ium atoms, a number of groups have done an amazing variety of experiments—demonstrating atom lasers, studying the interaction of two condensates, exploring the regime of second sound and so forth. BEC researchers now have one more, qualitatively different condensate to play with. For example, Bose–Einstein condensates in hydrogen might offer more promise for exploring effects that depend on large numbers of atoms, because hydrogen atoms do not have to be laser cooled, a process that grows more inefficient as the number of atoms increases. Hydrogen condensates should also allow precise comparison with many-body theories because the hydrogen interactions are so well known from exact theoretical calculations. However, such precise tests are increasingly available for condensates in the alkalis, because the theorists, no doubt stimulated by the recent progress, now have an excellent handle on the interactions in those atoms as well.

Greytak mentioned that the atoms excited from the hydrogen condensate by the absorption of two copropagating photons pick up enough momentum to be ejected with low divergence, so that they might provide a narrow, intense beam of coherent atoms. (This has recently been done with sodium atoms from a condensate.) The hydrogen system also lends itself to high-resolution spectroscopy, with possible applications to metrology. Hänsch told us that a hydrogen Bose–Einstein condensate has potential as a fountain of cold hydrogen atoms, in which the resolution of the 1S–2S two-photon resonance could approach the natural linewidth of 1.3 Hz. Finally, the MIT researchers hope to use the low-temperature gas to continue work they have already begun, exploring the interactions of ultracold atoms with solid or liquid surfaces.

Of course, superconductors and superfluids are also examples of Bose–Einstein condensates, albeit in much more strongly interacting systems. One challenge for the future is to see a Bose gas act as a superfluid in the sense of having persistent currents.

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Giant Air Shower Array Shows Cosmic-Ray Spectrum Violating Greisen Cutoff

For almost nine years, the Akeno Giant Air Shower Array in Japan has been accumulating data on the most energetic cosmic rays. AGASA, with its 111 scintillation detectors deployed over 100 km^2, is by far the world's largest air shower array. (See PHYSICS TODAY, January 1998, page 31.) This collaboration of 14 Japanese institutions is led by Masahiro Teshima (University of Tokyo). The recent publication[1] of its observations through October 1997 appears to confirm a provocative astrophysical paradox: How can it be that the cosmic-ray energy spectrum is extending beyond 10^{20} electron volts without any clear sign of a cutoff?

In 1966, not long after the discovery of the 3 K cosmic microwave background (CMB), Kenneth Greisen at Cornell pointed out that this ubiquitous swarm of low-energy photons must impose a strict upper limit on the cosmic-energy spectrum. Above a threshold energy of about 5×10^{19} eV, a proton plowing its way through the cosmic microwave backgound would be producing pions (and e^+e^- pairs) in

> The highest-energy cosmic rays appear to be thumbing their noses at what was thought to be an inviolable upper limit.

collisions with the low-energy photons at such a rate that it could not maintain itself above the threshold energy for more than a few tens of megaparsecs. But the only plausible astrophysical sources of such ultrahigh-energy protons are radio-loud quasars and active galactic nuclei of a kind that are simply not found within 100 Mpc of us. (One Mpc is about 3 million light-years. The Andromeda galaxy, our nearest full-grown neighbor, is about 1 Mpc away.)

This abrupt end predicted for the cosmic-ray spectrum has come to be called the Greisen-Zatsepin-Kuzmin (GZK) cutoff, because it was independently pointed out, also in 1966, by Georgi Zatsepin and Vadim Kuzmin in the Soviet Union. One can't get around the GZK cutoff by assuming that the highest-energy cosmic-ray primaries are really heavier nuclei rather than protons. Such nuclei would indeed have higher photopion-production thresholds, but too few would survive photodissociation over a long journey through the CMB.

Where's the cutoff?

