Hard Probes and Soft Ones for Testing the Quark-Gluon Soup

By Paul Preuss

"We call short-wavelength probes 'hard'; the shorter the wavelength, the smaller the features it can resolve. For example, you can study smaller objects with x-rays than with visible light," says theorist Xin-Nian Wang of the Nuclear Science Division, explaining the title of the recent Second International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions. "We need the hardest probes of all to study the hot, dense state of matter that exists when two heavy nuclei like gold collide with enough energy to temporarily free the quarks and gluons in their constituent protons and neutrons."

This state of matter is termed a quark-gluon plasma, although it resembles a perfect liquid, not a gas. As NSD experimentalist Peter Jacobs cautions, "There's no way we can look into such a short-lived, dense event from the outside. What we call 'probes' are coming from inside, jets of quarks and gluons, or the hadrons into which they decay, plowing through the medium and strongly interacting with other matter. From many such probes coming from different parts of the event we build up a tomographic picture, like a CAT scan, of what's going on inside."

Advances in studies with jets were one of the main topics of discussion at the recent conference, held June 9 to 16 in Pacific Grove. A well-known phenomenon in high-energy physics, symmetrical, back-to-back jets of particles fly out of head-on collisions. But a few years ago Xin-Nian Wang and colleagues including Miklos Gyulassy, then at Berkeley Lab, came up with the idea of jet quenching.

Because a collision of gold nuclei, the heavy nuclei used in the twin beams of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, is actually a collision of many individual nucleons, most collisions will be off center. Of a pair of jets, one will have an easier time escaping to the edge of the event, whereas the other, the recoil jet, will be "quenched" -- hidden from detection -- by the superdense interior.

Jet quenching was indeed observed in RHIC's experiments, including the giant STAR detector whose core time projection chamber was built at Berkeley Lab. Says Jacobs, a member of the STAR collaboration, "at first we studied the jets that were easier to see, which are mostly from the edge of the event. What's new is that we're now starting to plot what happens to the recoil guy who needs to plow through all this stuff."

"One effect is that the recoil jet heats matter, and we're beginning to see how the medium responds," says Wang. "These are the color-charge interactions of the strong nuclear force, or QCD."

Another topic of lively interest at the conference was the kind of particles in the jets. Initially, the only quarks that could be easily identified were lighter quarks, like the up and down quarks that combine to make ordinary protons and neutrons. More recently, very massive charm and bottom quarks have been identified. But they don't behave as expected.

"Theoretical expectations were that heavy quarks would lose less energy than light quarks do as the jet pushes through the medium," says Wang. "The data don't correspond to those expectations -- the heavy quarks are suppressed just like the light ones -- and the theorists are facing a dilemma."

Peter Jacobs cautions that experiments aren't definitive yet, because charm and bottom quarks can't be distinguished from each other using the signals that have been employed to identify them. "To do that, we'll need vertex detectors closer to the interaction point that can better measure the decay products."

The conference was wholly devoted to hard probes -- those that can be calculated using QCD, which is concerned with the color charge of quarks and gluons -- but attention was also devoted to "soft" probes that interact electromagnetically -- namely, photons and dileptons (e.g., positron-electron pairs).

"Electromagnetic interactions are a lot weaker than strong interactions," says Wang, "exactly 1/137th weaker, in fact, than the color interaction. These experiments have also thrown the theorists into turmoil."

The problem arises because of how quarks acquire their mass. The total mass of three up and down quarks is a lot less than the mass of the proton or neutron they constitute, but the effective mass of the quarks is much greater because of something called "chiral symmetry breaking." Chiral symmetry is broken at low temperatures, not at the high temperature attained in quark-gluon plasmas, where quark masses are expected to drop.

As a probe, dilepton pairs are sensitive to chiral symmetry breaking, but the results of an experiment at CERN are not what theorists expected to see, and seem to rule out the dropping of the mass of rho mesons, which are pairs of up or down quarks and antiquarks.

On a different tack, conference participants were also stimulated by the successes of at least one brand of string theory in interpreting some experimental puzzles much more easily than QCD can deal with the same phenomena. "We don't understand how these theories are related," says Wang, "but there's a startling resemblance in their results."

As might be expected, a final area of intense discussion at the conference was progress toward future heavy-ion experiments, especially at CERN's Large Hadron Collider.

"The Large Hadron Collider at CERN won't just accelerate protons," says Jacobs. "It will also be able to accelerate heavy ions like lead to energies never before achieved."

Jacobs and NSD Director James Symons are heading an effort to equip a CERN experiment named ALICE with a detector called a calorimeter, which will push heavy-ion experiments and the physics of jets into new realms of exploration.

Visit the conference website at http://hp2006.lbl.gov