Modern tests of special relativity

Recent experiments that provide the strictest limits on violations of Lorentz invariance may be viewed as direct descendants of the Michelson–Morley experiment.

Mark P. Haugan and Clifford M. Will

From our perspective one hundred years after the fact, the null result of the Michelson–Morley ether-drift experiment[1] clearly marked the beginning of the end for the Newtonian notions of absolute space and time. At the time, however, it took 20 years of work by H. A. Lorentz, Henri Poincaré and others for most physicists to come to the same conclusion. In 1887, fundamental physics appeared to be essentially complete. Newtonian mechanics and Maxwell's electrodynamics were in hand, and a grand unification of physics seemed within reach. It was expected that a purely mechanistic basis for the ether interpretation of Maxwell's equations could be constructed and would provide a final unity of physics. This was a concise and powerful world view that was not easily discarded, but the null result of Michelson–Morley challenged its very heart.

Where was the effect of motion through the ether? Initial work showed that simple explanations of the null result, such as the dragging of the ether along with the Earth's motion, were untenable. In 1892, Lorentz wrote to Lord Rayleigh,[2] "I am totally at a loss to clear away this contradiction. . . . Can there be some point in the theory of Mr. Michelson's experiment which has been overlooked?" In later work both Lorentz and Poincaré anticipated special relativity, deriving the Lorentz transformations and framing a principle of relativity.[3] However, the bold step of letting go of absolute space and time fell to Albert Einstein,[4] working in isolation. His operational interpretation of the Lorentz transformations implied the relativity of simultaneity, and from that all of special relativity followed.

Today, Einstein's ideas about the nature of space–time are as pervasive and influential as the ideas of absolute space and time were in 1887. His theory is built upon the principle of relativity, which states that the outcome of any experiment is independent of the uniform velocity of the apparatus with which it is performed. This is simply an operational definition of Lorentz invariance, which guides our construction of fundamental theory. In its first use by Einstein in 1905, the principle of relativity demanded the modification of Newtonian dynamics. Today, Lorentz invariance is woven deeply into the structure of quantum field theory. We find support for the principle of relativity in our research experience in high-energy physics, atomic physics and other fields, all filled with phenomena that match the predictions of special relativity. Even the layman, whether he is aware of it or not, runs up against the consequences of special relativity in everyday life—from the extended lifetimes of relativistic cosmic-ray muons, which can cause genetic mutations on Earth, to the Pauli exclusion principle, which determines the shell structure of atoms and the laws of chemistry and is deeply connected to special relativity. Even "everyday" issues such as national security are imbued with relativistic aspects: Time dilation and the relativistic synchronization of clocks are routinely accounted for in the operation of the precision navigation and timekeeping satellites of the US Air Force's NAVSTAR global positioning system.[5]

How, though, do we test these fundamental ideas more profoundly?

In principle, any precision experiment that examines a prediction of Lorentz invariant theory provides such a test, but in practice, however, it is often impossible to disentangle Lorentz invariance from other theoretical issues and experimental complications. As an example, the success of quantum electrodynamics in predicting lepton g-factors and the hyperfine structure of hydrogen and mesonic atoms[6] is impressive evidence that a great deal is "right" in Lorentz-invariant quantum field theory. But how strongly do these results test Lorentz invariance, as opposed to our quantization procedures and the details of our understanding of the strong and other particle interactions? Clearly, if we are to obtain quantitative limits on possible deviations from relativistic physics, we must

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design experiments that isolate effects of Lorentz invariance or of its breakdown.

In the past 25 years, the revival in the experimental testing of Einstein's general relativity has had its counterpart in renewed testing of special relativity using the latest high-technology, high-precision instruments. The Michelson–Morley experiment of a century ago is certainly the most familiar of all tests of Einstein's principle of relativity. Ironically, the recent experiments that provide today's sharpest tests of the relativity principle may be viewed as its direct descendants. In this centennial year of that classic experiment, it is appropriate not only to acknowledge its place as a driving force behind the introduction of special relativity and as one of the great experimental contributions from the early years of American physics but also to review the *modern* conceptual and empirical foundation for relativity and Lorentz invariance.

One way to study the foundations of Lorentz invariance is to think about the possibility that this invariance might be broken and to explore the physical consequences of such a breakdown. This can be difficult, given our taste for symmetry and the obvious beauty of special relativity. Nevertheless, it is quite conceivable that some entity whose influence cannot be shielded from our laboratories could establish a preferred frame of reference, that is, could cause the results of our experiments to depend on our velocity through space–time. Perhaps space–time itself has a discrete, lattice-like, structure on some small scale that might single out the lattice frame as a preferred frame of reference.[7] Another frequently discussed possibility is that cosmological fields that permeate space–time may establish a standard of absolute motion.[8]

The most natural candidate for a preferred frame, whether of cosmic or microscopic origin, is the rest frame of the cosmic microwave background. Our velocity relative to this frame is on the order of 300 km/s, and varies slightly because of the Earth's rotation and its revolution about the Sun.[9] Measuring this velocity is analogous to looking out the window of a train car to reckon our velocity with respect to the ground, as in one of Einstein's *gedanken* experiments. This is not a violation of the principle of relativity. However, any influence this velocity has on the outcome of experiments confined entirely to our laboratory would be a violation of Lorentz invariance. Experiments designed to search for such velocity dependence directly test this symmetry. We will consider several, including modern versions of the Michelson–Morley experiment.

