AN ULTRA HIGH VACUUM LOW TEMPERATURE GYROSCOPE CLOCK

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We propose to perform a null-gravitational redshift experiment by comparing a mechanical gyroscope clock with atomic clocks. The Gravity-Probe-B Relativity Gyroscope Experiment provides the opportunity for this co-experiment. The goal is to measure the effect to an accuracy of 0.01% of the gravitational redshift due to the eccentricity of the orbit of the earth about the sun. This corresponds to an integrated frequency measurement over one year of $\Delta \nu/\nu = 3 \times 10^{-14}$. A major disturbance torque on the gyroscope is due to fluctuations in the molecular drag of the residual gas caused by temperature variations. We propose to use a low temperature bake-out technique in order to achieve the required vacuum of $10^{-17}$torr.

1. BACKGROUND

The GP-B Relativity Gyroscope Experiment, whose goal is to measure the geodetic and frame-dragging precessions of gyroscopes in earth orbit, provides the opportunity for a proposed co-experiment to perform a null gravitational redshift measurement. In this experiment the spin frequencies of the orbiting gyroscopes are compared with earth based atomic clocks. A null result means equal redshift for the atomic and gyroscope clocks, therefore verifying the equivalence principle. These measurements will extend gravitational redshift observations to clocks based on the spin speed of a rotating mass. This experiment can also be interpreted as a check of the invariance of the fine structure constant $\alpha$; atomic clock frequencies depend on $\alpha^4$, while the mechanical gyroscope frequency varies as $\alpha^2$.

The principal change in gravitational potential experienced by the gyroscopes and the atomic clocks over a year is due to the eccentricity of the orbit of the earth about the sun. This leads to a peak-to-peak variation in the gravitational redshift of $\Delta \nu/\nu = 3 \times 10^{-10}$ over the year. The goal of the null-gravitational redshift experiment is to measure the gravitational redshift of the gyroscope clock relative to that of atomic clocks with an accuracy of 0.01% of the value of the gravitational redshift. A previous null-gravitational redshift experiment compared the shifts of a hydrogen maser and a superconducting cavity stabilized oscillator to an accuracy of 2% (1).

2. EXPERIMENTAL APPARATUS

The gyroscope is a very homogeneous ($\Delta \rho/\rho < 1 \times 10^{-6}$), very uniform ($\Delta \nu/\nu < 1 \times 10^{-6}$) 38mm diameter sphere of fused quartz (or single crystal silicon) coated with a 250$\mu$m layer of niobium of better than 2% uniformity. It is electrosstatically suspended and then spun with He gas to 170Hz. The operational temperature is 2K. Spin speed is measured by observing the rotating magnetic flux trapped in the superconducting rotor coating. The measuring pick-up loop is located on the gyroscope housing and referenced to the fixed stars. Figure 1 is a schematic diagram of the gyroscope clock and its instrumentation and data acquisition system.

The GP-B experiment already incorporates most of the essential characteristics needed for a gyroscope clock. These are: a) a drag free ($10^{-11}$g) environment which
reduces the external torques on the gyroscope, b) a
gyroscope read-out which can be used to measure spin
phase relative to the fixed stars, c) a Global Positioning
System receiver which allows time transfer from earth
based atomic clocks with an accuracy of about 10 ns, and
d) a stable low temperature environment (ΔT<1mK over
one year). Table 1 gives a summary of an analysis of the
principal gyroscope disturbing torques, their effect, and
the corresponding uncertainty in spin speed.

<table>
<thead>
<tr>
<th>Torque</th>
<th>Effect</th>
<th>(Δα/α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Drag</td>
<td>Exponential spin-down with a time constant</td>
<td>1 x 10⁻¹⁴</td>
</tr>
<tr>
<td></td>
<td>of τ = (3x10⁻⁴/P) years</td>
<td>for 10⁻⁷ torr</td>
</tr>
<tr>
<td>Mass Unbalance &amp; Rotor</td>
<td>Spin variations modulated at the polhode</td>
<td>&lt;10⁻¹⁴</td>
</tr>
<tr>
<td>Asphericity</td>
<td>frequency with filter &amp; modelling</td>
<td></td>
</tr>
<tr>
<td>Readout System</td>
<td>Exponential spin-down</td>
<td>&lt;10⁻¹⁴</td>
</tr>
<tr>
<td>Cosmic Radiation</td>
<td>Random spin fluctuations</td>
<td>3 x 10⁻¹⁴</td>
</tr>
<tr>
<td></td>
<td>modelled</td>
<td></td>
</tr>
</tbody>
</table>

