The Race to Understand Matter

Physicists around the world are building machines for the next frontier of high-energy physics—producing enough b-mesons to answer one of the most perplexing mysteries of matter

High-energy physicists on three continents are gearing up for a race to understand why the universe is made up mostly of matter. Theories that once posited equal quantities of matter and antimatter have been revised to accommodate this asymmetry, but physicists are still a long way from understanding it. The scientists who unravel this conundrum can lay claim to what is expected to be the next major discovery in high-energy physics—and a large measure of national glory.

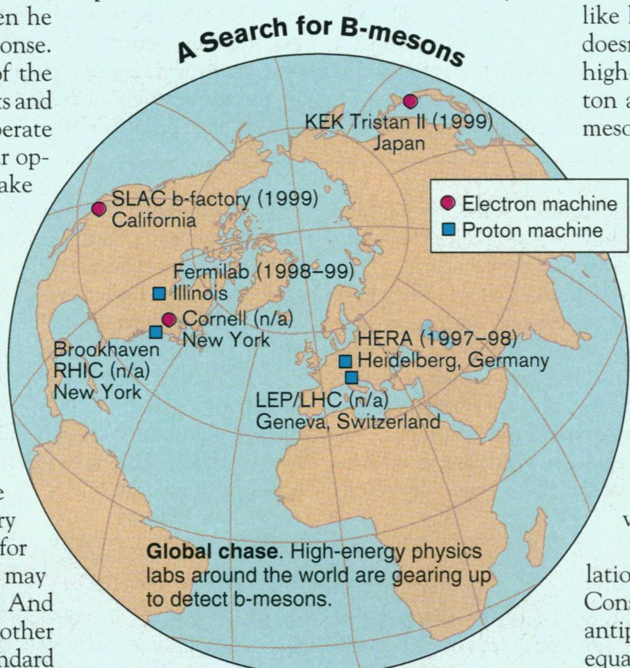
The prerace build-up has already begun. At the KEK laboratory outside Tokyo, for example, a team is preparing to build a $300-million accelerator to seize the prize. Earlier this year, after U.S. physicists had publicly questioned the design of the planned machine, Hirotaka Sugawara, KEK's director, invoked Japan's warrior traditions when he warned against an intemperate response. "Follow the Bushido Code, the way of the samurai," he advised a group of physicists and engineers who will design, build, and operate the KEK machine. "Never criticize your opponent unless it can help him and make him a more worthy opponent."

The objective of this competition is to study the exceedingly fleeting lives of particles called b-mesons. They are believed to hold the clue to a phenomenon, called charge-parity (CP) violation, that may explain the imbalance between matter and antimatter in the universe. The race is fast becoming the most heated in international physics. The recent announcement by the Fermi National Accelerator Laboratory that its scientists have found evidence for the top quark (*Science*, 29 April, p. 658) may have closed out one marathon chase. And the search for the Higgs boson—the other missing element predicted by the Standard Model of particle physics—will not begin in earnest until the completion in 2005 or later of the Large Hadron Collider (LHC) at the European acclerator lab CERN. That leaves CP violation as today's most tempting prize in the high-energy sweepstakes.

With at least a half-dozen physics facilities jockeying for position, the chances of success are likely to depend on the degree of government support for each contender and exquisite technical preparation. Some of the machines will collide electrons and positrons to produce matter and antimatter b-mesons; others will smash protons and antiprotons. Not surprisingly, backers of each type prefer their approach. "In the end, it'll come down to who comes on line first with the best detector, and who has the most sustained runs," says Roy Schwitters, former director of the Superconducting Super Collider (SSC) laboratory. "There's going to be an intense competition on both sides" of the electron-proton divide, he says.

At present, there are three clear favorites, and all expect to toe the starting line by 1999. In April, the Japanese Diet approved the start of construction of the KEK facility, known as Tristan II. Tristan II will be an electron-positron "b-factory," designed expressly to produce as many b-mesons as possible. Last October, the U.S. Congress approved construction of a similar b-factory at the Stanford Linear Accelerator Center (SLAC). And earlier this month, Fermilab, a proton acclerator, issued a call for proposals to enlist one or both of its two main detectors—CDF and D0—in a search for CP violation in b-mesons after the lab finishes upgrading its Tevatron accelerator.

But KEK, SLAC, and Fermilab are not the only entrants. There are also a half-dozen long shots hoping to slip ahead of the leaders and capture at least some of the initial headlines. Officials at the German high-energy physics facility DESY will soon decide whether to go ahead with an experiment at their new Hadron Electron Ring Accelerator (HERA). Although HERA might detect the first signs of CP violation in b-mesons by 1997 or 1998, it probably would not encounter enough particles to describe the phenomenon in detail. And if nature is generous and the CP violation is obvious enough, there is a chance that existing machines such as the Cornell Electron Synchrotron Ring (CESR) accelerator or experiments already underway at Fermilab could also detect the first hints of CP violation within a few years.



