

used in the model. All that is required to generate the small-world phenomenon is a network that is locally ordered (which means simply that two nodes with a mutual 'friend' are significantly more likely to be connected than two randomly selected nodes), and which has a small fraction of long-range shortcuts. The effect also does not depend on the specific nature of the network nodes or connections—only their topology—so the small-world phenomenon ought to arise in all sorts of large, sparse networks.”

To check this, Watts and Strogatz examine the length and clustering properties of three real networks: the collaboration graph of movie actors (including approximately 225 000 actors of all nationalities since the start of motion pictures); the power-transmission grid of the western US; and the neural network of the worm *Caenorhabditis elegans* (the only organism whose neural network is completely known). As Watts explains, they show that, in each case, the characteristic path length of the network is close to its theoretical minimum (that of an equivalent random graph), yet the clustering coefficient is far from minimal, indicating the presence of significant local order. So all three networks exhibit the small-world phenomenon.

Assuming that the appropriate data can be compiled, Watts thinks science citations would be an interesting network to study, with each point being a scientific paper and a directed link signifying a citation. A related example is the collaboration graph of scientists, traditionally centered around the late mathematician Paul Erdos.

“You could apply small-world network ideas to words, which can be connected because they are synonyms or antonyms or have similar roots,” says Watts. “The structure of this network may then be relevant to the flow of ideas in a conversation or the cognitive paths leading to creative insight.”

The Internet is an interesting network, of course. Says Watts, “Imagine a vertex being the Web page and the hot links being the connections. There

are probably millions of pages on the World Wide Web, and very few of these would have more than 100 hot links, yet it seems possible that any Web page could be reached from any other in only, say on the order of 10 links.”

Dynamical properties

Watts first started thinking about the small-world phenomenon in connection with coupled dynamical systems. While a graduate student at Cornell, he was studying the synchronization of populations of coupled oscillators, in particular crickets. He wondered if for a fixed population of oscillators and a fixed number of connections between them, the dynamics could be affected by altering the distribution of connections. More specifically, Watts asked, if certain coupling networks could be shown to have the property that all elements were, in a sense, close to all others, would those networks be predisposed to synchronize more easily or rapidly than, say, one-dimensional lattices?

Watts and Strogatz, having shown that small-world networks could arise under rather general conditions, then turned to finding dynamical properties of small-world networks.

Suppose the points of the network are neurons or a person telling a joke or spreading a disease, says Strogatz. In their simplified model the first infected person remains infected for one time step during which he has a probability, r , of infecting each of his healthy neighbors, and so on. If r isn't large, it's possible the disease would die out. The team finds that diseases “spread like wildfire through a small-world network. It takes very few shortcuts to make the time for global infection nearly as short as a random graph,” according to Strogatz. In a small-world network, diseases spread rapidly and tend to infect a larger fraction of the population than in “large-world networks.” Says Watts, “Because so few long-range connections are required to make the world small, it may appear to an individual that the danger of infection is remote whereas it in fact is quite close.” William Ditto at Geor-

gia Tech is now doing experiments to see what role small-world networks might play in epileptic seizures.

Another dynamical system that Watts and Strogatz have studied is a binary-state cellular automaton, in which cells are either on or off. The computational task of the automaton is to say whether the fraction of “on” cells is greater or less than one-half. James Crutchfield and Melanie Mitchell (Santa Fe Institute) called this task “density classification.”³ If the fraction is greater than one-half, the cellular automaton has to turn all cells on. If it's less, then it has to turn them all off. Although this sounds like a trivial problem, it's difficult for a locally connected system. And it's representative of a class of other problems, such as the functioning of an ant colony, which through local interactions alone appears to be coordinated globally.

Crutchfield and Mitchell used a genetic algorithm (which mimics Darwin's rule of natural selection, where the automata reproduce more automata in proportion to their performance at the computational task). Watts and Strogatz have tried a different approach, altering the architecture of the network using the model shown in Figure 1. They find that small-world cellular automata can outperform even the best performance of the genetic algorithm approach by using a naive “majority rules” approach, in which each cell simply adopts the state exhibited by the majority of its neighbors.

