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Static test for a gravitational force coupled to type II YBCO superconductors

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Abstract

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 ($\sim 10^{-6}$ g cm^3). Recent experiments have reported anomalous weight loss for a test mass suspended above a rotating type II, YBCO superconductor, with the 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. Changes in acceleration were measured to be less than 2 parts in 10^8 of the normal gravitational acceleration. This result puts new limits on the strength and range of the proposed coupling between static superconductors and gravity. © 1997 Elsevier Science B.V.

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1. Introduction

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." For comparison, Forward's electromagnetic analogy shares many features at the atomic scale (e.g. ion precession) with nuclear magnetic resonance (NMR) devices and at the laboratory scale with superconducting bearings or flywheels.

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. 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

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upon measurements in closed glass tubes encased in a stainless steel box. A subsequent simplified apparatus without rotation has reported transients of up to 5% weight loss [5] with lower strength magnetic fields. 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.

2. Superconducting disk

To achieve large area superconductors, two configurations were employed. A bulk, melt-textured YBCO disk (10 cm diameter, 1.25 cm height) provided by Superconductive Components (Columbus, OH) was used with mostly square-like multidomains 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. [12]) 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 × 20 cm) comparable to the actual footprint of the gravity measurement. An array of 48 single-domain YBCO hexagons (2.03 × 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/cm^2 at 77 K 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 [12]. 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 [13] 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:

$$F = \int AJr \,\mathrm{grad}\, H \,\mathrm{d}V. \tag{1}$$

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

2.1. 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 [1].

[1] 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 mGals (0.22 cm s^{-2}) in 50, 20 and 5 mGal increments, with 3–7 mGal 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.

