At the same time, the agency's own watchdog is pointing to holes in how current projects are managed. On 15 May, NSF IG Christine Boesz delivered a report to the Senate panel that sets NSF's budget, warning that the current accounting system does not guard against potentially large cost overruns. "NSF's policies and practices do not yet provide adequate guidance for program managers to oversee and manage the financial aspects of major research equipment and facilities," Boesz declared.

The report angered former presidential science adviser John Gibbons, who in a letter to the panel accused Boesz of "harassment" of NSF director Rita Colwell. The panel's chair, Barbara Mikulski (D–MD), and ranking member Kit Bond (R–MO) rushed to Boesz's defense, however, writing Gibbons on 10 June that the IG "has acted professionally and fairly … and has played a crucial role in protecting the interests of the American taxpayer." In its reply to the IG report, NSF defends its procedures and notes that it expects to have revised guidelines to further tighten up those practices by the fall.

NSF hopes its new office will also improve the situation. But it failed to deliver on a promise last fall to the House Science Committee to have the top job filled by January. NSF's first choice was James Yeck, project manager for the U.S. contribution to Europe's Large Hadron Collider. An 18-year veteran of large research projects at the Department of Energy and a politically savvy outsider, Yeck could have bestowed instant credibility on the beleaguered program. But in May, for personal reasons, he turned down NSF's offer to move from Illinois's Fermi National Accelerator Laboratory to suburban Virginia.

Yeck thinks that Boesz's criticism of the agency's accounting practices is "unfair." But he agrees with her recommendations for improving NSF's cradle-to-grave fiscal management of large projects, including better tracking of a project's total costs and making contingency plans for any overruns.

In the meantime, some approved projects are moving ahead without NSF's official monetary endorsement. Last year IceCube, a neutrino detector under the South Pole, received $15 million after supporters won over an influential appropriator, Representative David Obey (D–WI). And last month, Representative Felix Grucci (R–NY), who represents Brookhaven National Laboratory, asked House appropriators to earmark $26.6 million in NSF's budget to start building a proposed physics experiment at the lab, Rare Symmetry Violating Processes. "It's ready to go, and we hope to get it funded," says an aide to Grucci.

That request, and others like it, suggests that NSF has its hands full trying to satisfy both the scientific hunger for new projects and the political demand for greater oversight.

—JEFFREY MERVIS

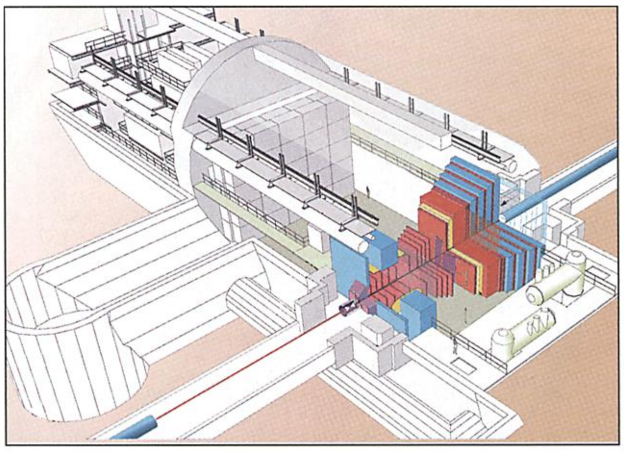
HIGH-ENERGY PHYSICS

Shadowy 'Weak Force' Steps Into the Light

After decades of work, the most mysterious of the fundamental forces of nature is poised to come into much sharper focus

The nuclear weak force is making strong claims on scientists' attention. A member of the quartet of fundamental forces in the universe, the weak force is feebler than the strong force that binds protons to neutrons and shorter range than both the electromagnetic force that ties electrons to atoms and the gravity that keeps stars and galaxies from flying apart. It is also particularly difficult to study. It exerts a subtle pull on matter and ignores common-sense rules that other forces obey. For example, the force behaves differently if you reflect it in a looking glass—behavior unlike anything else in physics.

Its quirky character makes the weak force irresistible to physicists. For more than 3 decades they have studied how the force interacts with quarks, the fundamental particles that make up most of the ordinary matter in the universe. Now, with that quest nearing its goal, they are gearing up to continue the exploration with a radically different class of particles: neutrinos. The past few weeks alone saw the debut of the MiniBooNE detector, a million-liter tub of mineral oil at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, and the dedication of the MINOS detector, an enormous set of neutrino-detecting plates in Soudan, Minnesota. Other labs are following hot on their heels, in hopes of understanding the full nature of the weak force. "By experimenting in the neutrino sector," says Michel Spiro of France's Center for Atomic Energy in Saclay, "we're writing a new chapter in *Alice in Wonderland*."



B-dazzler. Now under construction, B-particle detector at CERN's Large Hadron Collider will boost weak-force studies to new energies.

