Matter, Antimatter, and Why Are We Here?

CP violation may be the reason.

Photo by Fred Ullrich

Physicists long believed that fundamental physical processes would be identical in a world that was a mirror reflection of our own. But experiments in the 1950s showed that, for certain rare particle interactions, this mirror-image symmetry is broken. The broken symmetry in the behavior of matter and antimatter may explain the existence of the material universe.

by Meher Antia

Why do we exist? The age-old question has preoccupied philosophers for millennia—and physicists for decades. The philosophers ponder human purpose and destiny, but the physicists simply want to know why *anything*—people, rocks, stars —has a material composition. Physicists wonder why we are here, because, although there *is* a perfectly good reason for the entire universe to be no more than a seething mass of radiation, there appears to be no good reason whatsoever for there to be any matter at all.

When the universe exploded into being with the Big Bang, an equal number of particles and antiparticles sprang into existence. In close proximity, particles and antiparticles are extremely inhospitable: they immediately annihilate each other in a burst of light. Yet clearly the Big Bang produced something besides particle-for-particle annihilation. The universe now teems with matter, while physicists must laboriously create antimatter in huge particle accelerators. So when physicists ask why we exist, they are actually asking why, after the Big Bang, did more matter remain in the universe than antimatter? Paradoxically, one of the best ways to study such cosmic conundrums is to look closely at the innards of atoms, at the behavior of almost invisible subatomic particles at high energies. The answer to the physicist's "Why do we exist?" could lie with a seemingly insignificant particle, the *K* meson (or kaon), a tiny bit of matter that violates certain fundamental symmetries of nature.

The concept of symmetry is deeply ingrained in physics. Most symmetries are eminently sensible ones. For example, space has no intrinsic direction; there is a symmetry between left and right called parity (abbreviated P). If the length of a table is 20 inches measured from left to right, it does not suddenly become 21 inches when measured from right to left. Physicists long thought that all fundamental processes, from decaying particles to planetary motion, would look no different in a world that was mirror-reflected from our own.

Another symmetry, known as charge conjugation (abbreviated C), involved the behavior of matter and antimatter. If there existed a remote planet, just like ours but made

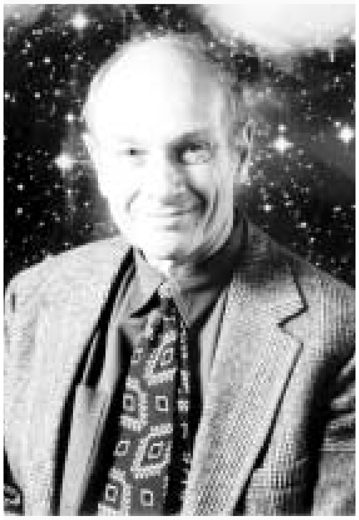

Photo by Reidar Hahn

In 1964, physicists James Cronin (above) and Val Fitch (below) discovered CP violation in rare decays of the K meson. In 1980, they won the Nobel Prize in physics for their discovery. Today, Cronin studies high-energy cosmic rays, whose collisions with atmospheric molecules create particles of antimatter. In fact, antimatter was discovered in cosmic-ray collisions.

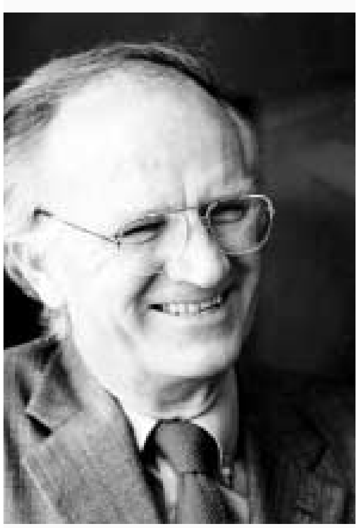

Photo by Bob Palmer

of antimatter, physicists believed there would be no way that people on the antimatter planet could know they were not made of the same stuff that we are. (Provided the two never came into physical contact and annihilated each other). If antiphysicists on the antiplanet performed the same experiments that physicists do to deduce the laws of nature, they would come up with laws identical to ours. Antiapples would still fall to antiearth, radioactive antielements would still decay, and antisugar would taste sweet. And the same would be true of a parity-reversed planet.

