1970

# LABORATORY EXPERIMENTS ON QUANTUM DETECTION OF NON-NEWTONIAN GRAVITATIONAL EFFECTS†

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The Lense-Thirring effect remains the only classical prediction of Einstein's General Theory of Relativity which has not to date been observed. Predicted[1] shortly after the General Theory appeared, the Lense-Thirring rotation survives as the single example of Mach's Principle in the various predictions of Einstein's theory. Early attempts at astronomical verification were beset with both experimental (observational) and theoretical problems: the predicted L.T. precession of Jupiter's 5th moon is nearly canceled by the direct Einstein precession! No other astronomical test of the L.T. effect has been suggested, except for the ambitious artificial satellite experiment proposed[2] by Schiff and Fairbank. Laboratory observation of the L.T. effect has not been regarded seriously because of a variety of noise problems. In this essay we describe an experiment in progress in which laboratory observations of the L.T. rotation and other effects are attempted by making use of the novel inertial response of quantum fluids. Before describing this detection scheme, some words about the L.T. rotation are in order.

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†An essay submitted to the Gravity Research Foundation, New Boston, N.H., April 15, 1970.

On typical laboratory scales of distance and density the L.T. effect, like all other non-Newtonian gravitational effects, is very small indeed. Only at nuclear densities or astronomical distances does the L.T. effect give rise to macroscopic departure from Newtonian behavior: A cylindrically symmetric mass M of dimension R spinning with angular velocity $\underset{\sim}{\omega}$ will cause a precession of the inertial frame nearby with respect to distant matter (the fixed stars) at a rate $\underset{\sim}{\Omega}$ given by

$$\underset{\sim}{\Omega} \approx (2GM/Rc^2)\ \underset{\sim}{\omega} \qquad (1)$$

where G is the gravitational constant and c is the velocity of light. The very small coefficient $GM/Rc^2$ is the familiar small parameter of all non-Newtonian expansions. On the sun's surface $GM_{\odot}/R_{\odot}c^2 \approx 10^{-6}$, but laboratory-size masses give values more than $10^{16}$ times smaller, although we can reach comparatively high $\omega$ by spinning small stiff masses to their bursting point. Solid cylinders and spheres usually fly apart[3] when the surface velocity reaches the speed of sound in the material. For matter of density $\rho$ and sound velocity s, equation (1) gives the maximum L.T. precession rate $\Omega_{max}$ as

$$\Omega_{max} \approx 10\ G\rho Rs/c^2 \quad . \qquad (2)$$

In order to help eliminate stray electromagnetic coupling, we should spin nonmagnetic ($\mu \approx 1$) matter. Thus, optimum material must correspond to a maximum in $s\rho/\mu$. Beryllium, Copper, Tungsten, and quartz are good candidates, corresponding to an average product $\langle s\rho \rangle \approx 5 \times 10^6$. The result for the laboratory-generated L.T. precession is

$$\Omega \lesssim 10^{-20} R \text{ rad/sec}, \tag{3}$$

where R is the radius of the critically rotating mass in cm. Available integrating gyroscopes could detect such a rotating mass 10 km in radius in one year, but a more practical laboratory mass (1 m radius) requires a much more sensitive detector ($\Omega \approx 10^{-18}$ rad/sec). We now explore the possibility of using macroscopic quantum inertial detectors for studying non-Newtonian gravitational effects, of which the Lense-Thirring effect is one example.

Rates of rotation smaller by several orders of magnitude than the limiting rates detectable by mechanical gyros can be measured through the effect of rotation on the propagation of light in a modified two-beam interferometer. The feasibility of such a system was demonstrated by the classical experiments of Michelson and Gale[4] and by Sagnac[5]. The two beams from a beam splitter are made to travel around a closed loop in opposite directions but along identical paths and then combined to produce an interference fringe pattern. The fringe shift, resulting from the differential path length changes for the clockwise and counterclockwise beams caused by rotation, is proportional to the rotation rate. Additional orders of magnitude improvement in sensitivity to rotation has been achieved, in principle, by the use of traveling wave ring lasers[6]. Unfortunately, these promising detectors fail at low rotation rates due to frequency pulling of the two laser modes involved. Thus, attempts to utilize macroscopic quantum phenomena for the detection of rotation are not new. We now describe a new macroscopic quantum inertial detector, using the properties of superfluidity and/or superconductivity.