So why does the newly published AGASA high-energy spectrum, repro-

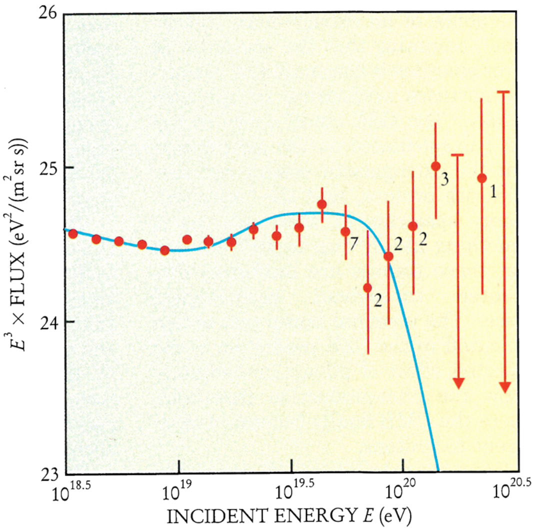

FIGURE 1. ENERGY SPECTRUM of high-energy cosmic rays observed by the AGASA shower array. The vertical axis is multiplied by E^3. The blue curve indicates the expected GZK cutoff, which the data seem to ignore. The highest energy data points are labeled with the observed number of events. The arrows indicate upper limits. (Adapted from ref. 1.)

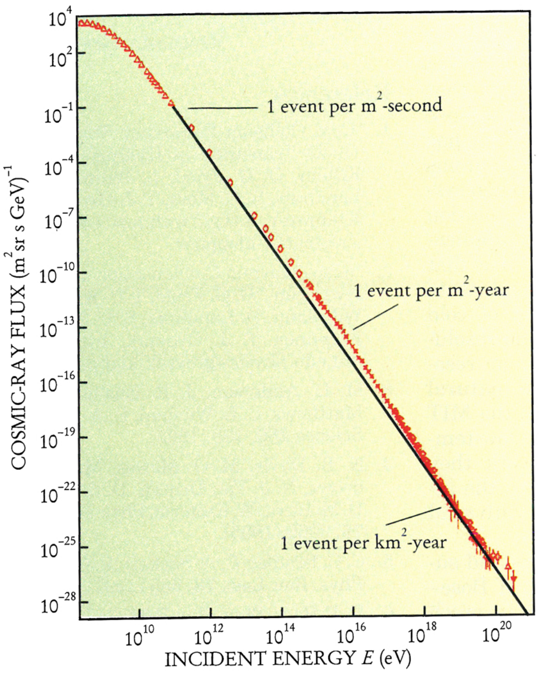

FIGURE 2. WORLD COMPILATION of the cosmic-ray spectrum over 12 orders of magnitude in energy. The black line indicates, for comparison, an E^{-3} power-law falloff. Expected observation rates by a ground air-shower array are indicated at various energies.

duced in figure 1, show no evidence of the predicted GZK cutoff indicated by the blue curve in the figure? The rather flat appearance of the spectrum in this figure is a convenient artifice created by multiplying the flux by E^3, where E is the incident energy of the cosmic-ray primary hitting the upper atmosphere. Figure 2, a worldwide compilation over 12 orders of magnitude in energy, shows the flux falling like $E^{-3.2}$ from 10^{16} eV to 10^{19} eV.

At about 10^{19} eV the AGASA data suggest a slight flattening of the spectrum, which might be marking the emergence of an extragalactic component—assuming that the spectrum at lower energies is dominated by cosmic-ray particles originating in our own Galaxy. The GZK cutoff curve in figure 1 is calculated on the assumption that the extragalactic cosmic-ray particles are protons, that the "injection" energy spectrum at their sources is something like E^{-2} up to 10^{22} eV, and that these sources are uniformly distributed throughout cosmological space. The terminal hump just before the cutoff in the GZK prediction is the expected effect of pileup immediately below the pion-production threshold, where the CMB finally becomes transparent to protons.

From the calculated GZK curve, one would expect to have seen less than one event beyond 10^{20} eV in eight years of AGASA exposure. But in fact the group reports six such events. That's still a painfully slow rate: Even if nature is, by some exotic means, circumventing the GZK cutoff, a ground array can expect to record only about one cosmic-ray shower above 10^{20} eV per square kilometer *per century.* Hence the big push for much larger air shower arrays and alternative detection techniques. (See PHYSICS TODAY, February 1997, page 19.)

Energy resolution

The credibility of the AGASA group's provocative result depends crucially on how well the array can measure the energy of an incident cosmic-ray particle. Each of the array's 111 surface detectors is a 2.2 m^2 scintillator that records the passage of charged particles. The scintillator array is augmented, at the moment, by 27 muon detectors that use concrete or lead shielding to distinguish the penetrating muons from hadrons or electrons. A shortage of muons in a shower would suggest that the primary was a high-energy gamma rather than a proton or heavier nucleus.

