Granular Superconductors and Gravity

David Noever and Ron Koczor

Space Sciences Laboratory, NASA Marshall Space Flight Center, Huntsville, AL 35812

As a Bose condensate, superconductors provide novel conditions for revisiting previously proposed couplings between electromagnetism and gravity. Strong variations in Cooper pair density, large conductivity and low magnetic permeability define superconductive and degenerate condensates without the traditional density limits imposed by the Fermi energy (~10^{-6} g cm^3). Recent experiments have reported anomalous weight loss for a test mass suspended above a rotating Type II, YBCO superconductor, with a relatively high percentage change (0.05-2.1%) independent of the test mass' chemical composition and diamagnetic properties. A variation of 5 parts per 10^4 was reported above a stationary (non-rotating) superconductor. In experiments using a sensitive gravimeter, bulk YBCO superconductors were stably levitated in a DC magnetic field and exposed without levitation to low-field strength AC magnetic fields. Changes in observed gravity signals were measured to be less than 2 parts in 10^8 of the normal gravitational acceleration. Given the high sensitivity of the test, future work will examine variants on the basic magnetic behavior of granular superconductors, with particular focus on quantifying their proposed importance to gravity.

Extending the early experiments on gravity and electromagnetic effects by Faraday [1] and Blackett [2], Forward [3] first proposed unique gravitational tests for superconductors in an electromagnetic field: "Since the magnetic moment and the inertial moment are combined in an atom, it may be possible to use this property to convert time-varying electromagnetic fields into time-varying gravitational fields."

Recent experiments [4-5] have reported that for a variety of different test masses, a Type-II, high temperature (YBCO) superconductor induces anomalous weight effects (0.05-2% loss). A single-phase, dense bulk superconducting ceramic of $YBa_2Cu_3O_{7-d}$ was held at temperatures below 60 K, levitated over a toroidal solenoid, and induced into rotation using coils with rotating magnetic fields. This phenomenon has no explanation in the standard gravity theories.

Without superconductor rotation, a weight loss of 0.05% was reported, a relatively large value which has been attributed to buoyancy corrections [6] or air currents [7] until further details of the experiment elaborated upon measurements in closed glass tubes encased in a stainless steel box. Three theoretical explanations have been put forward to account for a possible gravitational cause: shielding [4], absorption via coupling to a Bose condensate [5, 8] and a gravito-magnetic force [9-11]. The symmetry requirements of each explanation are different, as are the need for magnetic fields or superconductor rotation; most notably an absorption mechanism (based on an instability in the quadratic part of the Euclidean gravitational action in the presence of a Bose condensate [5,8]) may not require an external EM field (except to generate density fluctuation in the Cooper pairs), while gravitomagnetic effects in the ion lattice [9-11] depend on a time-varying gravito-magnetic potential, $\partial A_g / \partial t$. Careful experiments must identify and isolate the relative importance of thermal, magnetic, and any gravitational components.

Superconducting Disk

To achieve large area superconductors, two configurations were employed. A bulk, melt-textured YBCO disk (10 cm diameter, 1.25 cm height) was used with mostly square-like multidomains [12] with sizes up to 5 mm^2. The disk levitated 2-6 cm above a cylindrically symmetric, permanent magnet ($\langle B \rangle$=0.52 T) with one central south pole and four peripheral north poles. Both the vertical and horizontal inhomogeneity of the magnetic field pins magnetic flux lines in the superconductor, damps oscillations and levitates rigidly within a continuous range of possible stable positions and orientations. A second set of 4 parallel pole AC magnets (B=600 Gauss; characteristic oscillation time of 0.75 s) did not levitate (but induced AC resistive losses in) the superconductor. Thus gravitational results were reported for both DC and low field strength AC effects on bulk YBCO superconductors.

Melt-texturing [see e.g. 13] was based on solidification of the Y-123 phase through the peritectic temperature (1020 C in air) following the reaction

$$Y_2BaCuO_5 + \text{liquid phase} \rightarrow YBa_2Cu_3O_x.$$

The second configuration introduced a compatible base dimension (15 cm x 20 cm) comparable to the actual footprint of the gravity measurement. An array of 48 single-domain YBCO hexagons (2.03 cm x 0.63 cm thick) was machined with a central hole and fabricated into a network. The surface of the hexagonal samples were examined using SEM (Fig. 1). To maximize the levitation force, the single domain hexagons showed high critical current densities (10^4 A/cm2 at 77K in a 1 T field) and when field cooled, a maximum trapped field of over 0.4 T in the presence of a 2 T applied field [13]. The hexagons were melt-processed using a top-seeded technique and nucleated at the surface of a flat $Nd_{1+x}Ba_{2-x}Cu_3O_y$ single crystal and epitaxially grown with a favorable temperature gradient. Diminishing gains in levitation force are observed for thicknesses >0.5 cm. Microcracks [14] from over 70 thermal cyclings introduce <3% variation in the levitation force F, where above the first critical field, H_{c1}, the force F otherwise depends on processing technique, a geometric factor, A, the critical current density, J, and the size of the shielding current loop, r, as:

$$F=\int A\, J\, r \,\mathrm{grad}\, H \, dV \qquad (1).$$

Further increases in the repulsive force, F, depend on increasing J or r.

