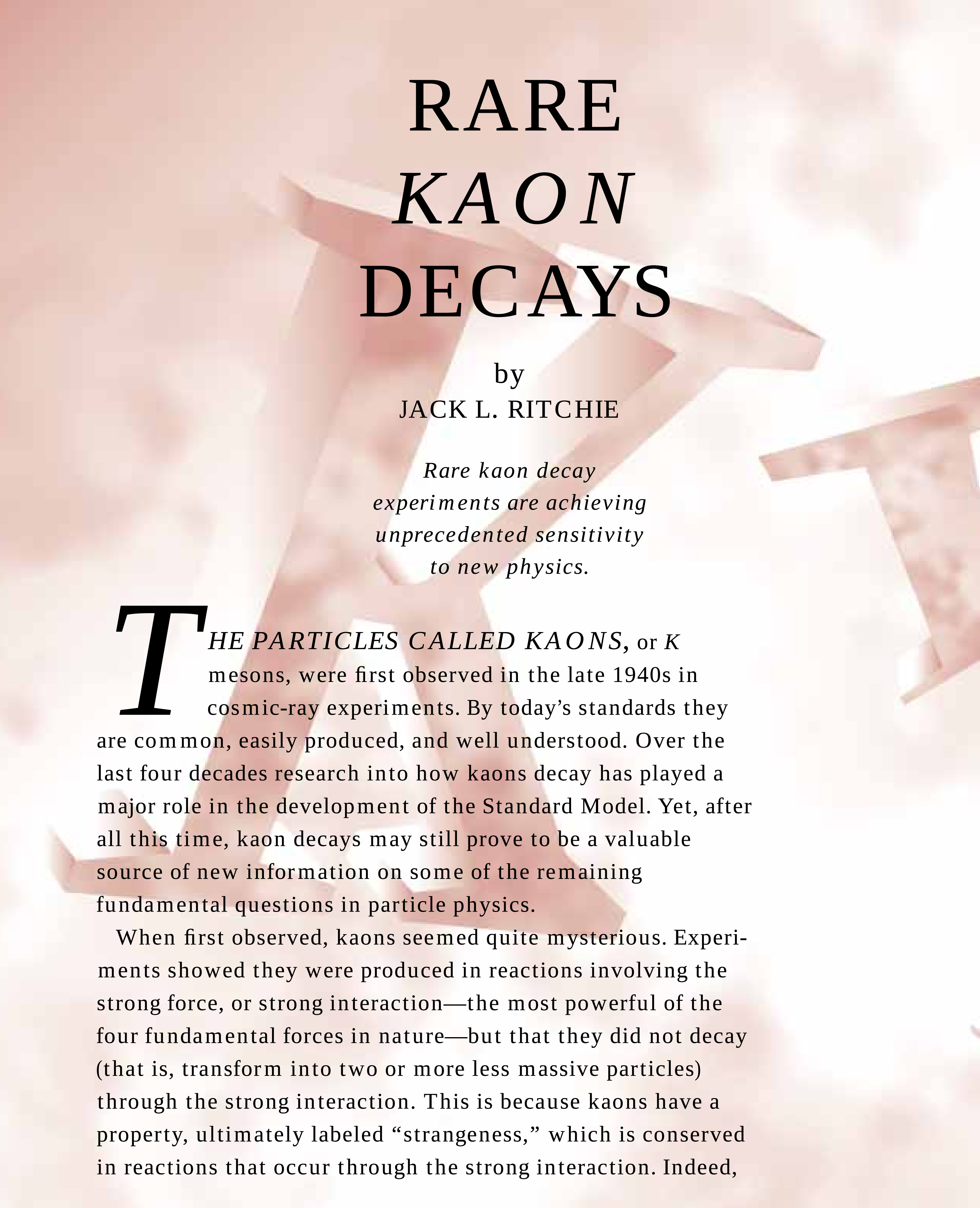


RARE *KAON* DECAYS

by
JACK L. RITCHIE

Rare kaon decay experiments are achieving unprecedented sensitivity to new physics.

THE PARTICLES CALLED KAONS, or *K* mesons, were first observed in the late 1940s in cosmic-ray experiments. By today's standards they are common, easily produced, and well understood. Over the last four decades research into how kaons decay has played a major role in the development of the Standard Model. Yet, after all this time, kaon decays may still prove to be a valuable source of new information on some of the remaining fundamental questions in particle physics.