3. LOW TEMPERATURE BAKE-OUT

A major disturbing torque on the gyroscopes is due to
the molecular drag exerted by the residual gas. This
results in a spin-down time constant:

\[ \tau = \frac{3}{10^4 M P^2} (kg T / 2 mm)^1/2 \]  

where \( r \) and \( M \) are the radius and mass of the gyroscope,
and \( P, T, \) and \( m \) are the pressure, temperature and
molecular mass of the gas. The dependence of the spin-
down torque on temperature fluctuations sets the He
pressure limit in the gyroscope to 10⁻¹⁷torr, assuming that the
temperature is measured with an accuracy of 10µK
and torque is modeled at this level.

We propose to perform a low temperature bake-out of
the gyroscope in order to achieve the required pressure.
For calculation purposes we use a simplified model with
uniform temperatures, a unique binding energy to the
walls \( E_B \), and a fully isolated cell. Note that the unique
binding energy assumption implies sub mono-layer wall
coverage. In the regime under consideration the total
number of atoms in the cell is very well approximated by
the number of atoms on the wall. The condition for this
approximation is:

\[ V/A << \lambda(T) \exp(E_B / k_B T) \]  

\[ \lambda(T) = (h^2 / 2mk_B T)^1/2 \]  

where \( V/A \) is the volume to area ratio of the cell and \( \lambda(T) \)
is the thermal wavelength of the gas. A cell pumped out
to \( P_1 \) at \( T_1 \) will have a pressure \( P_2 \) at \( T_2 \) equal to:

\[ P_2 = P_1 \exp(T_2 / T_1) \exp((E_B / k_B) * (1 / T_2 - 1 / T_1)) \]  

We use \( E_B = 150K \), the average measured value for
the binding energy of He on copper (2). Under these
conditions a cell with sub mono-layer wall coverage at 6K
will experience a drop in pressure of over twenty orders
of magnitude when cooled to 2K. The surface coverage
condition is satisfied at 6K for He pressures below about
10⁻⁷torr. The bake-out temperature of 6K is limited by the
requirement to keep the gyroscope coating below its
superconducting transition temperature.

Next we address the question of the pump-out time
during the bake-out at 6K. A Monte Carlo simulation
indicates that the fraction \( β \) of wall collisions inside the
gyroscope which result in a He atom escaping into the
pumping line is of the order of 10⁻⁴. The time dependence of the surface density \( σ \) while pumping on the
atoms in the bulk is given by:

\[ σ = σ_0 \exp(-tβ/τs) \]  

\[ τ_s = (4A(T) / νs) \exp(E_B / k_B T) \]  

where \( τ_s \) is the atom residency time on the surface, \( ν \) is
the thermal velocity, and \( s \) the sticking coefficient (s ≈ 1).
We make the assumption that the pumping speed is
limited by \( β \). The resulting pump-out time for the
gyroscope is of the order of 10h, consistent with
preliminary experimental results (2).

In conclusion we find that the opportunity and the
experimental techniques exist for the performance of the
null-gravitational redshift experiment using a gyroscope
clock. The low temperature bake-out at 6K with
subsequent cooling to 2K is a suitable method for
achieving the vacuum level needed for the operation of
this clock.

REFERENCES

(1) J.P. Turneaure, C.M. Will, B.F Farrel, E.M.
Mattison, and R.F.C. Vessot, Phys. Rev. D 27
(1983) 1705.

(2) J.P. Turneaure, E.A. Cornell, P.D. Levine and J.A.
Lipa, Ultrahigh Vacuum Techniques for the
Experiment, in: Near Zero, eds. J.D. Fairbank,
B.Š. Deaver Jr, C.W.F. Everitt and P.F. Michelson