LOW TEMPERATURE TECHNIQUES IN GRAVITATIONAL EXPERIMENTS

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OUTLINE

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Introduction

Physics in the last thirty years has changed slowly in some ways, quickly in others. There have been no theoretical advances comparable to relativity and quantum theory. Except possibly in elementary particle physics - and even there the claim is disputable - there have been few experimental discoveries that are truly fundamental. On the other hand, there have been splendid advances, both theoretical and experimental, in applying old physical principles to new fields: astrophysics, biophysics and the physics of the solid state, for example. And there have been great developments in experimental technique. Inventions such as the laser and the maser, devices based on the Josephson and Mössbauer effects, applications of modern electronics and the computer to the extraction and processing of data, all combine to create a revolution in the art of experimentation.

One of the fields that is beginning to come into its own is experimental gravitation. After languishing for two centuries with little to show beyond the Cavendish experiment and variant tests of the equivalence of gravitational and inertial mass, gravitation has at last become a coherent experimental discipline. The discipline is an exacting one: no one should undertake it lightly: but for any who have, or are prepared to cultivate, extremes of patient dedication, it is a good arena to be in. The subject matter is important; the challenges are great; the rewards, like the rewards to all great challenges successfully met, are spiritual as well as material.

Some but not all of the new experiments on gravitation depend on the use of low temperature technology. In this paper I deal with three experiments being developed at Stanford University:

(1) the Relativity Gyroscope experiment,
(2) a new test of the equivalence of gravitational and inertial mass,
(3) the Stanford-Louisiana State gravitational wave detectors,

not with the purpose of giving details which have been given elsewhere but in order to review how low temperature physics techniques are helpful in them and might be helpful in other experiments on gravitation and relativity.

The Three Experiments

(1) The Relativity Gyroscope Experiment

In 1959, the late Leonard Schiff of Stanford University and simultaneously G. E. Pugh, independently suggested a new test of General Relativity based on orbiting gyroscopes.

In Newtonian mechanics, an ideal gyroscope orbiting the Earth, being free from extraneous torques, would be expected to go on spinning in the same direction for all time. According to General Relativity, on the other hand, there are two effects which should make the gyroscope spin axis precess with respect to the framework of the fixed stars. In a 520 km orbit the larger of these, the geodetic precession, is expected to give a gyro drift of 6.9 arc-sec/year in the plane of the orbit. It measures a combination of the effects of space-curvature and the relativistic action of the ordinary gravitational potential. The smaller effect is due to the Earth's rotation. In a polar orbiting satellite at 520 km, it gives rise to a gyro drift of 0.047 arc-sec/year in the plane of the Earth's equator. It measures the gravitational action of the moving matter of the Earth, sometimes known as the gravitomagnetic field.

Since 1963 a team of physicists and engineers at Stanford University*, with support from NASA, has been developing an experiment designed to measure these effects with a precision of 1 milliarc-sec/year or better. The experiment uses a cryogenic gyroscope consisting of a fused quartz sphere, coated with superconducting niobium, electrically suspended inside a fused quartz gyro housing. The gyro is spun up by means of gas jets to a speed of 170 Hz, after which the gas is exhausted to a pressure of 10^{-9} to 10^{-10} torr and the gyro is allowed to coast freely in a vacuum. The direction of spin is measured by observing the London moment in the spinning superconductor with the aid of a SQUID (Superconducting QUantum Interference Device) magnetometer connected to a superconducting loop around the gyro. Four gyroscopes with their spin vectors parallel or anti-parallel to the line of sight to the star are mounted in a quartz block assembly attached to the fused quartz reference telescope. The entire gyro-telescope structure is maintained at a temperature of 1.6 K by a helium dewar which forms the main structural element of the spacecraft. Boil-off gass from the helium dewar is used for attitude and translational control of the satellite. The satellite is rolled about the line of sight to the star in order to average out various errors and distinguish the two relativity signals in data reduction.

(2) The Equivalence Principle Experiment

Historically, three approaches have been taken to testing the equivalence of gravitational and inertial mass: the methods of Galileo, Newton and Eötvös. Galileo's method was to compare the falls of two masses of different materials dropped from the Leaning Tower of Pisa. Newton's was to compare the times of swing of a pendulum with bobs of different materials.