This happy state of affairs did not last long. By the late 1950s, experiments showed that certain rare interactions involving the weak force—the force responsible for radioactivity—violated both C and P. These violations came as a shock. They meant that if scientists living on a C- or P-reversed planet performed one of the C- or P-violating experiments, their results would look different from ours. There was indeed a way to distinguish matter from antimatter, and left from right.

But physicists recovered quickly from this unexpected blow. They found that, although nature did not always conserve C and P alone, it did appear to conserve both added together, in a symmetry called CP symmetry. Now it was no longer sufficient that a mirror-reflected planet alone could have the same laws of nature as we do. The planet also had to be made of antimatter.

Good-bye CP symmetry

In 1964, an experiment by physicists James Cronin and Val Fitch caused an uproar. Cronin and Fitch found that certain rare decays of the K meson violated CP. The neutral kaon, before decaying into particles called pions, exists in a strange schizophrenic state. Not quite able to make up its mind whether to be a particle or an antiparticle, it constantly switches between the two, existing first as the particle, then the antiparticle, then back to the particle and so on. In fact, its indecision is more complicated; it does the switching in two different ways. One type of kaon-antikaon mixture looks the same in a mirror; it is a symmetric state. The other is an antisymmetric state; its mirror image does not look the same. The symmetric state is supposed to decay into an even number of pions, the antisymmetric into an odd number,

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Fermilab Photo

In a universe made of matter, physicists must use powerful particle accelerators to create antimatter. When it is operating Fermilab's Antiproton Source, shown here, holds the world's largest supply of antimatter in the form of antiproton beams circling in a magnetic field.

CP violation

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so that the symmetry is preserved before and after the decay. Most of the time, the kaons behave themselves and decay just as they should, into two and three pions respectively. However, Cronin and Fitch found that one in every few hundred antisymmetric kaons decayed into two pions, not three. This seemingly innocuous result destroyed the belief in CP symmetry.

For years, physicists tried to find alternative explanations for the observed decay of the kaon, but none stood up to experiment. Eventually, they had no alternative but to abandon CP symmetry. This was disturbing, in a way that is perhaps difficult to understand, because everyday life is so riddled with asymmetries that it might seem that symmetries are the exception rather than the rule. For example, a wine glass can easily shatter into a thousand pieces, but a thousand pieces of broken glass never spontaneously reassemble into a wine glass. The letters of the alphabet look nonsensical when reflected; the real alphabet is easily distinguishable from its mirror image.

But neither a shattering wine glass nor the alphabet is governed by any *fundamental* law. A glass breaks but does not reassemble because it starts out in a very special condition; its atoms are arranged in an orderly form that took work to create. Broken, its atoms assume one of billions upon billions of possible disordered arrangements, a situation overwhelmingly more likely than the wineglass's ordered arrangement. In the same way, the alphabet and the gibberish in the mirror only seem distinct to us because we start out with a preconceived notion of how the letters look. To a person familiar only with Chinese characters, say, the alphabet and its mirror image look equally meaningless.

A decaying kaon, however, is described by truly fundamental laws of nature. It should be truly indifferent to whether it decays in this world or in a CP-reversed world. The fact that it distinguishes between them meant that nature had cavalierly chosen one set of laws over another set of equally plausible ones. This seemingly arbitrary behavior shook physicists and forced them to reconsider the intricacies of the physical universe.

Photo by Reidar Hahn

Rutgers University graduate student Eva Halkiadakis works in the KTeV control room.

