MEASURING THE GRAVITATIONAL CONSTANT WITH A CRYOGENIC TORSION PENDULUM

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Abstract

Concluding results from an extensive program to measure the gravitational constant G will be presented. Data were obtained from y2000 to 2006 using a torsion pendulum in the ‘dynamic’ (“time-of-swing”) mode, operating at temperatures ~2.7 K. Six torsion fibers of three types were used with torsional oscillation amplitudes between 0.3 and 7.4 radians: BeCu as-drawn, BeCu heat treated, and Al5056 as-drawn. A metrology scale factor is hidden until data and metrology analysis are complete, to minimize danger of experimenter bias. Some evidence for both amplitude and fiber material dependence is found which is expected to limit our uncertainty to about 50 ppm. A final G value will be reported at CPEM2008.

Method

We determine G by measuring the change in oscillation frequency of a thin-plate torsion pendulum due to a pair of ring-shaped source masses positioned alternately as indicated in figure 1. The thin plate geometry was chosen to reduce sensitivity to pendulum dimensions and mass distribution. The ring shape, with a particular spacing, produced an extremely uniform field gradient by nulling multipole couplings for $\ell = 3$, 4, and 5.

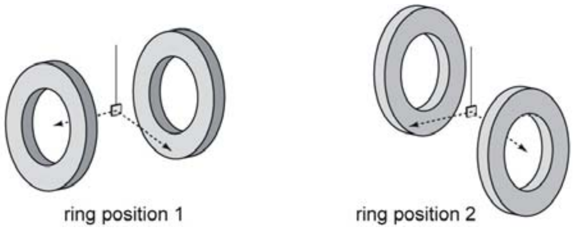

Figure 1: The pendulum and source mass rings. The pendulum is an 11 gram fused silica square plate 40x40x3 mm, suspended by a fiber 20 μm or 25 μm diameter and 24 cm long. Each copper ring is 59 kg with dimensions: 52 cm OD, 32 cm ID, 5 cm width.

The pendulum is in an evacuated chamber ($<10^{-6}$ mBar) within a dewar filled with liquid helium. Its suspension point is maintained between 2.6 K and 4.6 K, normally controlled within 0.2 mK. The source mass rings are suspended outside the dewar at room temperature. Details of this apparatus are reported elsewhere [1,2]. Advantages of low temperature operation include: reduced thermal noise, increased frequency stability, improved thermal stability, and superconducting magnetic shielding. The high Q afforded by low temperature operation also minimizes bias due to fiber anelasticity [3,4]. The frequency shift due to the source mass rings is given to within a few ppm by $\omega_1^2 - \omega_2^2 \cong \mathrm{KG}\, \mathrm{J}_1(2\mathrm{A})/\mathrm{A}$. Here ω_1 and ω_2 are the pendulum’s torsional oscillation frequencies for the ring positions indicated in figure 1, K is a geometric factor determined by the mass and dimensions of the pendulum and rings, G is the gravitational constant, J_1 is a Bessel function, and A is the oscillation amplitude of the pendulum. Thus by measuring the frequencies and amplitude of the pendulum, the product KG may be determined. Before finally entering the exact source mass values into the calculated value of the metrology scale factor K, we will complete all data and metrology analysis for the entire 2000-2006 period. In this way we conduct a “blind” experiment, minimizing potential bias in data selection and analysis as well as in evaluating uncertainties in measured quantities. The uncertainty contribution from dimensional and mass metrology is expected to be less than 10 ppm.

Data and Statistical Uncertainty

Over 2500 hours of data were collected between y2000 and 2006. The oscillation periods were between 105 and 135 seconds, depending on fiber material and exact length. The period shift due to the source mass rings depends on fiber and oscillation amplitude, ranging from 7.2 msec at amplitude 0.3 radians to 0.21 msec at 7.4 radians. The oscillation amplitudes were chosen to be near extrema of $J_1(2A)/A$ where the signal was relatively large and weakly sensitive to error in A. Data were taken as well at ~0.3 radians. Six data groups totaling 105 accepted data runs of 20 hours average duration were acquired by setting the pendulum’s amplitude to about 50 mrad above an extremum of $J_1(2A)/A$, then allowing the pendulum to “ring down” while alternately moving the source mass rings every 20 pendulum cycles. Between sets of several runs, the source mass rings were flipped around their vertical and/or horizontal axes to average out small variations in mass density and geometry; four unique ring configurations were used. Two different pendulums were used as well. Six different support fibers were used, made from as-drawn BeCu wire (Q~80,000), a heat treated fiber of the same material (Q~120,000), and three Al5056 fibers (Q~170,000). Figure 2 displays the KG results for the three types of torsion fibers as a function of oscillation amplitude, while figure 3 shows the variation of Q^{-1} with amplitude for the three fiber types. Plotted KG values are corrected for variation in parameters such as ambient pressure and temperature, but not for anelastic fiber effects. Error bars reflect statistical uncertainties only.

