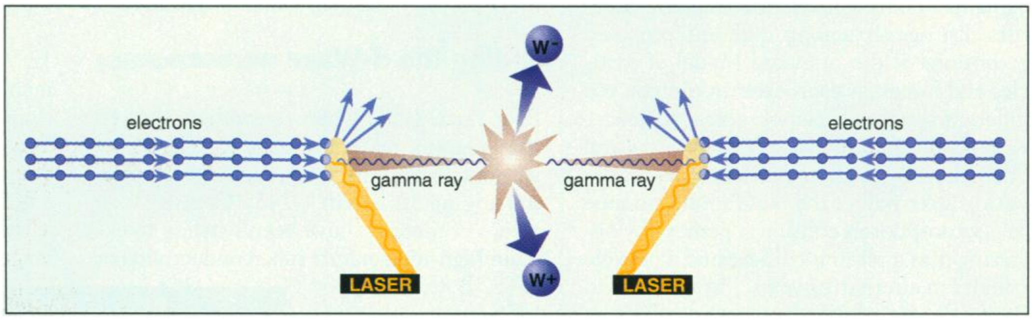
HIGH-ENERGY PHYSICS

Lighting a Route to the New Physics—With Photons

In the world of high-energy physics, seemingly fixed boundaries have a habit of dissolving. Subatomic particles can switch from one type to another, and the apparently empty vacuum can unleash showers of particles. Under the right circumstances, light and matter can even switch identities. Now groups of physicists are laying plans to take advantage of this alchemy. They hope to conjure up new forms of matter and probe the surprisingly complex structure of photons by colliding streams of these particles—beams of light, in effect—boosted to unimaginably high energies.

Such a light smasher, which these optimists say could be up and running in a decade, would bear a striking resemblance to a traditional particle accelerator. The photons would gain the energies needed to reveal striking new phenomena by ricocheting off high-energy particle beams. But at the machine's collision point, says theorist Stanley Brodsky of the Stanford Linear Accelerator Center (SLAC), "a whole new domain of particle physics would be accessible." Key to this domain is the ability of photons, at very high energies, to change spontaneously into other particles or pairs of particles. At energies orders of magnitude greater than those of the highest energy gamma rays seen in nature, says Brodsky, you would get the equivalent of "a gigantic array of particles" whizzing down the collider's beam lines.

The result would be an array of collisions that are rare at best in existing accelerators—quarks with electrons, massive W particles with other W's, photons with photons. By studying the rates of these collisions and the nature of their debris, physicists could test predictions of current theory and perhaps discern routes beyond it. Says Brodsky, "I can imagine that 20 years from now this will be one of the main areas of particle physics."



SOURCE: MICHAEL PESKIN

Light smasher. In a hypothetical photon-photon collider, lasers would siphon energy from electron beams, generating gamma rays that spawn massive particles as they collide.

Some of Brodsky's colleagues are already laying the groundwork; last spring Andrew Sessler of the Lawrence Berkeley Laboratory ran a symposium there on the prospects for photon-photon colliders. Meanwhile, a group at SLAC is taking a practical step toward photon physics with an experiment in which laser light collides with narrow particle beams. That exercise is a test of the interaction that would pump up photon energies in a full-scale light-on-light accelerator.

They are preparing for an opportunity that could arrive within 10 years if a gigantic linear accelerator known as the Next Linear Collider (NLC) is built. The financing and location of this multibillion-dollar machine are still uncertain, but many physicists support the NLC as a complement to the largest ongoing accelerator project, the Large Hadron Collider (LHC) planned at CERN in Geneva. The NLC would be designed primarily to collide beams of electrons and positrons, their antimatter counterparts. But Brodsky and his colleagues argue that it could easily be adapted to duty as a light smasher as well.

