years ago, that is far more recent than is generally accepted.

One interpretation is that some of the putative hominid fossils from East Africa have nothing to do with human evolution, because they are older than 2.5 million years. Alternatively, the apparent intimacy and recency of the human/chimpanzee association is the result of an interspecific hybridization 2.5 million years ago between the two lines, which had separated some time earlier. Interspecific transfer of mitochondrial DNA is known to have occurred between different species of mice, which left them with different nuclear genomes but identical mitochondrial genomes.

Fitch switched the attention from men to mice and produced a puzzle. He and Atchley recently discovered that genetic evolution proceeds apace in inbred mice strains, but showed nevertheless that several methods of analysis of the molecular data were able to reconstruct the known history of the different lines. Given that their albeit brief phylogeny—a mere 70 years—is securely known, inbred mice apparently offer a perfect system in which to test methods of phylogentic reconstruction. The molecular data and analysis appear to pass the test, which contrasted markedly with similar attempts based separately on seven life-history variables and 14 measurements on the lower jaw. The best trees from these latter two sets of data were different from each other, from that produced by the molecular analysis, and hence from the known history.

Patterson was unsurprised by this apparent failure of morphology, saying that the data are morphometrics, which are distance statistics and therefore noisy; they are not characters, he says, which could be expected to tell the truth. Felsenstein believes it is stretching the point to make a clear distinction between characters and distance statistics in this kind of situation, but is as yet uncertain how the results should be interpreted.

If the use of inbred mice strains is valid, in spite of their somewhat unnatural history, and the results are substantiated with more thorough anatomical analysis, the message will be difficult for morphologists to swallow. But this should not be viewed as molecules versus morphology, but rather an opportunity to use molecular data in order to learn something of the evolution of morphology. Instead of conflict, here is a pathway for gaining keener insights into evolutionary change.—**Roger Lewin**

Atomic Physics Tests Lorentz Invariance

Accurate measurements of the frequencies of atomic transitions lead to tighter limits on the velocity dependence of the laws of physics

One of the fundamental assumptions of modern physics is that physical laws do not change with the velocity of the frame of reference in which experiments are done. Two recent atomic physics measurements by groups at the National Bureau of Standards, Boulder, Colorado, and the University of Washington provide the most stringent limits yet on the magnitude of any violations of this assumption, which physicists call local Lorentz invariance.

A velocity dependence could enter into the laws of physics if there were in the universe a preferred frame of reference. An obvious candidate for such a preferred frame is that in which the mean distribution of matter in the universe is at rest. For example, if one supposed that the distribution of matter in the universe affects the nongravitational laws of physics by means of some as yet undiscovered long-range force (some new aspect of gravity), this would single out the frame of reference at rest with respect to the mean distribution of matter in the universe as a preferred frame.

If such a force existed that influenced the laws of electromagnetism, for example, there could be many observable consequences. In particular, the rate at which an atomic clock ticked could depend on the orientation of the atoms in the clock relative to their velocity through the distribution of matter. The NBS and Washington experiments, as well as in a third project that has started at Princeton University, test just this idea.

As the earth rotates, the orientation of a clock fixed to its surface does in fact change relative to its motion through the distribution of matter in the universe. So, the physicists compared the rates at which an atomic clock ticks at different times throughout the day or, equivalently, looked for changes in the position (frequency) of an atomic spectral line with time of day. However, neither group (John Prestage, John Bollinger, Wayne Itano, and David Wineland at NBS, and Blayne Heckel, Frederick Raab, E. Norval Fortson, and Steve Lamoreaux at Washington) found any measurable change.

What difference would it make if researchers eventually did find that there was a preferred frame of reference? One far-reaching consequence would be the violation of the Einstein equivalence principle, of which local Lorentz invariance is a fundamental component. Simply put, the equivalence principle says that scientists can count on physical laws being the same at all times and everywhere in the universe. More precisely, there exist local Lorentz frames, anywhere and anytime in the universe, in which all the nongravitational laws of physics must take on their familiar special-relativistic form. A Lorentz frame is one in four-dimensional space-time in which bodies are freely falling, so that gravity "disappears," as in an orbiting satellite. It is always possible to establish a Lorentz frame, even near a black hole, by considering sufficiently small volume of space-time that gravity is constant within it.