When first observed, kaons seemed quite mysterious. Experiments showed they were produced in reactions involving the strong force, or strong interaction—the most powerful of the four fundamental forces in nature—but that they did not decay (that is, transform into two or more less massive particles) through the strong interaction. This is because kaons have a property, ultimately labeled "strangeness," which is conserved in reactions that occur through the strong interaction. Indeed, the only fundamental force that does not conserve strangeness is the weak interaction—the force responsible for nuclear beta decay. Therefore, kaons can only decay in reactions occurring through the weak interaction. This fact has several important consequences, one being that kaons are long-lived compared to most other subatomic particles. One type of kaon, the K_L^0 (called the "*K*-long"), survives without decaying an average of 52 nanoseconds (that is, 52×10^{-9} seconds). While that may seem like an infinitesimal amount of time, on the particle physics scale it is extremely long. Of all the particles that are not absolutely stable, only the neutron and muon are longer lived than the K_L^0.

Today we know that all the particles affected by the strong interaction (particles that we collectively call "hadrons") are made up of quarks. There are six types, or "flavors," of quarks: down (*d*), up (*u*), strange (*s*), charm (*c*), bottom (*b*), and top (*t*). Kaons, it turns out, are particles consisting of a strange quark and an up or down antiquark (or alternatively, a strange antiquark and an up or down quark), which are bound together by the strong force. The resulting kaons can have one unit of electric charge, or they can be neutral. Both charged and neutral kaons have been important in the history of particle physics and may yet be the source of new discoveries.

Kaons have some interesting properties because of the way the weak interaction works. Today we understand the weak interaction in terms of the electroweak theory of Sheldon Glashow, Abdus Salam, and Steven Weinberg, which successfully explained electromagnetism and the weak interaction as different manifestations of the same interaction. A large body of experimental evidence supports the validity of the electroweak theory, and when it is taken together with quantum chromodynamics—the modern theory of the strong interaction—we call the combination the Standard Model. However, in the 1950s and early 1960s when the early kaon decay experiments were performed, the weak interaction was still not understood. In this brief article, it is not possible to review the whole history of kaon physics or to describe all the instances where studies of kaons made decisive contributions to our current understanding. Let us consider the single instance of *CP* violation to provide a hint of the importance of kaon decays.

Conservation laws are among the foundations of physics. Much of the history of particle physics has been the struggle to find and to understand the underlying conservation laws that govern the behavior of subatomic particles. Prior to 1964, it was believed that all fundamental interactions conserved the "charge conjugation-parity," abbreviated *CP*, of a physical system. In 1964 a kaon decay experiment discovered otherwise. That experiment found that a particular type of kaon decay that should have been forbidden by the principle of *CP* conservation actually takes place, albeit infrequently. The experiment was performed by James Christenson, James Cronin, Val Fitch, and Rene Turlay (those were the days when particle physics experiments could be carried out by a small team) at the Brookhaven National Laboratory, using an accelerator called the Alternating Gradient Synchrotron (AGS). Specifically, the experiment observed the decay $K_L^0 \to \pi^+\pi^-$. The π^+ and π^- are pions, the least massive of the hadrons. The frequency with which this decay occurs compared to all K_L^0 decays, a quantity called the branching fraction, is only 2×10^{-3}—meaning that only two in 1000 K_L^0's decay this way. Since this discovery, trying to understand the reason for the *CP* violation seen in the weak interaction has been one of the principal problems in particle physics. It remains so today, as ever more sophisticated tools are brought to bear. The PEP-II *B*-factory now under construction at Stanford Linear Accelerator Center has as its goal the study of *CP* violation in the decays of *B* mesons. The *B* mesons are particles which are similar to the *K* mesons, except that the more massive bottom *b* quark takes the place of the strange *s* quark (see box on next page).