The best argument for doing so, they say, comes from existing colliders, which already offer fleeting glimpses of the physics such a facility might reveal. Photons come into play even in some particle collisions, and their presence has been strongest at electron-positron colliders such as CERN's LEP and Japan's TRISTAN. That's because photons are not only the smallest packets of light but also the carriers of the electromagnetic force; as a result, they emanate continually from electrons and positrons. In LEP and TRISTAN, a photon from one beam sometimes slams into a particle in the other beam. The subatomic debris of the collision, says Brodsky, reveals hints of the surprisingly complicated structure of photons of light.

The light fantastic. "The photon you normally think of as structureless, but that's an illusion," he says. Because quantum mechanics allows the photon to metamorphose into many other particles, the photon behaves to some extent as if it were a miniature particle zoo. The stray photon collisions offer a way to probe this zoo, as physicists at TRISTAN have been learning by studying one class of collisions in which a photon emanating from one beam briefly becomes a pair of quarks—and in that guise encounters an electron in the opposite beam.

The TRISTAN researchers hope that the tracks left by debris from these collisions will enable them to measure a characteristic of the photon known as its "structure function"—in essence, how readily it produces a pair of quarks. But even in electron colliders such as TRISTAN, photon collisions come about only occasionally and by chance. By making photons themselves into the collider's ammunition, say physicists, they could open new windows on the structure of the photon as well as on the exotic particles that materialize from it.

The first step in that direction, explains SLAC theorist Michael Peskin, is to learn how to boost photons to the enormous energies needed to spawn new particles. To do so, his colleagues are using a SLAC facility called the Final Focus Test Beam, a 300-meter-long electron beam that has been running since May. The facility is a testbed for technologies that could focus the NLC beam to a diameter of a few billionths of a meter, an order of magnitude narrower than beams in existing electron-positron colliders. But the SLAC group is also learning how to tap into the beam's energy with a laser that generates light in trillion-watt pulses. Using an idea developed by researchers at the Budker Institute in Novosibirsk, Russia, they direct laser photons into the path of the electron beam, so that a few photons interact with hurtling electrons. Because of the quirky laws of quantum mechanics, the photons steal away 90% of the electrons' energy. The result: streams of photons with trillions of times more energy than the original laser photons.

Reproduced on a larger scale in both arms of the NLC, this effect could generate a pair of photon beams with enough energy to conjure up a host of exotic particles. Occasionally, for example, theorists predict that the photons would spontaneously transform into W's—the massive "force particles," discovered at CERN in the early 1980s, that convey the electroweak force. If photons going in opposite directions happened to become W particles at the point of collision, says Brodsky, still more exotic things might come out of the fray. Among them might be the Higgs particle, a hypothetical particle that is thought to explain the nature of mass.

If the Higgs particle does materialize in a photon collider, the frequency of its creation might yield clues to the shadowy world of physics beyond the bounds of current theory. For one, the rate at which light can convert to Higgs particles could reveal what other particles remain to be found, explains Peskin. So long as these unseen particles have mass, they would "couple" with the Higgs, just as they do with the photon. Their presence should affect how readily one turns into the other. As a result, the rate at which photon collisions generate the Higgs could hint at "the sum of all the particles that could exist," explains Peskin. That sum could help theorists distinguish among different proposed extensions of the Standard Model of particles and forces, as each extension predicts a different set of as-yet-unobserved particles.

How bright a prospect? To Brodsky and other theorists, such potential argues for devoting up to half of the NLC's running time to photon-photon collisions, perhaps by operating it as a photon collider and a particle collider in alternating years. Physicist David Burke, leader of NLC planning efforts at SLAC, agrees the facility should be set up to accommodate photon experiments. He says he'd like to see it include two detectors, one for particle collisions and the other for collisions between photons.

But Howard Haber of the University of California, Santa Cruz, warns that such dual use is "a very difficult thing to accomplish, though I don't want to say it's impossible." One hurdle is inventing powerful enough lasers, notes Burke. "Establishing photon-photon collisions requires lasers we don't have now," he says. Conventional lasers can generate enough power, but only for fractions of a second. Producing an observable number of photon-photon collisions would take lasers with more stamina, explains Lawrence Berkeley's Sessler. One candidate is the free-electron laser (FEL), a device studied during the Star Wars era as a possible anti-missile defense. "Right now, the FEL has neither the peak power nor the average power you need," Sessler says, but with further work, it might do the job.