A general theoretical framework

If Lorentz invariance is broken, physical systems are affected by motion relative to the preferred frame that is singled out. To design experimental tests of Lorentz invariance, we require a set of mathematical tools—such as a set of dynamical physical laws that apply in the preferred frame—with which to analyze such effects. In principle, we can use the physical laws to analyze the behavior of any physical system at rest in or moving through the preferred frame, and to predict the outcome of any experiment.

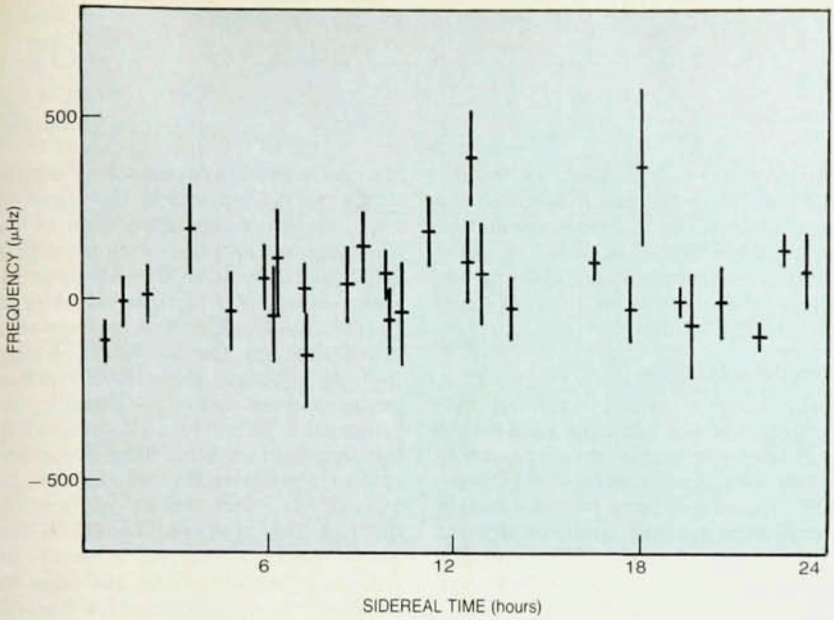
Under these circumstances, the form of the applicable set of laws is determined by the particular mechanism that breaks Lorentz invariance. By considering a broad range of forms we can explore the effects of a broad range of symmetry-breaking mechanisms. To construct self-consistent sets of laws for study it is useful to rely on fundamental dynamical principles, for example, by deriving the laws from an action principle. To avoid considering physics that is trivially at odds with experiment it is customary to restrict one's attention to laws that predict Newtonian behavior for systems that move slowly through the preferred frame. We also assume that the laws of physics exhibit a rotational invariance in the preferred frame. Thus, the only anisotropy of physics that will concern us is anisotropy in a moving frame, such as might be correlated with the orientation of the frame's velocity vector relative to the preferred frame.

It is convenient, although not absolutely necessary, to imagine constructing a set of physical coordinates in the preferred frame, using physical length standards (rulers) and time standards (clocks) to lay out a system of Cartesian coordinates and to set up a system of synchronized clocks. The restrictions on dynamics that we imposed above guarantee that synchronization of clocks using light pulses ("Einstein synchronization") agrees with synchronization by slowly transporting throughout the preferred frame a set of clocks originally synchronized at a single point. Using such coordinates, we can easily formulate dynamical laws that exhibit rotational invariance and a Newtonian limit in the preferred frame but are otherwise quite arbitrary.

To illustrate the procedure, we will discuss below a particular parametrized dynamics for the physics of charged particles and electromagnetic fields. Such a formalism allows us to explore the physical effects of broken Lorentz invariance in a range of models. The values of a particular model's "preferred-frame parameters" characterize the degree to which Lorentz invariance is broken in it; experimental effects that violate the principle of relativity (preferred-frame effects) are proportional to these parameters. Experimental limits on such effects force the model dynamics to approach a Lorentz invariant form. We will also discuss the limits imposed by several high-precision experimental tests.

The framework we have sketched provides a complete, self-consistent set of tools for studying the effects of broken Lorentz invariance. This approach reveals an important consequence of broken Lorentz invariance: The response of a system to motion through the preferred frame generally depends on the detailed structure of the system. Consider, for example, an observer at rest in the preferred frame who measures the transverse Doppler shift of the frequencies of transitions in different types of atoms moving together through his frame. Because the fractional shift in a particular transition frequency depends upon the internal structure of the atom undergoing the transition, the time dilation measured for different transitions will be different. Time dilation is not universal! This example brings out two important points.

First, precise null experiments sensitive to such structure-dependent effects can be powerful tests of Lorentz invariance. For example, contrast a measurement of the transverse Doppler shift with a null experiment that compares the relative frequencies of two different types of clocks that move together through space–time. The measurement of the transverse or second-order Doppler shift tests Lorentz invariance by revealing any deviation from the relativistic shift that is larger than the uncertainty in the measurement. Herbert Ives and G. R. Stilwell[10] were the first to test relativity in this way by measuring the difference in the Doppler shift of spectral lines emitted in the forward and backward directions by a beam of hydrogen atoms. Recently Matti Kaivola and his collaborators[11] achieved a precision of 4×10^{-5} in an experiment of this type. On the other hand, an experiment that compares the frequencies of two different types of



Null second-order Doppler shift experiment of John D. Prestage (NBS). Beryllium-9 ions are aligned in a laboratory magnetic field, and the frequency of the $M_I = -\frac{1}{2} \to -\frac{3}{2}$ in the $2\,^2S_{1/2}\,M_J = \frac{1}{2}$ state is monitored by comparison with a passive hydrogen maser. As the Earth rotates, the direction of the magnetic field rotates relative to the Earth's velocity through the preferred frame. A violation of Lorentz invariance could cause the Be frequency to depend on this direction, and thus to vary periodically relative to the hyperfine frequency of unpolarized atoms. Data points show the observed variations against sidereal time. Upper limits on the amplitudes of 12- and 24-hour variations were approximately 70 μHz. Figure 1

clocks to determine whether their relative frequency depends on their velocity through space–time can have an accuracy much higher than that with which either clock's frequency can be measured. Such an experiment is sensitive directly to a violation of the principle of relativity. Vernon Hughes and his collaborators and Ron Drever were the first to test Lorentz invariance by this technique (although their results were not interpreted in this way until long after the experiments were performed).[12] We will discuss these classic experiments below.