Instrumentation

Magnetic flux density was measured to 2 T with a Hall effect device unidirectionally over a sensing area of 0.093 cm^2. Gravity was computer-monitored using a modified LaCoste-Romberg gravimeter [15]. The instrument reports very small changes in the gravitational force acting on a mechanical spring-mass. Gravitational changes are expressed as the electrical force (measured as voltage) required to maintain the spring-mass system at a predetermined position (the null point). The dimensions of the gravimeter's base were 38 cm x 26 cm, with instrumental resolution in the variation of gravity of one part per 10 billion (resolution, 10^{-7} cm s^{-2}; repeatability, 10^{-6} cm s^{-2}; average operating conditions, >5×10^{-6} cm s^{-2}). The observed gravity value includes tidal corrections varying with time and location (measured on 8-satellite GPS [15], where an error of one mile [one minute of latitude or longitude] or equivalently one minute in time will cause an error of 1 μGal (10^{-6} cm s^{-2}) in the tidal correction). Approximately 1 μGal of error results from a 9 arc second leveling error, which is automatically calculated and off-level corrections are included in the final value. The instrument's range is 5 $\times10^{-3}$ cm s^{-2} without resetting the counter, which would correspond in the present experiments to full scale readings for less than one part per million variation in gravity [16]. Instantaneous gravity was recorded at 1 s intervals and displayed with a variable averaging time interval of 1-15 s. Calibration was done using the USAF Gravity Reference Disk for a local absolute measurement, then relative tests were conducted: 1) height variation (1 m) of the gravimeter altitude (~300 microGal/m); 2) uncorrected and corrected tidal measurements over 12 hours; 3) thermal constancy for internal instruments (+<0.3 C) during a 20 C external temperature variation. The results of these three calibration steps are shown in Fig. 2.

Vibration, buoyancy and thermal isolation

The mass-spring system is insensitive to longitudinal and transverse vibration and the instrument was placed on large concrete blocks to isolate the vertical direction from background disturbances. The instrument box is sealed from outside air to avoid any small apparent change in the buoyancy of the mass and beam with air pressure; in the event of leakage, a buoyancy compensator is added as counterweight to the balance arm and its mass/volume ratio removes 98% of any change in atmospheric pressure should the sensor enclosure leak. The gravimeter is temperature compensated with a thermistor heating circuit at 53.7 C; the box itself is thermostated externally and internally. When placed 5 inches above a 1 liter straight-walled dewar of boiling liquid nitrogen (77K), thermal variations were monitored at <0.05 C for internal temperature and <0.70 C for external temperature in the course of 0.8 hours.

Magnetic isolation

To maintain relative magnetic isolation, few ferrous metal parts are used. The meter is demagnetized, then installed in a double μ metal shield (magnetic saturation >0.75 T). In some measurements, a 1.3 cm thick iron plate (1 m x 1 m) was used as a base plate separating the gravimeter from the magnet and superconductor; iron's high magnetic permeability diverts or shunts the magnetic flux. Measured flux reductions at the instrument were approximately 1/10 the unshielded value for 0.5 T permanent magnets. Without magnetic leakage, the nearly quadratic decay of a DC magnetic field was also accounted for using spatial isolation.

Geometric Constraints

Magnetic levitation forces depend on the magnet and superconductor geometry, as does the apparent lack of a height dependence for observations of changes in the gravitational force above a superconductor [4-5]. Above the permanent (0.4-0.5 T) magnets, the flux intensity decays quadratically to a value of 50-120 Gauss at the gravimeter when leveled 23 cm above the magnet and 18 cm above the YBCO disk or array. The superconductor was either field cooled (FC to 77 K using liquid N_2) in contact with the magnets (flux-trapping) or zero field cooled (ZFC or flux excluding) and then stably levitated in a foam walled cryostat to an average height of 2-6 cm.

For both FC and ZFC superconductors, a deductive protocol [17] can separate the thermal, magnetic, and superconductive contributions, while the gravimeter remains stationary and a wheeled platform is moved beneath it. This protocol has the additional feature of excluding eddy currents from influencing the gravity measurement, since the magnetic field is not AC over the relevant time scale. The magnitudes of the various contributions to an apparent gravity change are summarized succintly below.

As indicated in Figure 3, vibration is measured with an empty platform moved underneath the gravimeter ($<1\text{-}3\times10^{-6}$ cm s^{-2}); cryogenic contributions to instrument drift are measured with an open cryostat of boiling liquid nitrogen moved underneath the gravimeter (15 cm below the baseplate, $<2\times10^{-6}$ cm s^{-2}); magnetic contributions are measured with the magnets alone moved underneath the gravimeter ($<6\times10^{-6}$ cm s^{-2}); cryogenic YBCO superconductor contributions are measured with a zero field cooled disk moved underneath the gravimeter in the absence of any magnetic effects ($<2\times10^{-6}$ cm s^{-2}); and finally the static (non-rotating) but magnetically pinned superconductor contributions are measured with both the zero field cooled and field cooled disk or array moved underneath the gravimeter ($<2\text{-}5\times10^{-6}$ cm s^{-2}). When measured multiple times, the effects of each contribution are seen as a series of step functions with a repeatable offset which constrains its relative importance. Using a similar protocol measured AC effects using the parallel pole magnets showed a similar but smaller influence (Fig. 4).

