Experimenting With 40 Trillion Electron-Volts

It takes hundreds of physicists several years to design experimental detectors for the Superconducting Super Collider

By DIETRICK E. THOMSEN

With much of the emphasis recently on the competition among 25 states to be the site of the proposed Superconducting Super Collider (SN: 9/12/87, p. 167), the ambitious physics of the project tends to get lost. But to anyone involved in particle physics, the SSC involves a fantastic amount of energy, and physicists' eyes tend to gleam as they talk about what they will do with it — or rather, what nature will do with it while they watch. Each head-on collision of two protons in the SSC would provide 40 trillion electron-volts (40 GeV) of energy. That's 40,000 times the mass of a proton.

For several years now, particle physicists have gathered for a couple of weeks each summer to work out their ideas on how to design the equipment that will record the results of those collisions, and gradually the designs are beginning to jell. This year's Workshop on Experiments, Detectors and Experimental Areas for the Super Collider, held at the University of California at Berkeley, produced drawings of large pieces of experimental equipment that seem to be settling into basic categories.

The installations the experimenters discuss are large and complicated. As Roger Cashmore of the Fermi National Accelerator Laboratory in Batavia, Ill., points out, it takes about five years to build one of these detectors. If construction of the SSC goes forward on schedule, completion is expected in 1996. Therefore, in a couple of years physicists will have to develop these concepts into plans out of which hardware can be made.

They are not there yet, but scientists *are* standing at blackboards drawing up arrangements of different elements they think they need. As they do, they get sardonic comments from the audience:

"Amazing," says one observer, "how they plan to levitate a heavy magnet like that!"

"They intend it to be superconducting," says another, pushing in the needle a little farther.

Yes, they intend it to be superconducting, but no, they do not intend to levitate many tons of magnet by the Meissner effect. (A piece of metal in a superconducting state will expel a magnetic field from within itself. As has been demonstrated recently in television news reports of the new high-temperature superconductors, the repulsion so generated will levitate a small object.) As Cashmore points out, "These things don't just float in midair." There is a lot of engineering design to be done, and that could require tradeoffs with characteristics important to the data-taking. Particularly, the supports for heavy items like magnets could invade and degrade the hermeticity, the self-contained and sealed-off character, that experimental physicists desire in elements of the detecting equipment.

The physicists want the detectors to be able to identify the stable and the fairly long-lived radioactive particles that come out of the proton-proton collisions and determine the energies they carry and the size and direction of their momenta. Most of the unknown particles they seek will be too short-lived to make much direct impression on the detectors, so the presence of any of them will be revealed by the identity and behavior of its decay products. The name of the game is by their fruits shall ye know them.

The list of things they want to look for is fairly long. All these things are apparently heavier than particles now known and so require more energy for their production. Some of the things on the list would contribute to a rounding out and deeper understanding of the present "standard model," which contains successful theories of two important parts of particle physics. Others pertain to attempts to go beyond the standard model to unite its elements with explanations of phenomena not now included and produce a more comprehensive theory. Finally, some theoretical exercises seek to go below the standard model to see whether there is a level of reality and structure below the most basic one now contemplated by the standard model.

One part of the standard model is the theory known as quantum chromodynamics. This deals with quarks, the particles made out of quarks (which are all but a dozen of the known particles) and the force that animates them, the short-range "strong" force or strong interaction. The other part of the model is the theory called electroweak or sometimes electroasthenodynamics, which covers particles and phenomena animated by the electromagnetic force and the other kind of short-range force, the "weak" interaction.

Related to the standard model are searches for new kinds of quarks, particularly for heavy kinds. Some physicists still hope to find free quarks, although the usual theory says quarks cannot be free. Experimenters talk of looking for gluons, the particles that embody the strong force and carry it from place to place. They also want to study the detailed physics of things now known but on the edge of current experimental capability.

One such instance is the "b" quark, the heaviest now definitely known. At the workshop many physicists spoke of the importance of studying the behavior of the B particles, the family of things made from b quarks. Another example is the z and w particles that play a central role in electroweak theory. How do they behave in detail? Are there more of them than we now know — heavier ones, perhaps?

The icing on the cake, so to speak, is the Higgs particles. One of the important unsolved questions is how different particles get mass and how each kind gets the specific amount it has. At the basis of the standard model is a mechanism, the Higgs mechanism, that purports to deal with the question of how mass comes about. If the Higgs mechanism exists, then a family of particles, presumably very heavy particles, called the Higgs particles, exists. Finding them would cause great rejoicing among physicists.

Going beyond the standard model, supersymmetry theory attempts to unite the standard model with phenomena controlled by the force of gravity. It gets its name because it proposes that for every particle known to the standard model there exists a supersymmetric partner that has the same properties but obeys the opposite of the two kinds of statistical law that apply to subatomic particles, Bose-Einstein statistics and Fermi-Dirac statistics. Many want to search for these supersymmetric partners, particularly those corresponding to particles that play important roles in the standard model. These partners would be photinos, gluinos, squarks, sleptons, zuinos and winos (pronounced "weenos").