Says Strogatz, to do parallel computing, optimizing the architecture is important. What is perhaps less obvious, he says, is that the new architecture can be close to the original, but you don't need much randomness to improve performance.

GLORIA B. LUBKIN

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Search at SLAC Finds No Millicharged Particles

The quantization of electric charge is very well tested: The proton and electron charges $\pm e$ are equal and opposite to better than a part in 10^{21} , and the neutrality of the neutron, photon and neutrino have been experimentally affirmed with comparable precision. And all attempts to find naked fractionally charged quarks have failed thus far, as the theory of quark con-

No established theory excludes the possibility of particles with charges a thousand times smaller than the electron's. So why not look for them, especially when you already have just the right accelerator?

finement tells us they must.

So why would a group at the Stan-

ford Linear Accelerator Center spend several years looking for elementary particles with electric charge on the order of $10^{-3}e$? The SLAC group, headed by John Jaros, has described the final outcome of its search in the 10 August *Physical Review Letters*.¹ If they had found any such “millicharged particles,” dear reader, you would already have heard about it.

Charge quantization

The quantization of electric charge is something of a mystery. It is not derivable from the group structure of the standard model of particle physics, with its three generations of quarks, leptons and massless neutrinos. In the absence of a higher embedding theory, the lepton charges ($\pm e$) and quark charges ($\pm \frac{2}{3}e$ and $\mp \frac{1}{3}e$) are *ad hoc* ingredients. They have to be put into the standard model by hand.

The most popular grand unification theories (GUTs) that have been proposed for uniting the strong and electroweak sectors of the standard model bring along automatic charge quantization as an added attraction. At first, it was thought that such unification schemes rigorously excluded the possibility of millicharged particles. But a particularly attractive GUT variant proposed by University of Toronto theorist Bob Holdom in 1986 produced millicharges as a consequence of adding a second, unobservable "shadow" photon to the theory.

The shadow photon is the result of having a second unbroken $U(1)$ gauge symmetry in the theory, in addition to the usual $U(1)$ symmetry that describes electromagnetism. Holdom showed that observable millicharges of order $e\alpha/\pi \approx 10^{-3}e$ could appear quite naturally in such GUT models, even though the shadow photon has no coupling to ordinary matter. (The fine structure constant $\alpha \approx 1/137$.) The interactions of these spin- $\frac{1}{2}$ millicharged particles with ordinary matter, on the other hand, would be fully described by conventional quantum electrodynamics, albeit with a very small electric charge.

"Holdom's scheme is genuinely persuasive," says SLAC theorist Michael Peskin. "It has stimulated the experimenters to look for millicharged particles," he told us. "No one would bet on their existence, but if you *can* look, you should. Superstring theories, with their abundance of $U(1)$ symmetries at the GUT energy scale, would provide a good opportunity for Holdom's mechanism to occur." Millicharged particles would also be interesting candidates for some of the dark matter called for by the large-scale astrophysical data.

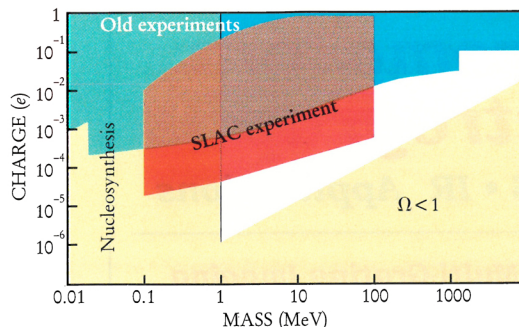


FIGURE 1. SEARCHING FOR MILlicharged PARTICLES, the SLAC experiment was able to exclude, at the 95% confidence level, the region of the mass-charge plane shown in red hues. Some of that area overlaps regions excluded by reinterpretation of old accelerator and atomic physics experiments (blue and green) and regions (yellow and green) excluded by cosmological constraints (primordial nucleosynthesis and the presumption that the cosmic mass density Ω does not exceed its critical value). (Adapted from ref. 1.)