Discussion

Error Analysis

Error analysis is critical to this experiment. The reports from Podkletnov range from a 0.05% to 2% peak weight loss. For their 5.48 g silicon dioxide test mass, these values correspond in absolute values to 2.74 to 109.6 mg. These values are large relative to traditional gravity experiments, which have reported no gravity shielding to one part in 10 billion for a variety of materials. For comparison, a standard level, electronic toploading balance has specifications of: repeatability, ≤0.5

mg; linearity <$\pm$2 mg; temperature drift sensitivity 3ppm/C; and readability to 1 mg. Built-in vibration damping and a draft shield enhance repeatability to nearly an order of magnitude below the level required to see the lowest weight loss (2.74) on Podkletnov's original test mass. Since the effects are reported as the same order of magnitude for different masses and materials, even more massive samples can bring a laboratory scale test of gravity into the unconventional, but accessible realm of a low-cost balance. Environmental compensation for electromagnetic and temperature effects are a prerequisite however for reporting meaningful results.

Summary of Effects and Explanations

Probable

Unidentified electromagnetic interaction

1. Pinned flux lines rotating with the disc coupled to small diamagnetism in the weight (control: direct independent measurement and error limits for 110 mg weight loss)
2. Electromagnetic effects on an electro-optic balance (control: sensitive torsion pendulum or gravitometer)
3. Radio-frequency effects on unshielded weight (although in one experiment, the measured weight loss persists in the absence of R-F fields)

Unidentified interactions between gravity and superconductors

1. Quantum gravity (Modanese, Max Planck Institute, 1996)
2. Generalized Meissner effect in moving superconductor (Schiff and Barnhill (1966); DeWitt (1966); Li; Torr; Peng, UAH ,1988, 1990, 1991, 1992,1993)
3. Dense, degenerate matter (Bose-Einstein condensate inside superconductor, Forward, 1963)

More Mundane

1. Air currents due to enclosed cryogenic temperature differences (control: vacuum)
2. Drags and convective effects from rotation affecting the sample on the balance (control: disk balance and vacuum)

Any apparent gravitational contribution of the superconductor can be derived by subtracting the contribution of the magnet and superconductor together from the magnet alone; however, since the relative gravimeter responds (weakly, <2-5x10^{-6} cm s^{-2}) to the magnetic field, the uniquely superconductive contribution must combine any gravitational effect with the diamagnetic shielding of the magnets by the YBCO superconductor itself (~20-90% shielding of the field depending on hysteresis during cooling and magnetization). In any case, the maximum contribution to a change in gravity of a static superconductor in a constant magnetic field was measured as less than 2 parts in 10^8 of the normal gravitational acceleration.

This measurement extends an approximately 4-5 order of magnitude improvement over that previously obtained with the use of an opto-electronic balance [4-5] instrumented without either thermal or magnetic compensation.

An important question remains unresolved, namely whether any small magnitude of gravity variation has a theoretical explanation. Among the three possible theories (shielding, absorption, or gravitomagnetic counterforces), these results are more relevant to an absorption mechanism based on local density fluctuations. This interpretation is not particularly sensitive to the magnetic field configurations, which the experiments reported here are not optimized to probe. It is an open question whether the fluctuations of carrier density in superconductors at transition, would be sufficient to perturb any gravitational coupling and thus induce a signal. Regardless of the relative orders of magnitude, a coupling term (quadratic) to Euclidean gravity based on the Bose condensate and radial absorption does not necessarily require either rotation or a magnetic field to induce density fluctuations in the Cooper pairs, particularly in the limit of infinite conductivity.

Relative to a gravito-magnetic force [9-11; 18] which depends more particularly on an AC magnetic drive or source term, $\partial A_g / \partial t$, the static case more strongly constrains interpretations based on either simple material shielding [4-5] or absorption of gravity [8]. In concordance with the Schiff-Barnhill and DeWitt effects [18], the residual internal electric and magnetic field generated (by lattice distortions arising from the solid's tendency internally to counteract gravity) do not go to zero at the onset of superconductivity. DeWitt describes the result as "free-floating electrons," but in any case, the linear combinations of electromagnetic terms are the relevant terms to describe. The coupled role of ion lattice distortion in a gravity field modifies both the internal electric field (Shiff-Barnhill effect) and the internal magnetic field (DeWitt effect), much akin to a gravitational analog to the Zeeman shift. Thus the gravitomagnetic permeability is persistant and finite, while the magnetic permeability goes to zero. In mks units, the gravitomagnetic field, Bg, has dimensionality of 1/time and equals the precessional angular velocity for the ions or "quasi-bodies" possessing spin. If an appropriate geometry arises that can induce organized (partially aligned) or precessional ion motion, then any observed gravitomagnetic field strength (2%?) will experimentally translate to a proportional contribution from any non-zero angular momenta, including ions, vortices or larger percolation centers. Vortices also can possess spin angular momentum (in Type II superconductors) and can be regarded as a quasi-body; they should also be subject to precession. The rotating verion of this experiment will be reported in subsequent work.

Criteria for Future Work

Some further considerations for deductive experiments should include a mapping of the various effects and their potential artifacts.