*Present members of the team are J. T. Anderson, J. V. Breakwell, B. Cabrera, J-H. Chen, W. S. Cheung, D. B. DeBra, T. Duhamel, W. M. Fairbank, R. Farnsworth, G. M. Keiser, P. D. Levine, J. A. Lipa, J. M. Lockhart, J. P. Turneaure, R. A. Van Patten. Former members include T. D. Bracken, J. Bull, J. J. Gilderoy, D. Klinger, B. C. Leslie, J. R. Nikirk, P. M. Selzer, G. J. Siddall, F. van Kann, R. Vassar. Research colleagues at NASA Marshall Center are R. Decher, P. Eby, P. L. Peters, E. Urban. Colleagues at the University of Aberdeen, Scotland are J. Bates, M. Player and their students in the Aberdeen Instrumentation Group, and at the University of Alabama, [illegible] and G. Karr. Special acknowledgement is due to

Eötvös's was to look for torques on a torsion balance with masses of different materials at the ends of the arm, when the balance was rotated in a combination of gravitational and centrifugal fields. Eötvös's method has proved much the most accurate. In the hands of Roll, Krotkov and Dicke, with gold and aluminum proof masses, using the Sun's acceleration as the source, it has yielded a check of equivalence at the level of 3 parts in 10^{11}.

Some years ago, P. W. Worden Jr. and I conceived of an Earth-orbiting test of equivalence which should be able to attain a precision of about 1 part in 10^{18} - more than seven orders of magnitude advance over the Roll-Krotkov-Dicke result. The experiment uses many of the same techniques as the Relativity Gyroscope experiment. Two concentric test bodies of different materials - one a rod, the other a cylinder - are supported in cylindrical superconducting bearings which constrain them laterally but allow free motion along the common axis. They orbit the Earth in a satellite whose orientation is held fixed in inertial space. Motions along the free axis are measured by superconducting circuits. Since both test bodies are subject simultaneously to the Earth's attraction, which acts on the gravitational mass, and the orbital acceleration, which acts on the inertial mass, any difference in the ratios of the two kinds of mass for the two bodies will cause a differential acceleration between them at orbital period which can be determined very accurately with the superconducting position detectors. Evidently an experiment of this kind reverts in principle from Eötvös to Galileo, with test bodies dropped not for a few seconds from an Italian tower but over a 100 minute period all the way around the Earth. The rationale for this approach is to avoid the disturbances from gravity gradient torques which become impossibly large in a torsion balance experiment in Earth orbit.

A preliminary version of the experiment now in progress uses the Sun as the accelerating source as in Roll, Krotkov and Dicke's experiment. It aims at a precision of 1 part in 10^{13}.

(3) The Stanford-LSU Gravitational Wave Experiment

The gravitational wave experiment is in essence simply a low temperature version of the bar antenna invented by Joseph Weber.* A ten-ton mass of aluminum is supported inside an evacuated chamber and cooled to a temperature of 2K. In later operation it will be cooled to temperatures approaching 10 mK. Oscillations of the bar are measured by a superconducting position detector connected to a resonant transducer mounted on the end of the bar. A gravitational wave signal will set the bar ringing. Precise measurement of this signal is a balance of two considerations. The longer one observes, the more precise is the displacement measurement. On the other hand, the longer the observation time, the more the thermal noise in the bar will pollute the original signal. Evidently there is an optimum observation time.

*Present members of the Stanford team include M. Bassan, W. M. Fairbank, E. Mapoles, M. S. McAshan, P. Michelson, B. Moskowitz. Former members include S. Boughn, R. P. Giffard, H. Paik, R. Taber. Members of the LSU team include W. O. Hamilton, A. Mann, W. Oelfke, B. Pipes, G. Wang, A. Sibley, G. Spetz, B-X. Xu.

The present sensitivity of the Stanford detector corresponds to a noise temperature of 10 mK, about a factor of 10^4 more sensitive than Weber's original bar.

Why Cryogenics?

Each of the experiments just described depends for its success on cryogenic techniques, yet the reasons for low temperature operation are different in the three cases. For a gravitational wave detector, the fundamental advantage of low temperatures lies in the reduction of thermal noise in the bar. For the equivalence principle experiment, it lies in isolating the test bodies from external disturbances. For the Relativity Gyroscope experiment, the advantages are mechanical stability and the provision of an angular readout capable of measuring with adequate precision the direction of spin of an extremely round, extremely homogeneous gyro rotor.

Let us examine these advantages of low temperature operation in more detail.

(1) Thermal noise

A well-known expression, usually referred to as the Nyquist formula and more correctly as the Einstein-Smoluchowski formula, gives the limit due to thermal noise on detecting a small force acting on a body of mass M as

$$\langle F \rangle = \sqrt{2M\beta kT/S}$$

where k is Boltzmann's constant, β the damping coefficient of the system, T the temperature, and S the time of observation. In gravitational experiments, one is usually interested in detecting an acceleration rather than a force, so with f for acceleration one can rewrite the formula

$$\langle f \rangle = \sqrt{2\beta kT/MS}$$

which means that if thermal noise is the limiting factor, it is advantageous to make β and T as small as possible and M and S as large as possible.