The second point brought out by our clock example is the deep connection between kinematics and dynamics. Clocks and rulers are physical systems governed by the laws of dynamics. When these laws are Lorentz invariant, they predict universal dilation of clock rates and universal Lorentz contraction of rulers. Thus, measurements with clocks and rulers of different types must agree no matter what the state of motion of an observer who uses them. Because the results of measurements do not depend on the devices used to make them, observers can conclude that the results of their measurements reveal intrinsic geometrical properties of space–time, for example, the proper time between events at their location or the proper separation between events they judge to be simultaneous. Clearly, when the laws of dynamics are not Lorentz invariant and predict nonuniversal time dilation and "Lorentz" contraction there cannot be a unique operational geometry of space–time. The class of null experiments we have just described, therefore, directly tests for the existence of such an operational space–time geometry.

This connection between dynamics and the behavior of clocks is so strong that we conjecture that universal time dilation implies Lorentz invariance. If Lorentz invariance is indeed broken, the laws of dynamics in the preferred frame must differ from a Lorentz-invariant form. Suppose that we have a representation of these laws in the form of a Hamiltonian function. We can think of the difference between this function and a Lorentz-invariant Hamiltonian as a perturbation, and it seems inconceivable that this perturbation will fail to affect the relative spacing of the energy levels of some system in a way that depends on the velocity of the system relative to the preferred frame. If the relative spacing of different pairs of levels does exhibit velocity dependence, then clocks based on the transition between these pairs will exhibit different time dilation. Because the velocity vector in the preferred frame singles out one direction, we expect that these effects will often be anisotropic.

The theoretical framework for analyzing tests of Lorentz invariance that we have described differs markedly from the framework most often encountered in the literature on tests of special relativity. This alternative framework is distinctly kinematic in character, and the laws of dynamics are never explicitly discussed. It can be traced back to a beautiful paper by H. P. Robertson,[13] which discussed the Michelson–Morley[1] experiment and its variant—using unequal interferometer arm lengths—carried out by Roy Kennedy and Edward Thorndike.[14] Robertson began the construction of his formalism from the same sort of physical coordinates in the preferred frame and in a moving frame that we employed above. The most general coordinate transformation that can connect the preferred frame and the moving coordinate system is

$$\begin{aligned} t' &= \alpha t + \beta v(x/c^2) \\ x' &= \beta x + \alpha v t \\ y' &= \gamma z \\ z' &= \gamma z \end{aligned}$$

where α, β, and γ are functions of v, the velocity of the moving coordinate system.

Robertson then used the Michelson–Morley and Kennedy–Thorndike experiments, for example, to establish that moving "light clocks" (clocks whose rates are determined by the round-trip light-travel time along a standard distance and back) suffer the same time dilation as the standard clock he used in constructing his coordinate systems. He thereby constrained the form of the transformation to approach that of a pure Lorentz transformation within the experimental error.

Local Lorentz invariance

Special relativity is a theory set in gravity-free space–time, and so the discussion of tests of Lorentz invariance is also generally set in gravity-free space–time. Gravity does exist, however, and it cannot be shielded from our laboratories. The best we can do is to work in a small, freely falling frame, which is locally gravity-free according to the principle of equivalence. Consequently, any discussion of tests of Lorentz invariance will involve aspects of gravitational physics. It is useful to describe briefly this connection between Lorentz invariance and gravitation because of its intrinsic interest and because, historically, it is the source of the dynamical framework we have described above. The physics of Lorentz invariance and the testing of this symmetry have benefited from bringing together the traditional literature on tests of special relativity and the gravitational physics literature.

One of the central questions of gravity physics is whether gravitation is a metric phenomenon. Metric theories such as general relativity describe gravity in terms of a dynamic, curved geometry of space–time. Local observers—that is, observers who work within regions of space–time sufficiently small that inhomogeneities of external gravitational fields may be ignored—find that the structure of space–time is just that of special relativity. There is a *local* Lorentz invariance of space–time in a metric gravitational field. The outcome of any local nongravitational experiment is independent of the velocity of the freely falling apparatus that is used to perform it. This principle of local Lorentz invariance is one component of what is known as the Einstein equivalence principle. This principle also states that the trajectories of neutral freely falling test bodies are independent of their structure and composition (weak equivalence principle) and that the outcome of any local nongravitational test experiment is independent of where and when in the universe a freely falling observer performs it (local position invariance). It turns out that if the Einstein equivalence principle is valid, then gravity is a metric phenomenon.

