City College of the City University of New York have recently found a symmetry between the resistivities measured near the transition between two phases,[8] which is very much like the symmetry seen by the Princeton–Illinois team. In this study, the system was a silicon metal-oxide semiconductor field-effect transistor, in the absence of a magnetic field.

At first blush, this experiment might appear to confirm the Princeton–Illinois result, but, in fact, it raises some questions about the interpretation of the experiments. First, it suggests that the symmetry, at least in the City College experiment, has nothing to do with charge–vortex duality, because of the absence of magnetic field-induced vortices. Second, it makes one wonder whether some other mechanism is at work, if a similar symmetry can arise in such apparently diverse systems.

Superuniversality

The possible appearance of duality near a phase transition in the quantum Hall state is of great interest to those who have been studying the nature of those phase transitions. There are several, ostensibly different, phase transitions: from a fractional quantum Hall state to an insulating state, from an integer quantum Hall state to an insulator, from an integer quantum Hall state to another integer quantum Hall state, and so forth. But experiments indicate that at least some of these transitions are governed by the same critical exponent and amplitudes.[9]

Several theorists have proposed the concept of "superuniversality," according to which all the quantum Hall transitions are governed by the same critical exponent.[6,10] That is, in a way, a surprising assertion, as one might expect that the different particles and different statistics governing each phase would be quite different. Kivelson feels, however, that the Princeton–Illinois results strengthen the case for superuniversality: If the particle dynamics are fairly independent of the phase of the system, as the Princeton–Illinois experiment indicates, then the phase transition can't depend very strongly on the properties of the individual phases.

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Auger Project Seeks to Study Highest Energy Cosmic Rays

Fifty-nine years ago, Pierre Auger discovered the extensive air showers generated by high-energy cosmic rays when he saw that two Geiger counters several hundred meters apart in the Alps were recording coincident counts. Five years from now, if the funding is forthcoming, a pair of 3000 km^2 air-shower detector arrays bearing his name will begin their concerted assault on the greatest remaining mystery posed by cosmic rays. The Pierre Auger Project, a collaboration of physicists and astronomers from 40 institutions in 19 countries, plans to have one array in Utah monitoring the northern sky while an identical array in the high desert of western Argentina keeps watch over the southern sky.

The mystery that this $100 million undertaking seeks to address is the provenance of the highest-energy cosmic rays, with energies of order 10^{20} eV. These are single-particle energies comparable to the kinetic energy of a tennis ball in flight—far beyond anything one can make in a particle accelerator. Fewer than a dozen cosmic-ray events with incident energy above 10^{20} eV have been recorded in the 35 years since the first one was discovered by John Linsley and colleagues at a modest air-shower array near Albuquerque.

The observer's principal problem is the painfully low flux at these energies. The steeply falling high-energy cosmic-ray energy spectrum yields only about one incident event near 10^{20} eV per square kilometer *per century*. Japan's Akeno Giant Air Shower Array, the largest now in existence, covers only 100 km^2. Even with its 3200 water-Čerenkov detector modules arrayed over 6000 km^2, the Auger Project is expected to harvest only about 30 events above 10^{20} eV per year in each hemisphere. The highest energy cosmic-ray event ever seen, with an incident energy of 3×10^{20} eV, was recorded in 1991 by the Fly's Eye atmospheric-fluorescence detector in Utah.

> We have no idea how protons can get accelerated to energies above 10^{20}eV, but they occasionally do. Existing air-shower arrays have seen less than a dozen in 35 years.

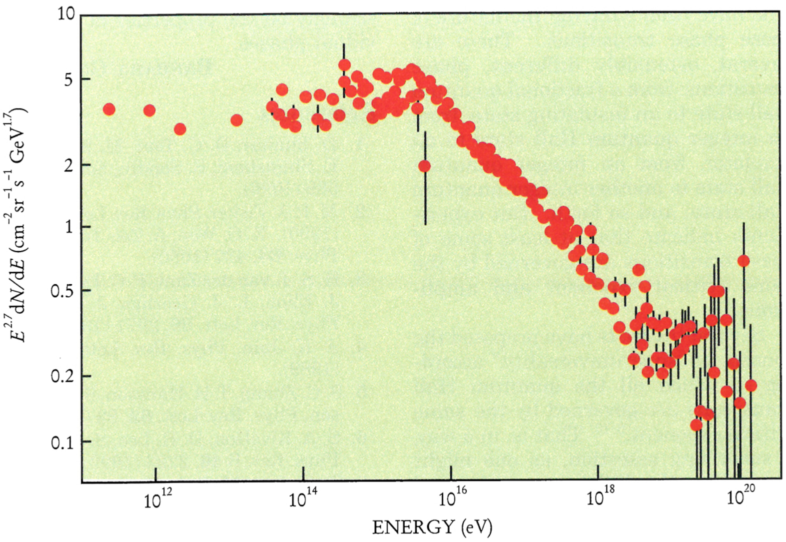
Why bother?