Violation of the equivalence principle would require changes in the way of thinking about physics. Consider the famous rods and clocks that figure in discussions of special and general relativity. " If the length and time intervals measured with different rods and clocks depended on their location in and motion through the universe, then the ability to define a unique geometric structure of space-time like that in relativity would be lost," notes theorist Mark Haugan of Purdue University. Fortunately, because of the already tight experimental limits, the practical effects of any violation would be not be as catastrophic as the philosophical ones.

Without the equivalence principle, for example, general relativity would no longer suffice as a complete description of gravity. General relativity is the leading member of a broader class of so-called metric theories, in which gravity is explained as a manifestation of the geometry of space-time. Violation of the equivalence principle would therefore also mean that geometry alone does not suffice to represent gravity. The addition of nongeometrical effects to general relativity would destroy the simplicity and elegance that now so forcefully appeal to physicists' sense of esthetics. However, particles in gravitational fields would still follow paths that deviate only slightly from the geodesics (shortest distance between two points in space-time) prescribed by general relativity.

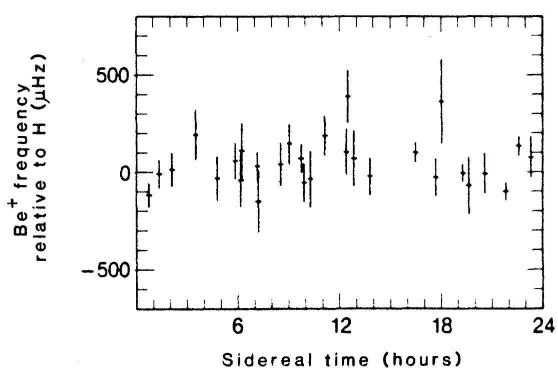
No single experiment tests all aspects of the equivalence principle. For example, it might be that the nongravitational laws of physics obey local Lorentz invariance at a given point in space-time but do not from point to point. The fundamental constants could vary with time, for example, although recent experiments place extremely stringent limits on this possibility (*1*). Tests for preferred frames of reference, on the other hand, look for violations of local Lorentz invariance at a fixed point.

The most well-known search in the modern era for a preferred frame of reference is that of the American physicists Albert Michelson and Edward Morley, who began experiments in 1880 that were aimed at measuring the speed of the earth through the ether, an otherwise noninteracting medium, which was supposed to pervade the universe and support electromagnetic radiation. The frame of reference in which the ether was at rest would be special in that the speed of light would be independent of its direction of travel. In any other reference frame, the apparent speed would depend on the motion of the reference frame relative to that of the ether. With their interferometer, Michelson and Morley failed to find any shift in the speed of light as the earth rotated, thereby dooming the ether theory and contributing to the subsequent development of special relativity.

While physicists no longer worry about the ether, as metrological technology improves, they continue to be interested in testing for the existence of preferred frames of reference. The use of lasers whose frequencies can be made ultra-stable for precision length measurements has enabled the most sensitive interferometric tests of this type.

For example, the most recent search was reported in 1979 by Alain Brillet of the Laboratory of Atomic Timekeeping in Orsay, France, and John Hall of the Joint Institute for Laboratory Astrophysics (NBS and the University of Colorado). They looked for length changes in an optical cavity (Fabry-Perot interferometer) mounted on a rotatable slab but found none. Their laser test for the existence of a preferred frame of reference set limits 500,000 times smaller than those of Michelson and Morley (*2*).

The first atomic physics experiments sensitive to the existence of a preferred frame of reference were performed in 1960 by a group headed by Vernon Hughes of Yale University and in 1961 by Ronald Drever, who is now at the California Institute of Technology. Both experiments searched for frequency shifts in nuclear magnetic resonance transitions in lithium-7 that were correlated with orientation of the nuclei in space but found none.



Be*$^+$ *Frequency

Variation throughout the day of the transition frequency of the beryllium-9 ion clock referenced to a hydrogen maser is consistent with zero at the 100-microhertz level (*5*).

Interestingly, the experiments were not originally interpreted as tests for a preferred frame of reference. The experiments were motivated by a desire to test a 1958 proposal by G. Cocconi and Edwin Salpeter of Cornell University of a model for the inertial mass of particles. The inertial mass is the one that appears in the equations of motion of particles subjected to forces other than gravity; in general relativity the inertial and gravitational masses are the same.