Robert H. Dicke's pioneering work in the 1960s led to the modern view that the meaning and significance of the equivalence principle lies in the constraints it imposes on the nature of the coupling of gravity to matter and nongravitational fields. This coupling determines the structure of the dynamical laws that govern local physics. Dicke emphasized the role of precise null experiments, such as the Eötvös experiment (see PHYSICS TODAY, October, page 17), as tests of the equivalence principle. Leonard Schiff explicitly noted the connection between dynamics and kinematics in his discussion of the relation between the Eötvös and gravitational redshift experiments. Kip Thorne, Alan Lightman and David Lee consolidated the modern picture of the equivalence principle and introduced a theoretical framework specifically for the analysis of local physics in a broad range of gravitational environments. Kenneth Nordtvedt and Will built on the insights of Dicke and Schiff to reveal the importance of "null" gravitational redshift experiments as tests of local position invariance, and Haugan extended these ideas to tests of local Lorentz invariance.[15]

A model dynamics

The insights gained from the Einstein equivalence principle have served as guideposts for the development of specific dynamical models that incorporate violations of Lorentz invariance in a self-consistent way, and that provide a quantitative formalism for analyzing experiments. We describe here a very simple, yet powerful, version of such a model.

In the preferred coordinate frame we described above, we now define a dynamics of charged particles and electromagnetic fields via an action abstracted from work of Lightman and Lee[15]

$$I = \sum_i \int [\, -m_i(1 - v_i^{\,2})^{1/2} + e_i A_\mu v_i^{\,\mu}]\,\mathrm{d}t + \frac{1}{8\pi}\int [E^2 - c^2B^2]\,\mathrm{d}^3x\,\mathrm{d}t \qquad (1)$$

where m_i, e_i and $x_i^{\,\mu}(t)$ are the rest mass, charge and world line of particle i, and

$$\begin{aligned} x^0 &= t \\ v_i^{\,\mu} &= \mathrm{d}x_i^{\,\mu}/\mathrm{d}t \\ A_\mu &= (-\phi, \mathbf{A}) \\ \mathbf{E} &= \nabla A_0 - \partial\mathbf{A}/\partial t \\ \mathbf{B} &= \nabla \times \mathbf{A} \end{aligned}$$

We have chosen units in which the fundamental limiting velocity of massive particles is unity; this is reflected in the form of the free-particle action, $-m_i(1 - v_i^{\,2})^{1/2}$. When the speed of light, c, is also equal to unity this action is the familiar Lorentz-invariant action of relativistic electrodynamics. When c is not equal to 1, Lorentz invariance is broken. For arbitrary c, the action is unique in predicting linear electromagnetic field equations, an isotropic speed of light in the preferred frame and the usual gauge invariance and minimal coupling. We demand these features of our model so that we may study the effects of breaking Lorentz invariance in isolation.

We are interested in the behavior of bound electromagnetic systems—atoms—predicted by the action (1) and in the interaction of such systems with light. Such is the stuff of experimental tests. When we restrict our attention to charged-particle systems whose components do not approach the speed of light, we can construct a form of the Lagrangian that refers only to particle degrees of freedom. We introduce internal and center-of-mass variables so that we may easily treat systems that move through the preferred frame, that is, systems that have nonzero center-of-mass velocity. Finally, we construct a Hamiltonian description of the dynamics of the charged particle system, a description that may be quantized. The effect of motion through the preferred frame on the energy and the internal structure of charged-particle systems can then be analyzed using perturbation theory, using the small center-of-mass speed as the expansion parameter.

By computing the effect of motion with velocity $\mathbf{v}$ relative to the preferred frame on the internal wavefunction of a charged particle system, we find, for example, that an observer in the preferred frame will measure the extension of the system along the direction of motion to be contracted relative to that in the perpendicular directions by a factor $1 - v^2/2$, accurate to order v^2/c^2. Notice that the fundamental limiting particle velocity and not the speed of light appears in this factor. This 'Lorentz' contraction result applies to systems with isotropic average internal structure, for example, a polycrystalline solid as opposed to a single crystal. Perturbation theory also yields expressions for the energy and momentum measured by a preferred-frame observer for a bound charged-particle system moving with velocity $\mathbf{v}$,

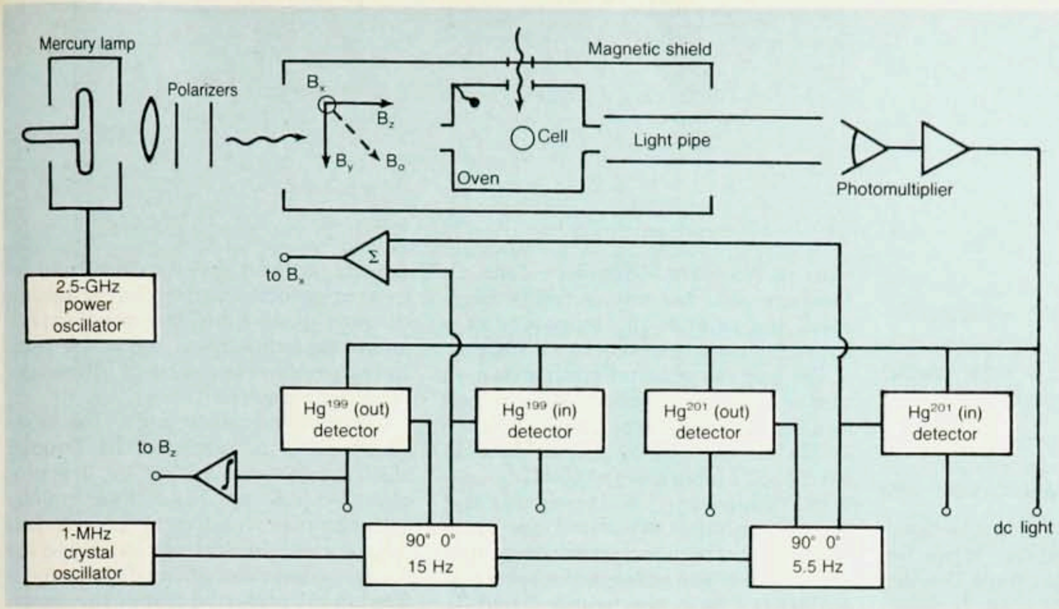
$$E = M_R + \tfrac{1}{2} M_R v^2 + \tfrac{1}{2}\, \delta M_I^{ab} v^a v^b \qquad (2)$$

