THEORETICAL PHYSICS

Limits for spatial anisotropy

All metric theories of gravity (including general relativity) are based on the **Einstein equivalence principle** (EEP), which states in part that the outcome of any local nongravitational experiment is independent of the velocity and orientation of the freely falling laboratory apparatus. This part of the EEP is called local Lorentz invariance (LLI). As a test of LLI we have compared the frequency of a nuclear spin flip hyperfine transition in the ground state of ^{9}Be$^+$ (see figure 1) with the frequency of a passive hydrogen maser clock, to see if a correlation between the relative rates of these two clocks and the orientation of the ^{9}Be$^+$ nuclear spin in space could be found. Searches for preferred frames of reference by comparing the rates of two clocks are interpreted as the most stringent tests of LLI.

The most well-known search for a preferred frame of reference was performed by A Michelson and E Morley beginning in 1880. They tried to use an optical interferometer to measure the velocity of the earth through the ether, a substance which was thought to fill all of space and provide a medium for the propagation of electromagnetic radiation. Of course, no such motion was detected and so the experimental foundations for LLI were established.

The first atomic physics experiments to test LLI were reported in 1960 by V Hughes and co-workers at Yale University and in 1961 by R Drever (now at the California Institute of Technology). Both searched for frequency shifts of NMR transitions in ^{7}Li which were correlated with the direction toward the galactic centre, but found none.

Fundamentally *any* EEP violation is due to a breakdown of the universal coupling of gravity to all types of mass–energy. This universality of coupling characterises metric theories of gravity. An anomalous coupling to some type of mass–energy results in a nonmetric theory. As pointed out by theorist M Haugan of Purdue University, in theories for which LLI is invalid a nucleus will experience an interaction between its internal structure and centre of mass motion of the form $\delta E = \Sigma \delta m_1{}^{ij} V^i V^j$ where $\delta m_1{}^{ij}$ is called the anomalous inertial mass tensor and V is the velocity of the nucleus through some preferred frame. For example, the frame in which the 3 K cosmic microwave background radiation appears isotropic may be one such. The earth moves through this 3 K radiation with a velocity of about 300 km s^{-1}, and this is sometimes referred to as the new ether drift.

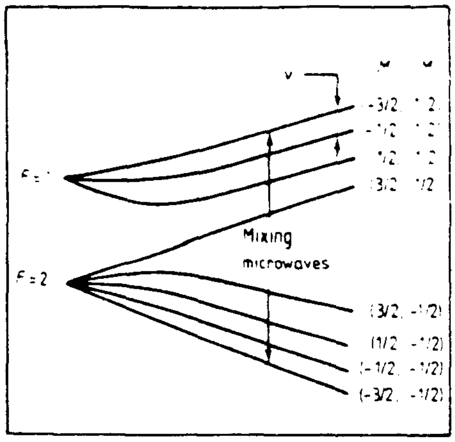

Figure 1 Hyperfine structure (not drawn to scale) of the ^{9}Be$^+$ 2s^{2}S$_{\frac{1}{2}}$ ground state as a function of magnetic field

To compare the various experimental tests of LLI we use a model of electrodynamics in a gravitational field which includes the possibility of nonuniversal couplings. This model, called the $TH\epsilon\mu$ formalism, was developed by Caltech physicists A Lightman and D Lee. Here the parameters T_0 and H_0 describe the coupling of gravity to material particles, while ϵ_0 and μ_0 describe gravity's coupling to electromagnetic fields. Because it incorporates LLI-violations the limiting speed for material particles, c_0, can be different from the speed of light, c, the two speeds being related by $c_0/c = (T_0\epsilon_0\mu_0/H_0)^{\frac{1}{2}}$.

If $c_0 \neq c$ there is an interaction between the electric quadrupole moment of the ^{9}Be nucleus and its motion through some preferred frame. Because the hydrogen atom has no such moment (to first order) in the maser states there is no shift of the maser clock rate. Due to the quadrupolar symmetry of this interaction, if $c_0 \neq c$, the relative clock rates will vary as $P_2(\cos\beta)$ where β is the angle between the quantisation axis of the ^{9}Be$^+$ ions and the direction toward any preferred frame.

The clock comparison experiment recently reported by our group (J D Prestage, J J Bollinger, W M Itano and D J Wineland) follows the report earlier this year of a frequency standard based on trapped laser-cooled ^{9}Be ions. In this experiment up to 2000 ^{9}Be ions were stored in a Penning trap, which made use of a quadrupolar electric field and a uniform magnetic field (directed along the symmetry axis of the electric field) to confine the ions.

This experimental arrangement is well suited to a clock comparison for a number of reasons. The first is the high resolution of the ^{9}Be$^+$ transition frequency measurement. Two experimental factors determine the sensitivity of the measurement: the time, T, that the nuclear spin flip resonance frequency is monitored; and the signal to noise ratio achieved in detecting the resonance. Because the ions are confined to a small region of space, T can be large. For our measurement $T = 20$ s, which gives a linewidth of 25 mHz for the 303 MHz ^{9}Be$^+$ clock transition. In a two hour measurement the signal to noise ratio was sufficient to locate the centre of this resonance line to about 0.5%.

Another reason for using trapped ions is the accuracy with which the clock transition frequency approaches the perturbation free atomic transition frequency. This is due in part to the absence of material walls and the consequent 'wall shift' of the transition frequency.