Global chase. High-energy physics labs around the world are gearing up to detect b-mesons.

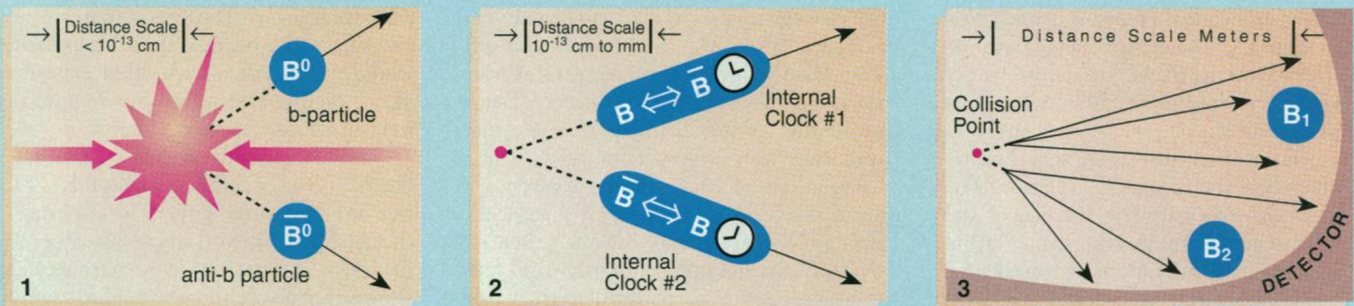
ILLUSTRATION: C. FABER SMITH

Budget breakthroughs

The profusion of potential competitors stems from a key aspect of the search for CP violation in b-mesons: It's relatively cheap. Unlike looking for the Higgs, b-meson physics doesn't require a new multi-billion-dollar high-energy machine. In fact, dozens of proton and electron colliders are producing b-mesons already. The trick, however, is to spot the particles amid the clutter of debris produced when protons or electrons annihilate each other. That will require a specialized detector for proton machines, or a second beam for electron machines. Still, the cost is modest enough—$300 million or so for a dedicated b-factory and less than $50 million for a new detector on a proton machine—that none of the b-physics experiments are formal international collaborations, although virtually all the teams will include individual physicists from other countries.

Physicists are anxious to study CP violation to answer a puzzle in quantum theory. Conservation laws dictate that particles and antiparticles must be created in pairs, with equal and opposite charge and parity (right-handed versus left-handed orientation). Moreover, symmetry laws for charge and parity require that a particle decay with the same lifetime as its antiparticle, and into mirror-image sets of decay products. But more than 30 years ago, researchers discovered this wasn't always true. Joseph Cronin and Val Fitch won the 1980 Nobel prize in part for showing that the rate at which a neutral k-meson, or kaon, particle turns into its antiparticle differs by about 0.2% from the reverse transformation, violating what was thought to be the sacrosanct law of CP symmetry. Although the effect in kaons was far

STUDYING B'S IS AS EASY AS 1, 2, 3



1) High-energy particles collide in an accelerator with each other or a fixed target, producing a meson and its antimatter counterpart containing "bottom" quarks. (Quarks are one of two basic building blocks in the so-called Standard Model of matter.)
2) Each member of the pair of b-particles moves away from the collision point and, if it is electrically neutral, shifts back and forth between particle and corresponding antiparticle during its brief lifetime. (Only electrically neutral mesons and anti-mesons exhibit this oscillation.)
3) The b-particles soon decay into longer lived particles that can be detected. Analyzing the identities, paths, and electric charges of the decay particles sheds light on differences between the lifetimes of b- and anti-b mesons, which in turn leads to a better understanding of charge-parity violation, a fundamental asymmetry between matter and antimatter.

SOURCE: R. SCHWITTERS ILLUSTRATION: C. FABER SMITH

too small to systematically explore CP violation, Andre Sakharov suggested in 1968 that the phenomenon could be a clue to the matter domination of the universe.

Although such a first glimpse of CP violation in b-mesons will no doubt capture headlines, physicists emphasize the point is to fully characterize the phenomenon—an effort that will take years and probably require machines, such as the SLAC and KEK b-factories or Fermilab, that can record hundreds or thousands of CP-violation events. The primary goal, they say, is to measure three parameters of CP violation, complex numbers that are expressed in terms of angles. If the Standard Model is correct, these should add up to 180 degrees—a triangle.

"In that case," says David Cassel, a Cornell University physicist now at CERN, "although you still haven't found the origin of matter in a deep fundamental way, you at least know where it's coming from." The other possibility is that the parameters just don't agree with the Standard Model. "Then you know that CP violation is coming from something far away, something entirely different, and that's new physics," says Cassel. "Either way, you've won."