$$P^a = M_R v^a + \delta M_I^{ab}\, v^b \qquad (3)$$

where M_R is the net mass of the system, that is M_0, the sum of the particle rest masses, minus E_B, the electrostatic binding energy of the system; the inertial mass tensor is given by

$$\delta M_I^{ab} = (1/c^2 - 1)\Lambda^{ab} \qquad (4)$$

where Λ^{ab} is a symmetric tensor formed by summing the expression $\tfrac{1}{4} e_i e_j r_{ij}^{\,-1}(\hat{n}_{ij}^{\,a}\hat{n}_{ij}^{\,b} + \delta^{ab})$ over all pairs of charged particles in the body, where r_{ij} and $\hat{n}_{ij}$ are the distance and unit vector between the particles i and j. The quantity $1/c^2 - 1$ is a preferred-frame parameter whose magnitude reflects the degree to which Lorentz invariance is broken in the model.



Measurement of nuclear-spin-coupled spatial anisotropy for two isotopes of mercury, performed by S. K Lamoreaux and his collaborators at the University of Washington. Cell containing vapor of Hg^{199} and Hg^{201}, optically pumped by a Hg^{204} lamp, is maintained in an oven at constant temperature in the center of three Helmholtz coils. The entire apparatus is magnetically shielded. The light pipe transmits the light that passes through the cell to a photomultiplier. Four phase-sensitive detectors measure the in-phase and quadrature components of the signal for each isotope. Figure 2

The electromagnetic field dynamics given by equation 1 can also be quantized and one can treat the interaction of photons with atoms via perturbation theory. The energy of a photon is $\hbar$ times its frequency ω, while its momentum is $\hbar\omega/c$.

Some experimental tests

We now replay the familiar analysis of the Michelson–Morley experiment, but using the results of light propagation and "Lorentz" contraction appropriate for our model dynamics. A photon traverses an arm of the Michelson interferometer oriented perpendicular to its motion at velocity **v** relative to the preferred frame. Let L_0 denote the length of this arm as measured by a preferred-frame observer. When Lorentz invariance is broken this length does not equal the length of the arm measured when the interferometer is at rest in the preferred frame. Since the speed of light in the preferred frame is c, the preferred-frame observer finds that the photon completes its trip in a time $(2/c)(L_0^{\,2} + X^2)^{1/2}$, where X is the distance the interferometer moves while the photon propagates. To order v^2/c^2, X is equal to L_0v/c; the light-travel time is then approximately $(2L_0/c)(1 + v^2/2c^2)$. This and the relation of L_0 to the length of the interferometer arm when at rest in the preferred frame determine the time dilation factor for this light clock.

A preferred-frame observer measures the length of the arm oriented parallel to its motion to be contracted to a length L equal to $L_0(1 - v^2/2)$ to order v^2/c^2. The preferred-frame observer therefore measures a light-travel time $(L + X_1)/c + (L - X_2)/c$, where X_1 is the distance the interferometer moves while the photon propagates to the end-mirror, and X_2 is the distance moved while the photon propagates back. To order v^2, X_1 is $L_0v/c + L_0v^2/c^2$ and X_2 is $L_0v/c - L_0v^2/c^2$. To this order, then, the total light-travel time is

$$\frac{2L_0}{c}\left[1 + \frac{v^2}{2c^2} - \left(\frac{1}{c^2} - 1\right)\frac{v^2}{2}\right]$$

This light clock suffers a different time dilation—an example of the nonuniversal response to motion that we have emphasized.

The Michelson–Morley experiment constrains the two light travel times we have calculated to be equal to within some measurement error. The most recent and most precise repetition of this experiment, by Alain Brillet and Jon Hall[16] using laser techniques, constrained the two times to be equal within a fractional error of 10^{-15}. Taking the velocity relative to the preferred frame to be our velocity relative to the cosmic microwave background, we conclude that the preferred-frame parameter, $1/c^2 - 1$, must be less than 10^{-9}: a strong limit.

Next consider an experiment by a preferred-frame observer to measure the Doppler shift of a photon emitted by a system moving with velocity **v** through the preferred frame. Our analysis of this simple experiment will provide the tools we need to analyze transverse-Doppler-effect experiments that compare the rates of different atomic clocks that move together relative to the preferred frame.

Consider a photon emitted when a bound state forms from a collection of charges at relative rest. (Conceptually, the case of a transition between bound states is no different, but because the inertial properties of the initial state are trivial in the case we analyze, the resulting formulas are simpler.) We compute the frequency measured by a preferred-frame observer for the emitted photon by using the applicable conservation laws for energy and momentum.