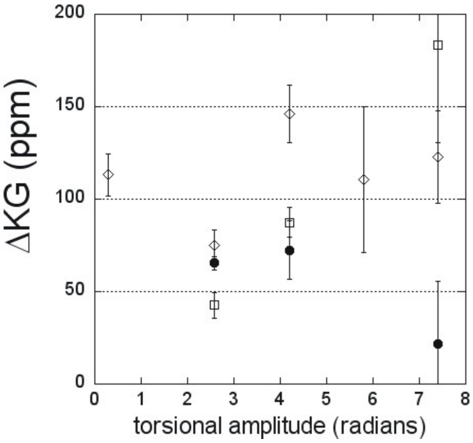

Figure 2: KG results expressed as ppm differences from an arbitrary reference value for BeCu as-drawn (circles), BeCu heat treated (squares), and Al5056 (diamonds) at various amplitudes.

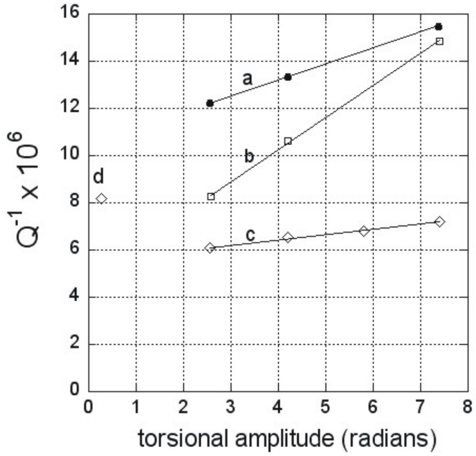

Figure 3: Q^{-1} as a function of oscillation amplitude using fibers of a) BeCu as-drawn, b) BeCu heat treated, and c) Al5056, with linear fits. Point d) is also for Al5056.

Prior to this work we made extensive studies [3] of the anelastic behavior of BeCu and Al5056 fibers which led us to believe that anelasticity would not be a significant source of error in our G measurement. However, the data of figure 2 give indications of both material and amplitude dependence. For the commonly accepted model of linear anelastic behavior, the fractional G uncertainty measured in the "dynamic" method is of order $1/\pi Q$ [4] and is bounded by $1/2Q$ [3]. The bounding correction based on the Qs displayed in our experiment range from about 2 to 5 ppm, insufficient to account for the observed variation in KG values. Of the fibers used the Al5056 fiber had both the highest Q and the weakest dependence of Q on amplitude. Thus we expect the KG values determined using that fiber material to be the more trustworthy. The KG values displayed in figure 2 correspond to a wide range of torsional amplitudes and Qs, and to fiber materials of very different characteristics. Except for two values with large uncertainties, all lie within a band ±55 ppm. Thus we anticipate announcing a G value with uncertainty about 50 ppm.

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References

[1] R.D. Newman and M.K. Bantel, "On Determining G Using a Cryogenic Torsion Pendulum," *Meas. Sci. Technol.*, vol. 10, pp. 445-453, 1999.

[2] M.K. Bantel and R.D. Newman, "A Cryogenic Torsion Pendulum: Progress Report," *Class. Quantum Grav.*, vol. 17, pp. 2313-2318, 2000.

[3] M.K. Bantel and R.D. Newman, "High precision measurement of torsion fiber internal friction at cryogenic temperatures," *Journal of Alloys and Compounds,* vol. 310, pp. 233-242, 2000.

[4] K. Kuroda, "Does the Time-of-Swing Method Give a Correct Value of the Newtonian Gravitational Constant?," *Phys. Rev. Lett.*, vol. 75, no. 15, pp. 2796-2798, October 1995.