

area. The thinner the wire, the less ohmic heating for a given spin current density. And once the spin current is transformed to a spin wave in the insulator, Saitoh adds, the transmission generates no ohmic heating.

Although YIG has an exceptionally low spin damping—largely because it can be grown nearly defect free and generates no eddy currents—it's unclear whether that alone can account for the low threshold current densities that are observed. Part of the mystery lies in YIG's complex band structure and the fact that the research team had to rely

on films at least a micron thick. "Thinner YIG films exhibit greater scattering and spin damping, which means researchers will have to turn to other materials to scale dimensions down," explains Burkard Hillebrands (University of Kaiserslautern in Germany). "But that's minor criticism. I feel sure that many groups will follow [Saitoh's] work to optimize experimental parameters and explore more deeply the nature of the spin-wave excitations."

It's premature to speculate on device technologies that may emerge from the research. The transmitted signal is

small: Even with 80 mA coursing through the circuit, the researchers measure an electromotive force less than a nanovolt. But the proof of principle itself plays a crucial role: By demonstrating that one can transmit a spin current into and out of a magnetic insulator, Saitoh, Maekawa, and their colleagues have opened to spintronics a rich new class of materials.

Mark Wilson

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The highest-energy cosmic rays may be iron nuclei

Or perhaps, at energies far beyond what terrestrial accelerators can produce, protons just look fat.

Up against the Andes in the high plains of Argentina, the 3000-km² Pierre Auger Observatory has, since 2004, been recording the particle and fluorescence showers initiated by ultrahigh-energy cosmic-ray (UHECR) particles—mostly protons and fully ionized nuclei—hitting the top of the atmosphere. Such an enormous expanse, studded with 1600 surface detectors watched over by four fluorescence-telescope complexes,

is appropriate because UHECRs become ever more scarce with increasing energy. Above 10¹⁹ eV, one can expect to find only a few dozen CRs per square kilometer *per century*.

A lot has been learned in the past decade from Auger and similar, albeit smaller, facilities worldwide. But a newly reported Auger result challenges much of what had become conventional wisdom.¹ And it has sent astrophys-

cists and particle theorists scrambling for explanations.

Seeking to determine the nuclear identities of the highest-energy CRs, the Auger collaboration examined the development of their enormous showers of secondary particles in the atmosphere. The shower observations seem to indicate a transition, at primary-particle energies *E* of a few times 10¹⁸ eV, from a CR flux dominated by

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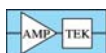
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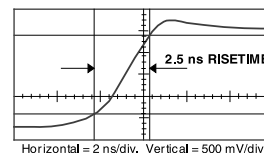
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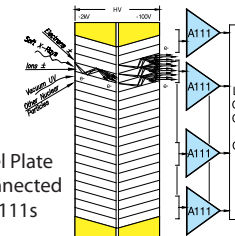


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protons to one increasingly dominated at higher energies by iron nuclei.

A problematic surprise

The new result comes as a considerable surprise: Previously most observations and arguments seemed to support proton dominance at the highest energies. And indeed, in the weeks since its publication, the Auger paper has not gone unchallenged.

The so-called ankle of the CR energy spectrum—a well-known kink near 4×10^{18} eV—is related to the transition from galactic to extragalactic predominance in the CR flux. And the most plausible extragalactic sources are active galactic nuclei (AGNs)—galaxy cores energized by particularly voracious black holes. So a straightforward reading of the new Auger shower data would be that the most energetic nuclei arriving from AGNs are mostly Fe nuclei. But that conclusion poses problems.

For example, if the highest energy CRs really are highly-charged Fe ions, how could their distribution of arrival directions be exhibiting significant correlation with the anisotropic distribution of potential sources in the local cosmos? An Auger study of such correlations concluded last year² that for E above 5×10^{19} eV, the observed correlation was *inconsistent* with an isotropic flux lacking any imprint of the distribution of galaxies within a few hundred million light-years (Mly). One would expect such an imprint for protons, which at those energies are deflected only a few degrees by intergalactic and Milky Way magnetic fields. Indeed, Auger was built with the fond hope that the highest-energy protons would point back to their sources. But the trajectories of Fe^{26+} ions should be severely scrambled by the intervening magnetic fields.