PRESENT KAON decay experiments are active in two general areas: (*i*) precision studies of *CP* violation that usually focus on ever-better measurements of the K_L^0 decays into two pions, and (*ii*) searches for "rare" kaon decays. In this article, the focus will be on the second category. Decays are rare when they are so uncommon that they are hard to observe. Over time, and with improvements in accelerators and detectors, our standard of rarity changes. The decay $K_L^0 \to \pi^+\pi^-$ with its branching fraction of 2×10^{-3} was once rare. Now an experiment sensitive to decays a billion times more rare is in progress at the AGS. That

CP VIOLATION

SYMMETRIES IN PHYSICS refer to the fact that when certain types of changes are made, often called transformations, the behavior of a system is not altered. These transformations can be of two types: continuous or discrete. An atomic clock keeps the same time in Chicago and New York. The symmetry in this instance is that in different places the same laws of physics apply. Thus, the transformation of moving the clock from Chicago to New York, or indeed anywhere in between, does not alter its behavior. This transformation would be called continuous, since the distance the clock is moved can take on any value.

A discrete transformation makes a change that cannot take on a continuous range of values. There are three discrete transformations of special importance: charge conjugation, parity (also called space inversion), and time reversal. Charge conjugation (*C*) transforms all the particles in a system into their associated antiparticles and all the antiparticles into their associated particles. Parity (*P*) reflects each point of a system through the origin of coordinates; thus a particle at position (x, y, z) is transformed to the position ($-x$, $-y$, $-z$). Time reversal (*T*) reverses the direction of time.

All processes involving both the strong and electromagnetic interactions are unaffected by *C*, *P*, and *T* transformations. The weak interaction was found in the late 1950s to violate *P*; that is, weak interaction processes are affected by a parity transformation. The belief at the time was that a combination of simultaneous *C* and *P* transformations restored the symmetry. So it was surprising in 1964 when an experiment showed that *CP* was not an exact symmetry of the weak interaction.

A very fundamental symmetry of all interactions is that any physical system will behave the same if it simultaneously experiences all three of these discrete transformations. This is called the *CPT* theorem. In addition to having a strong theoretical basis, it has also been tested experimentally to great accuracy. Conservation of *CPT*, but violation of *CP*, means that *T* alone cannot be an exact symmetry of the weak interaction. Thus, even on the most microscopic scale possible—the interactions of elementary particles—there is a difference between going forward and backward in time.

CP violation is now recognized as an important ingredient in the evolution of the universe. Immediately after the Big Bang the universe must have consisted of equal quantities of matter and antimatter. Over time it evolved toward the situation we see today, namely an overwhelming excess of matter over antimatter. Andrei Sakharov pointed out in 1967 that *CP* violation was necessary for the matter dominance of the universe to come about. This is one of many instances where particle physics has cosmological implications. Indeed, many theoretical physicists believe that the amount of *CP* violation we know about so far is insufficient to account fully for the matter dominance in the universe. Clearly, understanding the origin of *CP* violation is one of the most basic and far-reaching problems in particle physics.

It is possible to assign a definite value to the *CP* of some particles, called *CP* eigenstates. Also, some combinations of particles have a definite value of *CP.* For example, consider two charged pions π^+ and π^-. Pions are *P* eigenstates with parity –1. The *C* transformation changes the π^+ into a π^- and the π^- into a π^+, so the full *CP* transformation returns a state with the same particles we started with, but with two factors of –1, which we multiply together to get +1. That is, the *CP* of the two-pion state is +1. (For simplicity we have ignored the orbital angular momentum of the pions, but for this discussion no harm is done.) So, if *CP* is conserved, we should never see a particle with *CP* of –1 decay into a π^+ and π^-. This is why the observation in 1964 of the decay of long-lived neutral kaons into two pions was recognized as *CP* violation. Such *CP* violation can occur in two ways: i) the parent kaon can be a quantum mechanical mixture of different *CP* eigenstates because of a *CP*-violating interaction, or ii) a *CP* eigenstate may decay directly to a state of different *CP*. The *CP* violation in the $K^0_L \rightarrow \pi^+\pi^-$ decay is mostly of the first type, but may also include a small contribution from the second, which is called “direct” *CP* violation. The amount of *CP* violation of the first type is measured in terms of a quantity usually denoted ε, which is a complex number whose magnitude is about 2×10^{-3}. The amount of direct *CP* violation, expressed in terms of an analogous parameter ε', is known to be at least five hundred times smaller.

