that all the current structure-determining methods are hampered somewhat by the difficulty in manufacturing sufficient amounts of protein. But, as stronger and stronger magnets become available, NMR methods become more sensitive, making it possible to use smaller samples. Higher magnetic fields will also add another arrow to the solid-state NMR quiver: the ability to exploit the ^{1}H chemical shift as a third, orientation-constraining dimension.

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Theorists and Experimenters Seek to Learn Why Gravity Is So Weak

At the recent Marcel Grossmann Meeting on General Relativity in Rome, Jens Gundlach of the University of Washington's Eot-Wash laboratory reported a provisional result from the group's examination of gravity at submillimeter distances. At distances as small as 0.2 mm, he said, the group's specially designed torsion balance has not, as yet, revealed any departure from Newtonian $1/r^2$ gravity.

Just a few years ago, this result might have elicited little more than yawns. Why, after all, should one doubt that Newtonian gravity holds at such macroscopic distances? Admittedly, Cavendish-type experiments had not been able to test the gravitational force at separations smaller than a millimeter. But surely that was only the concern of specialists obsessed with checking things that most of us take for granted.

Nowadays, however, it's all different. In the past two years, testing gravity at submillimeter distances has become a cottage industry. The Eot-Wash group (whose name is a play on that of Baron Roland von Eötvös, who tested the equivalence principle with a torsion balance a century ago) is but one of perhaps a dozen groups that have recently set out to look for departures from Newtonian gravity at these small but macroscopic distances. Their results are eagerly awaited.

> If gravity leaks out into macroscopic extra dimensions, we may soon find departures from the inverse-square law at millimeter separations.

The hierarchy problem

Why all the fuss? The principal impetus was a 1998 paper entitled "The Hierarchy Problem and New Dimensions at a Millimeter"[1] by particle theorists Nima Arkani-Hamed, Savas Dimopoulos (both then at Stanford), and Gia Dvali (then at Trieste, now at New York University). The hierarchy problem, simply stated, is the nagging question: Why is gravity so many orders of magnitude weaker than the other fundamental forces? The provocative answer suggested by Arkani-Hamed, Dimopoulos, and Dvali (ADD) supposes the existence of two or more as yet undetected spatial dimensions, in addition to the four dimensions of ordinary spacetime.

String theorists have long since inured us to the notion of half a dozen extra dimensions, unseen because they are presumed to be curled up ("compactified," as they say) into loops about 10^{-33} cm in diameter. That's the so-called Planck length L_P, the distance at which, in standard particle theory, gravity finally becomes equal to the strengths of the other forces. Examining such absurdly tiny distances would require probe energies of order 10^{19} GeV, the "Planck mass" $M_P = \hbar/L_P c$, far beyond the capabilities of any conceivable accelerator. (Specifically, M_P is the mass at which a particle's Compton wavelength becomes equal to its Schwarzschild radius.)

But ADD were enticing experimenters with much more accessible prospects. They argued that the extra dimensions might be curled up on a scale as large as a few *millimeters*, making it possible to detect departures from Newtonian gravity with a new generation of sensitive tabletop experiments. Furthermore, they pointed out, the Large Hadron Collider (LHC), which will be providing experimenters with 10 TeV (10^4 GeV) protons by mid-decade, should also exhibit manifestations of these surprisingly large extra dimensions.

Why should one believe in extra dimensions 32 orders of magnitude larger than the Planck length? If there are n extra dimensions curled up with diameters R, anyone looking on scales smaller than R would see a straightforwardly generalized Newtonian potential energy

$$V(r) = \frac{G_n^* m_1 m_2}{r^{n+1}} \quad \text{for } r \ll R \quad (1)$$

between test masses m_1 and m_2, where G_n^* is the appropriate gravitational constant for n extra dimensions. Gravity, because of its intimate relation to the fabric of spacetime, must spread out in all the dimensions. And the extra dimensions make the gravitational force grow faster with decreasing separation. But if you're only looking at scales *larger* than R, you would see a Newton-like potential

$$V(r) = \frac{G_n^* m_1 m_2}{R^n}\frac{1}{r} \quad \text{for } r \gg R. \quad (2)$$

Long before the Planck scale

In natural units ($\hbar = c = 1$), Newton's constant G is essentially L_P^2, or equivalently, $1/M_P^2$. The central point made by ADD is that a real $4 + n$ dimensional gravity would become equal to the other fundamental forces long before the remote Planck scale. This unification, they suggest, occurs at the same modest length scale $L_{ew} \approx 10^{-17}$ cm at which electromagnetism is unified with the weak nuclear force (and the strong nuclear force is not far off). In other words, the implausible, yawning chasm between electroweak unification and the Planck scale is abolished. The electroweak distance scale, corresponding to a mass M_{ew} of about 1 TeV, becomes the only unification scale, and the hierarchy problem is gone.