The initial energy of the unbound charges that move together through the preferred frame is $M_0(1 + v^2/2)$, and their momentum is $M_0\mathbf{v}$. The binding energy E_B of the final state is assumed small compared with M_0. After the transition and emission of the photon, the charged particle system will have a velocity $\mathbf{v}'$ that differs from $\mathbf{v}$ because of recoil effects. The total final state energy of the photon and bound state

$$\hbar\omega + (M_0 - E_B)(1 + \tfrac{1}{2}v'^2) + \tfrac{1}{2}\delta M_1^{\;ab}\,v'^a\,v'^b$$

and total final state momentum components,

$$(\hbar\omega/c)n^a + (M_0 - E_B)v'^a + \delta M_I{}^{ab} v'^b$$

must equal the energy and momentum of the initially unbound constituents. Solving for ω and neglecting E_B relative to M_0, we find

$$\hbar\omega(1 - \hat{n}\cdot\mathbf{v}/c) = E_B(1 - v^2/2) + \tfrac{1}{2}\delta M_I{}^{ab} v^a v^b \qquad (5)$$

The unit vector $\hat{n}$ points in the direction of photon propagation. When $\hat{n}\cdot\mathbf{v}$ is 0, this yields the transverse Doppler shift. In general, equation 5 determines the time-dilation factor for an atomic clock based on the transition considered. Note once again the structure dependence due to the presence of the anomalous mass tensor $\delta M_I{}^{ab}$.

Suppose photons are emitted in the same direction by transitions in two different atoms that move together with velocity **v** through the preferred frame. The frequency ratio a preferred-frame observer measures for this pair of photons is the same as the ratio determined by an observer who moves with the clocks. Since the anomalous mass tensors of the two atoms will generally differ, this ratio will depend on **v**, violating Lorentz invariance. Since the anomalous inertial mass is a tensor, the ratio will also depend on the orientation of the emitting atoms, say of their angular momentum, relative to **v**.

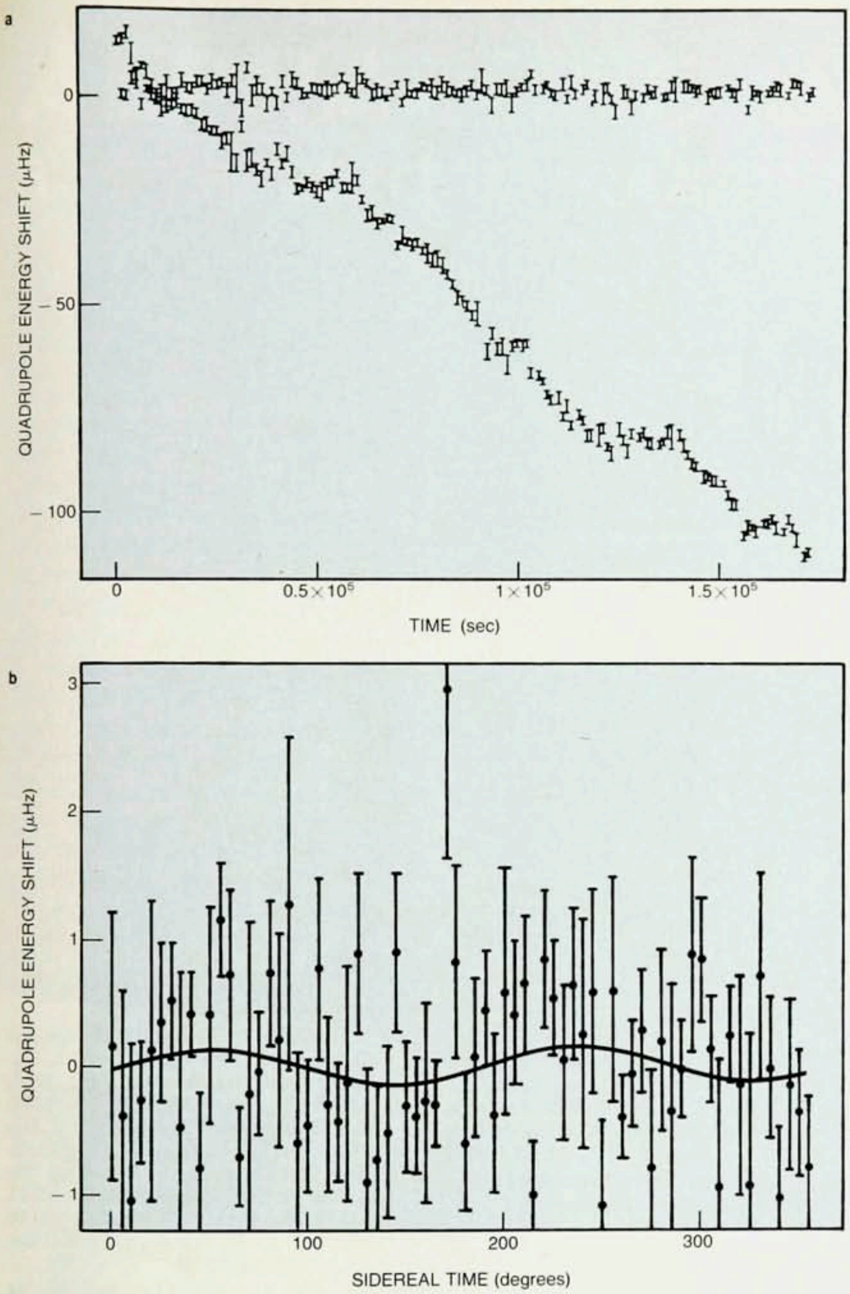
The first tests of this idea were performed around 1960, independently (and for somewhat different purposes) by Vernon Hughes at Yale University and Ron Drever at Glasgow University. These classic experiments are now referred to collectively as the Hughes–Drever experiment. In the Glasgow version, for example, Drever studied Li^7 nuclei in the four $J = 3/2$ ground state energy levels, split by a magnetic field. Because the nuclear wavefunctions for different M_J have different orientations relative to the Earth's velocity **v**, the anomalous mass tensors for each state differ, and the three $\Delta M_J = 1$ transitions will emit photons of slightly different frequency, thereby broadening or splitting the line. To high accuracy, Drever and his group saw no such broadening. Two recent experiments of this type made dramatic improvements in precision. In a 1985 experiment[17] at the National Bureau of Standards (Boulder), John D. Prestage and his collaborators measured the ratio of the frequency of a hyperfine transition of a small number of Be^9 ions stored in a Penning trap, to that of a passive hydrogen maser clock as a function of sideral time (see figure 1). In an experiment[18] performed in Fred Raab's laboratory at the University of Washington, S. K. Lamoreaux and his collaborators measured the ratio between the frequencies of nuclear spin precession of two isotopes of mercury in a magnetic field (see figures 2 and 3).

