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Particle Physics Braces for the Next Big Thing

By JAMES GLANZ

GENEVA — Gerard Bachy, an engineer, stands 250 feet underground in an immense, bottle-shaped cavern that scientists around the world might regard as a kind of magic lantern. Thousands of those scientists hope, in effect, to rub this lantern and conjure a mysterious subatomic particle called the Higgs boson that their most trusted theories say is the source of all mass in the universe, the reason matter has weight.

CERN
Torsten Akesson, left, a spokesman for the particle detector Atlas, and Gerard Bachy, Atlas' chief engineer, inside the cavern that will house it.

If they are granted a few more wishes, those scientists may find strange things predicted by more speculative theories, like new dimensions, beyond the usual four, hidden in the fabric of space, and swarms of other unknown particles with odd properties — discoveries that would remake humanity's view of the cosmos.

Mr. Bachy is the chief engineer for a colossal particle detector called Atlas that will be assembled, piece by piece, inside the cavern once it has been fully carved out of the gray rock. Science being what it is, researchers hope to create detectable bits of matter and explore reality not by actually putting their palms to a lamp but by smashing together other particles at a point about 30 feet below where Mr. Bachy is standing.

A vertical tunnel for lowering detector parts from the surface tapers away over his head. Mr. Bachy, who is French, reaches for an analogy to describe the task of constructing the 7,000-ton detector, which will nearly fill the cavern when finished.

"In matter of space, I would say it is like a submarine," he said. "But in matter of technical complexity, it's close to the space program."

CERN
Prof. Luciano Maiani of CERN laboratory made a critical choice in the race for the Higgs boson.

Under construction here at CERN, the leading European particle physics laboratory, Atlas will be one of two giant detectors huddled around what will be the world's most powerful particle accelerator. Known as the Large Hadron Collider, the accelerator will occupy the same underground tunnel, a circle 17 miles in diameter, that now houses a less powerful machine that is marked for demolition. If all goes as planned, the $4 billion machine will begin collecting its first data in 2005.

The project's organization might be called massively international. Atlas alone will involve 1,800 scientists in 34 countries, including more than 30 institutions in the United States, which will contribute a total of about $500 million to the overall L.H.C. project.

The new accelerator will not be alone in its quest. At the Fermi National Accelerator Laboratory, near Chicago, an accelerator called the Tevatron is being upgraded and will begin collecting data in March. Although it will be less powerful than the

L.H.C., the Tevatron has a chance of snatching away a discovery of the Higgs and other particles because it will start operating earlier.

Whoever gets there first, scientists all over the world are bracing for a flood of discoveries that could help them sort out nature's order at its deepest levels — or leave them horribly confused.

"We have big expectations of what may appear at the new colliders," said Dr. Marcela Carena, a theorist at Fermilab. "At the moment, we have a very good understanding of our world, but we know that this understanding is not final. We really want to get deep into the essence of particle physics and deep into the essence of understanding how nature works."

Dr. James Siegrist, a professor of physics at the University of California at Berkeley and board chairman of the American institutions collaborating on Atlas, said that even if the Tevatron wins the Higgs race, there should be plenty of other discoveries to go around.

"We would be astounded if we turned on and the Higgs was the only thing that was there," he said.

Particle Politics

Beyond the scientific intrigue, the push to dig deeper into the structure of matter and space comes with a heavy dose of politics as well.

Since July, the accelerator — called LEP, for Large Electron-Positron collider — that is now in the circular tunnel to be occupied by the L.H.C. has been generating sketchy data hinting that it may already be seeing the Higgs. (That accelerator has its own set of four underground detectors, each much smaller than Atlas.)

Scientists on the experiments pleaded with the laboratory's management to delay the start of L.H.C. construction for a year so that they could either confirm or refute the evidence, but the request was ultimately turned down by CERN's director general, Prof. Luciano Maiani.

The decision not to change plans in order to chase one of the most important prizes in science has divided the worldwide physics community, which is already trying to form a consensus on what the successor to the L.H.C. might be — probably a decades-long project that would require the participation of many countries.

"Politically and scientifically, it's a tenuous time in our field in thinking about the future," said Dr. Howard Haber, a particle physicist at the University of California at Santa Cruz.

Quickly determining the Higgs's existence and properties would give a powerful boost to that project, he said, as well as guiding physicists who are groping for a more encompassing theory of the cosmos than they have now. "The benefits of the Higgs discovery would be enormous," Dr. Haber said.