What does this tell us about the size R of the compactified extra dimensions necessary to make the trick work? If there are n extra dimensions and the fundamental unification scale of gravity is L_{ew}, then the true coupling constant G_n^* in equation 1 is (again in natural units) L_{ew}^{2+n}. So equation 2 tells us that the familiar Newton's constant G we've been measuring at separations larger than R is really $G_n^*/R^n = L_{ew}^2(L_{ew}/R)^n$. In effect, gravity is intrinsically comparable to the electroweak forces. Only its leakage into the extra dimensions makes it appear so much weaker to us. And the compactification size of the n curled-up dimensions is given by

$$R^n = L_{ew}^n \left(\frac{L_{ew}}{L_P}\right)^2 \approx L_{ew}^n \times 10^{32}. \quad (3)$$

For $n = 1$, equation 3 yields an astronomical R that would have an obvious effect on Solar System dynamics. The case $n = 2$ is the most intriguing possibility, giving an R on the order of a millimeter. As we see in the figure at right, that's just about the lower limit of separations at which Newtonian gravity has been adequately tested. "Who says we have to believe that the inverse-square law must prevail over 32 untested orders of magnitude?" asks Arkani-Hamed, who is now at Berkeley.

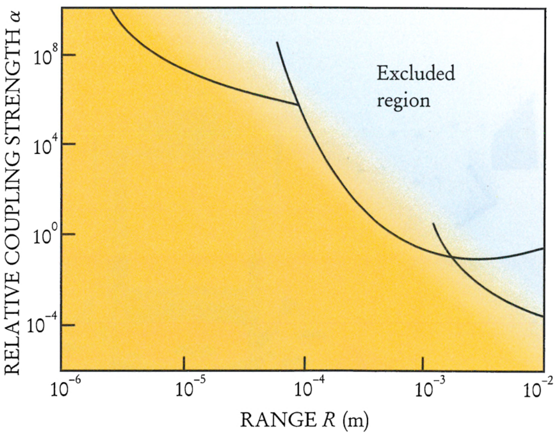
Trapped on the membrane

What about electromagnetism and the nuclear forces, which have been probed down to 10^{-17} cm without revealing any evidence of extra dimensions? ADD argue that these other forces, unlike ubiquitous gravity, are restricted to the four-dimensional subspace (or "brane," short for membrane) on which we live. That makes sense in terms of string theory, which treats all the spin-1 gauge bosons that mediate these forces—the photon, the gluons, and the heavy weak bosons—as open strings, like the quarks and leptons, whose ends are stuck on our brane. Only the spin-2 graviton, being a closed-loop string, is free to wander off into the extra dimensions.

This special freedom for the graviton accords with the general-relativistic presumption that gravity is a manifestation of spacetime geometry. The ADD theory does not require strings. But if the fundamental bosons and fermions really are strings, ADD would give them lengths of order L_{ew} rather than the forbidding Planck length, thus rendering string excitations observable at LHC energies.

Attempts to unify the forces by invoking extra dimensions go all the way back to Oscar Klein and Theodor Kaluza in the 1920s. Ten years ago, Ignatios Antoniadis (Ecole Polytechnique) suggested that the compactification sizes of some of the extra dimensions required by string theory might be as big as L_{ew}. But ADD were the first to suggest that there might be macroscopic extra dimensions accessible to tabletop searches for gravitational anomalies. "Their paper is certainly what got us started," says Eric Adelberger, who with Blayne Heckel heads the Eot-Wash submillimeter effort.