Absorption vs. Shielding of Gravity

Appropriate geometries should test for weight loss above and below the superconductor. An absorption mechanism can be speculated to lead to weight loss in the neighborhood of the superconductor (including below and to the sides), while a strict shielding or shadow effect would lead to no weight loss except directly above the disk.

Height dependence

The suprising lack of height dependence in Podkletnov's results poses a number of problems for theoretical interpretation. **The reported weight loss did not change within one part in a thousand over a distance ranging from 10 cm to 3 m. A traditional $1/r^2$ force would be expected, on the contrary, to vary over 3 orders of magnitude over this distance.** Unless the length scale of any proposed force field is exceedingly long, then the interaction would not correspond to any traditional electromagnetic, gravitational or gravitomagnetic description. In the linear approximation, the gravitomagnetic force shares a similar Maxwellian description. The usual picture would ascribe much longer characteristic lengths to gravitomagnetism, but would share the same characteristic decay as the EM field.

Buoyancy and convection

There is some incongruity reported between the various groups on the effects of air pressure on the weight measurement. Since the first dramatic observations by Podkletnov involved rising aerosol particles, considerable attention must be paid to the effects of buoyancy, air currents and thermal convection. These effects should be eliminated by taking the weight measurement under vacuum conditions, which has the additional feature of excluding any stray ultrasonic or buoyancy corrections. Podkletnov has noted a 2% drop in air pressure in a cylindrical air space above the superconductor, although Modanese interprets the latest set of weight measurments as occuring under vacuum conditions. The buoyancy corrections under lower atmospheric pressure would account for weight loss and have a long history in gravity experiments as giving analous conclusions. Bull (1995) has treated these effects in the context of the Finland experiment. A simple test of convective effects is either temperature control or variation in the aerodynamic shape (cross-section) of the test mass while keeping the same material and mass. Moldable wax provides a convenient way to vary independently the shape, while keeping material and mass constant.

Electromagnetic coupling

With time-varying magnetic fields, the production of eddy currents can produce substantial levitation effects; induced diamagnetic effects should be measured independently, but different materials of the same mass will typically produce several orders of magnitude difference in the repulsive force. Relatively low cost shielding foils are commercially available with specifications of 1/1000 reductions in electrostatic (Cu or Al foil laminates), electromagnetic (Ni or Fe foil laminates) and stray radio-freq. fields (Cu/Al foil laminates). Thus an intelligently nested isolation box is essential to meaninful interpretation of the results.

Decoupling changes in the gravity from changes in mass in the weight measurement

One method to decouple changes in mass from any measured changes in the gravitational acceleration is called the Wilberforce pendulum, named after Lionel Robert Wilberforce (1861-1944), a demonstrator at the Cavendish Laboratory in Cambridge, England around the turn of the century. It consists of a mass suspended from above by a spring. Such a pendulum has three modes of oscillation: 1) the ordinary swinging mode, 2) an oscillation along the axis of the spring and 3) a torsional (twisting) mode. If the resonant frequencies of the second two modes are nearly identical and one mode is initially excited, the other mode will slowly acquire energy, and the energy will slowly transfer back and forth between the modes.

The swinging mode of the Wilberforce pendulum is independent of test mass, but depends on gravitational acceleration. A change in the angular frequency above the superconductor would indicate direct variation in gravity. The angular frequency of the swinging mode is given by $(g/L)^{1/2}$, where $g = 9.8\ m/s^2$ and L is the length of the pendulum. The spring reciprocation mode is idenpendent of gravitational acceleration, but inversely proportional to the square root of mass. A change in the oscillation frequency of the spring above the superconductor would indicate direct variation of the test mass value. The frequency of the spring oscillation is given by $(k/m)^{1/2}$, where k is the spring constant and m is the mass supported by the spring. Finally, the torsional frequency is given by $(K/I)^{1/2}$,where K is the torsional constant and I is the moment of inertia of the suspended mass. Usually the moment of inertia is controlled by having several bolts threaded into the mass in a symmetric arrangement. Nuts threaded on the bolts can then be moved back and forth to change the moment of inertia without altering the mass. Thus the two frequencies can be made nearly equal.

If there were no coupling between the modes, the energy in each mode would remain constant, ignoring friction, and the modes could be excited in any combination with no subsequent interaction. In reality, the stretching of the spring produces a small torque that excites the torsional mode. The torsional mode, in turn, alternately stretches and compresses the spring, exciting the spring mode. The necessity of having the frequencies nearly equal is that the coupling between the modes is small, and thus the energy must be transferred over a number of cycles. The effect is quite impressive if the frequencies are carefully adjusted. This is an example of a harmonic oscillator driven at its resonant frequency by a small driving force and provides an exotic, but potentially novel way to clarify interpretation of the results in the event of a measured weight loss.

In addition to superconductors, other Bose condensates such as superfluid helium have been investigated for gravitomagnetic field exclusion [19], but the low thermal conductivity of helium limits measurable power transfer from an AC magnetic field by several orders of magnitude below a YBCO superconductor.

Acknowledgements: JR Gaines and Superconductive Components, Inc. (Columbus, OH) kindly provided assistance with the superconducting levitators. Edcon, Inc. (Denver, CO) provided their substantially modified LaCoste-Romberg gravimeter.

References

[1] M. Faraday, Experimental Researches in Electricity (1965) Dover, NY, vol 3 p. 161 (originally published, 1850).