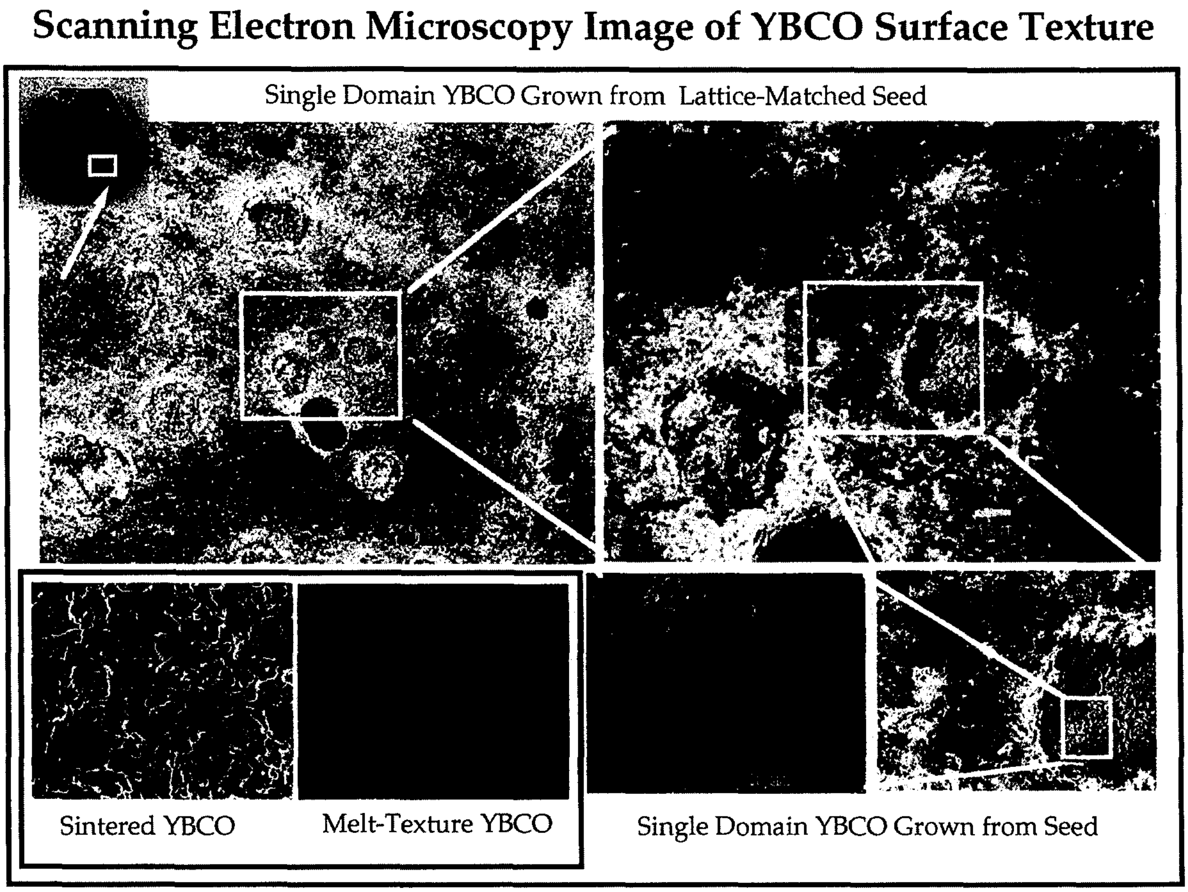

Fig. 1. Scanning electron microscopy of hexagonal, single-domain YBCO superconductor at increasing magnification. Surface machining textures the domain.

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 × 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, $> 5 \times 10^{-6}$ cm s^{-2}). The observed gravity value includes tidal corrections varying with time and location (measured on 8-satellite GPS, 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 levelling error, which is automatically calculated and off-level corrections are included in the final value. The instrument's range is 5×10^{-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 [2]. Instantaneous gravity was recorded at 1

[2] 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 2×10^4 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 3×10^{-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.

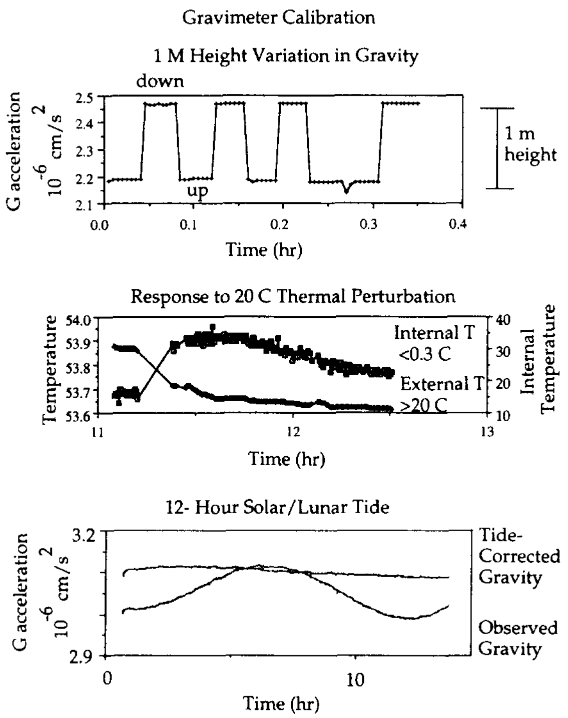

Fig. 2. Calibration and proof-testing gravimeter: (1) altitude variation of 1 m and resulting gravity change (3.08×10^{-7} cm/s^2 per m altitude); (2) thermal constancy of gravimeter interior during 20°C external temperature change; (3) solar and lunar tide during long duration reading (12 h).

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 ($\sim$ 300 mGal/m); (2) uncorrected and corrected tidal measurements over 12 h; (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.

2.2. 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 12.5 cm (5 inches) above a 1-l straight-walled dewar of boiling liquid nitrogen (77 K), thermal variations were monitored at < 0.05°C for internal temperature and < 0.70°C for external temperature in the course of 0.8 h.

2.3. 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 × 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.

2.4. 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 levelled 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 deduc-