For gravitational wave detectors, there is, as already remarked, an optimum observation time. This optimum, being itself a function of β, T and M, is not a fixed quantity for all detectors, but its existence means that S cannot be treated as an independent variable. M is settled by practical considerations: one takes the largest bar one can get. Thus only β and T remain to be played with, and the two drives in the design of gravitational wave detectors of the bar type are to make β and T small. The lowest damping (highest Q) is got with bars made of single crystals of sapphire or similar materials, isolated from external sources of dissipation, but since single crystal detectors are limited in size, the best systems in present practice consist of large bars of 5056 aluminum operated at low temperatures - the lower the better. The problem of gravitational wave detection by the Weber bar method reduces to making a large low temperature antenna, isolating it from ground vibrations at the antenna frequency, and coupling it efficiently to a low noise displacement detector. Of the displacement detector I shall say more below.

The foregoing analysis of gravitational wave detection is not intended to be rigorous. It is indeed somewhat inaccurate since it treats the problem from the point of view of acceleration rather than the more normal views that start from the strain in space created by the gravitational wave or from the energy deposited by the wave in the bar. Nevertheless it has the advantage of enabling to get a feel for the problem in a way that is easily comparable with similar analyses of the Relativity Gyroscope and orbiting equivalence principle experiments. The great difference in these experiments is that there is no intrinsic limit on the time of observation S. For an equivalence principle experiment, the limitation due to thermal noise can easily be reduced to a part in 10^{19} after a week. For the Relativity Gyroscope experiment, it becomes comparable with the gyro drift rate to be detected after only a few seconds. In the one year lifetime of the mission, its effect is utterly negligible.

(2) Mechanical stability of the apparatus

The question of mechanical stability has been one of great historical importance in the design of precision experiments. Few things are more striking than the contrast between Michelson's original design for his aether-drift apparatus, in which the interferometer mirrors were mounted on long cantilevers, and the final design of 1886, in which the whole apparatus was set on a massive granite slab floated on a mercury pool. Pursuing the same theme, Rowland remarked that in the design of an optical experiment one should picture the apparatus as made of jello.

Questions of mechanical stability reach a new level of subtlety in an experiment such as the Relativity Gyroscope experiment in which one is trying to measure the drift of a gyroscope with respect to the line of sight to a star with an absolute accuracy of 0.001 arc-sec over the course of a year. Many sources of drift are eliminated by the trick of rolling the spacecraft about the line of sight to the star, but if the telescope were at room temperature and the Sun's radiation were allowed to fall on it, there could be unpredictable distortions as large as an arc-second, variable over the course of a year in or near the plane of the ecliptic. Effects of this kind become vanishingly small at low temperatures since the telescope is thermally very well isolated, and the coefficient of expansion of the material from which it is made becomes vanishingly small.

Similar considerations apply in lesser degree to the equivalence principle experiment, but for gravity wave detectors, thermal distortion is a non-problem even at room temperature because the duration of the effect to be measured is extremly short in comparison with the thermal time constant of the detector.

(3) Precise measurement of angular and linear displacement

SQUID magnetometers with superconducting circuits provide an admirable means for measuring small linear or angular displacements.

For the Relativity Gyroscope experiment, the London moment readout described above has four vital merits: (1) It measures the direction of the spin vector of the gyro rather than of any quantity tied to the body axes of the rotor, and can therefore be applied without difficulty to an ideally round, ideally homogeneous rotor. (2) It is more sensitive by a factor of about 20 than the optical or electrical pickoffs used in conventional electrically suspended gyroscopes, and this factor of 20 is an essential one. (3) It is sensitive only in second order to displacements of the rotor with respect to the gyro case, whereas an optical pickoff is sensitive in first order. (4) The reaction torques of the readout system on the gyroscope are negligible.

All four points are essential to the success of the Relativity Gyroscope experiment and no other scheme yet proposed satisfies them.

A curious story attaches to the development of the readout systems for the equivalence principle and gravitational wave experiments. In principle they are identical. In each, a superconducting body is placed between two superconducting coils L_1, L_2, joined in a common circuit in which a supercurrent i flows, and a third coil L_3 is connected across them. When the body is displaced towards L_1, L_1 decreases and L_2 increases, and a current Δi flows through L_3 proportional to the displacement Δx, the trapped current i and the circuit parameters. The magnetic field generated in L_3 by Δi is imeasured by a SQUID magnetometer. The only difference between the two systems is in the condition for optimizing the current i. For the gravitational wave experiment, the optimum current is tens of amperes; for the equivalence principle experiment, it is milliamperes. The reason for this difference is that in the gravitational wave experiment what is being measured is the motions of a drum-like membrane mounted on the end of the Weber bar, and the maximum sensitivity comes when the magnetic field from the current exerts a restoring force on the membrane large enough to make it resonate with the 900 Hz bar, whereas in the equivalence principle experiment what is being measured is the displacement of the test body, and maximum sensitivity comes when the resonant period corresponds to the 100 minute orbit period of the satellite.