Another reason for presupposing protons is related to the expectation that the highest-energy CRs originate within a few hundred Mly. Above a threshold energy of about 5×10^{19} eV (the so-called GZK—Greisen, Zatsepin, Kuzmin—threshold), a proton plowing through the cosmic microwave background is expected to lose energy by creating pions in occasional collisions with CMB photons. That energy loss creates an effective horizon of about 500 Mly beyond which a proton can't maintain an energy above the GZK threshold. The effect was predicted to produce an abrupt falloff (the GZK cutoff) of the CR energy spectrum at about 5×10^{19} eV. The 2007 discovery of the GZK cutoff at the expected energy by the HiRes fluorescence-telescope col-

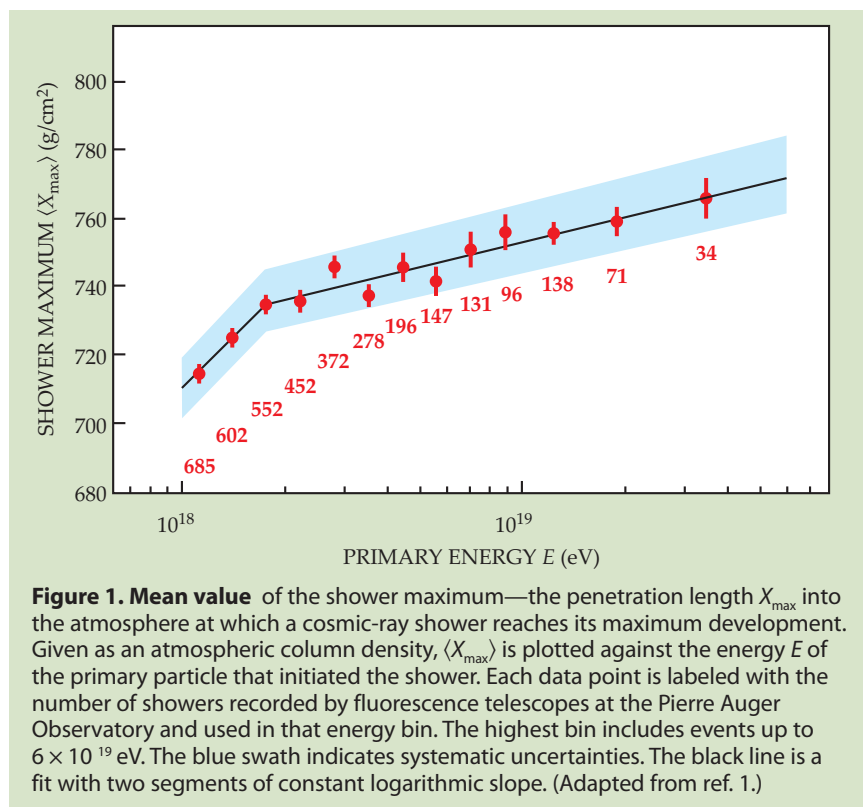


Figure 1. Mean value of the shower maximum—the penetration length X_{max} into the atmosphere at which a cosmic-ray shower reaches its maximum development. Given as an atmospheric column density, $\langle X_{\text{max}} \rangle$ is plotted against the energy E of the primary particle that initiated the shower. Each data point is labeled with the number of showers recorded by fluorescence telescopes at the Pierre Auger Observatory and used in that energy bin. The highest bin includes events up to 6×10^{19} eV. The blue swath indicates systematic uncertainties. The black line is a fit with two segments of constant logarithmic slope. (Adapted from ref. 1.)

laboration was taken as strong evidence of a proton-dominated UHECR flux (see PHYSICS TODAY, May 2007, page 17).

Proton dominance was also bolstered by the presumption that the binding energies of nuclei are too puny to survive the jolts a nucleus would experience in the accelerating engine of an AGN. On the other hand, if the acceleration is gradual enough for nuclei to survive intact, the maximum energy to which a nucleus could be accelerated in an AGN would be proportional to its charge Z , and Fe has the highest Z of any abundant species.

Furthermore, Fe nuclei can travel much farther without fragmenting in collisions with CMB photons than the lighter nuclei can. In fact, the effective horizon imposed by photofragmentation of Fe nuclei above 5×10^{19} eV is roughly the same as the GZK horizon for protons. So what appears in the CR energy spectrum to be a clear GZK cutoff indicative of protons might, in fact, be a photofragmentation cutoff for Fe nuclei. Or the observed cutoff might simply be marking the acceleration limit of some class of extragalactic sources.