Cocconi and Salpeter started with the 1872 conjecture of the Austrian physicist Ernst Mach that the inertial mass is determined (in some unspecified way) by the overall distribution of mass in the universe (Mach's principle). Since the local distribution of mass, in our disk-shaped galaxy, for example, is anisotropic, argued Cocconi and Salpeter, the inertial mass might be as well. Nuclear magnetic resonance was chosen to test this idea because the frequency of the resonance is dependent on the inertial masses of the protons and neutrons (nucleons) that make up an atomic nucleus.

It was soon realized by Robert Dicke of Princeton and others that the significance of the experiments actually lay in their ability to test the universality of the coupling of gravity to all types of particles and all forms of energy. It is such a universal coupling that establishes the validity of the Einstein equivalence principle in a gravitational field. In particular, if there were some new aspect of gravity whose effect on electromagnetic and other forms of energy depended on velocity relative to the source of the gravitational field, then local Lorentz invariance would no longer hold. It is specifically as a test for velocity-dependent couplings that could establish a preferred frame of reference for which the nuclear magnetic resonance experiments of Hughes and Drever are now noted.

There is no specific gravitational theory incorporating nonuniversal couplings that is also consistent with all the experimental tests passed by general relativity. Theorists have to make do with general frameworks or formalisms that allow for nonuniversal couplings without proposing specific mechanisms, such as a new long-range force. One of these frameworks, which was introduced in 1972 by Caltech physicists Alan Lightman (now at Harvard University) and David Lee, deals with electromagnetism in gravitational fields and now carries the awkward title $TH\epsilon\mu$ formalism.

T_0 and H_0 are free parameters that describe the strength of the coupling between gravity and material particles, whereas ϵ_0 and μ_0 describe the coupling between gravity and electromagnetic fields. A particular feature of the formalism is that the maximum speed of material particles, c_0, need not be the same as that of light, c. The two are related by $c_0/c = (T_0\epsilon_0\mu_0/H_0)^{1/2}$.

As more recently developed by Haugan at Purdue, the formalism gives the dependence of the frequencies for nuclear magnetic resonance or other atomic transitions on the orientation of the atoms relative to their velocity through a preferred frame of reference. The frequency shifts with orientation are expressed in terms of the $TH\epsilon\mu$ parameters, the physical properties of the atoms, and their velocity relative to the preferred frame. Specifically, $\delta\nu \sim 1 - (c_0/c)^2$. Since there is no model to provide predicted values for the parameters, experiments set limits on the maximum value of the ratio c_0/c. Any theory of gravity, for example, would have to be consistent with this value.

Haugan points out that there is a connection between the Michelson-Morley type experiments and the atomic physics experiments as tests for the existence of a preferred frame of reference. The measurement of a length change with an optical interferometer is actually the measurement of a time delay as the light travels through the arms of the interferometer. This time delay corresponds to a frequency shift in a spectroscopy experiment. The outcomes of interferometer and spectroscopy experiments can therefore be directly compared within the $TH\epsilon\mu$ formalism.

Haugan has done this for several possible frames of reference. The one of most interest is the sea of 3 K microwave radiation that fills the universe and is the presumed relic of the Big Bang from which the universe originated. From recent mesurements of anisotropies in the radiation, physicists know that the earth is moving with respect to a frame of reference in which the radiation appears isotropic at a speed of about 300 kilometers per second (*3*). For this frame of reference and the experiments already mentioned, Haugan finds values for $1 - (c_0/c)^2$ of 10^{-4} for the Michelson-Morley experiment, 5×10^{-9} for the Brillet-Hall laser interferometer experiment, and 10^{-16} for the nuclear magnetic resonance tests of Hughes and Drever.

The NBS and Washington groups have pushed the value down still further to 5×10^{-19} and 10^{-20} respectively, although the latter value is a preliminary result that is yet to be published.

While the two groups used different experimental techniques, the idea underlying them is the same. An atomic nucleus has a spin angular momentum whose magnitude is given by a nuclear spin quantum number. It turns out that a nucleus with a spin quantum number of 1/2 is so symmetric that it would feel no effect due to a preferred frame of reference in the universe for any value of the $TH\epsilon\mu$ parameters. However, a nucleus with a larger spin quantum number, such as 3/2, is not so symmetric and preferred-frame effects can distort its electronic structure, thereby giving rise to a frequency shift. To test for a frequency shift with orientation due to any preferred frame of reference, both groups of researchers chose nuclei with spin quantum numbers of 3/2.