To interpret these experiments, one evaluates in detail the anomalous mass tensors for the initial and final states for each of the two transitions involved and uses the results of the analysis of the transverse Doppler shift to determine the variation in the frequency ratio as the atoms rotate relative to **v**. In the recent experiments, the rotation of the Earth was exploited to change the orientation of the emitting atoms, which were fixed in a laboratory magnetic field, relative to our velocity through the cosmic microwave background. The null results of Prestage and Lamoreaux constrain the preferred-frame parameter $1/c^2 - 1$ to be less than 10^{-18} and 3×10^{-22}, respectively. The latter is an improvement by a factor of roughly 10^6 over the limit provided by the Hughes–Drever experiment.

The Michelson–Morley and Hughes–Drever experiments search for anisotropy induced by motion through a preferred frame. They impose powerful constraints on the anisotropic part of the anomalous mass tensor $\delta M_I{}^{ab}$ and thereby on the preferred-frame parameter that characterizes our illustrative model dynamics. However, they do not directly constrain the scalar part of $\delta M_I{}^{ab}$, because this part produces no anisotropic effects. In more general model dynamics the scalar and tensor inertial anomalies may be independent. (See, for example, the weak interaction dynamics studied by Ephraim Fishbach and his group.[19]) Another class of experiments is thus required to explore fully the possible effects of broken Lorentz invariance. In principle, one can test these effects with null experiments using the transverse Doppler effect that measure how the rates of different atomic clocks depend on their speed rather than on their orientation as they move together through space–time. One set of experiments that constrains the scalar inertial anomaly is the class of Mössbauer rotor experiments.[20]

These experiments exploit the Mössbauer effect to measure the Doppler shift for γ-rays emitted by a source mounted on the edge of a rapidly spinning disk, relative to the resonant frequency of an absorber located at the center of the disk. If the disk center is fixed in the preferred frame, this experiment is nothing more than a measurement of the transverse Doppler shift by a preferred-frame observer as described above. However, when the disk is in motion through the preferred frame the experiment corresponds to the measurement of the Doppler shift by an observer in motion through the preferred frame. This experiment will reveal effects of the observer's motion when Lorentz invariance is broken. In particular, the anomalous inertial masses of the initial and final Mössbauer states involved in the transition cause the Doppler shift to vary periodically at the rotation frequency of the disk. This variation of the Doppler shift is observed as a modulation of the absorption at the center of the disk. Kenneth Turner and Henry Hill (both at Princeton), and the groups led by D. C. Champeney and G. R. Isaak (both at the University of Birmingham) searched for and failed to find such an effect, thus setting limits on the strength of a breakdown of Lorentz invariance.[20] For example, Isaak places an upper limit on the preferred-frame parameter of our model dynamics, $1/c^2 - 1$, of 10^{-6}. This is a weaker limit than those obtained in the Hughes–Drever experiments, but the experiment is sensitive to scalar inertial mass anomalies.

Figure 4 shows the preferred-frame geometry of the photon exchange between a source at the edge of a spinning disk and a receiver at the disk center. As in our earlier discussion of the Doppler shift, we consider a photon emitted when an unbound collection of charges at relative rest forms a bound state. The photon must be emitted in a direction $\hat{n}$ to arrive at the center of the disk, which moves at **v** during the photon's time of flight τ. Because the



Frequencies of transitions between Zeeman-split energy levels of mercury-201 nuclei compared with those of mercury-199 as the Earth rotates.[18] **a:** Raw comparisons over six runs of 2.5 days each, before (sloping curve) and after a regressive analysis to remove instrumental and other effects. **b:** Data for the 15 days plotted against sidereal time. The solid curve is a fit to Fourier components at 12-hour and 24-hour periods. Figure 3

total source velocity is $\mathbf{v} + \mathbf{V}$, where $\mathbf{V}$ is the rotational velocity at the edge of the disk, the preferred-frame frequency, ω_s, of the emitted photon is given by equation 5 with $\mathbf{v}$ replaced by $\mathbf{v} + \mathbf{V}$. We take $\delta M_I{}^{ab}$ to be a scalar for this analysis because we are interested in illustrating the sensitivity to a scalar anomaly. Equation 5 as it stands gives the frequency ω_a of a photon emitted in the direction $\hat{n}$ by an identical source at the center of the disk. This frequency is the resonance frequency for the absorption process considered in the Mössbauer experiments. The ratio of these frequencies is the same as reckoned by any observer. It is