Prior constraints

As a first step, Sacha Davidson at the University of Alberta and other theorists, Peskin among them, examined what regions of the mass-charge parameter plane were already excluded by cosmological and astrophysical constraints (the yellow and green regions in figure 1), and by the reanalysis of existing accelerator and atomic physics data (the blue and green regions in the figure). It turns out that the limiting cosmological constraint comes from the good agreement between the theory of Big Bang nucleosynthesis and the observed abundance of the lightest elements. (See PHYSICS TODAY, August 1996, page 17.) A sufficiently light millicharged species would affect the predictions of the theory by providing

extra degrees of freedom at primordial nucleosynthesis.

This constraint appears to exclude any charge greater than $10^{-8}e$ for any new particle lighter than about 1 MeV. Recycled data from old experiments exclude millicharged particles with charges exceeding $10^{-3}e$ for masses around 1 MeV. This constraint becomes weaker with increasing presumed mass: For particles as heavy as 100 MeV (10% of the proton mass), the old data can only exclude millicharges greater than $10^{-2}e$.

These prior constraints left unexplored an interesting region of the mass-charge parameter plane that was particularly opportune for the two-mile-long SLAC linac, which nowadays feeds the Stanford Linear Collider (SLC) with beams of 50-GeV electrons and positrons. "Marty

Perl, who has an incredible nose for new physics, started us thinking about this in 1990," Jaros recalls, "when he threw on my desk a paper by two Russian theorists² showing that a high-current electron accelerator would be a good place to look."

Looking for millicharges

Eventually Jaros and SLAC colleagues concluded that they should place a modest array of plastic scintillation counters 110 meters directly downstream of the linac's tungsten positron production target. When the SLC is running, intense picosecond pulses of 30-GeV electrons hit the target at a repetition rate of 120 Hz. The principal purpose is to make positrons that will be accelerated to 50 GeV and then

fed into the electron-positron collider. But the group calculated that each pulse of 3×10^{10} electrons might also be producing a few thousand light millicharged particles on the side while it's doing its main job in the tungsten target. The 100 meters of soil and rock between the positron target and the millicharge detector would easily stop any ordinary charged particles associated with the beam that have not already been deflected away by bending magnets. The idea was to run parasitically, searching for millicharged particles while the collider was going about its usual business.

The calculated rate of millicharge production increases as the square of the particle's supposed charge q , but it falls rapidly with increasing mass. A

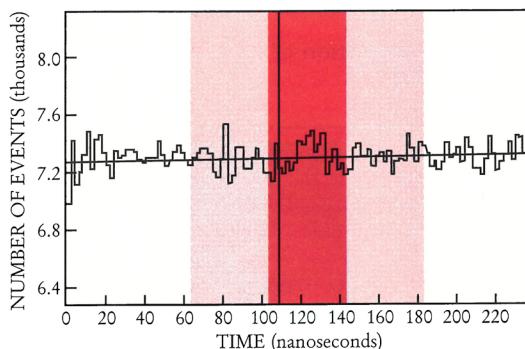
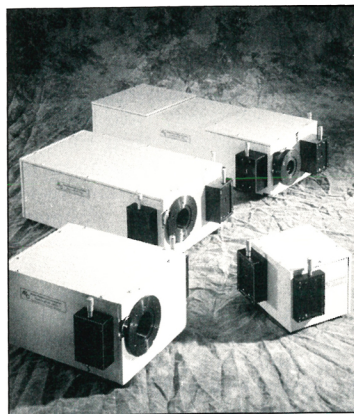


FIGURE 2. TIME SPECTRUM of scintillation counts in the SLAC millicharge detector array, summed over 2.6×10^8 accelerator pulses. The black line at $t = 108$ ns indicates the expected arrival time of a relativistic particle produced by the electron beam hitting the tungsten target. Any millicharge signal should show up in the dark red band. The lighter sidebands serve for comparison. (Adapted from ref. 1.)