There are several very important reasons to wonder about cosmic-ray particles hitting the Earth's atmosphere with energies exceeding 10^{19} eV. The steep power-law descent of the high-energy cosmic-ray spectrum kinks and flattens somewhat at 10^{19} eV. (See the figure on page 20.) That feature, called "the ankle" because the spectrum beyond the "knee" at 10^{16} eV resembles a dangling leg, suggests the emergence of a population of cosmic rays from outside the Milky Way galaxy. The Galactic magnetic field is too weak to confine protons above 10^{19} eV.

But there seems to be no credible astrophysical mechanism, either inside or outside the Galaxy, for accelerating protons to energies above 10^{19} eV. "If we hadn't actually seen the 10^{20} eV events," says theorist John Bahcall (Institute for Advanced Study), "there'd be many convincing papers proving that such high energies are impossible." So one has to look for exotic new kinds of sources, perhaps even involving new particle-physics phenomena or topological spacetime defects left over from the Big Bang.

Theoretical flights of fantasy, however, are rather constrained by the fact that no charged particle traversing the cosmos can maintain an energy above 10^{20} eV for more than a few hundred million light-years. That's because 5×10^{19} eV is the threshold energy for protons to create pions in collisions with the ubiquitous 2.7-kelvin blackbody photons of the cosmic background radiation. In fact, the record 3×10^{20} eV invader seen by the Fly's Eye in 1991 could not have traveled farther than 150 million light-years, even if it began its journey with an energy of 10^{22} eV. By cosmological standards, that's still in the well-scrutinized local neighborhood.

At ordinary energies, the arrival direction of a cosmic ray tells us noth-



ENERGY SPECTRUM of high-energy cosmic rays, multiplied for display purposes by $E^{2.7}$, where E is the energy of the incident primary. Beyond the "knee" at 10^{16} eV, the spectrum falls very steeply until the "ankle" near 10^{19} eV, where its flattening suggests the emergence of an extragalactic component. An air-shower array can expect to see about one event above 10^{20} eV per km^2 per century. (Adapted from ref. 2.)

ing about its origin; charged-particle trajectories are thoroughly scrambled by the microgauss magnetic field of the Galaxy. But above 10^{19} eV, the trajectory of a proton is so nearly straight in the Galactic and intergalactic magnetic fields that one can hope, with sufficient statistics, to identify point sources on the celestial sphere.

Adult-onset cosmology

"I knew nothing of this fascinating enigma before I started going to cosmic-ray conferences in the late 1980's," recalls James Cronin (University of Chicago), leader of the Auger Project. Nobel laureate Cronin, who has spent most of his career studying elementary particles created by high-energy accelerator beams, readily admits to being afflicted with "adult-onset cosmology," a condition currently rampant among senior particle physicists. "The gargantuan collaborations nowadays at the big accelerators do essential and admirable work," he says, "but some of us old-timers are not temperamentally suited for them. On the other hand," he adds, "particle physicists going into astrophysics do bring along some very useful experience, particularly in complex data acquisition and the construction of big international facilities. Besides, the center-of-mass energy of a 10^{20} eV proton hitting an atmospheric nucleon exceeds what you'll be able to get at the Large Hadron Collider [see page 58 of this issue] by a factor of 30. I'm not saying it's very likely we'll discover new particle physics," Cronin cautions, "but it is worth recalling that almost all the new particles discovered before the mid-1950s were seen first in cosmic rays."

The Auger Project's Northern Hemisphere site, on grazing land 1400 m above sea-level in Millard County, Utah, was selected by the collaboration in September over competing sites in Mexico and Spain. The Southern Hemisphere site, chosen a year earlier, sits at a similar altitude in the shadow of the Andes, in Argentina's Mendoza province. One wants an altitude at which the cascade of particles initiated in the atmosphere by the incident primary has reached maximum population and lateral extension before it begins to die out.

Hybrid

The clarity of the air and the absence of light pollution are also important considerations, because the Auger Project sites are to be hybrid facilities: In addition to its array of 1600 water-Čerenkov ground detector tanks, which will be quite indifferent to clarity or even daylight, each site will have three atmospheric-fluorescence telescopes, not unlike the venerable Fly's Eye, deployed among the ground detectors. Above 10^{17} eV, observers can avail themselves of the trail of atmospheric nitrogen flourescence a cosmic ray leaves in its wake. Unlike atmospheric Čerenkov radiation, the fluorescence is isotropic; the trail across the sky can be imaged by any local telescope, irrespective of the cosmic-ray's incident direction, as long as the night is dark and clear enough.

In each fluorescence detector, a mosaic array of mirrors will focus the sky onto a plane of photomultiplier tubes. The longitudinal profile of a fluorescence trail provides useful information about the mass of the primary particle, and the integrated luminosity measures the roughly 90% of the primary's energy that is dissipated in electromagnetic showering—as distinguished from the energy deposited in the ground by muons. The muon component, originating in the decay of pions and kaons produced in nuclear collisions in the atmosphere, increases with the mass number of the incident primary nucleus. If an ultrahigh-energy primary turns out to be a gamma, the muon population of its shower will be unusually scanty.