[2] P.M.S. Blackett, Phil. Trans. R. Soc. London Ser. A. 245 (1952) 309; J.F. Woodward, Gen. Relat. Gravit. 12, (1980) 1055-1069

[3] R.L. Forward, Amer. J. Phys. (1963) 166-170.

[4] Podkletnov E. and Nieminen R., Physica C 203 (1992) 441; Podkletnov E., 1995, report MSU-chem 95, Tampere Univ. Finland; improved version (cond-mat/9701074)

[5] Modanese G. and Schnurer J., "Possible quantum gravity effects in a charged Bose condensate under variable e.m. field", report UTF-391/96, November 1996, Los Alamos database nr. gr-qc/9612022; ASCII version available from authors.

[6] Bull M., De Podesta M., Physica C 253 (1995) 199.

[7] Unnikrishnan, C.S., Physica C 266 (1996) 133.

[8] Modanese G., Europhys. Lett. 35 (1996) 413; Modanese G., Phys. Rev. D 54 (1996) 5002.

[9] N. Li, D.G. Torr, Phys. Rev. B, 46 (1992) 5489.

[10] N. Li, D.G. Torr, Phys. Rev. D, 43 (1990) 457.

[11] D.G. Torr and N. Li, Found. Phys. Lett. 6 (1993) 371.

[12] Disk kindly provided by Superconductive Components, Inc. Columbus, OH.

[13] F. Frangi, L. Jansak, M. Majoros, S. Zannella, Physica C 224, (1994) 20-30 and references therein.

[14] S. Sengupta, J. Corpus, J.R. Gaines, V.R. Todt, X Zhang, D.J. Miller, July, 1996 Proceedings 3rd Intl Symp. on Magnetic Suspension Technology, Tallahassee, FL, ed. N.J. Groom and C.P. Britcher, NASA Conf. Public. 3336, Pt. 2, p.679

[15] The modified LaCoste-Romberg gravimeter (Edcon, Inc. Denver, CO) measures relative gravity until calibrated against a reference. The instrument is routinely

calibrated along the 10-station Rocky Mountain Calibration range established by NOAA, Edcon and the Colorado School of Mines over known gravity values extending across 220 milli-Gals (0.22 cm s^{-2}) in 50, 20, and 5 milli-Gal increments, with 3-7 micro-Gal standard deviations. To validate instrument operation, an absolute gravity measurement was additionally calibrated from USAF gravity disk reference values (airport Huntsville, AL) and an 8-satellite global positioning reading for the test site as latitude 34.654244 and longitude -86.663638 at an altitude of 116 m. above sea level.

[16]. For comparison, 10^{-3} cm s^{-2} is the relative gravitational influence of a 5-storey office block (perturbing mass) at a distance of 1 m. Equivalently a 2% variation in the gravitational force would require $2x10^4$ copies of such a perturbing mass. Using the radial dependence of the gravitational inverse square law, 1 m displacement in height corresponds to approximately a change in measured gravitational acceleration of $3x10^{-4}$ cm s^{-2}, such that for example, a 2% variation in the gravitational force would correspond to a vertical displacement of the test mass equal to approximately 10^2 km.

[17] This method is the inverse technique employed in traditional gravity surveys where the gravimeter is moved to different stations; instead an apparent gravity perturbation is introduced to a stationary meter by moving the components of the superconductor, magnets and cryostat individually to the measuring apparatus. In all cases, internal temperature stability was maintained $\pm$0.05 C. The effect of the increased mass beneath the gravimeter can be calculated as much less than the instrument resolution ($<10^{-8}$ cm s^{-2}) and confirmed using room-temperature, non-magnetic test mass.

[18]. Later work has generalized the Meissner effect in a gravitational field as a superconductive analog of a Zeeman shift. Schiff and Barnhill (Bull. Am. Phys. Soc. 11, (1966), 96) and DeWitt (Phys. Rev. Lett. 16, (1966), 1092) showed that it is not the electrical and magnetic fields which vanish inside a superconductor, but the linear combination of the internal fields plus a gravitational component. This additional

term lends itself to "free-floating" electrons which have effects on the background of lattice ions. Li and Torr [refn. 8-11] proposed that a superconductor's London moment and the absence of charge separation lends to high angular momenta for rotating ions such that calculated gravito-magnetic effects can arise as the electron velocity v is replaced by the velocity of the lattice. Using the London moment, large values for conductivity (which define the superconducting state) coupled to the resulting low magnetic permeability observed in the Meissner effect lend to a coupling between a dense contribution of high angular momenta ions and gravitomagnetism. In the superconductive limit, the calculation depends sensitively on the vanishing magnetic, but finite gravitomagnetic permeabilities and the ion's much larger gyromagnetic ratio (m/e) compared to the electronic Cooper pairs.

[19] J.P. Brown, Ph.D. Thesis, The Post Newtonian Approximation for Self-Consistent Perfect Fluids with Spin Density, Univ. Ala. Huntsville, 1989.; H. Peng, Ph.D. thesis, Experimentally Verifiable Yang-Mills Spin-2 Gauge Theory of Gravity with Group U(1)xSU(2), Univ. Ala. Huntsville, 1987.