But it's hard to understand how the tiny occasional asymmetry that occurs in k-mesons could lead to an entire universe dominated by matter. "The cosmologists," says University of Hawaii physicist Stephen Olsen, "all believe that the Big Bang had to start off with symmetry. But now the universe is enormously asymmetrical. Something has to have happened to make this asymmetry. Yet the only difference people have seen is this small effect in k-mesons."

That's where b-factories come in. Certain rare b-meson decays are predicted to show a 30 to 40% rate of CP violation. But observing these rare b-decays, which occur in about 1 in 10,000 b-meson decays, requires either a whole new class of machines that can preferentially generate lots of b's or the development of detectors discriminating enough to filter through enormous amounts of other subatomic particles to pick out the few of interest. Electron accelerators generate a high fraction of the right kind of b's. But because the process that creates the two particles leaves them with very little kinetic energy, they travel just a tiny distance before decaying, making decay-time–dependent measurements practically impossible.

The trick behind b-factories is to give the b-mesons an additional kick, extending their decay tracks. That's why SLAC and KEK will have "asymmetric" beams. By colliding beams of different energies, typically 9 giga electron volts and 3 GeV, the collision debris—including the b-mesons—will start life with a hefty boost in the direction of the higher energy beam, making them easier to detect.

Proton accelerators, on the other hand, produce a blizzard of subatomic particles, of which only a small fraction may be b's. Spotting them will be like finding a needle in a haystack thousands of times per second—a task that will require unprecedented computer and detector technology, says Fermilab director John Peoples. "The counting rate for the garbage is in the tens of thousands [of particles] per second, and at the same time you're generating maybe 1250 [b/anti-b] pairs. It's incredibly difficult to separate out what's interesting from what's not."

Physicists agree that each approach has its advantages and that it's too early to pick a winner. At the moment, says Schwitters, physicists are presented with a dilemma: "Make the detection easy, but you're limited to small numbers, or make the detection difficult, but you've got gobs of them coming out with good luminosity." On top of that, electron machines are best at detecting b's that decay into two pions, while proton machines are better at detecting decays that include a j-psi particle, because the pion is too common in proton collisions to serve as a unique trigger. "Both systems measure different aspects of CP violation, so they're complementary," and both types of machines will be needed, says Fermilab physicist William Carithers.

Japan's second shot

The first facilities being built are the electron machines, the dedicated b-factories. Although KEK's is called Tristan II, Phoenix might have been a more appropriate name. The machine approved earlier this year will rise from the ashes of the original Tristan, Japan's first major particle accelerator, completed in 1986 and designed to find the top quark or Higgs boson. Those two particles appear to be more massive than theorists had predicted, and the machine's 60-GeV energy was too low to generate the heavier particles. Now KEK is building an 11.5-GeV asymmetric electron-positron accelerator within Tristan's 3-kilometer tunnel to give Japanese researchers a second shot at a major physics discovery.

Tristan II is being built in two phases. The first, scheduled for completion by 1999, will use mostly existing accelerator technology to generate a beam with a relatively modest luminosity of 2×10^{33} particles per square centimeter per second. Three years later, KEK plans to add special superconducting pulse drivers and other advanced accelerator components designed to increase the luminosity by a factor of five. "The plan is to have a pretty long program of measurement, and to upgrade the machine as you go along," says Olsen, a team member. The risk, of course, is that the first phase of Tristan II will fail to detect CP violation and that another accelerator will spot it before KEK can get the second stage on line.

That other accelerator is SLAC's b-factory. The SLAC accelerator is also an upgrade of two machines, the Stanford Linear Accelerator, which will serve as an injector, and an existing 30-GeV electron storage ring, which will provide the higher energy of the two asymmetrical electron beams. The complementary low-energy beam will be built from scratch. SLAC's machine is designed to have a luminosity 50% higher than that of Tristan II.

But more than just technical hurdles stand between SLAC and CP violation: The lab must also navigate the hazards of the U.S. political system. As the cancellation of the SSC painfully demonstrated, the start of construction is no assurance of success, and continued no-growth budgets for high-energy physics could seriously delay SLAC's b-factory plans.

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Indeed, with money so tight, some physicists question whether the United States should be building a b-factory nearly identical in capability to Tristan II. "SLAC and KEK appear to be very similar in terms of their competitiveness," says Schwitters. "The real question in my mind is why you need both." But Lawrence Berkeley National Laboratory physicist Kevin Einsweiger says that the decision to pick SLAC over Cornell for the US b-factory was so hotly debated (*Science*, 15 October 1993, p. 328) that few high-energy physicists are eager to revisit the issue of whether the United States should have a dedicated b-factory at all. SLAC b-factory director Jonathan Dorfan says that two b-factories are not too many: "This is much too important to leave to one detector. You need a cross-check."

A proton future?