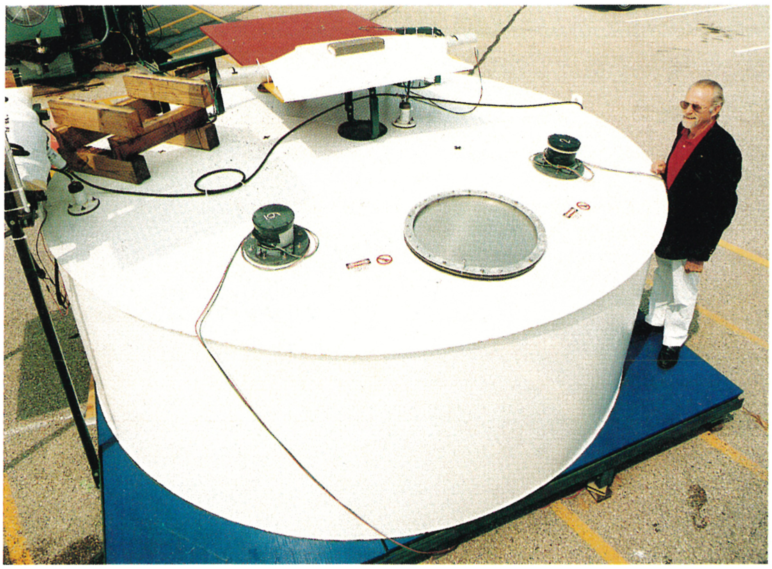
Unfortunately, the fluorescence detectors can work only on clear, dark nights. At the chosen sites it is estimated that they will provide useful information only 10 or 15% of the time, limited primarily by moonlight.

The ground arrays

The air shower generated by a 10^{20} eV proton includes about 10^{11} charged particles—mostly electrons and positrons with energies near 10 MeV—spread out horizontally over a diameter of about 4 km. The muons, about 10% of the total, have typical energies near 1 GeV. All of these relativistic charged particles traveling through water generate an amount of Čerenkov light that depends, to good approximation, only on path length.

The 1600 ground detectors at each site will be spaced 1.5 km apart over an area somewhat larger than the state of Rhode Island. Each detector will be quite simple and inexpensive—a light-tight, pillbox-shaped container holding about 12 tons of water monitored for Čerenkov light by three 8-inch photomultiplier tubes. The array will not have to be cabled together. A solar panel on each detector will power all of its electronics and its radio communications with a central computer and satellites of the Global Positioning System. (See the photo on page 21.)

The incident direction of a cosmic ray can be determined within a degree or two from arrival-time differences between the half dozen or so detectors that record the shower, and even better than that when one also has tracking information from the flourescence detectors. The distribution of Čerenkov light among the struck ground-array detectors provides a measurement of the primary's incident energy with an uncertainty of about 20%. For events that occur on clear, dark nights, the



FERMILAB

PROTOTYPE ČERENKOV DETECTOR, built at Fermilab for the Pierre Auger Project, contains 12 tons of water monitored by three 8-inch phototubes. Design details are still being optimized by Peter Mazur (right) and colleagues at several collaborating institutions. Each of the project's two air-shower sites will have 1600 such detectors arrayed over 3000 km^2. Each detector will communicate with a central computer only by solar-powered radio.

fluorescence detectors provide an independent energy measurement. The penetrating GeV muons make themselves conspicuous in the ground detectors by the large, distinctive Čerenkov light pulses they generate as they traverse a water tank. The far more numerous low-energy electron and positron tracks are much shorter, because they are stopped in the water.

Optimizing

The Auger collaboration produced a "reference design" in October 1995. But hardware development and computer simulation continues at the various collaborating institutions, with the goal of optimizing the components of the proposed arrays and their overall layouts. For example, the Fermilab prototype water-Čerenkov detector in the photo may well give way to a less expensive design with a flexible plastic container supported by a corrugated steel housing of the kind used to store water for cattle. One function of the detector housing will be to stop any .22-caliber rifle bullets from some misguided soul out in the hinterlands for an afternoon of target practice.

Last December the Auger Project submitted its request for $30 million from the National Science Foundation and the Department of Energy over the next five years. "We have a fairly solid commitment from Argentina, Brazil and Mexico for an additional $30 million," Cronin told us, "and I'm confident we'll be able to raise the remaining $40 million from our European, Japanese, Indian and Australian collaborators—if the US funding comes through."

A recent report[1] by the Akeno group lends provocative support to the hope that the Auger Project will be able to identify point sources for the highest energy cosmic rays. Having harvested 36 events above 4×10^{19} eV in six years of operation, the group reports statistically marginal evidence for three point sources on the sky, two of them very close to the plane of the local cluster of galaxies. One of those two involves a pair of events with energies of 2×10^{20} and 5×10^{19} eV, separated in time by two years, but in direction by less than 2°. If any of these point sources is real, the Auger Project, with its ability to accumulate statistics, at either site, 30 times faster than the 100 km^2 Akeno array, should be able to confirm it in just a few years of operation. Then the next question will be: Does the source have any optical, radio or x-ray counterpart?

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