The superconducting quantum inertial detector, (SQUID) has been shown[7] to be moderately sensitive to rotation, although it is most sensitive to magnetic fields. The SQUID is no more than a superconducting analog of the ring laser interferometer gyro. Figure 1 shows the basic interferometer formed by inserting two superconductive weak links (Josephson junctions), i.e. slits, into the loop. Rotation or external magnetic fields will induce a fringe shift when the phase coherent supercurrents are made to interfere. Unfortunately, sensitivity to inertial effects is strongly limited in the SQUID due to its magnetic response and limiting self inductance. A multiturn, superconductively self-shielded SQUID could detect rotations with respect to the fixed stars as small as $10^{-10}$ rad/sec. For more sensitivity, however, we must turn to superfluid Helium detectors.

Looking again at Figure 1, if we imagine the loop and connecting arms to be filled with superfluid $He^4$ in equilibruim at a temperature below its transition temperature, then the macroscopic occupation of a single quantum state implies the usual quantization of circulation:

$$\oint m\underset{\sim}{v}_s \cdot d\underset{\sim}{s} = nh \qquad , n = 1,2,3 \ldots \qquad (4)$$

where m is the mass of the $He^4$ atom, $v_s$ is the local superfluid velocity, and h is Planck's constant. Except for a term involving the electromagnetic vector potential, this quantization of circulation forms the basis for the operation of the SQUID. However, we will attain much greater sensitivity to <u>inertial</u> effects in the superfluid quantum inertial detector for two reasons: (1) Coupling to the electromagnetic field is absent in the weak field limit. (2) Inertial response is enhanced due to the large mass of $He^4$ relative to the electron mass. The weak links (Fig. 1) in the case of the superfluid detector, have been successfully made by separating two superfluid baths by a wall containing a small hole.[8] The required constant superfluid current bias generators have been operated previously. Net superfluid flow should show an interference fringe shift proportional to $\Omega$, as in the case of the self-shielded SQUID. If we surround the rotating mass with a multi-turn superfluid interferometer, we have locally $v_s = \Omega R$. (A three-turn interferrometer loop, which preserves the position of the central fringe, is shown in Fig. 2). Since the quantum of circulation $K_o$ is given by $K_o = 2a_o\Omega_o = h/4m_p$ ($m_p$ = proton mass, $a_o$ = area of basic loop). The single fringe shift corresponds to a change in rate of rotation of $\Delta\Omega$ given by $\Delta\Omega = \Omega_o = h/4\ a_o m_p$, where $a_o = \pi R^2 N$ (N = # of turns in multi-turn interferometer loop). As in all interferometer measurements, one can usually detect a small fraction of a fringe shift. In one second integration time, we should be able to see about $10^{-4}\Omega_o$. Using again the convenient laboratory size of $R = 10^2$ cm, a $10^4$ turn superfluid interferometer gyro would have a rotation rate sensitivity of $10^{-15}$ rad/sec after one second integration. Substantial improvement in sensitivity may be achieved through the use of further phase sensitive detection schemes involving more than one detector, and varying the angle between $\underset{\sim}{\omega}$ and the normal to the detector plane at some higher frequency $\Omega^*$.[9] (In this connection we should note that the earth's rotation can be used conveniently as reference calibration). Phase sensitively integrating in this way, the $10^{-15}$ rad/sec may be improved to better than $10^{-18}$ rad/sec in one month. This is just the level of response required for the proposed laboratory Lense-Thirring rotation.

Random and systematic error enter into the experiment in different ways. Largest contributors to "random" noise are (1) noise in the output of the superfluid chemical potential difference detectors (which can be made negligible by increasing the number of turns N) and (2), vibration coupling into the interferometer and output detectors. Vibration must be shielded by acoustic and mechanical isolation. Without such protective shielding, estimates indicate vibration is a prohibitive noise source. Systematic errors also come in two types: Those systematic drifts due to stray electromagnetic or mechanical coupling with the generator (rotating mass) are largely eliminated through the detection and integration scheme and by repeating the experiment for different positions of the generator. Systematic drifts due to wobble in the earth's rotation are another matter. Wobble of amplitude comparable to $\Omega_{L.T.}$ and period commensurate with $\Omega^*$ will have to be understood before their contribution can be subtracted, although varying $\Omega^*$ offers some handle on this problem. The small L.T. effect due to the earth's rotation is completely negligible, but coriolis forces must be dealt with by mounting the detector on an equatorial mount.