Kaons and the early universe

As physicists recovered from the shock of the Cronin and Fitch experiment, they incorporated the mysterious behavior of the kaon into the grand scheme of particle behavior as expressed in the Standard Model. It allows for CP violation to occur if more than two sets, or generations, of quarks exist. And indeed, physicists have discovered three generations of quarks: the up and down quarks, the strange and charm quarks and the top and bottom quarks. University of Chicago physicist Bruce Winstein likens the three generations of quarks to the presence of three sets of dance partners

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rather than two. With only four dancers, if one couple decides to pair up for a dance, the other couple has no choice but to dance with each other. With three couples, however, even if one couple has paired up, the other four dancers still have some choice in partners.

In the same way, three generations of quarks have a freedom to explore choices of combinations that would not be open to them if there were only two generations. So as the kaon is vacillat-ing between being a particle and an antiparticle, the quarks within are busy exploiting their freedom to explore CP-violating options that would not otherwise be open to them.

In the Standard Model explanation, the antisymmetric kaon-antikaon mixture decayed symmetrically into two pions because it was somehow contaminated with a little bit of the symmetric mixture. The CP violation did not occur in the decay process itself, but rather had its roots in the mixing of the particle and antiparticle. CP violation due to such mixing was termed indirect CP violation. However, the Standard Model also predicts direct CP violation, a result of the actual decay of the kaon. If direct CP violation exists, it means there is a fundamental difference in the way the laws of physics treat matter and antimatter.

And therein lies the link to the excess of matter in the universe today. If there were no CP violation, the laws of the universe would have no way to distinguish the decay process of the kaon or antikaon. But at some point soon after the Big Bang when particles were scooting all over the place decaying, combining, creating new particles and annihilating others, there was an excess of matter over antimatter. The asymmetry between kaons and antikaons could very well be related to this early excess in the universe.

So the answer to the physicist's "Why do we exist?" may possibly be "Because of CP violation." As a result, physicists naturally have a tremendous interest in trying to detect and measure direct CP violation. Is the effect big enough to account for all the matter in the universe? Does the Standard Model correctly predict the magnitude of the effect; and, if not, could CP violation lead to physics beyond the Standard Model? In search of answers to these questions, accelerator laboratories around the world have poked and prodded the kaon, but the effect is so incredibly tiny—a thousand times smaller than the already minuscule indirect CP violation—that all experiments to date have come up empty handed.

The latest effort to measure direct CP violation at Fermilab, by the KTeV collaboration, completed the first round of data-taking in September 1997. Unfortunately, simply measuring the decay rates of the kaon and antikaon is out of the question because the rates are so similar that it would require billions of events to detect any difference. Instead, the experiment relates CP violation to the different rates of decay of the antisymmetric mixture of the kaon: into two neutral pions or into two charged pions, a ratio that is difficult but not impossible to measure.

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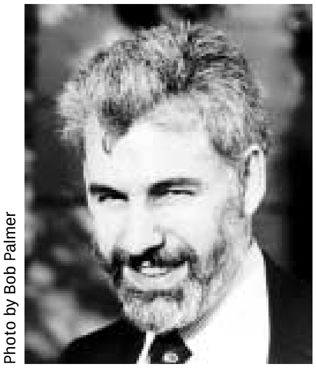

Photo by Bob Palmer

University of Chicago physicist Bruce Winstein, cospokesman of Fermilab's KTeV experiment, whose goal is to study CP violation and kaon decays with unprecedented precision.

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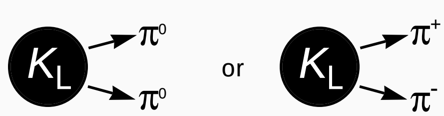
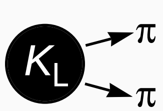
Indirect and Direct CP Violation in Kaon Decay



Symmetric neutral kaons , called K_1, decay into two pions. Antisymmetric neutral kaons, K_2, usually decay into three pions. However, because each of the two kaon states is "contaminated" with a tiny amount of the other, once in about 500 times, the state that is mostly K_2 (called K-long or K_L), decays into only two pions, violating CP symmetry, in a phenomenon called indirect CP violation.