The Auger data

For 3754 particularly well-measured shower events, the Auger collaboration has determined the so-called shower maximum—the penetration path length X_{max} in the atmosphere at which

the shower reaches its maximum number of secondary particles. The mean value $\langle X_{\text{max}} \rangle$ for a given E , and its root-mean-square fluctuation, are thought to be informative about the nuclear-species composition of the CR flux at that energy.

Fluorescence telescopes image UHECR showers streaking across the sky in the UV fluorescence of atmospheric nitrogen excited by the charged shower particles. The total luminosity of the fluorescent streak provides a good measurement of E , and X_{max} is deduced from where the streak is brightest. Because fluorescence imaging requires clear, moonless nights, Auger's telescopes record far fewer events than does the surface array of detectors that record the arrival of shower particles on the ground. For its shower-maximum analysis, the collaboration accepted only so-called hybrid events—showers recorded by at least one telescope and the surface array. The surface-array data provide good geometrical reconstruction of the shower's axis.

The penetration length X_{max} to the shower maximum is given as an atmospheric column density. For the dependence of $\langle X_{\text{max}} \rangle$ on E and nuclear mass A , a simplified model of how UHECR showers develop in the atmosphere gives

$$\langle X_{\text{max}} \rangle = \alpha (\log E - \langle \log A \rangle + \beta),$$

where $\langle \log A \rangle$ is the mean logarithm of

A in the CR flux at E , and the hadronic-interaction coefficients α and β are presumed to have no significant E dependence. The depth to which a CR shower penetrates the atmosphere before reaching its maximum development increases with the primary's energy and decreases with its nuclear mass.

Figure 1 shows the observed energy dependence of $\langle X_{\max} \rangle$ for the 3754 Auger hybrid events. The slope, proportional to $1 - d(\log A)/d \log E$, is well described by a straight line with a kink at 2×10^{18} eV, very close to the spectral ankle. The most straightforward implication of the $\langle X_{\max} \rangle$ data, when compared in figure 2a with model simulations for pure-proton and pure-Fe fluxes, is that with increasing energy, the mean nuclear mass of the extragalactic CR flux becomes heavier and heavier. The simulations don't consider intermediate nuclear species abundant in the galactic CR flux because, above 10^{19} eV, their intergalactic photofragmentation horizons are all much closer than iron's.

Figure 2b shows Auger's measurements of the complementary observable $RMS(X_{\max})$, the rms fluctuation of $X_{\max}$ from event to event at a given E . The fluctuation variable has the virtue that its expected composition dependence relies less than that of $\langle X_{\max} \rangle$ on shower-model assumptions. In essence, one expects that the bigger the incident CR nucleus, the less random will be the hadronic cascade it engenders in the atmosphere. And indeed, the Auger fluctuation results appear to make an even stronger case for Fe dominance at the highest energies than do the $\langle X_{\max} \rangle$ data.

Challenges and speculations

Just a month after the publication of Auger's shower-maximum results comes a paper from the HiRes collaboration that reaches a different conclusion.³ From 1999 to 2006 the HiRes team took UHECR data with a pair of fluorescence telescopes on hilltops 13 km apart in the Utah desert. The paper reports the final $X_{\max}$ analysis of the team's total of 814 events stereoscopically recorded by both telescopes. HiRes had no surface array, but its stereoscopic capabilities served a similar function for geometric shower reconstruction.

The HiRes $\langle X_{\max} \rangle$ observations are, within uncertainties, consistent with what Auger reports. But the HiRes data analysis, taking account of systematic effects like the growth of effective stereo aperture with increasing E , leads the team to conclude that proton dominance persists to the highest CR energies. The HiRes fluctuation data, shown