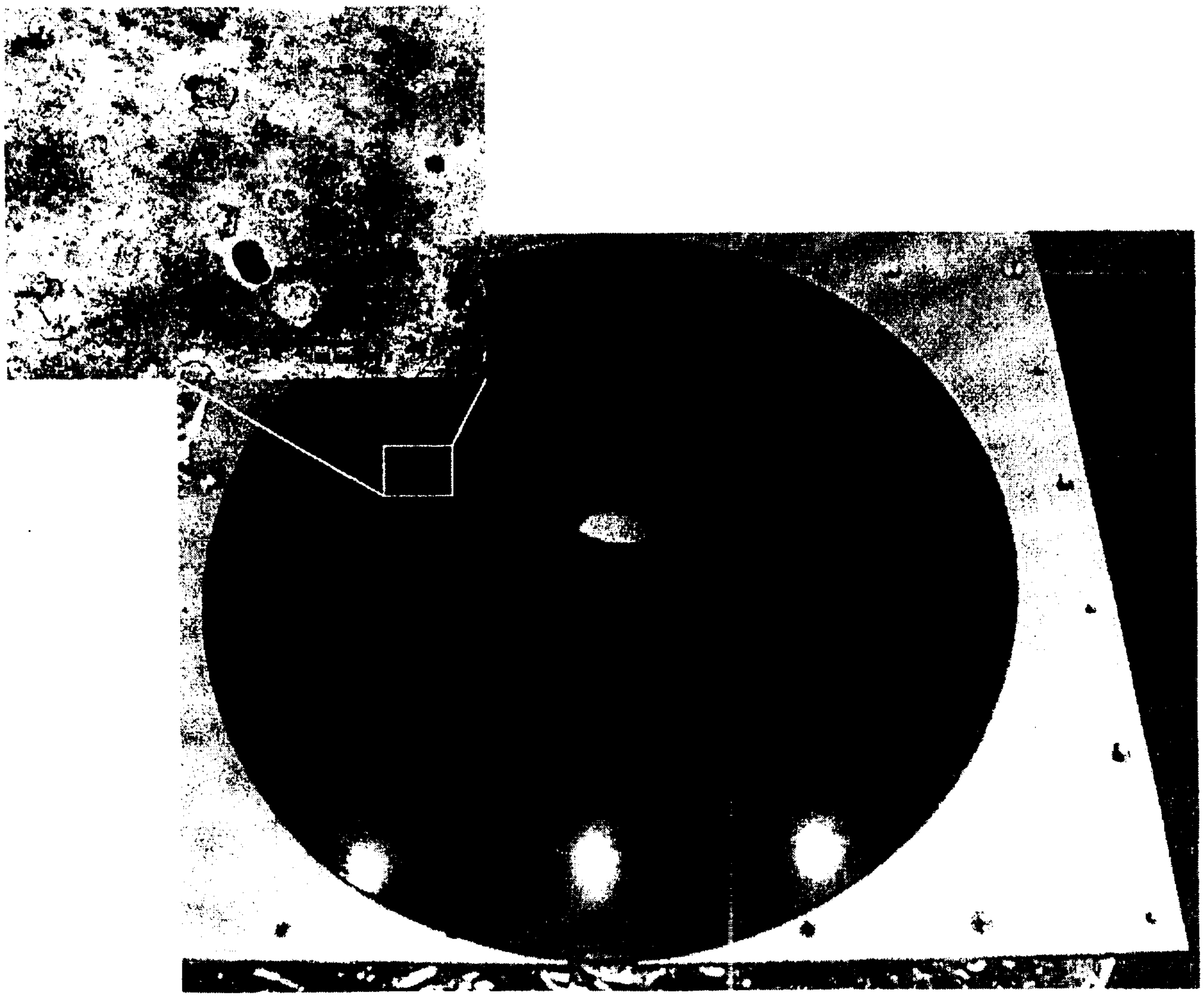

Fig. 1. Scanning electron microscopy of hexagonal, single-domain YBCO superconductor at increasing magnificantion. Surface machining textures the domain.