The source of the *CP* violation observed in kaon decays has not yet been established. A number of theories exist. According to some of them, direct *CP* violation should not occur. Within the Standard Model, direct *CP* violation is expected, although it may be very small in kaon decays. In the last decade, a tremendous amount of effort has gone into experiments trying to measure ε'. A non-zero value would establish that direct *CP* violation occurs, thereby eliminating an entire class of theories, and it would be a step toward establishing the Standard Model picture. Thus far the experimental results are inconclusive, but new experiments are being prepared at CERN and Fermilab that should be sensitive to values of ε' as small as one part in 10^4 of ε. Also, a very elegant approach, described in the following article, is planned for an experiment in Frascati, Italy.

In addition to these ever-more precise studies of the two-pion decays of neutral kaons, some rare kaon decays may help provide an answer. For example, the decay $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ would be an almost perfect probe of direct *CP* violation in kaon decays. Unfortunately, the branching fraction is expected to be very small, roughly in the range between 1×10^{-11} and 1×10^{-10}. It will be years before we know whether making a measurement is even possible, since enormous technical problems must be overcome. Some current experiments are searching for related decays in which charged leptons take the place of the neutrinos. Finally, the tremendous excitement surrounding the potential for studying decays of *B* mesons, where the effects of *CP* violation should be much more striking, has motivated a number of new initiatives, including the construction of the PEP-II *B*-factory and its associated detector BaBar at SLAC.

experiment is searching for the violation of another conservation law called lepton-flavor conservation.

Leptons are particles that are believed to be as fundamental as quarks. That is, they are part of the minimal set of particles out of which the entire Universe is constructed. The electron, familiar as one of the building blocks of atoms, is a lepton. The leptons differ from the quarks in a couple of key respects. For one thing, they are not affected by the strong interaction. For another, they have integer values of electric charge (either –1 or 0), while the quarks have fractional charges (either +2/3 or –1/3). The leptons come in three types: electron, muon, and tau. For each type, there is a charged lepton and a neutral lepton, called a neutrino. Hence, the electron e^- has a partner neutrino ν_e. Likewise the muon μ^- and tau lepton τ^- have partners ν_μ and ν_τ, respectively.

A mystery is that quarks of one flavor can decay into quarks of another flavor via the weak interaction—as long as requirements such as electric charge, energy, and momentum conservation are satisfied—resulting in a net change of quark flavor, but leptons of one type never are seen to decay or to transmute in a way that results in a net change of lepton-type. To be more precise, a quantum number is associated with each type of lepton and its sum is conserved in all interactions. For instance, a muon decays by emitting an electron, a muon-type neutrino, and an electron-type antineutrino ($\mu^- \to e^- \nu_\mu \bar{\nu}_e$). The number of muon-type particles is one before the decay, and after the decay it is still one. The number of electron-type particles is zero before the decay, and it is also zero afterwards, since the electron-type antineutrino cancels with the electron. This type of additive conservation of the number of each type of lepton is sometimes called lepton-flavor conservation (see box on the right).

Lepton-flavor violation could show itself in kaon decays if the decay mode $K_L^0 \to \mu^\pm e^\mp$ is ever observed. The notation $\mu^\pm e^\mp$ means the K_L^0 may decay into either $\mu^+ e^-$ or $\mu^- e^+$, since both combinations of electric charge are possible. A simpler notation is to ignore the charges altogether, and use $K_L^0 \to \mu e$ to represent both $K_L^0 \to \mu^+ e^-$ and $K_L^0 \to \mu^- e^+$. Notice this decay does not include any neutrinos. If neutrinos (or antineutrinos) were present after the decay to cancel the additive separate lepton numbers of the electron and muon, the decay would not violate anything. Searching for such a decay mode of the K_L^0 is an interesting gamble. There is no convincing theoretical prediction to suggest $K_L^0 \to \mu e$ should occur with a branching fraction large enough to observe in today's experiments. On the other hand, if an experiment observes $K_L^0 \to \mu e$, then it will be a breakthrough of great importance. It is a situation reminiscent of that in 1964 when there was no particular reason to expect to observe *CP* violation. It is fortunate that someone looked anyway.

A NATURAL QUESTION is, however, why kaons? Of all the particles in the subatomic zoo, why search for lepton-flavor violation in kaon decays? In fact, such searches are not limited to kaon decays. Some very sensitive

LEPTON-FLAVOR VIOLATION

NO EXPERIMENT has ever observed a process that failed to conserve additively the quantum number associated with each type of lepton. The underlying basis for this conservation law remains mysterious. There are other additive conservation laws that are known to hold in particle interactions. Some, such as the conservation of electric charge, are understood on fundamental grounds.