Neighboring surface detectors are 1 km apart. All are cabled to a central computer. The incident energy and direction of the primary are determined from the spatial and temporal distribution of charged flux signals from the detectors near the shower's core. The more energetic the primary, the denser and wider is the shower of charged secondaries it generates in the atmosphere. Figure 3 shows the spectacular pattern of signals produced by a 2×10^{20} eV event. Recorded in 1993, this most energetic cosmic-ray shower ever seen by AGASA produced signals in 23 detectors, some of them 3 km from the core.

The ground-array data from a shower are translated into the energy of the incident primary by means of an algorithm calibrated by Monte Carlo simulations of atmospheric showering and comparision with spectra up to 10^{19} eV from smaller arrays. The AGASA group estimates that its energy determinations above $10^{18.5}$ eV are uncertain by about ±30%.

The hadronic physics one puts into these shower simulations is burdened by our unfamiliarity with collisions at such energies: A 10^{20} eV proton hits an atmospheric proton with a barycentric energy of about 500 TeV, far beyond anything we've seen in accelerator experiments. Furthermore, whatever the hadronic details, atmospheric showering is surely subject to much fluctuation, as is the process of gathering data by sampling small, widely dispersed detectors.

All this leads to concern that the tail of the energy resolution function might be larger than gaussian. Convolving a steeply falling physical distribution with a nongaussian error function could mask features like the GZK cutoff. Therefore theorists and observers look forward to confirmation of the AGASA result, especially by the complementary technique of atmospheric fluorescence detection. At lower energies, the two techniques agree on the primary's energy within about 10%.

Exotic speculation

Not waiting for more data, the theorists have already been offering us a variety of "new physics" scenarios for the arrival of cosmic rays beyond the GZK cutoff. The least exotic of these is a suggestion by Thomas Weiler (Vanderbilt University).[2] The only thing Weiler requires beyond the standard model of the elementary particles is neutrino masses of order 1 eV contributing to an accumulation of dark matter within about 50 Mpc of our Galaxy. This hypothesis is not without some support from neutrino-oscillation searches and observations of galactic dynamics and clustering. (See PHYSICS TODAY, July 1998, page 17.)

Weiler suggests that very high-energy neutrinos from the decay of pions produced in distant active galactic nuclei would come this way and produce 10^{20} eV protons when they hit the local halo of nonrelativistic dark-matter neutrinos surrounding us. Neutrinos traversing cosmological distances are, of course, immune to the inelastic scattering losses that dictate the GZK cutoff. By the same token, however, their cross section for annihilating with other neutrinos to produce the requisite protons is very small indeed. But Wieler points out that the annihilation cross section experiences enormous resonant enhancement at the barycentric energy corresponding to the 91-GeV mass of the Z^0 gauge boson.

This resonant neutrino annihilation, he calculates, might well produce enough ultrahigh-energy protons and photons to account for the cosmic-ray flux above the GZK cutoff. The majority of these primaries would in fact be photons. But distinguishing between photon- and proton-induced showers is a delicate business that would ultimately serve to test Weiler's hypothesis.

Another way of allowing very distant sources without a GZK cutoff below 10^{20} eV is suggested by Glennys Farrar (now at New York University) and colleagues.[3] They point to a relatively light supersymmetric hadron, designated S^0, whose existence was predicted in the mid-1980s in attempts to expand the standard model. If the S^0 really exists, this neutral bound state of three quarks and a light gluino (the putative supersymmetric partner of the ordinary gluon that holds quarks together) would have all the right properties for explaining the AGASA spectrum, *and* it has not yet been excluded by accelerator searches. Its predicted mass (two or three times that of the proton), neutrality and rather large energy gap before its first pion-production resonance all conspire to let it traverse cosmological distances through the CMB without falling below 10^{20} eV. Simple kinematics tells us that any really heavy hadron could do that, but if it were much heavier than the S^0, it would not lose enough energy in the atmosphere to simulate a high-energy proton shower.

Looking backwards

In both the Weiler and Farrar conjectures, the incident direction of an ultrahigh-energy cosmic-ray shower should point back to its distant astrophysical source. That's because the intergalactic traveler is electrically neutral and therefore impervious to the magnetic fields that bend the trajectories of protons and nuclei. Farrar and Peter Biermann (Max Planck Institute for Radio Astronomy in Bonn) have looked for likely sources in the directions of the five highest-energy cosmic-ray showers for which celestial coordinates are available.