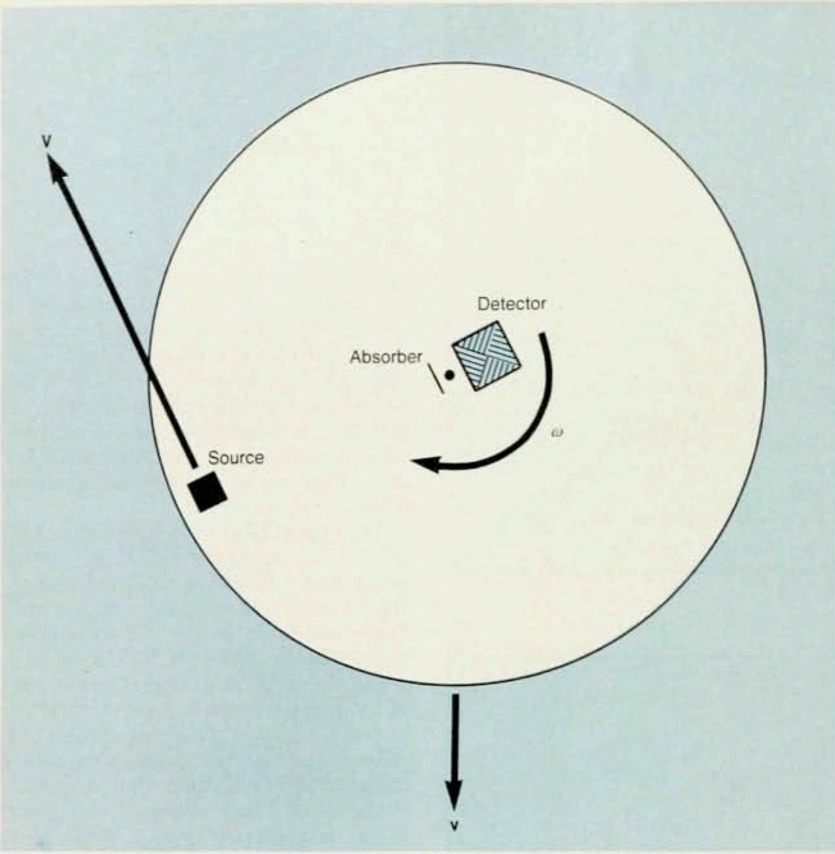
$$\frac{\omega_s}{\omega_a} = 1 - \frac{V^2}{2} + \left(\frac{1}{c^2} - 1\right)\mathbf{v}\cdot\mathbf{V} + \frac{\delta M_I}{E_B}\left(\mathbf{v}\cdot\mathbf{V} + \frac{V^2}{2}\right) \qquad (6)$$

where we have used the fact that the angle κ between $\hat{n}$ and the radius is, for the small velocities considered, equal to the component of $\mathbf{v}$ perpendicular to AB divided by the speed of light c, so that $\hat{n}\cdot\mathbf{V}/c$ is nearly $\mathbf{v}\cdot\mathbf{V}/c^2$. It is the dependence of the frequency ratio on $\mathbf{v}\cdot\mathbf{V}$ that is limited by the Mössbauer rotor experiments. The dependence of this effect on a scalar inertial mass anomaly is apparent.

The experiment that places the sharpest limit on preferred-frame effects while being sensitive to a scalar inertial anomaly is actually not a clock experiment. It is the Eötvös–Dicke–Braginsky experiment.[21] Up to this point we have concentrated on the role of the inertial mass in determining the kinetic energy of a moving system. Of course, the inertial mass also determines the acceleration that a system experiences when subjected to a given force. If the extra force is given by a potential $W(\mathbf{X})$, where $\mathbf{X}$ is the center-of-mass coordinate of the system, then the expression for the conserved energy of a bound electromagnetic system, equation 2, becomes

$$E = M_R + {}^1\!/\!_2\, M_R v^2 + {}^1\!/\!_2\, \delta M_I^{ab} v^a v^b + W(\mathbf{X}) \qquad (7)$$

The anomalous mass tensor then affects the acceleration suffered by the system so that it depends on the details of the structure of the system in addition to the rest energy M_R and the potential gradient. The EDB experiment is designed to look for such a dependence of the acceleration caused by a gravitational potential gradient. In a weak gravitational field, the potential has the form $W(\mathbf{X}) = M_P U(\mathbf{X})$, where M_P is the passive gravitational mass of the bound system and $U(\mathbf{X})$ is the Newtonian gravitational potential. If the principle of equivalence is not valid, M_P may depend on the detailed structure of the system. Because this dependence is unlikely to cancel the effects of the inertial mass anomaly, we will suppose that M_P is equal to M_R. If $\delta M_I{}^{ab}$ is approximately a scalar, the anomalous gravitational acceleration of the bound system is given by $-(\delta M_I/M_R)\mathbf{g}$, where $\mathbf{g}$ is the gradient of U. The EDB experiment compares the accelerations of systems having different internal structures and there-



Rotor experiment of Kenneth Turner and Henry Hill, as seen from the preferred frame. The velocity of the rotor as a whole is $\boldsymbol{v}$; the rotational velocity is $\boldsymbol{V}$. Figure 4

fore different inertial mass anomalies. In the context of our model dynamics, the upper limit on $1/c^2 - 1$ due to structure dependence of the gravitational acceleration from the Braginsky experiment is 10^{-9}, representing the sharpest available limit on scalar mass anomalies.

The scientific legacy of the Michelson–Morley experiment is not something to be consigned to musty old books on special relativity that languish on the scientist's bookshelf. Nor is it merely the province of the historian of science, who is primarily devoted to an understanding of what was thought in the past, or of who influenced whom "way back then." Our 1980s viewpoint on Lorentz invariance, local Lorentz invariance and the connection between special relativity and gravitational physics has provided us with a new insight into experiments of this type. When we view the Michelson–Morley experiment as a null experiment comparing two different clocks, we see that the legacy of this famous experiment lives on in new versions having vastly improved precision and providing potent confirmation of one of the deepest principles of physics.

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