A year after the ADD paper, Lisa Randall (Princeton) and Raman Sundrum (then at Boston University) took a different extra-dimensional approach to the hierarchy problem. They argue that a millimeter compactification scale seems quite as unnaturally large as the gap between the electroweak and Planck scales. Gravity appears so weak, they suggest, because its real home is on an otherwise inaccessible brane separated from ours by an extra dimension not much bigger than the Planck length.[2] The gravitational effect of this other brane on the metric of spacetime would exponentially attenuate gravity as a function of the tiny separation between the branes. Although this scheme does yield interesting predictions for physics at the LHC, it is not amenable to testing with tabletop experiments.



POSSIBLE SHORT-RANGE DEPARTURES from Newtonian gravity parameterized, for convenience, by the exponential term in equation 4, have already been excluded from the indicated upper right region of the R–α parameter plane by experimental results published in previous years.[3] Not yet excluded by these older experiments is much of the submillimeter strip around $\alpha = 3$ or 4, suggested by the theory of Arkani-Hamed *et al.*[1] A new generation of sensitive experiments is now probing this and other regions of the parameter plane.

Submillimeter testing

Because the attraction between test masses is so very weak, laboratory testing of gravity continues to be a difficult and exacting business more than two centuries after Henry Cavendish's pioneering measurements of G. (See PHYSICS TODAY, July, page 21.) And it's all the more difficult at submillimeter separations.

Looking for a transition from the Newtonian regime to the faster falloff described by equation 1, experimenters generally parameterize the potential in the submillimeter region by

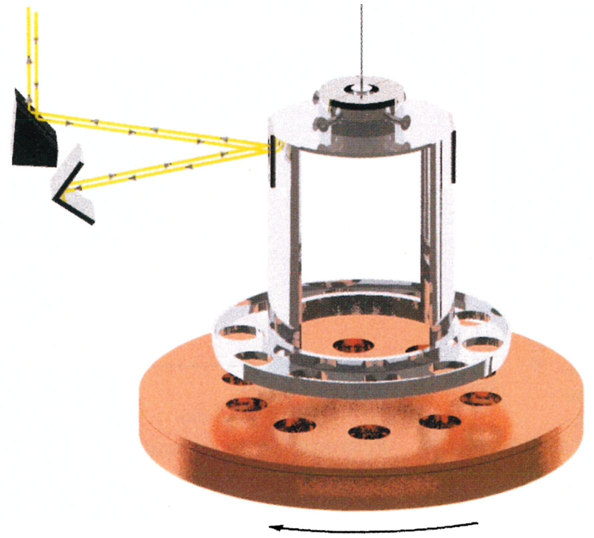
$$V(r) = \frac{Gm_1m_2}{r}\,(1+\alpha e^{-r/R}). \qquad (4)$$

For two extra dimensions, the ADD theory predicts $\alpha = 3$ or 4 (depending on compactification topology) for the coefficient of the non-Newtonian exponential term. Described by these empirical parameters, the provisional Eot-Wash null result already excludes α greater than 2 for R bigger than 200 μm. The experiment is the thesis project of C. D. Hoyle.

The figure on page 24 illustrates the Eot-Wash group's short-range apparatus. The pendulum is suspended by a fine torsion fiber above the attractor, with a separation variable down to 100 μm. On each we see 10 equally spaced holes that serve, in effect, as negative test masses. As the attractor is rotated continually on a turntable, these holes subject the pendulum to 10 gravitational torque pulses per rotation.

But the experimenters want to minimize the pendulum's sensitivity to ordinary gravity as they search for effects of the short-range exponential term in equation 4. Therefore they've made the attractor a pair of cylindrical copper plates of unequal thickness, bolted together. The thicker, lower plate has its own 10 holes (not visible here) arrayed precisely halfway between adjacent holes of the upper plate. Thus the lower, deeper holes approximately cancel the periodic cylindrical asymmetry created by the holes of the upper plate, so that the pendulum sees an almost symmetric attractor. Therefore the pendulum experiences very little periodic torque—to the extent that the gravitational force falls off like $1/r^2$. But any additional non-Newtonian force of short range, being largely blind to the more distant lower plate, would accentuate the torque pulses.

Instead of uniformly rotating an attractor mass, several of the other new submillimeter experiments use designs in which one of the test masses is made to oscillate at a resonant frequency. One such experiment is being done by John Price and Joshua Long at the University of Colorado. The figure above comes from their 1999 compilation and recalculation of the previous generation of tests at separations less than a millimeter.[3] None of the new-generation results has as yet been published. And of the preliminary results reported at conferences thus far, only the Eot-Wash report encroaches upon the zone in the figure not yet excluded by the older experiments.