In physics there is a deep relationship between symmetry principles and conservations laws. An additive conservation law can hold only if there exists a particular type of symmetry principle, called a global phase invariance. In the case of electric charge conservation, the global phase invariance arises from a symmetry property of electromagnetism—in particular, the property known as gauge invariance. Some readers may have encountered gauge invariance, perhaps in a physics course, in the guise of the electric field not changing when a constant is added to the electric potential. (A similar property holds for the magnetic field for certain changes of the vector potential.) When electromagnetism is carried into the quantum mechanical world, this gauge invariance determines the properties of photons.

In the case of lepton-flavor conservation, the additive conservation laws imply the existence of global phase invariances. But unlike the case of charge conservation, we know of no underlying gauge invariances to cause them. Thus, most theoretical physicists expect these conservation laws to be inexact—that is, for violations to occur, but at levels too small to have been seen so far. This is the general motivation for testing these rules to the most stringent possible levels.

Many recent theoretical speculations attempt to extend the Standard Model and to address some of its perceived shortcomings. These theories go by names such as "supersymmetry" and "technicolor." These are topics well outside the scope of this article, but it is interesting that these theories along with many others predict that lepton-flavor conservation is not exact.

Brookhaven National Laboratory

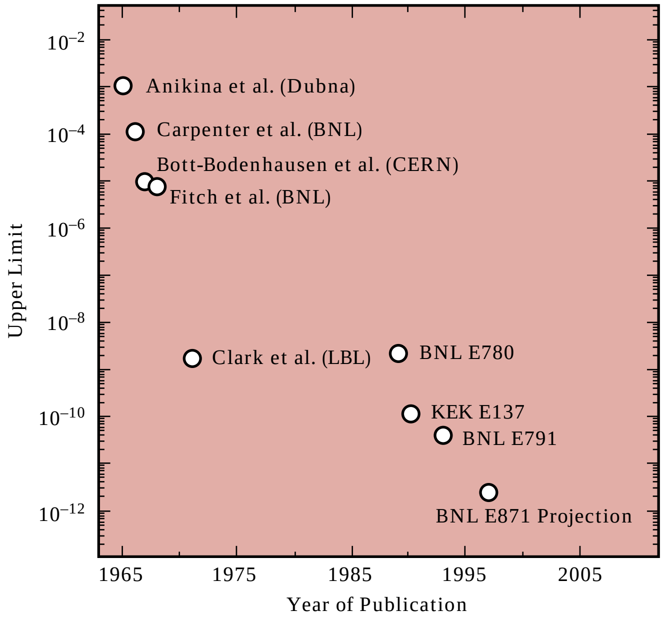
Brookhaven National Laboratory on Long Island, New York, is the home of the Alternating Gradient Synchrotron, a proton accelerator first operated in 1960. While the energies of AGS beams are low compared to other proton accelerators in use at Fermilab in Illinois and CERN in Geneva, Switzerland, for high-energy physics experiments, upgrades over the last three decades have increased the intensity of available beams more than a thousandfold, allowing the AGS to continue forefront research. The AGS currently provides the highest intensity multi-GeV hadron beams in the world, making possible an ambitious program of rare kaon decay experiments. The recent commissioning of the Booster, which feeds bunches of protons into the AGS, has increased the available proton flux to a time-averaged value of about 3 microamperes. Other Brookhaven facilities are also visible in the photograph, including the Relativistic Heavy Ion Collider (RHIC) under construction.

experiments have been and continue to be performed with muons, searching for lepton-flavor violating decays such as $\mu^- \to e^-e^+e^-$ or $\mu^- \to e^-\gamma$ (the symbol γ represents a photon). Indeed, virtually every experiment with a large data sample takes the time to look for processes that would be lepton-flavor violating. For instance, experiments at electron-positron colliders have tried to find decays such as $B \to \mu e$, $B \to \mu\tau$, $\tau \to \mu\gamma$, $\tau \to e\gamma$, $Z \to \mu e$, $Z \to \tau e$, and many others. But indeed there are reasons why kaon decays are a particularly promising place to look.