CREDIT: CERN GENEVA

News of the weak

The through-the-looking-glass properties of the weak force puzzle and delight the physicists who try to understand it. Unlike the strong, electromagnetic, or gravitational forces, the weak force can change the identity of a subatomic particle, transforming an up quark, say, into a down quark or an electron neutrino into a muon neutrino. The force's parlor tricks first came to light in the early 1930s, when physicists were puzzling over a subatomic process known as beta decay. If you watch a clump of cobalt-60 long enough, a neutron in one of its atoms will spit out an electron and become a proton, turning the cobalt atom into nickel. That transformation, the beta decay of the neutron, seemed to violate one of the most hallowed rules of physics, the conservation of momentum. When physicists compared the "action" of the hurtling electron with the "reaction" of the recoiling proton, a little bit of recoil remained unaccounted for.

German physicist Wolfgang Pauli sought to close the gap by suggesting that, along with the electron, the neutron emitted a tiny neutral particle. In 1934, his Italian colleague Enrico Fermi dubbed that particle a "neutrino" and explained beta decay by invoking a new force, the weak force. Today, physicists realize that beta decay is caused by the interaction of a quark with a carrier of the weak force known as a W particle. In cobalt-60, the W turns a neutron's down quark into an up quark, changing the neutron into a proton and emitting an electron and a neutrino (technically, an antineutrino) in the process. Fermi's version "didn't talk about exchange of particles, but it described beta decay beautifully," says Jim Cronin, a physicist at the University of Chicago.

Feeble as it is, the weak force affects all known subatomic particles—quarks as well as leptons, such as the electrons and neutrinos. Neutrinos, in fact, are affected only by the weak force. That makes them exasperatingly hard to detect and experiment with. As a result, researchers turned to other particles to unravel the nature of the weak force. They soon realized that the force has a unique property—one that makes it responsible for all the matter of the universe.

The weak, the strange, and swarms of B's

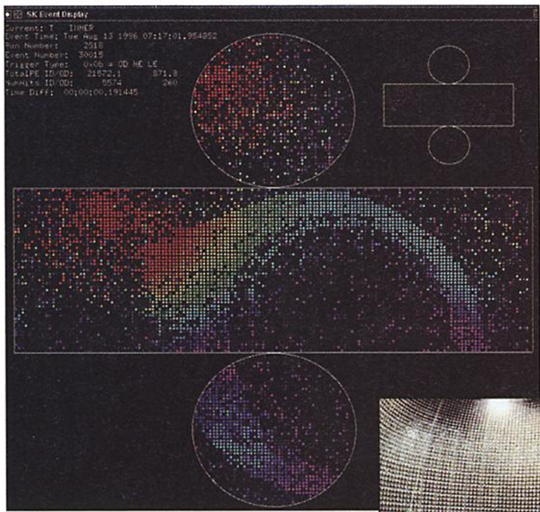
The property, known as charge-parity (CP) violation, is rooted in symmetry. Physicists long assumed that any experiment performed with matter would give the same result as a corresponding experiment with antimatter. This symmetry is known as charge, or C, symmetry. Similarly, they thought, experiments should be identical even if you swap right and left, up and down, front and back, a property known as parity, or P, symmetry. The strong force, the electromagnetic force, and the gravitational force all obey C and P symmetry. The weak force obeys neither. "With the weak force, when a neutrino comes out, it has a handedness, a spin," says Cronin. "Nature is showing a preference: Nature is left-handed."

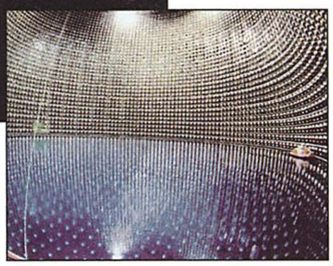
That partiality breaks the symmetry of the weak force. In the early 1950s, physicists showed that decaying cobalt atoms prefer to spit out electrons in the up direction rather than down—and that in a mirror-image repeat of the experiment, with the orientations of all the particles reversed, electrons would prefer to go down rather than up. You could tell the difference between the two; the weak force violated P symmetry. Soon thereafter, experiments showed that weak interactions also violated C symmetry. Physicists hoped that if they swapped matter with antimatter *and* reflected the particles' orientations, the weak force would look the same, but the weak force disdained to obey even this CP symmetry.

These symmetry violations seem to be responsible for the matter in the universe. If matter and antimatter were exactly the same, then the energy from the big bang would have created an equal amount of matter and antimatter—which would then have collided and annihilated each other, leaving a soup of energy. But the early universe had a tiny, tiny preference for matter over antimatter, thanks to CP violation. The wee excess of matter became the stuff of stars and planets and living creatures.