Prof. Torsten Akesson, a physicist at Lund University in Sweden who is a deputy spokesman for Atlas, agreed that the evidence was consistent with what was expected from a Higgs detection. But he said that the evidence was sketchy enough to be a statistical fluke and that he favored moving ahead with the new machine.

Even Dr. Gordon Kane, a particle theorist at the University of Michigan who expressed shock at the decision to close the machine, said the coming wave of discoveries could salve many wounds.

He said new particles beyond the Higgs could begin turning up at the Tevatron if an advanced but still speculative particle theory called supersymmetry is correct. The L.H.C. would then be able to probe more deeply into the predictions of supersymmetry, which seeks to erase lingering mysteries and inconsistencies in the established theory of the structure of matter, called the Standard Model.

"It will be unbelievably exciting," Dr. Kane said, "and just really an astonishing achievement for mankind. I really do think it will rather deeply affect people's view about the meaning of the world."

Recipe for Reality

The excitement begins with the Higgs and the Standard Model, a tried-and-true theory that has become the bedrock of particle physics over the last several decades.

"Once upon a time, we understood very little about particle physics," said Dr. Alvaro de Rujula, a CERN theorist. "That was prior to 1970," he said, referring to the years before the Standard Model began falling into place.

There are four known forces in nature: the strong force, which holds atomic nuclei together; the weak force, which causes radioactive decay; electromagnetism, a combination of electric and magnetic forces; and gravity.

The Standard Model encompasses all known particles as they interact via the first three forces; a separate formalism, Einstein's general theory of relativity, deals with gravity.

The model separates fundamental particles into three great classes: quarks and leptons, which are the subatomic building blocks of matter, and bosons. The bosons are the vehicles, or force carriers, by which all particles interact. For instance, photons, or particles of light, transmit the electromagnetic force, while particles called gluons transmit the strong force.

Quarks and leptons differ in that only the former exchange gluons, allowing them to interact via the strong force. Both types of particles can feel electromagnetic and weak forces.

While that distinction may sound abstract, it lets physicists account for all known matter in the universe. The strong force binds quarks together to create protons and neutrons, which collectively form the nuclei of atoms. Electrons, which are in the lepton family, orbit the nuclei to complete the atomic structure.

Other known subatomic particles either fall into the lepton family or can be explained as different combinations of quarks.

When tested against experiments, the predictions of the Standard Model "turned out to be correct with a level of precision which is astonishing," Dr. de Rujula said.

Even more impressive, the model is not simply a zoological arrangement of the particles. Within the model, their properties are largely determined by elegant though highly abstract principles involving mathematical symmetries.

There is at least one major glitch in this elegant picture. The preferred menu of particles predicted by this model, in its simplest and most symmetrical form, is one in which all particles are exactly the same and have zero mass.

That Last Building Block

To rescue the standard model from this absurd prediction, physicists have postulated an entity called the Higgs field, which breaks some of the symmetry and allows particles to have mass. The field exists as a well of energy permeating all of space and interacting by a sort of frictional or viscous force with particles; the greater the friction experienced by a given particle, the higher its mass. (The friction can also be thought of as the cause of the inertia of massive bodies.)

The energy cannot be detected directly, but physicists can use that friction to shake up the field and knock a new particle from it: the Higgs boson. The physicists do that by smashing together ordinary particles in accelerators.

For all its importance, the Higgs, which some theorists regard as an unattractive but unavoidable expedient, remains the last undetected particle whose existence is predicted by the Standard Model.

"It's presumably the ugliest feature of the theory; it's also the most indispensable part," Dr. de Rujula said. "It would help a lot if we found it."

The precise mass of the Higgs is not predicted by the model. The higher its mass, the more powerful the accelerator required to create it. That is because Einstein's equation showing the equivalence of mass and energy allows the violence of collisions in the machine to be turned into a particle.

The hints from the existing CERN accelerator, LEP, suggest a Higgs that is light by physicists' standards, around 115 billion electron volts, or GeV. A proton weighs about 1 GeV.

Once created, the Higgs would live too briefly to be seen directly, so those hints consist of detections of the sprays of other particles it is thought to decay into.

A Higgs of 115 GeV, or slightly heavier, would be just within the reach of the Tevatron. The L.H.C. could see Higgs particles all the way up to about 1,000 GeV.

But Wait, There's More

Alas, for all the beauty and experimental success of the Standard Model, physicists know that it cannot be the end of the story. That is why they are sure they will bag something besides the Higgs in the new accelerators.