(CP violating)

When this happens, the two pions may be neutral (π^0) or electrically charged (π^+, π^-). Fermilab's KTeV experiment measures the ratio of these two kinds of neutral kaon decays with extreme precision. Experimenters combine these measurements with measurements of CP-conserving two-pion decays for short-lived kaons (K_S). If experimenters find that the ratio of these decays does not equal 1, that would be evidence of direct CP violation, in which the decay itself violates CP symmetry.

CP violation

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In the KTeV experiment, a proton beam veers off from the main accelerator ring and smashes into a fixed beryllium target. The collision spews out kaons, along with other elementary particles. About 20 million kaons are generated every second, explains Bob Hsiung, a Fermilab physicist. Of the 20 million, about one million decay in the experiment. Of those, only about a thousand decays per second are recorded onto tape to be analyzed later. Going from a million events to just a thousand means that even before the data are stored, they are painstakingly sorted so that only events that yield potentially useful information make it all the way to storage. Much of the 200-meter-long experiment is dedicated to expelling unwanted particles. For the first 100 meters, collimators create two parallel beams, and magnets sweep away all charged particles, leaving only neutral ones behind. Veto detectors identify and discard the uninteresting CP-conserving decays of the kaon.

The neutral pions decay to photons, which zip all the way through the vacuum decay region, magnetic fields and scintillators until they reach a calorimeter, a huge array of cesium iodide crystals attached to 3,100 photo-multiplier tubes. The photons deposit their energy in the crystals and are duly recorded. The charged pions from probable CP-violating decays are recorded, after wire chambers and scintillators mark out their trajectories and magnets determine their momenta. Again, if the instruments deem them interesting enough, they are stored for future scrutiny.

The computational power to make instant decisions on which events to veto and which to keep makes experiments of this sensitivity possible. The number of raw events is staggering. Even the small fraction of data that eventually gets stored uses 40 million million bytes. While it is impossible to analyze every event, there is also a danger in making detectors that trigger only on events predicted