One possible advantage of kaons (over muons, tau leptons, or the Z, for example) has to do with the generation structure of the quark and lepton families. Just as with the leptons, the quarks fall into a natural grouping of three pairs. The up and down quarks along with the electron and electron-type neutrino make up the first generation. They are the lowest mass members of the hierarchy. The charm and strange quarks along with the muon and muon-type neutrino make up another generation, intermediate in mass. Finally, the top and bottom quarks and the tau and tau-type neutrino comprise a third generation, with the highest masses. Some theories exploit this apparent hierarchy. A common result of such theories is that reactions which involve a change of generation number are either forbidden or suppressed. Suppose we assign a "generation number" of 1 to members of the first generation (and –1 to its antiparticles), of 2 to the members of the second, and 3 to those of the third generation. Then a muon decay such as $\mu^- \to e^-\gamma$ involves a net generation number change of one unit. However, the kaon decay $K_L^0 \to \mu e$ involves no net change in generation number. Thus, if such theories have any validity, kaon decays may be a more promising place to observe lepton-flavor violation.

Other advantages of kaons (over B mesons, tau leptons, or the Z, for instance) are the relative ease with which they can be produced (making it possible to produce them in large numbers) and their long lifetimes, which make it possible to form kaon beams. The result is that kaon decay experiments today can observe decays whose branching fractions are about a million times smaller than is possible with B's, τ's, or Z's. While it is dangerous to generalize, this typically means that kaon decay searches have a greater sensitivity to various potential sources of lepton-flavor violation.

The power of rare kaon decay experiments to uncover new physical processes can be put into quantitative terms by making a simple observation. The force responsible for a decay such as $K_L^0 \to \mu e$ would be carried by a particle, just as the electromagnetic force is carried by photons and the weak force by W and



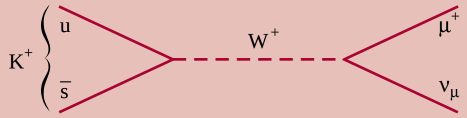
When an experiment searches for a decay such as $K^0_L \to \mu e$ without finding it, the result of the experiment is an "upper limit" on the branching fraction—-that is, the largest value of the branching fraction consistent with the experiment not observing the decay. The graph above shows the history of upper limits on $K^0_L \to \mu e$. The experiments divide naturally into two groups separated by a hiatus of over a decade, during which improvements in both accelerator and detector technology made large gains in sensitivity possible.

Z bosons. For the branching fraction to be as small as we know it must be from experiment, the mass of that particle must be extremely large. Indeed, based on the sensitivity of current experiments, the particle would have a mass of at least 90,000 GeV (or 90 TeV since 1 TeV = 1000 GeV). This mass is so large that it is impossible to produce such particles in collisions at any existing, or foreseeable, accelerator. Consequently, one can think of rare kaon decay experiments as probing the highest energy scales possible, even though the method is somewhat indirect (see box on the left).

PROGRESS IN RARE KAON decay experiments has been rapid in the last decade. It is the result of two simultaneous developments. The first is the availability of much higher intensity kaon beams than in the past, owing to improvements in accelerators. The second is progress in particle detector technologies, particularly those associated with high-speed data handling. The experiments that have achieved the highest sensitivity to rare kaon decays have been performed at the AGS facility at Brookhaven. This is because the AGS can provide the most kaons per unit time to experiments of any accelerator in the world. The AGS accelerates protons to an energy of typically 24 GeV. The protons are then extracted from the circular accelerator and are

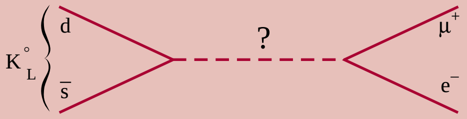
MASS REACH

PARTICLES INTERACT through the electromagnetic interaction by exchanging a photon. The photon is a boson, because its spin has an integer value (one). Particles interact through the weak interaction by exchanging either a *W* or *Z* boson. When such interactions occur, the bosons which are exchanged are "virtual." A virtual particle can very briefly exist with a mass which is larger than that allowed by energy conservation because of the principles of quantum mechanics. As an example, a charged kaon (K^+) can decay to a muon and neutrino through the exchange of a virtual *W* boson, as illustrated below.



The mass of a *W* boson is about 80 GeV, while the K^+ mass is only about 0.5 GeV. The *W* boson can only appear as a virtual particle, since a real *W* would violate energy conservation.