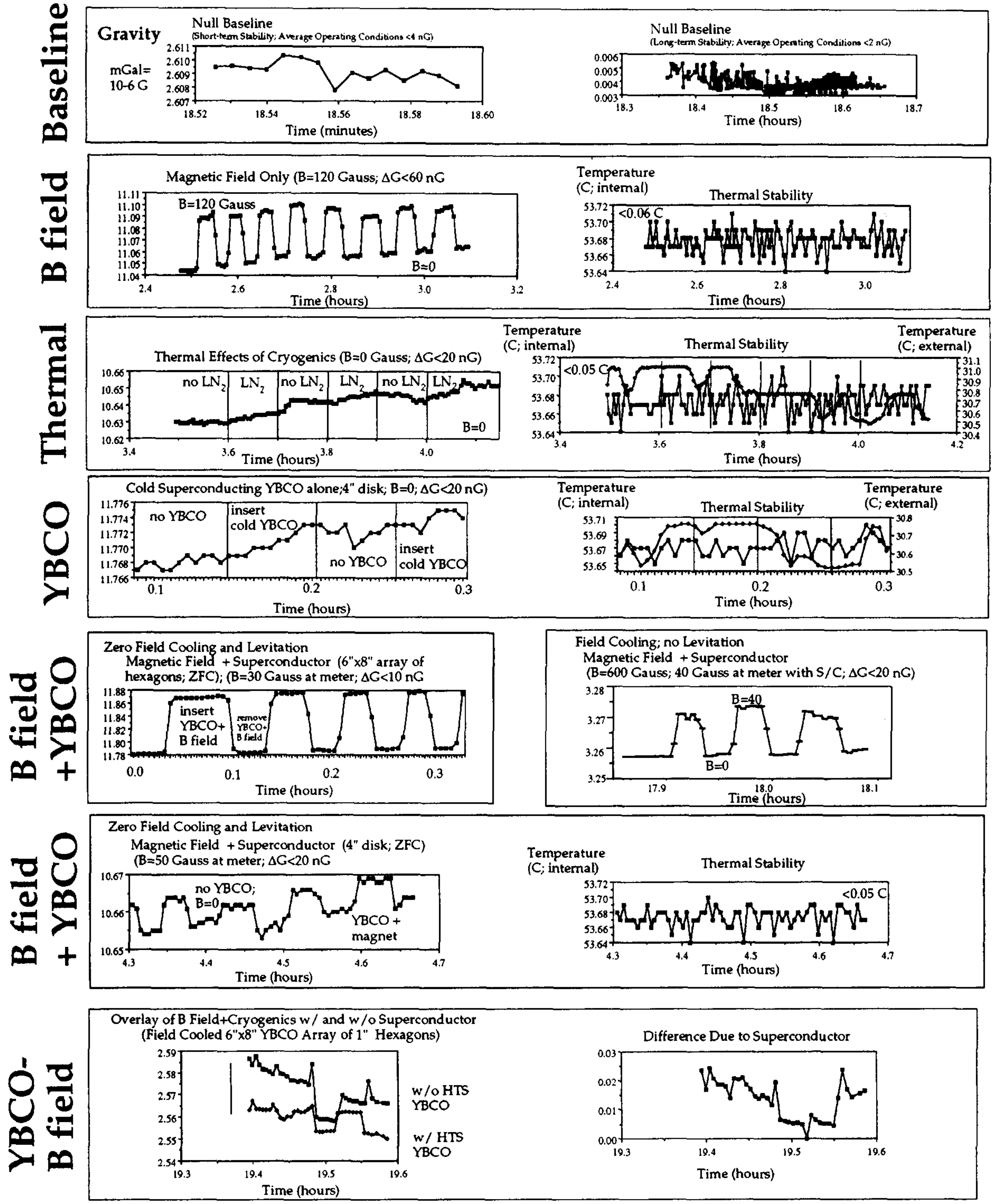

Fig. 3. Experimental results for measured DC magnetic field and gravimeter fluctuations (baseline plus magnetic, thermal and superconductive contributions). If not otherwise indicated the vertical axis is apparent gravity in units of mGals or 10^{-3} cm s^{-2}. See text for protocol details.