There's also the problem of rounding up funding for the NLC from the U.S. government and others. And even in the physics community, some factions support alternatives, such as upgrading the country's most powerful current accelerator, the Tevatron at the Fermi National Accelerator Laboratory in Illinois. But physicists eager to probe ever more remote corners of the subatomic world have gotten used to hanging their hopes on dreams, schemes, and speculations. And perhaps it's not so hard to imagine such schemes materializing into real projects once you've seen matter appear out of light.

–Faye Flam

MEETING BRIEFS

Superconductivity Researchers Tease Out Facts From Artifacts

High-temperature superconductivity researchers are a skeptical bunch. But they can be drawn in by a good mystery. And at the Seventh Conference on Superconductivity and Applications earlier this month in Buffalo, New York, about 100 researchers were treated to both hard evidence and tantalizing clues. Among the progress reports on applications of high-temperature superconductors, researchers viewed new evidence pointing to the mechanism behind such superconductivity and a review of strange glimmers of superconductivity near and above room temperature.

Riding the d-Wave

Ever since 1986, when researchers showed that certain materials conduct electricity without losing any energy at temperatures starting at 30 kelvin (-243° Celsius), two camps of theorists have been battling to explain high-temperature superconductivity, or HTS. Both hold that HTS involves electrons traveling in pairs, but they differ on the crucial question of how these pairs form. In Buffalo, one of the two camps, which argues that pair-bonding is the result of magnetic attraction brought about by the electrons' spins, got a big boost from an elegant new experimental result.

IBM RESEARCH

Is that d-wave? A computer image shows a magnetic field emanating from a circular superconducting crystal, designed to prove a mechanism called "d-wave symmetry" is behind high-temperature superconductivity.

At the Buffalo meeting, researchers led by Chang Tsuei and John Kirtley at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, reported detecting a quantum mechanical phenomenon known as d-wave symmetry in a superconductor made of yttrium-barium-copper-oxide, or YBCO. D-wave symmetry is associated primarily with spin-paired electrons. The alternative theory, which holds that pairing is a product of interactions between the electrons' charge and their surroundings, suggests such electrons will show a different signal, called s-wave symmetry. The new result "seems to be the most irrefutable experiment I've seen that shows it's d-wave," says Ted Geballe, a physicist at Stanford University in Palo Alto, California.

Although s-wave still has adherents, recently the bulk of experiments has been coming up d-wave. Indeed, the IBM researchers followed up on work by Dale Van Harlingen and his colleagues at the University of Illinois that favored d-wave (*Science*, 12 August, p. 860). Despite that experiment's success, critics such as Argonne National Laboratory's Richard Klemm noted that the experiment compared superconducting behavior from edges and corners of a YBCO crystal to produce a signal of d-wave activity, but edges and corners have different magnetic properties, and that may have biased the outcome.

Enter Tsuei and colleagues. The IBM group circumvented the edge and corner problem by crafting superconductors of a circular shape and designing their experiment to show a unique magnetic signal if d-wave symmetry was present. The group arranged three separate wedge-shaped YBCO crystals into a shape like a pie, each wedge like a pie slice. They then used photolithographic techniques to etch away much of the pie, turning it into a ring shape. Each crystal still made up a segment of the ring. Because of the YBCO material's properties, quirks of quantum mechanics within the superconducting crystals spontaneously produce electron "pair waves." Once generated, the waves try to move around the ring. To do that, they must jump between crystals, each of which has a different orientation of its atomic grid.

For pair waves, making this jump may require changing "sign": shifting phase from a peak to a trough as they cross from one crystal to the next. If they make an odd number of sign changes during a single revolution, the result will be a quantum mechanical condition, the result of which is a superconducting current; the current then gives off a unique magnetic signature.

Pair waves with d-wave symmetry can change their sign in the absence of an external magnetic field and thus trigger this sce-