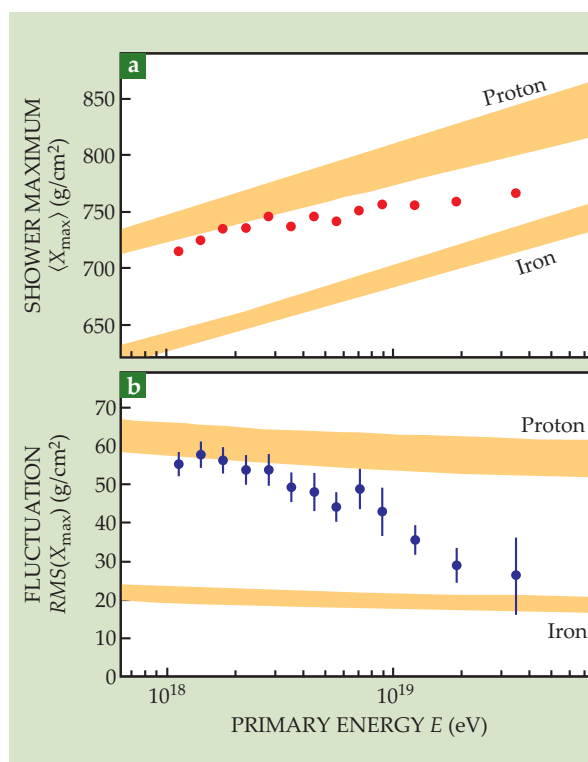


Figure 2. Comparing Auger shower-maximum data with a range of Monte Carlo simulations (yellow swaths) for showers initiated by protons or iron nuclei. **(a)** The mean-shower-maximum $\langle X_{\max} \rangle$ data of figure 1, shown here without error bars. **(b)** Root-mean-square fluctuation of the penetration length $X_{\max}$ from event to event at a given primary energy in the Auger data. (Adapted from ref. 1.)

in figure 3, make the disagreement with Auger quite clear. Unlike figure 2b, they show no evidence of Fe.

Ironically, another disagreement between the two collaborations seems to point in the opposite direction. A recent HiRes study of the arrival directions of CRs above the GZK cutoff finds⁴ a distribution consistent with isotropy and no correlation with galaxy distributions within a few hundred Mly. Isotropy is puzzling for protons and comforting for Fe dominance.

"Of course it's possible that the northern and southern CR fluxes really are different," says the University of Utah's Pierre Sokolsky, who led the HiRes collaboration. That could be the case if, as some suggest, the highest CR

energies are dominated by Fe from just a few local AGNs like Centaurus A—only 10 Mly away in the southern sky. "But," says Sokolsky, "we'll have to have a much firmer understanding of the systematics of stereo and hybrid observing before coming to such a conclusion." For more than a year now, Sokolsky and collaborators have, in fact, been making hybrid UHECR observations of the northern sky at the new Telescope Array Project in Utah, an 800-km² successor to HiRes and Japan's pioneering AGASA surface-array observatory.

One speculative resolution of Auger's intramural tension between its $X_{\max}$ results and its claims of directional correlations is of particular interest to particle theorists. "Suppose that at the highest

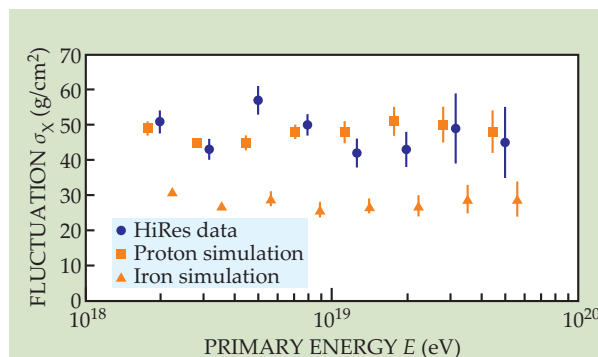


Figure 3. The HiRes collaboration's data on the event-by-event fluctuation of its $X_{\max}$ data for 814 events seen in stereo by both of the facility's fluorescence telescopes. Truncated Gaussian fluctuation widths σ_X are plotted as a function of the cosmic-ray primary's energy and compared

with Monte Carlo simulations of what the stereo data should look like for pure proton and iron fluxes. (Adapted from ref. 3.)

energies we're seeing not iron but protons behaving in atmospheric collisions more and more like heavy nuclei," says theorist Glennys Farrar (New York University), a member of the Auger team. The center-of-mass collision energy of a 10^{19} -eV proton hitting a nitrogen nucleus in the atmosphere is about 500 TeV, far beyond anything that could be studied at CERN's new Large Hadron Collider.

There's considerable wiggle room in extrapolating the standard model of

hadronic interactions to that terra incognita. But the observation that 10^{18} -eV protons still seem to behave normally in atmospheric collisions makes it questionable that anything short of an abrupt onset of new physics beyond the standard model could account for the requisite doubling of the proton's effective width. In the past, cosmic-ray observations have famously contributed to fundamental particle physics. "It would be wonderful if that's

happening yet again," says Farrar.

Bertram Schwarzschild

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Protein strangles membrane necks by polymerizing into a spiral collar

A biophysical experiment involving fluorescently tagged molecules, an optical trap, and artificial vesicles reveals how a key molecular actor, dynamin, plays its role in neural transmission.