Underneath the standard model is the realm of "compositeness." The standard model holds that everything is built out of six kinds of quarks and six kinds of leptons, and that these quarks and leptons are the most elementary forms of matter. Up to now, whenever physicists have thought they had reached the most elementary constituents of matter, they have been proven wrong. There is a faction of theorists who think they are still wrong. Believers in compositeness say the quarks and leptons are themselves composite, made of more elementary objects, which may be called preons or technicolor quarks or something else.

In addition to all this are things that even theoretical physicists call exotic, but that nevertheless may exist. Summing up for the working group that considered exotic particles, Allan Litke of the University of California at Santa Cruz said, "The search for exotics must proceed. The impact is so great." He cited a new energy range and the possibility of new physics and big surprises as reasons for it.

Litke specifically mentioned attempting to detect magnetic monopoles, free quarks, new kinds of heavy quarks and heavy stable particles. Physics now knows two kinds of stable particles, protons and electrons, which, with neutrons, are the constituents of ordinary atoms. The heavy stable particles would be at least 100 times as heavy as protons. They would have lifetimes greater than 10 million seconds (about 116 days), which amounts to stability compared to the millisecond, microsecond and shorter existences of typical unstable particles. This would be a strange new kind of matter indeed.

At the workshop, each important family of particles – the Higgses, the Bs, the supersymmetry particles, and so on – had a small group of physicists that discussed how best to study it. Then the groups dealing with specific particles got together with hardware specialists and fed their requirements into possible designs for general-purpose detectors.

These general-purpose detectors are usually called "four-pi" detectors because they aim to surround one of the six proton-proton collision points in the SSC

A matter of gravity and the SSC

Particle physics has never bothered much with gravity. Compared to the other forces at play among subatomic particles, gravity is so weak that its effect seems impossible to detect against the background of forces that are up to 10^{40} times as strong as it is.

Now, however, physicists are planning the Superconducting Super Collider (SSC), which will accelerate two beams of protons to energies up to 20 trillion electron-volts (20 TeV) each and bang them against each other. When protons get as close to the speed of light as 20 TeV represents, they gain a great deal of mass, and that means they exert stronger gravitational forces than ordinary protons.

At least one physicist, Adrian C. Melissinos of the University of Rochester (N.Y.), has asked himself with respect to the SSC, "Could you look for long-range forces – gravitation?" He outlined his conclusions in a discussion group on "exotic" particles at the recent Workshop on Experiments, Detectors and Experimental Areas for the Superconducting Super Collider held at the University of California at Berkeley.

Ordinary gravity is unlikely to be detectable, he calculates, but other conceivable long-range forces might be. In addition, the SSC could be instrumented as an antenna for gravity *waves*.

In the hope of detecting gravitational forces exerted by bunches of protons circulating in the SSC ring, Melissinos considered setting up Weber antennas near the ring. Mainly intended to detect gravitational waves, Weber antennas are specially designed bars of crystalline material that respond to gravitational effects by distortions or vibrations of their crystalline structure. Unfortunately, Melissinos calculates that even Weber antennas made of highly sensitive sapphire would not detect the gravitational effect of passing SSC proton bunches.

However, other long-range or medium-range forces dependent on the relativistic mass increase, the so-called gamma factor, might be detectable – if any exist. As Melissinos points out, the classic experiments that measured gravity with high precision, such as those of Lord Cavendish in the 19th century, did not contemplate such forces and were not designed to test for them. Thus it might be worthwhile to look for them at the SSC.

According to Melissinos's calculations, the SSC could be used to measure – or, as he more pessimistically put it, to "exclude" – such long-range forces if they happen to be at least 10 million times as strong as gravity. One possible candidate is a force that some theorists have suggested exists in connection with the as-yet-undiscovered particles called axions. This force would have a range around 20 centimeters.

If the gravity of relativistic protons can't be measured at the SSC, perhaps gravity *waves* coming from other parts of the universe can be. Melissinos proposes instrumenting the SSC itself to be a gravity-wave detector. Gravity waves, predicted by Einstein's general theory of relativity, are to gravity what radio waves are to electricity. As Einstein's theory connects gravity with the curvature of space-time, gravity waves are often regarded as undulations of the fabric of space-time itself. Physicists expect them to come from a number of astrophysical happenings, including supernovas and collapses of binary stars.

If this kind of cosmic surf really is up, the fabric of the SSC could be used to find it. Melissinos suggests using the quadrupole magnets that focus the bunches of protons and make fine adjustments in their orbit around the ring. He wants the designers of the SSC to hang four of the quadrupoles, located 90° apart around the circle, in a suspension that leaves them free to oscillate. (Usually they are rigidly supported.) Then if a gravity wave with the right characteristics passed by, the quadrupoles would oscillate in pairs. Two quadrupoles diametrically opposite each other would move inward as the other pair moved outward, then vice versa.