The first indication of the existence of the *W* boson came with the observation of nuclear beta decay, many years before the correct theory of the weak interaction was developed and even more years before the *W* was observed as a real particle in very high energy proton-antiproton collisions at CERN in Geneva, Switzerland. A similar situation would exist if a rare kaon decay such as $K^0_L \to \mu e$ is ever observed. It would mean that some virtual boson, thus far undiscovered, was being exchanged in the decay process, for example as illustrated below. We can relate the branching fraction for this decay to the mass of the undiscovered boson, subject to a few reasonable assumptions. When we do this, the result is that the current upper bound on the $K^0_L \to \mu e$ branching fraction of 3.3×10^{-11} implies the mass of the boson would have to be 90 TeV (1 TeV = 1000 GeV) or more. Thus, we can see how a search for rare decays is tantamount to a search for very massive *virtual* particles.



Brookhaven National Laboratory

An experiment designated E871 is in progress at Brookhaven National Laboratory in New York to search for $K_L^0 \to \mu e$ with sensitivity to a branching fraction as small as 10^{-12}. The detector is over 30 meters long, much of it surrounded closely by shielding to protect personnel against the radiation generated by the high-intensity beam. The part of the apparatus seen here, well removed from the beam region, measures the trajectories of the muons from kaon decays. E871 builds on the experience of a previous experiment, E791, which achieved the greatest sensitivity to rare kaon decays of any experiment to date.

directed onto external targets, which are the actual sources of the kaons. With recent upgrades, the AGS can now extract close to 6×10^{13} protons every three seconds.

Underway at the AGS are two experiments searching for rare charged kaon (K^+) decays. One of these focuses on lepton-flavor violation and the other seeks to measure an important Standard Model parameter which is related to how the top quark interacts with other quarks. A third experiment searches for rare neutral (K_L^0) decays, including $K_L^0 \to \mu e$. An earlier version of the K_L^0 experiment reached the best sensitivity ever obtained in a kaon decay experiment. No $K_L^0 \to \mu e$ decays were observed, but the experiment established that the branching fraction must be less than 3.3×10^{-11}. The newer version of the experiment will improve upon the previous sensitivity by an order of magnitude or more. The progress in these searches is shown as a function of time in the figure on the preceding page.

Rare kaon decay experiments are also underway at other laboratories. These experiments focus on rare kaon decays which can provide more insight into the phenomenon of *CP* violation. Such decays typically include a neutral pion (π^0) as one of the daughter particles. Neutrals pions in turn decay very quickly into two photons, so high-quality photon detection is essential in these experiments. The higher Fermilab energy (800 GeV for extracted protons) is an advantage for the detection of photons, and currently the most promising experiment in this area is being carried out at the Fermilab Tevatron facility. In the future, after construction on the Fermilab Main Injector is completed, this experiment should be able to make further improvements because of the availablity of a higher intensity kaon beam. An experiment with the same focus is in progress at the KEK Proton Synchrotron (PS) in Japan. A rare kaon decay program has been underway there for many years, but the experiments have thus far suffered from the rather low intensity beams available there. However, planning is underway in Japan for a new 50 GeV proton accelerator which could, if built, support state-of-the-art rare kaon decay experiments.

Progress in particle physics depends on experimentation on multiple fronts. Sometimes it is said that there are three experimental frontiers: the high energy frontier, the high precision frontier, and the high sensitivity frontier. Most of the public attention goes to the high energy frontier, because it involves building big and expensive new machines. Some truly basic questions in particle physics require this approach. Even so, experiments at modest energies which emphasize high precision or high sensitivity, as in the case of rare kaon decay experiments, may prove to be the next source of an important new discovery. The potential is surely there. ○

A Summary of Active Rare *K* Decay Experiments

Designation	Laboratory	Primary Decay Mode	Primary Physics Motivation
E787	Brookhaven	$K^+ \to \pi^+ \nu\bar{\nu}$	Top quark coupling to other quarks
E865	Brookhaven	$K^+ \to \pi^+ \mu^+ e^-$	Search for lepton-flavor violation
E871	Brookhaven	$K_L^0 \to \mu^\pm e^\mp$	Search for lepton-flavor violation
E799	Fermilab	$K_L^0 \to \pi^0 e^+ e^-$	Study of CP violation
E162	KEK (Japan)	$K_L^0 \to \pi^0 e^+ e^-$	Study of CP violation