TORSION BALANCE with which the Eot-Wash group at the University of Washington is looking for departures from Newtonian gravity at submillimeter separations. The pendulum (shown silvery) is suspended by a torsion fiber above a uniformly rotating attractor. The gap between them can be as small as 100 μm. Ten holes in the pendulum and 20 holes in the attractor (10 of them invisible in the attractor's lower plate) serve as negative test masses. Their deployment is such that only a short-range gravitational anomaly would produce significant torque pulses as the attractor rotates. Pendulum twists are monitored by a laser beam and mirrors.[5]

Some of the new submillimeter experiments will eventually run at cryogenic temperatures for greater sensitivity. To test gravity at even smaller separations—down to half a micrometer—a number of groups are looking for departures from the predicted Casimir force between conducting surfaces separated by a vacuum gap. Ephraim Fischbach and Dennis Krause at Purdue hope to test gravity at 10-nm separations by means of atomic-force microscopy.

At the accelerators

If gravity really is unified with the other fundamental forces at the TeV electroweak scale, then the LHC and the proposed TeV electron–positron colliders promise to become probes of quantum gravity. Abundant production of gravitons in collisions at these energies might manifest itself as apparent violations of energy conservation as the gravitons wander off in the extra dimensions. And when they do occasionally find their way back after a brief excursion, they might produce photon or lepton pairs with telltale kinematic distributions.

The ADD theory predicts a "Kaluza–Klein tower" of innumerable very light excited states of the graviton separated from one another by mass gaps of order 10^{-3} eV, corresponding to the millimeter sizes of the extra dimensions. The enhanced gravitational interaction at the TeV scale might also lead to the creation of tiny black holes with Schwarzschild radii on the order of 10^{-17} cm, which would quickly decay by Hawking evaporation.

Some constraint on graviton radiation in high-energy collisions has already been imposed by data from supernova 1987A, the first supernova in several centuries close enough to be seen by the naked eye. In fact, the supernova constraint suggests that the tabletop experimenters might have to look at separations smaller than 10 μm before they can hope to find a gravitational anomaly.[4]

The Randall–Sundrum theory, with no macroscopic compactified dimensions, predicts a Kaluza–Klein tower of heavy gravitons with TeV mass spacings appropriate to the electroweak scale. At the LHC, the lowest such excitations would manifest themselves as spin-2 resonances decaying, for example, into electron–positron pairs.

So the next generation of high-energy colliders may bring us much more than the Higgs boson and the supersymmetric particles we've been anticipating for so long. In fact, bringing gravity to the electroweak unification scale would largely obviate the need for supersymmetric partners of the ordinary quarks and leptons. A principal rationale for supersymmetry has been to combat instabilities in the standard theory that tend to push electroweak unification up toward the Planck mass scale.

At the Fermilab Tevatron collider, a search by the D-Zero detector group has as yet found no evidence of extra dimensions. While we're waiting for the higher-energy LHC, we should be hearing from all those tabletop gravity experimenters. But *more than two* extra ADD dimensions would presumably yield a gravitational anomaly too short-range for the tabletop experiments. No such restriction constrains the accelerator prospects.

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Pulse Shaping Improves Efficiency of Soft X-Ray Harmonic Generation

Delicate sculpting of femtosecond laser pulses can yield dramatic effects in nonlinear light–atom interactions.

As physicists seek to probe and control phenomena on increasingly smaller length scales, coherent sources of radiation in the extreme ultraviolet (EUV or XUV, 10–100 nm) and soft x-ray (1–30 nm) regions of the spectrum are increasingly in demand. The semiconductor industry, for example, is eagerly pursuing EUV sources that can generate smaller linewidths beyond the limits of optical lithography. And femtosecond chemistry could benefit from light sources capable of producing very short pulses at small wavelengths.

Synchrotron radiation facilities provide one means of generating short wavelengths in the range of 1–100 nm, and efforts are also underway at the German Electron Synchrotron (DESY) and at other facilities to use free-electron lasers for this task, but many potential applications for these wavelengths are not well suited to large-scale facilities. In the quest for tabletop sources in this spectral range, two complementary techniques have emerged so far: lasing in ionized plasmas and high-harmonic generation from intense femtosecond laser pulses.

Soft x-ray lasers typically use