The curious story is that the readout circuits for the two experiments were developed independently in the same laboratory at the same time by two separate groups - P. W. Worden, Jr. and myself for the equivalence principle experiment, and H. J. Paik, W. M. Fairbank and J. E. Opfer for the gravitational wave experiment - yet nearly two years passed before either group realized that the circuits were identical.

For the Relativity Gyroscope experiment, the London moment readout seems inevitable. The only variant on it we have been able to think of is a readout of essentially similar type based on trapped flux in the gyro rotor. Both require superconducting circuitry. Much the same can be said for the gravitational wave experiment. An alternative is a displacement monitor being developed by groups at Louisiana State University and the University of Western Australia, based on high Q resonant microwave cavities, but this, like the SQUID readout, requires superconducting circuits.

For the equivalence principle experiment, the readout is not the limitation on the experiment. At the 10^{-18} goal for testing equivalence, there are three orders of magnitude in position sensitivity to spare. Probably various room temperature position monitors could do equally well. The justification for cryogenic operation must be sought elsewhere.

(4) Reduction for disturbances on test bodies

Low temperature operation is of critical importance in the equivalence principle experiment for isolating the test bodies from external disturbances due to magnetic fields, gas molecules and radiation pressure.

Consider the requirement. We are trying to measure an acceleration difference between two bodies to a part in 10^{18}, when the driving acceleration is 1g. With a 10 gm test body, this means that the periodic disturbing force at the frequency of interest (orbital rate) must not exceed 10^{-14} dynes.

Take radiation pressure first. A black body at room temperature radiates an energy of 40 mW/cm^2 and generates a photon pressure of 2×10^{-5} dyne/cm^2. By coating the surfaces with gold, one could reduce the pressure by some three orders of magnitude to, say, 10^{-8} dyne/cm^2. Thus the pressures on opposite ends of the test body would have to be kept constant to a part in 10^8. But since radiation pressure depends on the fourth power of the absolute temperature, $\Delta P = 4P\Delta T/T$. In a room temperature apparatus, the maximum allowable cyclic temperature difference at orbital period between the two ends of the chamber containing the test body would be 1 μK. Since the satellite warms up and cools down at orbital period through many degrees in the sunlight, the problem at room temperature is utterly intractable. At low temperatures, on the other hand, radiation pressure, being proportional to T^4, becomes minute. At 2K, the total pressure is down to 4×10^{-14} dyne/cm^2 from a black body and 4×10^{-17} dyne/cm^2 from a gold-coated body. The problem has vanished.

Gas pressure effects require equal scrutiny. Suppose one is working at 10^{-10} torr - a very low pressure. The unbalanced pressure on one end of a test body is 10^{-10} dyne/cm^2 : six orders of magnitude greater than the limit on allowable periodic forces. At ordinary temperatures, stabilization at this level is impossible for the reason remarked on before: the satellite is heating and cooling at orbital period in the sunlight. At low temperatures, temperature stabilization is much easier and one can cryopump the gas to even lower pressures.

To eliminate varying magnetic forces on the test bodies, one uses superconducting shields. With proper design these can get rid of all disturbances from the Earth's magnetic field. However, it should be pointed out that a superconducting test body, having a relatively large apparent susceptibility ($-1/4\pi$ in c.g.s. units), is inherently more sensitive to such disturbances than properly chosen conventional materials.

Isolation from radiation pressure and gas pressure disturbances are less critical in the Relativity Gyroscope and gravitational wave experiments (though the gas damping torque on the gyroscope is important). Magnetic shielding is relatively unimportant for the gravitational wave experiment. For the gyroscope, however, it is all important, as explained in the next section.

(5) Low and stable magnetic fields

A beautiful technique has been developed at Stanford University by B. Cabrera for making large superconducting shields in which the field level is a few times 10^{-8} gauss. The technique consists in cooling a series of cylindrical superconducting lead bags one inside the next, taking advantage of the field reduction that comes with the increase in area while magnetic flux is conserved.

The low field bag isolates the gyroscope from torques due to magnetic fields and ensures that the trapped flux in the gyro rotor is small enough not to interfere with the London moment readout. Equally important is the need to prevent magnetic disturbances from the Earth's field getting into the gyro readout. The isolation required is at 10^{-13} gauss. It is provided by an appropriate combination of conventional mu-metal shielding, the superconducting bag, inner superconducting shields, and the self-shielding effect of the superconducting gyroscope in its readout loop.

Conclusion

The foregoing discussion illustrates the varied ways in which cryogenic techniques can aid experiments on gravitation. There are other advantages - for example, the shielding and stabilization of patch-effect electric fields. While our subject is too rich for us to stick slavishly to any one technique, we may expect that as new experiments on gravitation are developed in the years to come experimentalists will find new reasons for examining the possible advantages of low temperature operation.