurs not so infrequently and is easy to spot. Moreover, the interpretation of the results will be straightforward.

CP violation measurements are conveniently displayed in a figure called the "unitarity triangle," which represents the CKM matrix and thus the Kobayashi-Maskawa model of CP violation (see the article by David Hitlin and Sheldon Stone in the Winter 1991 *Beam Line*, Vol. 21, No. 4). Three sides of the triangle and its three angles can all be measured independently. The CP measurements using B mesons determine the angles of the triangle. By measuring $B^0 \rightarrow J/\psi K_S$ the angle known as β can be determined. Information on the sides come from a variety of experiments including B decays not involving CP violation. The goal is to check the consistency of all the measurements by seeing whether the triangle constructed from the knowledge of its sides has angles that agree with those measured independently in CP violation experiments.

The Cornell electron-positron collider, CESR, has equal energies for electrons and positrons and so the detector there, CLEO, cannot measure CP violation in the same way as the SLAC and KEK experiments BaBar and BELLE. The CLEO collaboration and the ARGUS collaboration at DESY discovered much of what is known so far about B mesons. CESR will contribute to tests of CP violation by extending its measurements of the sides of the unitarity triangle and by another kind of CP-violation measurement that does not require knowing time differences.

The decays of neutral B mesons into two pions can determine the angle known as α. This measurement will take much longer because these decays are very infrequent. Moreover, the interpretation of these results will not be straightforward. The third angle γ is also very difficult to measure. There will be very intense competition to measure β over the next two years or so. This will likely be followed by more detailed and difficult measurements directed at the remaining angles.

The competition between experimental teams, some using nearly identical techniques, and others using utterly different approaches, will surely provide stringent checks on the results obtained. Naturally, each team is anxious to show that its approach to CP violation experiments is a good one. Will the clean events of the electron-positron annihilation prove more effective than the messier, but much more copious, events found in proton-antiproton collisions? Will the stationary target used at HERA prove a better geometry than the colliding beams at Fermilab?

Will all the groups reach the end? And will they all reach the same end—the same picture of CP violation? Only when the race is over can we expect to know where the finish line is. This issue of the *Beam Line* serves as a program for this competition, outlining the teams and their strategies. Handicapping the race is left to the readers.