"The Higgs would be the last building block of the Standard Model," said Dr. Joshua Frieman, a physicist at Fermilab and the University of Chicago. "We have strong reason to believe that the Standard Model is not in itself a complete theory."

Some of those reasons are technical, some are aesthetic and some are both. On the aesthetic level, physicists are puzzled by the wildly differing strengths of the three forces in the model, each of which must be determined separately from experimental data, rather than fixed by some underlying principle. Physicists believe that at very high interaction energies, the forces should all merge, or unify, into a single universal force. But the Standard Model does not let them do that.

The same unattractive messiness turns up in the particle masses. While the Higgs mechanism does allow particles to have mass, each value has to be individually determined from experiments and plugged into the theory. Once again, there is no apparent pattern.

And in a glaring shortcoming, all attempts to graft the fourth force, gravity, onto the Standard Model have failed. It seems very unlikely that two separate unrelated theories govern the universe.

The technical failings of the model are, if anything, even more painful for the quantitatively minded physicists. According to the weird rules of the subatomic quantum world, a particle like the Higgs spends part of its lifetime sharing its existence with other particles — in essence, becoming other particles part of the time and picking up some of their mass. In the Standard Model, if all of those contributions were taken seriously and added up, the theoretical mass of the Higgs would explode beyond any reasonable value.

Theoretical calculations show that this last failing is closely related to the "hierarchy problem," the name physicists give to the unsolved question of why all four forces have such vastly different and unexplained strengths. The feebleness of gravity compared with all the others is especially problematical.

For all these reasons, said Dr. Carena of Fermilab, particle theorists "are very much inclined to believe that there should be some new physics beyond the Standard Model."

One possible extension, a theory called supersymmetry, has been studied intensively by Dr. Carena, Dr. Kane of the University of Michigan and many others. The theory predicts that each particle in the Standard Model has a yet-undiscovered partner that could appear as the new accelerators begin operating.

The particles, with whimsical names like squarks (partners of the quarks), selectrons (partners of the electrons) and gluinos (partners of the gluons), would exactly cancel their partners' exploding contributions to the calculated mass of the Higgs, restoring balance to the theory.

Although it does not fully include gravity, supersymmetry also seems to allow for the possibility that the other three forces unify at high energies. "Gluinos, winos, zinos, higgsinos," said Dr. Kane, listing some of the partners that could show up first. Winos and zinos (both rhyme with SEA-knows) are the partners of W and Z particles, which carry the weak force. The higgsino is the partner of the Higgs.

Seeking Extra Dimensions

Some physicists hope that an even more encompassing formalism called string theory will not only do all that supersymmetry does, but will also include gravity as well as predicting the strength of all the forces and the masses of the particles.

The mathematically arduous theory is still far from doing all that, but it has suggested a weird new possibility for taming the hierarchy problem that could have measurable experimental consequences.

The strings supposedly exist in 10 dimensions, and since our world apparently has only four dimensions, theorists speculate that entities related to the particles that are thought to carry the gravitational force could be created in the accelerators and speed away into the extra dimensions. That would leave behind a mysterious deficit of energy.

The attraction of extra dimension comes because theoretical calculations show they might solve part of the hierarchy problem.

"Certainly the prospect of identifying a signal for these things at a collider is a great hope," said Dr. Lisa Randall, a professor of physics at the Massachusetts Institute of Technology and innovator in some of the theories.

At CERN, many of those hopes center on the two big detectors, including Atlas, which will be a barrel- shaped package of radiation-resistant wires, magnets, silicon and microelectronics 150 feet long when finished. It will have to sort out the debris from collisions occurring every billionth of a second and handle data rates roughly equivalent to the transmission of 20 simultaneous telephone conversations by every person on Earth.

Moreover, while some of the parts are being assembled at CERN, said Dr. Ana Henriques Correia, a physicist who leads the construction of one section of the detector, most will arrive from far-flung laboratories around the world and then be lowered into the underground cavern for assembly. "The engineering component of this experiment is much, much bigger than any experiment until now," she said.

Mr. Bachy, the Atlas chief engineer, says in the cavern that he appreciates the grand plans of the physicists to change humanity's perspective on the cosmos using the detector he is building. But when asked about his greatest worry for the project, he steers clear of advanced particle theories or new dimensions. "Something which doesn't fit," Mr. Bachy said, glancing at the tunnel over his head.

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