Physica B 165&166 (1990) 155–156
North-Holland

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 $\Delta v/v=3*10^{-14}$. 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 α; atomic clock frequencies depend on α^4, while the mechanical gyroscope frequency varies as α^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 $\Delta v/v=3*10^{-10}$ over the year. The goal of the null-gravitation 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 ($\Delta\rho/\rho<1*10^{-6}$), very uniform ($\Delta r/r<1*10^{-6}$) 38mm diameter sphere of fused quartz (or single crystal silicon) coated with a 250µm layer of niobium of better than 2% uniformity. It is electrostatically 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.

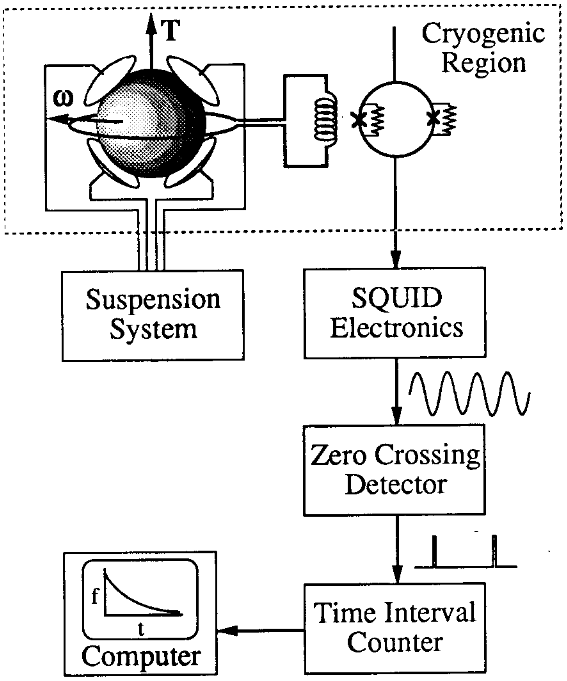

FIGURE 1
Schematic diagram of the gyroscope clock.

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 10ns, and *d*) a stable low temperature environment ($\Delta T<1$mK 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 1.
Summary of the principal gyroscope disturbing torques.

Torque	**Effect**	$(\Delta\omega/\omega)$
Molecular Drag	Exponential spin-down with a time constant of $\tau = (3\times10^{-7}/P)$ years	1×10^{-14} for 10^{-17} torr
Mass Unbalance & Rotor Asphericity	Spin variations modulated at the polhode frequency	$<10^{-14}$ with filter & modelling
Readout System	Exponential spin-down	$<10^{-14}$.
Cosmic Radiation	Random spin fluctuations	3×10^{-14} modelled

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:

$$\tau = 3/10*(M/Pr^2)*(k_BT/2\pi m)^{1/2} \quad (1)$$

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^{-17}torr, 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:

$$V/A << \lambda(T)*\exp(E_B/k_BT) \quad (2)$$

$$\lambda(T) = (h^2/2\pi mk_BT)^{1/2} \quad (2')$$

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:

$$P_2 = P_1*(T_2/T_1)^{3/2}*\exp[(E_B/k_B)*(1/T_1-1/T_2)] \quad (3)$$

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^{-7}torr. 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:

$$\sigma = \sigma_0\exp(-t\beta/\tau_S) \quad (4)$$

$$\tau_S = (4\lambda(T)/vs)*\exp(E_B/k_BT) \quad (4')$$

where τ_S is the atom residency time on the surface, v is the thermal velocity, and s the sticking coefficient ($s \approx 1$). 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

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