Physicists agree that, despite the appeal of the electron machines with their focused production of the right kind of b's, you can't beat proton accelerators for generating large numbers of particles—essential in a field where discoveries are measured in statistically significant numbers of very rare decays. "The reason people are persisting at Fermilab and HERA and ultimately at LHC is that, in the long run, you can produce many more b's in the hadron collider than you can with electron-positron machines," says Schwitters. Adds Brookhaven National Laboratory physicist Sebastian White: "Electron machines will never completely do the job. You just run out of statistics."

The challenge, of course, is detecting all those b's coming from the proton machines. Although researchers at proton facilities are optimistic that detector technology will someday allow them to do that, those at the electron machines feel confident that they will have years of productive running before proton machines can take advantage of their huge rate advantage. "If they can do very well in digging [the b's] out without major efficiency losses, they will have a clear statistical advantage," says SLAC's Dorfan. "But if they're not as successful as the optimists think, they won't overwhelm us."

Regardless of who is doing b-physics in proton machines at the end of the decade, Fermilab is expected to be the one to beat. Its Tevatron accelerator, currently the most powerful in the world, is scheduled to have an accelerator upgrade in 1998 or 1999 that will give it at least 50-fold greater luminosity. On top of that, its two main detectors, CDF and D0, are due for upgrades at around the same time. The upgrades will give them both improved "silicon vertex" detectors that use computer-chip technology to create large sensors that can determine the energy and position of particles with unparalleled accuracy. D0 will also get special magnets to help determine the momentum of the billions of particles that fly out of the proton/antiproton collisions; CDF used similar technology to detect evidence for the top quark earlier this year.

Peoples says that, while the silicon vertex detectors have greatly improved the efficiency of the Fermilab detectors, lab researchers will still need major advances in detection technology before Fermilab can be a CP-violation player. "You need electronics that can reconstruct a track or do some pattern recognition in a few microseconds," he says. "We're working on it, but the question is how far along will this stuff be by the time the [upgrade] is ready? Maybe we'll have it solved in 1998; if not, then in 2000."

In the meantime, Fermilab, too, must deal with the vagaries of U.S. politics. Its accelerator upgrade has already been delayed for 4 years for lack of funding, and many physicists doubt that the job will be done by 1998–99.

The wild cards

While the b-factories prepare to fight over the lion's share of b-physics and Fermilab remains a serious contender, researchers elsewhere are considering innovative ways to gain a toehold in the CP violation game. The proposal at Germany's new HERA accelerator is one of the most audacious. The idea is to place a tungsten wire target in the "halo" of its existing 820-GeV proton beam, where it would be struck by protons, creating b-mesons in the collision. Because b-physics is not part of HERA's primary research, the advantage of placing the target where it will only interfere with protons that are falling away from the beam is that the experiment would not interfere with other experiments at the facility and would not require major modifications to the accelerator.

The experiment is risky, concedes Albrecht Wagner, HERA's research director, but the potential payoff is enticing. Although HERA is working at just a fraction of its design current, he says experiments have shown that a wire target would get sufficient luminosity for b-physics at about 70% of HERA's design capacity. Still, even at that rate, the HERA experiment would see a factor of 10 fewer interactions than the Fermilab experiments, and CP violation would have to be relatively obvious to show up. "It is clearly a huge challenge," says Wagner. A HERA advisory committee will review the proposal later this year.

Another dark horse is the Relativistic Heavy Ion Collider (RHIC) being built at Brookhaven on Long Island, New York. Although RHIC is designed to study nuclear physics, in principle it can also collide protons to generate b's. Last month, 50 physicists from around the world gathered at Brookhaven to discuss the possibility of a b-physics experiment at RHIC. That decision, says White, depends a great deal on what the other accelerators are doing. A b-physics detector at Fermilab would make one unnecessary at RHIC because Fermilab is expected to generate about three times as many b's. White says RHIC's major contribution to the field is likely to be in making precise measurements of CP violation, not in first detecting it.

Finally, a few groups could stumble upon CP violation before 1999 if the phenomenon turns out to be relatively commonplace in b's. One machine with a chance for such an early glimpse is the Cornell Electron Storage Ring accelerator, which lost out to SLAC in its bid for federal funding. Its defeat left Cornell with its existing symmetric ring, which makes detection of decay particle lifetimes difficult, if not impossible. But the lab is currently the world's undisputed leader in generating and detecting b-mesons without measuring decay lifetimes, and lab scientists are not giving up. "Other people would say we don't have a chance, but we think we see ways of doing it" with indirect measurements, says Cornell physicist Maury Tigner.

Whichever lab receives credit for spotting CP violation first or for fully describing it, the search is likely to occupy several hundred high-energy physicists for the next decade or more. And given the slim chance that a more costly "big-science" project will be approved anytime soon, a handful of b-factories may be their only alternative.

–Christopher Anderson