Signals travel along neurons as pulses of electrical polarization, but they're carried between neurons by glutamate, serotonin, and other neurotransmitter molecules. Neurons keep neurotransmitters ready for use inside nanoscale bags called synaptic vesicles, whose skins are made from the same lipids as the neuron's outer membrane.

When it's time to pass on a message, the vesicles fuse with the inside surface of the neuron's membrane and break open. The debouched neurotransmitters diffuse across a gap of a few nanometers to reach the receiving neuron, where, by binding to the surface, they deliver the message. Spent neurotransmitters are broken up by enzymes floating in the gap.

Neurons remake vesicles in a process that's the reverse of the vesicles' destruction. A concave pit forms out of the neuron's membrane. As the pit becomes more spherical, the neck that connects it to the membrane narrows. Vesicle formation ends when the neck is cut to seal the vesicles and trap them inside the neuron. Transporter proteins in the vesicle membrane reload the vesicles with fresh neurotransmitters.

Biologists call the release and reabsorption of vesicles exocytosis and endocytosis. Both processes are rich ground for biophysical study. They involve the topological transformation and continuum mechanics of thin, almost liquid membranes and the participation of several molecular actors, among them a motor protein called dynamin.

Dynamin polymerizes to form a spiral collar around the vesicle's neck during the final stages of endocytosis. But until now, it wasn't clear how the protein is recruited at the right moment or how it begins squeezing the vesicle's

membrane. Aurélien Roux and his coworkers in Patricia Bassereau's group at the Curie Institute in Paris have cleared up both mysteries.¹ Surprisingly, the resolution lies not in a varied cast of biochemical actors, as is often the case in molecular biology, but in the polymerization process itself.

Endocytosis

Figure 1 depicts some of the steps in endocytosis. In the first, molecules of protein called clathrin bind to the inside surface of the neuron's membrane. Clathrin molecules also bind to each other, creating a crystalline cage that deforms the membrane into a spherical pit. Dynamin shows up when the clathrin cage is almost complete and a short neck has formed.

Clathrin is recruited by the advent in the membrane of a lipid called PIP₂. Like clathrin, dynamin also recognizes PIP₂, but without an additional means to sense membrane curvature, dynamin would bind promptly—and therefore uselessly—to the pit and not to the more highly curved neck that forms later. Certain proteins that bind to dynamin are sensitive to curvature and could in principle recruit dynamin at the right moment.

Other molecules might help dynamin when it forms a spiral collar. Energy is needed to deform the membrane into the thin tube that dynamin envelops. Conceivably, that energy could come from dynamin's polymerization, from a molecule that binds to dynamin, or from an unknown molecule that squeezes the membrane in advance of dynamin's adsorption.

Roux didn't set out to find how dynamin senses curvature. At first, he was more interested in dynamin's polymerization. In 1998 Sharon Sweitzer and

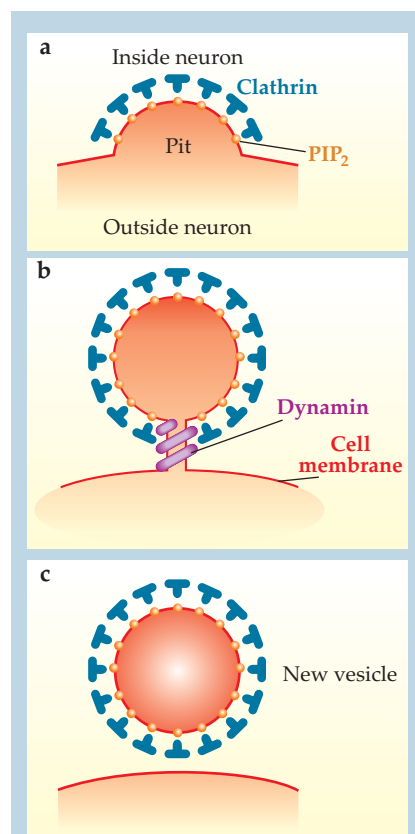


Figure 1. Endocytosis, as the creation of vesicles is known, involves two proteins, clathrin and dynamin, that deform a cell's membrane from inside the cell. **(a)** Clathrin arrives first. It binds to a lipid called PIP₂ and to itself, forming a pit. **(b)** Dynamin arrives when the clathrin-coated pit is almost complete. It polymerizes around the highly curved neck of the partially formed vesicle, squeezing and elongating the neck. **(c)** Dynamin acquires energy from molecules of GTP and twists into a tighter spiral (not shown) to sever the neck and complete endocytosis.