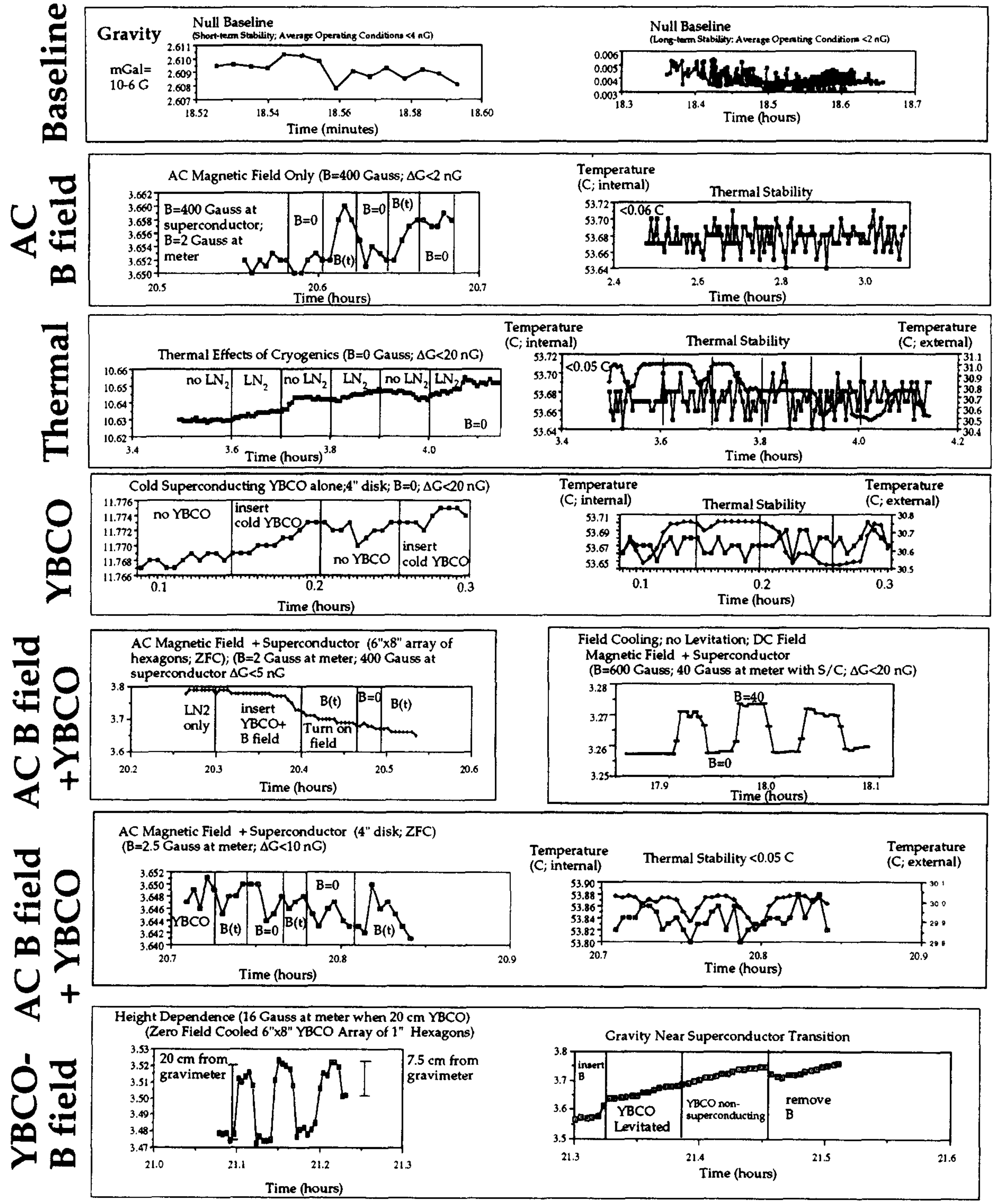

Fig. 4. Experimental results for measured AC magnetic field and gravimeter fluctuations (baseline plus magnetic, thermal and superconductive contributions). If not otherwise indicated the vertical axis is apparent gravity in units of mGals or 10^{-3} cm s^{-2}. See text for protocol details.

tive protocol [3] 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 succinctly below.

As indicated in Fig. 3, vibration is measured with an empty platform moved underneath the gravimeter ($< 1-3 \times 10^{-6}$ 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, $< 2 \times 10^{-6}$ cm s^{-2}); magnetic contributions are measured with the magnets alone moved underneath the gravimeter ($< 6 \times 10^{-6}$ 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 ($< 2 \times 10^{-6}$ 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 ($< 2-5 \times 10^{-6}$ 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).

3. Discussion

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, $< 2-5 \times 10^{-6}$ 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 ($\sim$ 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. Relative to a gravito-magnetic force [9–11] which depends 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]; 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. Later work has generalized the Meissner effect in a gravitational field as a superconductive analog of a Zeeman shift. Schiff and Barnhill [14] and DeWitt [15] 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 (Refs. [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 grav-

[3] 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 $+0.05$°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, nonmagnetic test mass.

itomagnetism. 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.

The rotating verion of this experiment will be reported in subsequent work. In addition to superconductors, other Bose condensates such as superfluid helium have been investigated for gravitomagnetic field exclusion [16], 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.

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