In an upcoming issue of *Physical Review Letters*, they report that every one of these five, within its directional error box on the sky, points back to a compact radio-loud quasar.[4] "The odds against this happening by accident are 200:1," Farrar told us. "We impatiently await AGASA's announcement of the direction of its most recent 10^{20} eV event, so we can go and look." (At these ultrahigh energies, even proton trajectories are so magnetically rigid that they would point back to within a few degrees of their sources.)

Not all the schemes for evading the GZK cutoff involve distant astrophysical sources one could find with a telescope. A number of theoretical conjectures posit the existence of long-lived supermassive particles—with perhaps 10^{12} times the proton mass—either left over from the Big Bang or appearing as decay products of primordial topological defects of the presumed cosmic scalar field. When these supermassive particles finally decay, 10^{20} eV protons and photons would be among their products. The GZK cutoff is circumvented by assuming that the resulting cosmic-ray spectrum we see is dominated by the decay of superheavies accumulated in the local cluster of galaxies.[5] As in Weiler's scheme, the majority of ultrahigh-energy primaries would be photons (from π^0 decay) rather than protons.

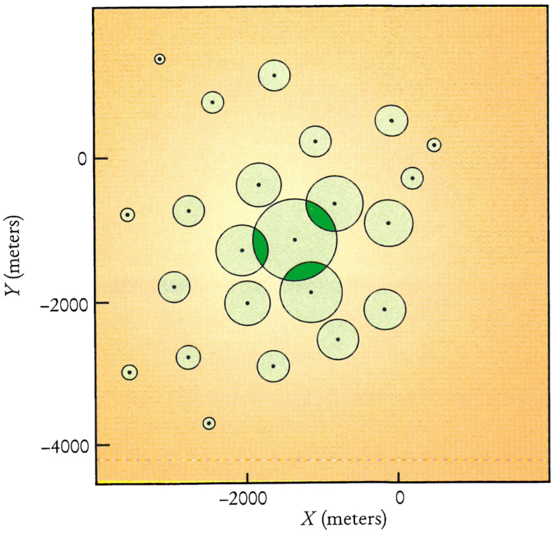

FIGURE 3. PATTERN OF SIGNALS recorded in 23 of AGASA's individual scintillation detectors for a record 2×10^{20} eV event observed in 1993 (second only to a 3×10^{20} eV event recorded by the Fly's Eye). Each AGASA detector is 1 km from its nearest neighbor. The circle widths are logarithmic measures of the number of charged shower particles recorded by each detector.

Looking forward

The most ambitious of the observational proposals still on the drawing boards is the Pierre Auger Project, headed by James Cronin (University of Chicago). Cronin and collaborators propose to build a pair of 3000 km^2 giant air shower arrays, one in Utah, the other in Argentina. Each ground array is to be augmented by atmospheric-fluorescence telescopes that image a high-energy cosmic ray shower passing overhead by the nitrogen fluorescence it generates. In July, DOE and NSF finally approved $7.5 million for the first four years of construction funding, provided that the construction begins with the Southern Hemisphere site and that Argentina contributes its share of the cost.

Currently nearing completion, also in Utah, is the High Resolution Fly's Eye Detector (HiRes), headed by Pierre Sokolsky (University of Utah). HiRes is the binocular offspring of the original Fly's Eye, the prototypical mosaic fluorescence telescope.

"When we start taking binocular data next fall," Sokolsky told us, "we'll already have two years of monocular HiRes data in hand. Assuming the published AGASA spectrum is right, our group should have about 16 events beyond 10^{20} eV by then. So, if the cosmic-ray spectrum really is thumbing its nose at the GZK cutoff, we should all know it with great confidence a year from now, having measured these elusive energies by two quite different techniques."

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Long-Pulse 60-Tesla Magnet Starts Routine Operation at Los Alamos

With the long-pulse 60 tesla magnet now running at Los Alamos, you can study electrical and magnetic properties of many materials.

For experiments in very high magnetic fields, there are DC electromagnets that have operated continuously at fields as high as about 35 tesla, and the National High Magnetic Field Laboratory (NHMFL) expects to generate fields close to 45 T early next year. Some high-field DC magnets are purely resistive, others are hybrids