In 1964, Cronin and colleagues first spotted CP violation in a particle known as a K^0 meson, which is made of a down quark and a strange antiquark. The K^0 also has a peculiar habit of changing its identity; it can turn into its antiparticle and vice versa. K^0 and anti-K^0 particles have the same lifetimes, but K^0 particles can zoom through a plate of matter much more easily than their antimatter siblings can.

For a while, physicists thought they had detected two extra K particles, quick-decaying ones known as K_{short} and longer lived K_{long}. Unlike K^0 and anti-K^0 particles, both these putative particles could penetrate matter with equal ease. But it turns out that, thanks to a weird feature of quantum mechanics known as superposition, the K_{short} and K_{long} particles can be considered to be a blend of K^0 and anti-K^0 particles; conversely, the K^0 and anti-K^0 particles are mixtures of K_{short} and K_{long} particles. Each way of looking at K particles is equally valid. It's something like describing a direction on a map: Ordinarily we think of, say, northeast as equal parts north and east, but it's equally valid to describe north as equal parts northeast and northwest. Either pair of compass headings will work as a "basis" for specifying any direction in a plane. Likewise, it doesn't matter whether you think of the particles as K^0 and anti-K^0 or K_{short} and K_{long}.





Next step. Neutrino detections such as this one from Super-K (*inset*) hold the future of weak-force research.

CREDITS: ICRR

On a map, northeast is canted at an angle to north; in an analogous manner, the basis for describing the K^0 is at an "angle" with respect to the basis for K_{short}. The bigger the angle, the more "blended" a K_{short} or K_{long} is. In a similar way, quarks under the influence of the weak force have three "mixing angles" that describe the mismatch between two ways of looking at particles: by their "flavor" basis and their "mass" basis. (Flavor is a property of quarks and leptons that separates each class of particles into different categories.)

To describe the interplay between the mass and flavor bases, physicists employ an array of numbers known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix. This matrix, which includes the three mixing angles as well as a "phase" that describes the CP-violating nature of weak interactions, provides a concise way of describing how the weak force affects quarks. "You can account for the phenomena with numbers, with certain values in the matrix," says Cronin. "It's not an explanation, but it's a very good model."

For 30 years, scientists have been filling in those values by watching particles decay—particularly K mesons, which, unlike most other particles, violate CP symmetry. By looking at how K mesons decay and react, scientists have measured the asymmetry between matter and antimatter as well as the weak mixing angles with reasonable accuracy.

Now, however, K mesons are no longer the only game in town. About 4 years ago, scientists started mass-producing their slightly heavier cousins, B mesons, which have bottom quarks instead of strange quarks. Like K^0 and anti-K^0, the B mesons oscillate between the particle and antiparticle varieties, and they also violate CP symmetry. Because B mesons are heavier than K mesons, they are harder to produce. However, they have a lot more energy and can participate in exotic reactions that are barred to K mesons. Thus, B mesons will give physicists a new way to understand the effect of the weak force on quarks. "In B physics, there are many more decays where you can observe it and measure it," says Richard Jacobsson, a physicist at CERN, the European laboratory for particle physics near Geneva. "And B physics is so rich, you can get at the same values in many different ways," reducing the errors dramatically.

Since 1998, physicists at the Stanford Linear Accelerator Center in California have been using B mesons to make increasingly precise measurements of the particle's ability to violate CP symmetry (*Science*, 18 December 1998, p. 2169; 23 February 2001, p. 1471). The Belle collaboration based at the KEK accelerator lab in Tsukuba, Japan, recently released its first measurements of CP violation in B mesons. The Tevatron II accelerator at Fermilab will also produce enough B mesons to measure CKM matrix values, as well as some of the properties of weak force–carrying W and Z particles. And where the B factory and Tevatron leave off, the Large Hadron Collider (LHC), the multibillion-euro mega-accelerator under construction at CERN, will continue (see upper table).

As a result, the role of quarks in studying weak-force physics might be nearing its triumphant final bow. By the time LHC comes online in 2007 or so—barring the discovery of non–Standard Model physics such as supersymmetry—the CKM matrix should be almost complete. "The additional correction on things you can't measure will probably be small," says Jacobsson. Barring the discovery of supersymmetry or some other exotic physics, he says, "the interest in B physics will definitely go down." Instead, many weak-force physicists say, the future of their field lies with the particle that started it all: the neutrino.

CENTERS OF B MESON RESEARCH

Start date	Detector	Location
1998	BaBar	SLAC, Stanford University, CA
1999	Belle	Kamioka, Japan
2001	Tevatron II	Fermilab, Batavia, IL
(2003)	CLEO	Cornell University, Ithaca, NY
(2007)	LHC-B	CERN, Geneva, Switzerland

Massless no more

Neutrinos feel the pull of the weak force just as quarks do. For decades, however, physicists considered them a lot less interesting, unable to perform the funky oscillation tricks that come naturally to quark-based particles such as K and B mesons. The reason was that theorists assumed neutrinos had no mass. No mass meant that the neutrinos' mass basis was irrelevant; hence, the weird mismatch of the flavor basis and mass basis couldn't be responsible for any bizarre oscillation behavior.