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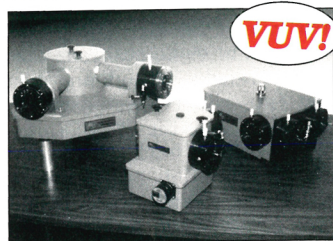
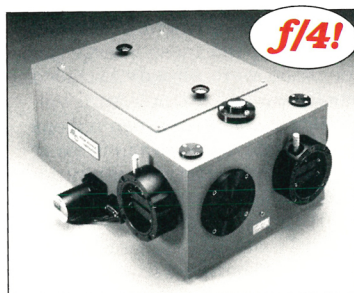
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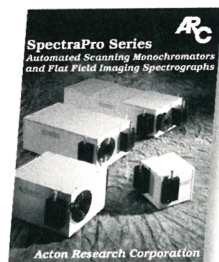


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millicharged particle with $q = 10^{-3}$ and a mass of 100 MeV, for example, would be produced at a rate of only 1 per 50 beam pulses. To make things even more difficult, any particle with $q < 3 \times 10^{-3} e$ would generate, on average, less than one excitation photon as it traverses the 1.3-m-long plastic scintillation detector.

"We realized, however, that we could get around these very low rates of production and scintillation by exploiting the beam's very fast time structure and high intensity," Jaros told us, "if we could get the noise low enough to detect single-photoelectron signals." Using the instant the electron beam hits the tungsten target as the initial time reference, one could superpose the scintillator signals from millions of machine pulses and look for telltale structure in the 40 ns after a relativistic particle from the target would be expected to reach the detector. Even though the electron beam is only a few picoseconds wide, any millicharge signals would be spread out over about 40 ns by random delays in the scintillator and the photomultiplier tube attached to it.

Single photoelectrons

Noise is the big problem. In the usual high-energy experiment, a charged particle will lose something like 10 MeV of energy by excitation and ionization in a much thinner scintillation counter, thus producing thousands of photoelectrons in the first stage of the photomultiplier tube. A millicharged particle, by contrast, might deposit only 10 eV in the SLAC experiment's unusually long scintillator, in which case one would be lucky to get even one photoelectron.

Many noise sources can overwhelm single-photoelectron signals. So Jaros and company had to take extraordinary measures: They cooled the detector to 0°C and shielded it with copper and lead to keep out radio frequency noise and background radioactivity. When cosmic-ray particles did get through—about 100 every second—they often excited the detector to generate afterpulses. To avoid mistaking such spurious afterpulses for real events, the system stopped recording data for 30 microseconds after any interaction in the detector.

"It's amazing how easily the scintillators and phototubes can become over-excited, and how long they stay that way," recalls Allen Odian, one of the group's veteran detector experts. "I had more fun doing this experiment than any other in my life," he told us. "We had the leisure to really study these spurious excitations, rather than just plowing ahead by brute force."

That's because the SLAC machine was uniquely suitable for this experiment; so there was no rival experiment breathing down our necks."

With the noise thus beaten down to a few kilohertz per scintillator, the group concluded that it could find, or exclude, a millicharged particle as massive as 100 MeV with a charge as small as $6 \times 10^{-4} e$. For lighter particles, all the way down to 0.1 MeV (20% of the electron mass), the limit of detectable millicharge goes down to $2 \times 10^{-5} e$. (See the red hued regions in figure 1.)

A hundred days

"We recorded almost 300 million machine pulses in 14 weeks of running," says Alyssa Prinz, for whom this unusual search was her PhD thesis experiment. "We didn't find any millicharges, but we were able to exclude a significant region of the parameter plane."

Figure 2 shows the time spectrum of detector pulses for the entire run, in 2-ns bins. The 40-ns-wide red band is where one would expect to see evidence of millicharges created in the target. The pink bands on either side served for comparison.

Finding no such evidence, the group arrived at the mass-dependent, 95% confidence upper limit of millicharge shown as the lower border of the red region in figure 1. The upper border of the SLAC exclusion region reflects the fact that getting through 100 meters of earth becomes ever more difficult with increasing charge and decreasing mass.

Even though the SLAC experiment cost very little by the standards of high-energy physics, it will probably be a long time before anyone does better. The sensitivity of the search was limited by noise rather than statistics. The next generation of electron-positron colliders (see PHYSICS TODAY, November 1997, page 21) will have much higher collision energies. But because the plans call for most of the requisite electron acceleration to be done after the positron-creation target, these new machines would have no clear advantage over the SLC in the search for millicharged particles.

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