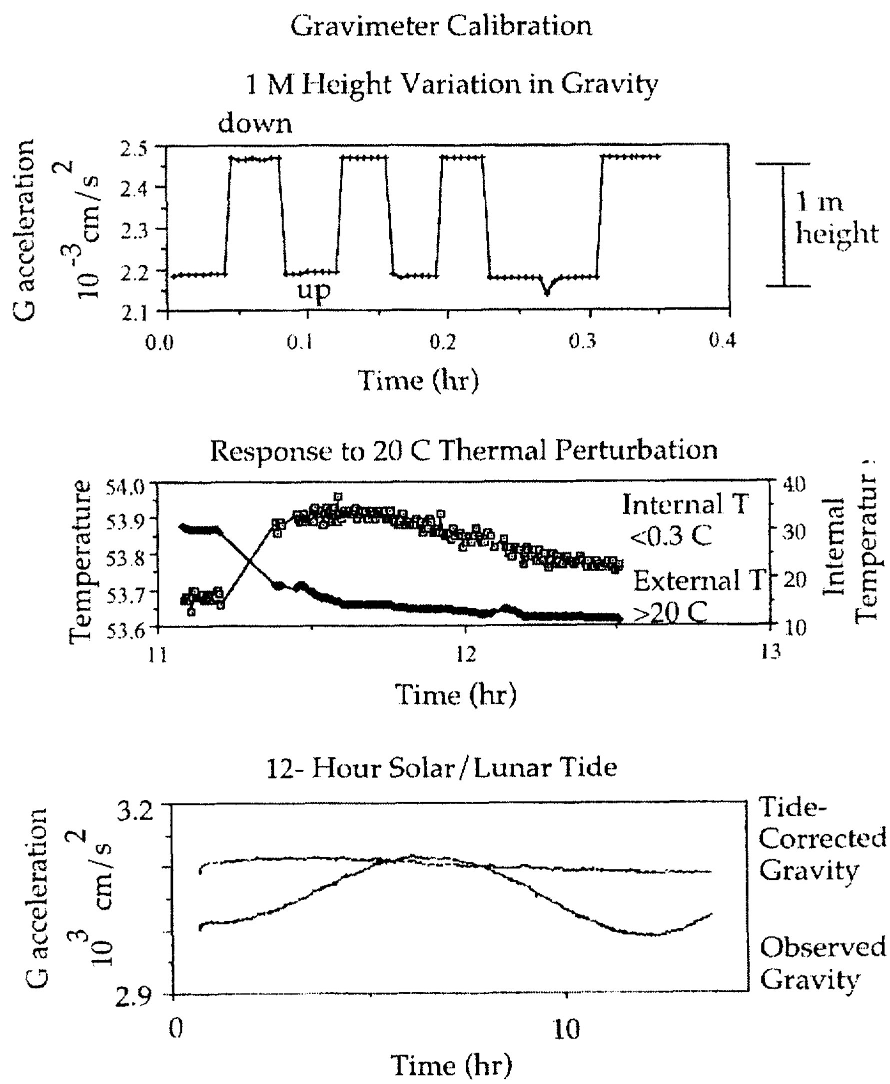

Fig. 2. Calibration and proof-testing gravimeter: 1) altitude variation of 1 m and resulting gravity change ($3.08x10^{-4}$ cm/s^2 per m altitude); 2) thermal constancy of gravimeter interior during 20 C external temperature change; 3) solar and lunar tide during long duration reading (12 hr).