Although not normally regarded as a perturbation, the motion of the ions in the trap will shift the frequency of the clock transition via the second-order Doppler effect. These motional perturbations are reduced by 'laser cooling' the cloud of ions to temperatures below 1 K. This involves tuning radiation ($\lambda = 313$ nm) from a frequency-doubled dye laser slightly below the $2^2S_{1/2}(-\frac{3}{2}, -\frac{1}{2}) \rightarrow 2^2P_{3/2}(-\frac{3}{2}, -\frac{3}{2})$ transition frequency. Here the ions absorb radiation more strongly when their motion is toward the laser. When averaged over all angles of re-emission, the ions' momentum is reduced by h/λ per scattered photon, where λ is the laser wavelength and h is Planck's constant. This results in the required cooling of the Be$^+$ cloud.

In our experiment the ^{9}Be$^+$ transition is driven by a synthesiser the frequency of which is computer controlled so that it remains centred on the clock transition. The timebase for this synthesiser is provided by a passive hydrogen maser. Any shift of the ^{9}Be$^+$ transition frequency relative to the maser transition will appear as a variation of the synthesiser's output frequency. The results of 29 such two-hour measurements plotted against sidereal time are shown in figure 2.

We have searched for a variation in the ^{9}Be$^+$ clock transition frequency of the form $\nu = \nu_0 - AP_2(\cos\beta(\tau))$ where A

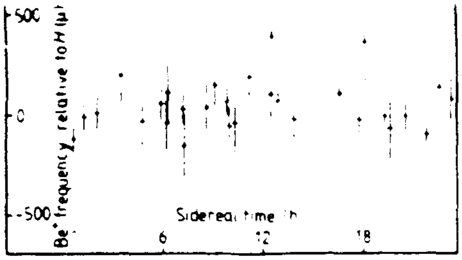

Figure 2 Variation of the ^{9}Be$^+$ clock transition frequency referenced to a hydrogen maser plotted against sidereal time

measures any dependence of the relative clock rates on orientation in space. The sidereal time τ enters because we use the daily rotation of the earth to modulate β. The data of figure 2 imply that A is consistent with zero at the level of 100 μHz for an arbitrary direction in space. In particular, $A = 35 \pm 46$ μHz for the direction of the earth's motion through the 3 K background radiation (see 1985 *Phys. Rev. Lett.* **54** 2387).

M Haugan has used the $TH\epsilon\mu$ formalism to compare the Michelson–Morley type experiments with the atomic physics tests of LLI. Taking the frame in which the 3 K cosmic microwave radiation appears isotropic as the possible preferred one, Haugan finds upper limits on the difference $(1-(c_0/c)^2)$ of 10^{-4} from the Michelson–Morley experiment, 5×10^{-9} from the modern-day version of the Michelson–Morley experiment (performed by A Brillet and J Hall at the Joint Institute for Laboratory Astrophysics), and 10^{-18} for the NMR measurements of Hughes and Drever.

Our recent measurements have decreased the limits to 5×10^{-19}. Preliminary results from a University of Washington group (B Heckel, F Raab, E N Fortson and S Lamoreaux) indicate a limit of 10^{-20} □

John D Prestage

ELECTRON DEVICES

Josephson junction array voltage standard

The elegance of the superconductive tunnelling effects predicted by Brian Josephson in 1962 has been matched by that of the subsequent devices, particularly the SQUID magnetometer or galvanometer. The allied application of the AC Josephson effects led first to a measurement of $2e/h$ and subsequently to the use of Josephson junctions for maintaining the SI unit of potential.

Because there is too great a production spread in their characteristics, attempts to manufacture large arrays ments has delayed production of commercial computers. However, there is a different application which requires about a thousand junctions in a small substrate area. Two groups have now found a method of forming a series-connected array of junctions such that each junction, when irradiated with microwaves, is set on a supercurrent step (Niemeyer *et al* 1985 *Appl. Phys. Lett.* **47** (11) 1222–3 and Hamilton *et al* devices is as a predictable voltage reference standard of very high accuracy.

A Josephson junction essentially comprises two superconductors separated by an oxide a few nanometres thick (see figure 4). The first superconductor is evaporated on to an insulating substrate, the metal is then oxidised, and a second superconducting strip evaporated so as to partially overlap the

ASTRONOMY

A polished performance

The primary mirror for the 4.2 m William Herschel telescope (figure 3) has recently been delivered by NEI Parsons to the Royal Greenwich Observatory. Believed to be the smoothest of its size ever made, the mirror is now awaiting shipment to La Palma in the Canary Islands to be fitted into the telescope.

A piece of CerVit – a glass ceramic made by the Corning Company in New York – was used for the mirror blank. The £0.5m cost of the material was matched by the cost of figuring the mirror at the NEI Parsons optical workshop in Newcastle.

Overall the mirror surface departs from ideal by less than 1/12th of the wavelength of light; on a 2 cm scale the surface is much smoother, with a roughness of about 1/80th of the wavelength of light. This kind of accuracy is necessary because of the properties of La Palma's atmosphere. At any time the air over the mountain top is made up of columns of perfect air tilted relative to each other, rather like the facets in a pane of bathroom window glass; the bigger the facets, the clearer the view through the window, and on La Palma the facets of pure air are often as big as 50 cm in diameter. So on a scale of 50 cm or less the Herschel mirror has to be almost perfect.

In addition to achieving the required smoothness, NEI Parsons managed to keep the waste zone at the edge of the mirror to only 7 mm (2 cm had been allowed for errors in the figuring process), thus giving an extra 41 cm of telescope collecting area.

When completed in 1987, the William Herschel telescope (named after the British astronomer who discovered Uranus in 1781) will be the third largest single-mirror telescope in the world □

Figure 3 The £1m mirror undergoing final polishing