The first blow to that view came in the late 1990s, when the Super-Kamiokande (Super-K) observatory in Kamioka, Japan, spotted hints that some muon neutrinos changed into tau neutrinos as the particles pass through Earth (*Science*, 12 June 1998, p. 1689). This oscillation—just as in the quark sector—meant that the neutrino's flavor basis must be different from its mass basis, something that can be true only if the mass of the neutrino is not zero. Thus, physicists concluded that neutrinos must have mass.

The discovery of the oscillations cleared up a long-standing discrepancy between theoretical and measured values of the numbers of electron neutrinos streaming from the sun (*Science*, 26 April, p. 632). It also implied that neutrinos and their lepton kin almost certainly have a mixing matrix analogous to the CKM matrix for quarks. "Barring non–Standard Model flavor-changing interactions between neutrinos and matter, there are neutrino masses and nonzero mixing," says Boris Kayser, a physicist at Fermilab. "This means that the leptons, including the neutrinos, are very much like the quark side."

But the similarities go only so far. Most theorists had assumed that neutrinos would interact with the weak force in roughly the same way quarks do. In that case, their matrix—known as the Maki-Nakagawa-Sakata (MNS) matrix—would be almost identical to the CKM matrix. Among other things, neutrinos' mixing angles, the mismatch between neutrinos' mass and flavor bases, should be small, like those of quarks.

Wrong. Over the past year or so, Super-K, Canada's Sudbury Neutrino Observatory (SNO), and other neutrino experiments have shown that the neutrino mixing angles are large. Large mixing angles mean big differences between the two ways of representing neutrinos. As a result, whereas a quark looks almost the same in its mass basis as in its flavor basis, an electron neutrino (the flavor-basis depiction of the most common of the three types of neutrinos) is an almost equal mix of two mass-basis neutrinos, with a little of the third thrown in for good measure. "That is an interesting contrast to what goes on in the quark sector," says Kayser, who hopes that the discrepancy might help theoreticians understand how the weak force and its peculiar mixing properties came to be. "This distinction between quark and lepton mixing probably is a clue to the origin of mixing, but we don't know how to read that clue yet."

NEUTRINO EXPERIMENTS

Start date	Detector	Location
1996	Super-K	Kamioka, Japan
1999	SNO	Sudbury, Ontario, Canada
1999	K2K	Kamioka, Japan
2001	KamLAND	Kamioka, Japan
2002	MiniBooNE	Fermilab, Batavia, IL
(2005)	MINOS	Fermilab and Soudan Mine, MN
(2007)	OPERA	CERN and Gran Sasso, Italy

The first step is to measure the elements of the MNS matrix. Apart from knowing that the mixing angles are large, physicists don't really have a grasp of what the matrix will look like, says Kevin Lesko, a neutrino physicist at Lawrence Berkeley National Laboratory in Berkeley, California: "You want to try to do experiments now that can begin to define the individual components better."

Already, experiments such as Super-K and SNO detect neutrinos from the sun and from cosmic ray interactions with the atmosphere. KamLAND, a Japanese experiment gathering data with an old neutrino detector in Kamioka, is measuring the oscillations of neutrinos produced by nuclear reactors at different distances from the detector. These and other experiments—including some in which beams of neutrinos are fired at detectors at various distances—will chip away at the mixing angles and will fill in some values of the MNS matrix (see lower table).

The work could also bear more exotic fruit. One tantalizing possibility is that neutrinos, like K and B mesons, will violate CP symmetry. If so, the implications could be cosmic in scale. According to Kayser, the tiny asymmetry between quarks and antiquarks can't account for the preponderance of matter in our universe: "It does not work. It's way too small." Many theorists believe that an extra asymmetry between leptons and antileptons would make up the difference. "The stage is set for exploration of CP violation in the lepton sector," says Kayser.

It's also possible that neutrinos, unlike quarks, will turn out to be their own antiparticles—that they are "Majorana" rather than "Dirac," in physics-speak. Such a discovery would reveal important details about the nature of their CP violation. Physicists have been looking in vain for a sign that neutrinos are Majorana. In particular, they have been searching for a certain "forbidden" atomic decay, a reaction that releases two electrons and no momentum-carrying neutrinos, which is allowed only if neutrinos are Majorana.

Physicists eagerly await the hard data that will help them tackle such questions. At present, however, they are just beginning to unravel the secrets of neutrinos, measure the elements of the MNS matrix, and understand how the weak force affects a whole family of fundamental particles. "This, right now, is wide open," says Lesko. "I don't think we have a good understanding right now what it's going to look like. It's kind of fun."

–CHARLES SEIFE