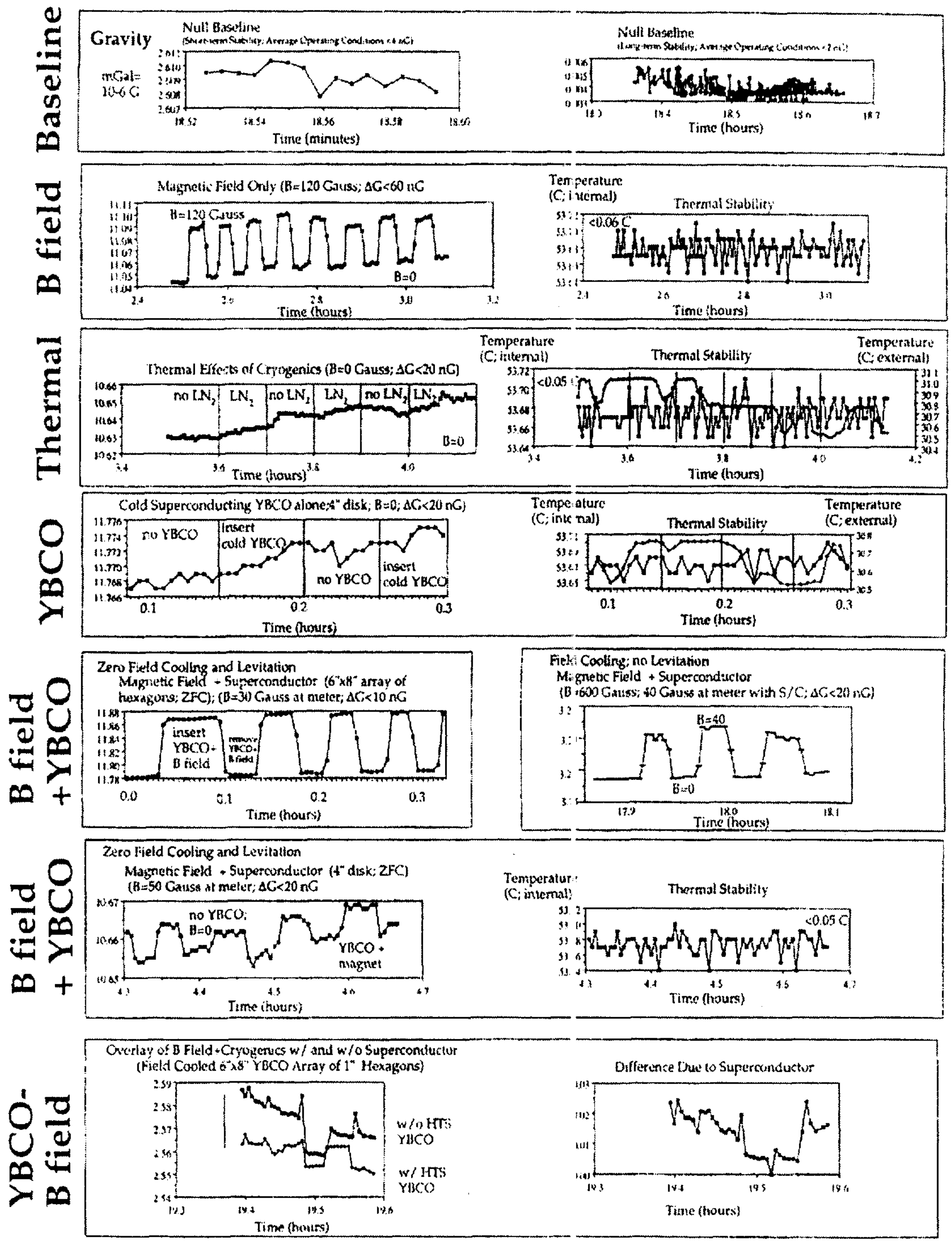

Fig. 3. Experimental results for measured DC-magnetic field and gravimeter fluctuations (baseline plus magnetic, thermal and superconductive contributions). If not otherwise indicated the vertical axis is apparent gravity in units of milli-Gals or 10^{-3} cm s^{-2}. See text for protocol details.

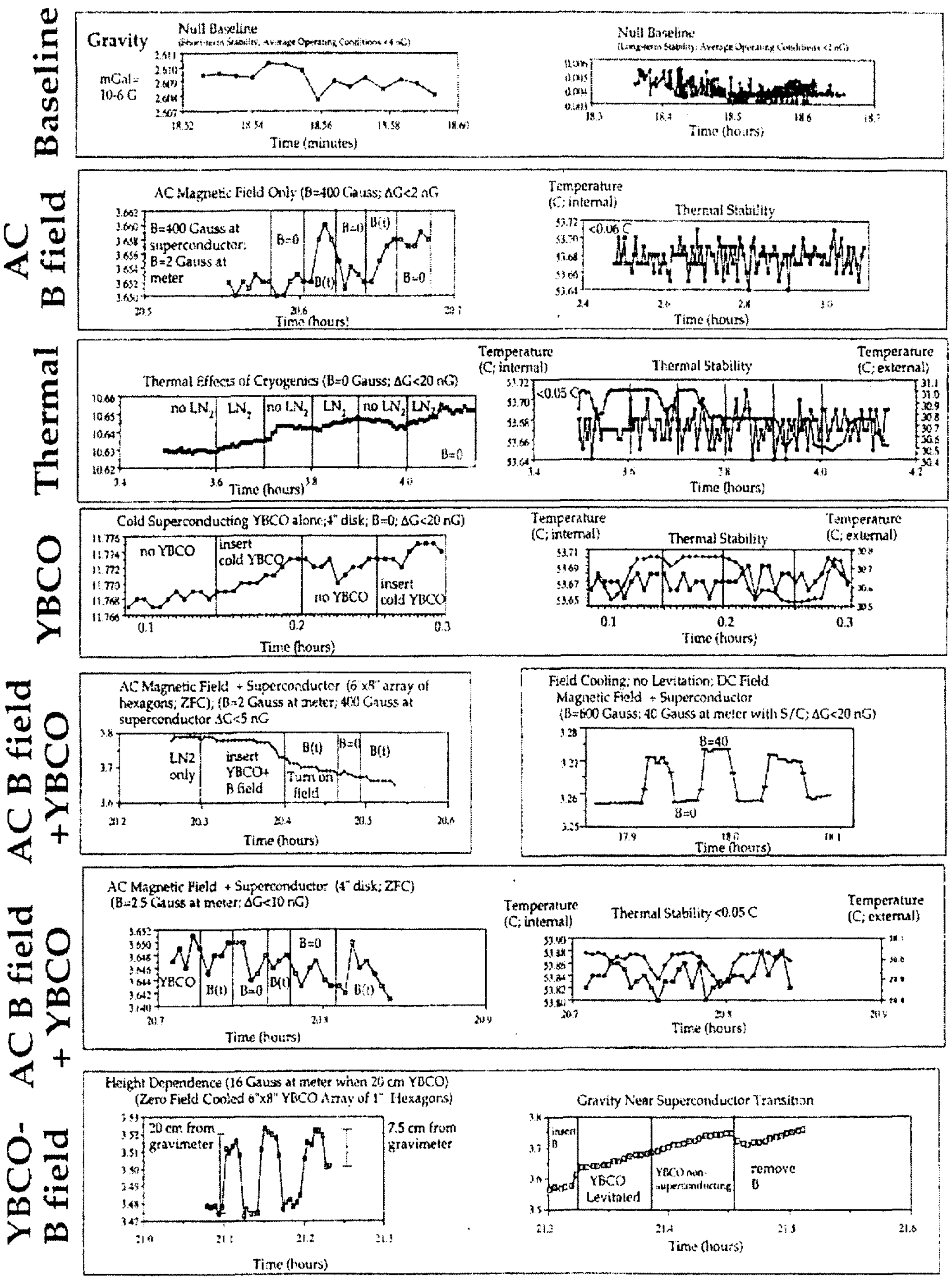

Fig. 4. Experimental results for measured AC-magnetic field and gravimeter fluctuations (baseline plus magnetic, thermal and superconductive contributions). If not otherwise indicated the vertical axis is apparent gravity in units of milli-Gals or 10^{-3} cm s^{-2}. See text for protocol details.