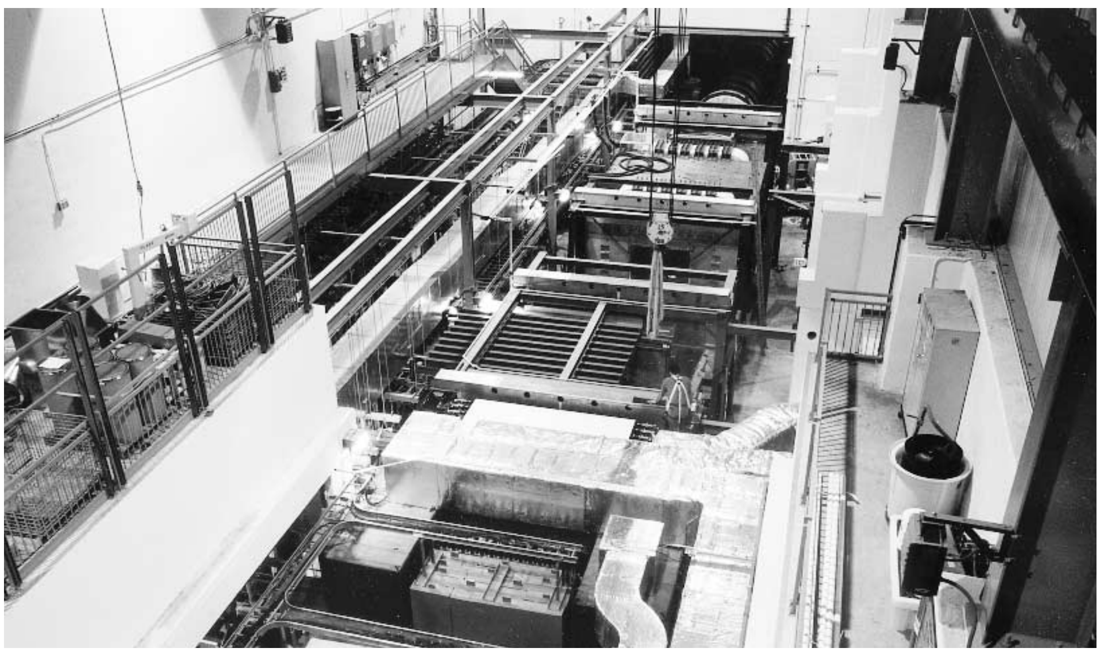
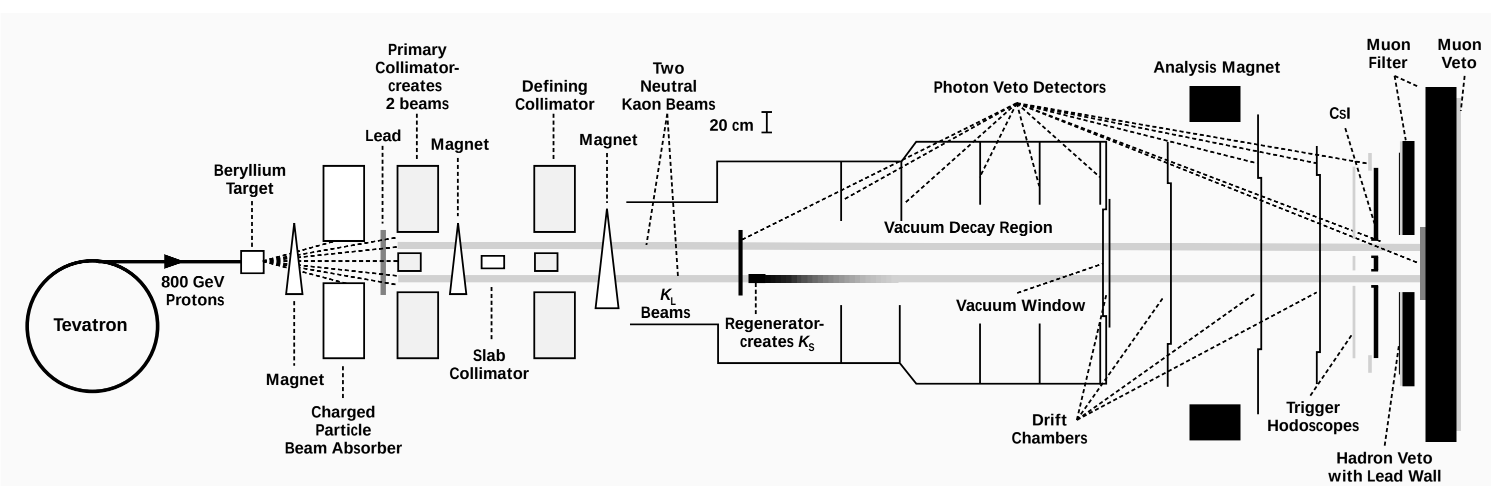
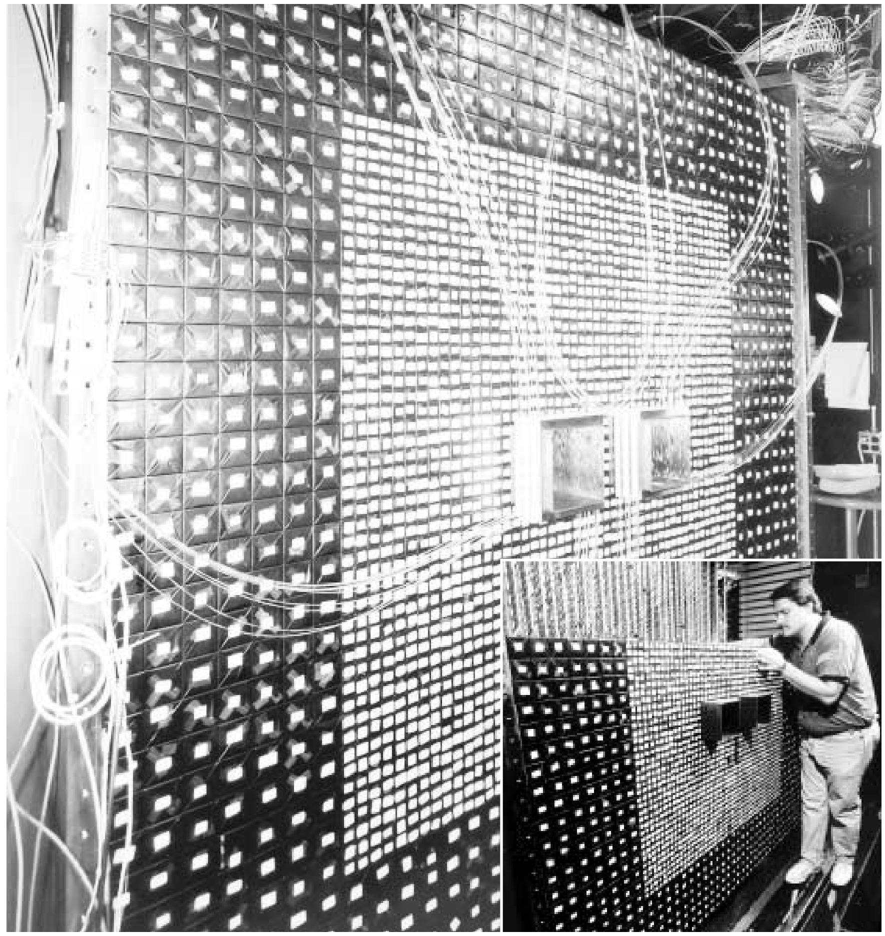