Each time a proton moved past one of these oscillating quadrupoles it would get a little kick out of its normal way. Assuming the gravity waves and the quadrupole oscillations were coherent for 5 seconds, the cumulative deviation of the proton beam – which in that time makes 10,000 turns around the ring – would be 4 billionths of a meter, 4 nanometers. At the smaller accelerator at the Fermi National Accelerator Laboratory in Batavia, Ill., Melissinos points out, the monitoring equipment has measured deviations as small as a ten-millionth of a meter or a tenth of a micron. At the SSC one might hope to do a little better.

This arrangement would be especially useful for detecting sources of gravity waves that put out pulsed or periodic signals, Melissinos suggests.

Right now the designers of the SSC are concentrating on basic questions of overall design and bread-and-butter particle physics, but these suggestions remain for them to consider when they get to the appropriate level of detail in their planning. *– D.E. Thomsen* as completely as possible with detecting equipment. "Four-pi" is mathematical jargon for a complete sphere. These detector designs have evolved over the years, and they will probably continue to evolve until the hardware is finally screwed down – or maybe until it is torn down. (One proposed design from previous years was completely junked at this year's meeting.)

The changes arise from new discoveries in ongoing experimental physics, from new theoretical insights and from developments in detecting technology. In this year's workshop, as in those of previous years and perhaps those also of a couple of years to come, the sessions in which the physicists considering particular kinds of particles got together with the hardware specialists tended to begin with someone going to the blackboard to draw as the others called out their desires for this or that piece of equipment.

In one such session, consideration started with the calorimeter that forms the centerpiece of each of these designs. This one was 2 meters in radius and 12 meters long – though some in the group thought it might be made shorter. A calorimeter consists of alternating layers of something dense and heavy like uranium that takes energy from passing particles and so enables observers to calculate how much energy they started with, and something that records the particles' presence. Inside the 2 meters of this calorimeter there will also be equipment to image the tracks of the particles. The consensus was that 1.5 meters of depth would be required for the tracking. The woman at the board drew it in.

Someone mentioned a flux return. This calorimeter will have a solenoidal magnetic field provided by a 7-meter superconducting coil. The field will bend the trajectories of electrically charged particles and aid their identification and measurement. The field must loop back outside the calorimeter and rejoin itself at the other end. In the open it could interfere with equipment placed outside the calorimeter. A lot of iron is provided to confine it. Add half a meter for the coil and a meter of iron for the flux return.

"Do we need to go beyond a calorimeter and tracking?" someone asked.

People interested in B particles and Higgs particles definitely want more. They want to be able to discriminate electrons and muons from the background. So 3 more meters of muon identifiers were added. The sketch then called for an object 16 meters in diameter and more than 12 meters long when end pieces are added. This is a small one. The other four are larger. All but one have magnetic calorimeters.

Questions of adjustment and accommodation continually arise in these discussions. As one discussion leader put it, "What components of the detector would you least like to give up? Suppose we came back and said the momentum resolution had to be poorer. How much compromise would you be willing to make?"

These large detectors are beginning to have family resemblances. Advocates of a dipole magnetic field point out that the UA1 detector that has done outstanding work at the CERN laboratory in Geneva, Switzerland, is a dipole. Another CERN detector, L3 (SN: 1/19/85, p.45), which is being built for CERN's new collider LEP, may have an offspring at the SSC. Samuel C.C. Ting of CERN described the proposal, which proponents call L3+1. "We're not good at naming these things," Ting confides. "We were never able to find a correct name."

L3, which is well on the way to completion, involves 440 physicists, represents an international industrial effort and will contain more iron than the Eiffel Tower. According to Ting, L3+1 will be even more collossal. An attempt to provide precision lepton (electron and muon) detection in the trillion-volt energy region, it will be an experiment lasting 10 years and involving "God knows how many physicists."

Ting and others believe that precise measurement of leptons will be an important way of discovering new phenomena at these ultrahigh energies. To do it, L3+1 will put lepton identifiers around a 17,700-ton magnet, which will provide a 7,500-gauss magnetic field in a 300-ton calorimeter. The whole detector will be 23.8 meters high and 20.8 meters long, using 27,500 tons of iron. They estimate a cost of $93 million.

In his summary talk Cashmore rated each of the proposed general-purpose detectors on a scale of 10 for each of its important characteristics. When he had added and weighted all the scores, all five detectors came out more or less even. Time and the development of detail will indicate preferences, he said.

As these are items whose cost goes into the hundreds of millions of dollars, an important question is how many of them the SSC will need. Obviously one, says Cashmore, and preferably at least two. There will probably never be another accelerator equal to the SSC in energy, he notes, so it would be good to have at least two independent detectors to confirm each other's discoveries. □