However, it is not so easy to measure the absolute value of a frequency and to look for small changes in its value. Hence, the physicists used spin-1/2 nuclei, which would exhibit no frequency shifts, as a reference. The NBS group used beryllium-9 ions as the test system and hydrogen as the reference, while the Washington researchers compared the frequency of transitions in mercury-201 atoms (spin-3/2) with mercury-199 (spin-1/2). The third experiment by Timothy Chupp, who is moving to Harvard, also follows this philosophy. Chupp is using neon-21 atoms as the spin-3/2 test system and helium-3 as the spin-1/2 reference.

The NBS investigators used ions rather than atoms because the main focus of their work has been on the use of ions captured in a trap composed of static electric and magnetic fields (Penning trap) to make the most accurate frequency standards possible. Having trapped several hundred ions, they then use the technique of laser cooling to slow the ions down and thereby reduce the troublesome Doppler effect. Absorption and reradiation of thousands of photons from the laser has the effect of cooling the ions to an effective temperature of 0.1 K. Earlier this year, the group reported a radio-frequency standard based on trapped, laser-cooled beryllium-9 ions that had an accuracy comparable to the best cesium atomic beam devices, which are the atomic clocks used in implementing the international definition of the second (*4*).

The maximum speed of material particles need not be the same as that of light.

In testing for an orientation dependence in the clock rate that might signal the existence of a preferred frame of reference, the NBS researchers compared the frequency of their beryllium-9 standard to that of a hydrogen maser. Ordinarily, atoms in a container are randomly oriented, so any effect causing a changing frequency with orientation would average out. An essential feature of the beryllium-9 clock, therefore, is the magnetic field of the Penning trap. In the magnetic field, the same laser light as that used for the cooling places the trapped ions in a specific quantum state, so that the spin angular momentum vectors are all at a fixed angle with respect to the field; that is, they are polarized.

The nominal frequency of the transition in beryllium-9 used for the standard is a little over 303 megahertz. In their search, the NBS invesitgators found no frequency variations with time of day down to a level of 100 microhertz (*5*).

The Washington group opted for an experimental technique more akin to nuclear magnetic resonance than microwave spectroscopy. Although their method can be explained in terms of quantum states, it is easier to consider the motion of the atomic spin angular momentum vector. In a magnetic field, if this vector is at an angle relative to the field, the component that is aligned with the field does not change, but the angular momentum vector as a whole precesses around the field vector, just as the axis of a spinning top on a table wobbles. The frequency of the precession is the same as that for transitions between the quantum states split by the Zeeman effect in the magnetic field. However, rather than using a spectroscopic method to measure the frequency as the NBS physicists did, the Washington researchers obtained it from a measurement in the plane normal to the magnetic field of the net atomic spin polarization due to all the atoms, which rotates at the precession frequency.

In brief, the Washington physicists use a resonance lamp to prepare a collection of some 10^{12} mercury atoms in a polarized state. For as long as the atoms move together, the net atomic spin polarization normal to the field rotates around the field direction, thereby causing oscillations in the light transmitted, whose frequency is the precession frequency. Eventually, the atoms get out of phase because of collisions with the walls of the bottle containing the atoms or other effects that make their precession frequencies vary slightly, so that the polarization also decays with a characteristic time, the transverse relaxation time (T_2 in nuclear magnetic resonance parlance).

With this technique, the Washington investigators were able to rule out any changes in the precession frequency of mercury-201 as the earth rotated with respect to prospective preferred frames of reference in the universe down to 3 microhertz.—**Arthur L. Robinson**

References

1. A. L. Robinson, *Science* **222**, 1316 (1983).
2. A. Brillet and J. L. Hall, *Phys. Rev. Lett.* **42**, 549 (1979).
3. G. F. Smoot, M. V. Gorenstein, R. A. Muller, *ibid.* **39**, 898 (1977).
4. J. J. Bollinger, J. D. Prestage, W. M. Itano, D. J. Wineland, *ibid.* **54**, 1000 (1985).
5. J. D. Prestage, J. J. Bollinger, W. M. Itano, D. J. Wineland, *ibid.*, p. 2387.