Photo by Reidar Hahn

The KTeV experiment starts with a beam of protons from the Tevatron. Magnets and collimators create parallel beams of neutral kaons, some of which decay in the experiment. Detectors measure the decay products, "vetoing" uninteresting CP-conserving decays and recording the ones that violate CP symmetry.



KTeV's cesium iodide calorimeter just after completion in August, 1996. (Inset: Earlier, University of Chicago physicist Aaron Roodman stacked a crystal in the calorimeter.) The calorimeter detects the energy of photons from the decay of pions produced in neutral kaon decays.



Photos by Reidar Hahn

Fermilab physicist Herman White, with photon veto counters for KTeV, before their installation in the experiment's beamline. The veto counters reject particles at very large angles to the beam line, to rule out false decay signals.

by the Standard Model. Something completely new could easily be missed, says Bob Tschirhart of the KTeV collaboration. There is a constant struggle to strike a balance between making triggers that are lenient enough to admit quirky yet meaningful data, and strict enough to discard junk.

KTeV has only begun combing through the mountains of data. Although there is as yet no hint of direct CP violation, the collaborators have discovered an extremely rare kaon decay into a charged pion pair and an electron-positron pair. This rare decay mode will offer a new window on CP violation.

What will come out of KTeVs roomfuls of sophisticated equipment and the masses of data will not be merely a mathematical jumble of numbers and formulas, but a simple concept that could shed light on why we're all here in the first place. ■

Meher Antia is a freelance science writer.

FermiNews Essay Contest

Champagne's on ice—start writing!

Deadline May 5, 1998

As announced in the last issue, *FermiNews* will award a bottle of Dom Pérignon as the first prize, and Congressman Verh Ehlers will award an American flag flown over the U.S. Capitol as the second prize for the best essays of 500 words or less to address the question "Why should the U.S. remain a world leader in high-energy physics?"

Submit essays by e-mail (ferminews@fnal.gov); snail mail (*FermiNews* , MS 206, Fermilab, P.O. Box 500, Batavia, IL 60510); fax (630-840-8780); or in person (Wilson Hall, 1 East.)

For more information, call the Fermilab Office of Public Affairs at 630-840-3351, or see the Essay Contest page on the World Wide Web: http://www.fnal.gov/pub/essay/contest.html