In this experiment we propose to measure the response of a quantum system to minute gravitational forces. It may be instructive to ask if there are other experiments at the juncture of Quantum Mechanics and General Relativity which may be possible today using macroscopic quantum systems. One question which could be investigated in this way is: Does the distant matter of the universe interact with the quantum nature of matter in any direct way? A possible test of this, using superfluid interferometers, would be to ask if the ground "zero momentum" state in a Böse-condensed macroscopic quantum fluid is formed at rest with respect to the fixed stars. Do "classical" General Relativistic effects operate in the same way on the quantum scale? Machian aspects of the behavior of macroscopic quantum fluids is one area open to exploration using these devices. Other possibilities include hypersensitive wide band antennas for low frequency gravitational tensor radiation. Weber[10] has shown that the angular momentum transferred by low frequency gravitational radiation is equivalent to a differential angular acceleration oscillating (wobble) at the frequency of the gravitational wave. The inertial detector described herein has a large effective capture cross section for low frequency gravitational radiation without being resonant. These experiments and others will be possible in the near future with the advent of large coherent quantum detectors of this kind.

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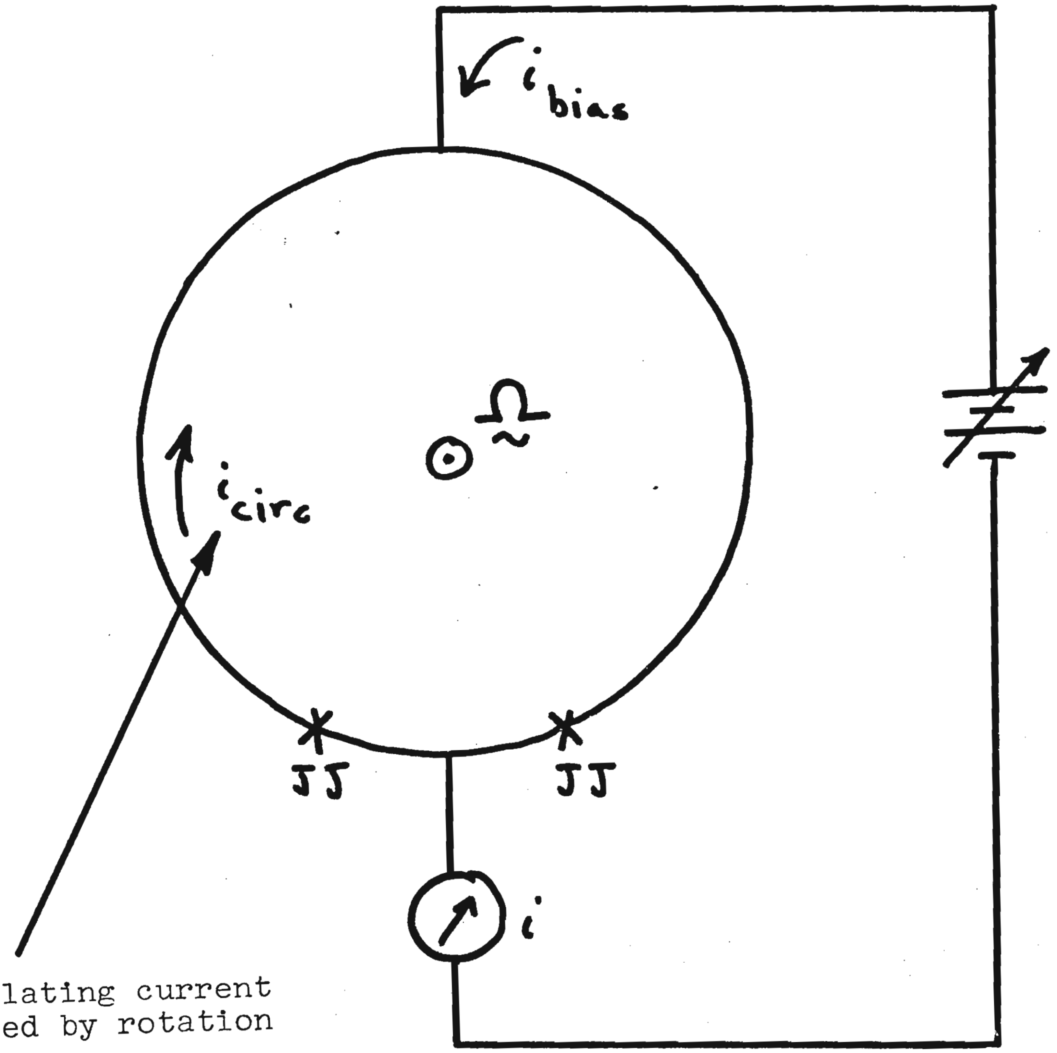

Circulating current induced by rotation

Figure 1
Superconducting Quantum Interferometer

FIG. 2

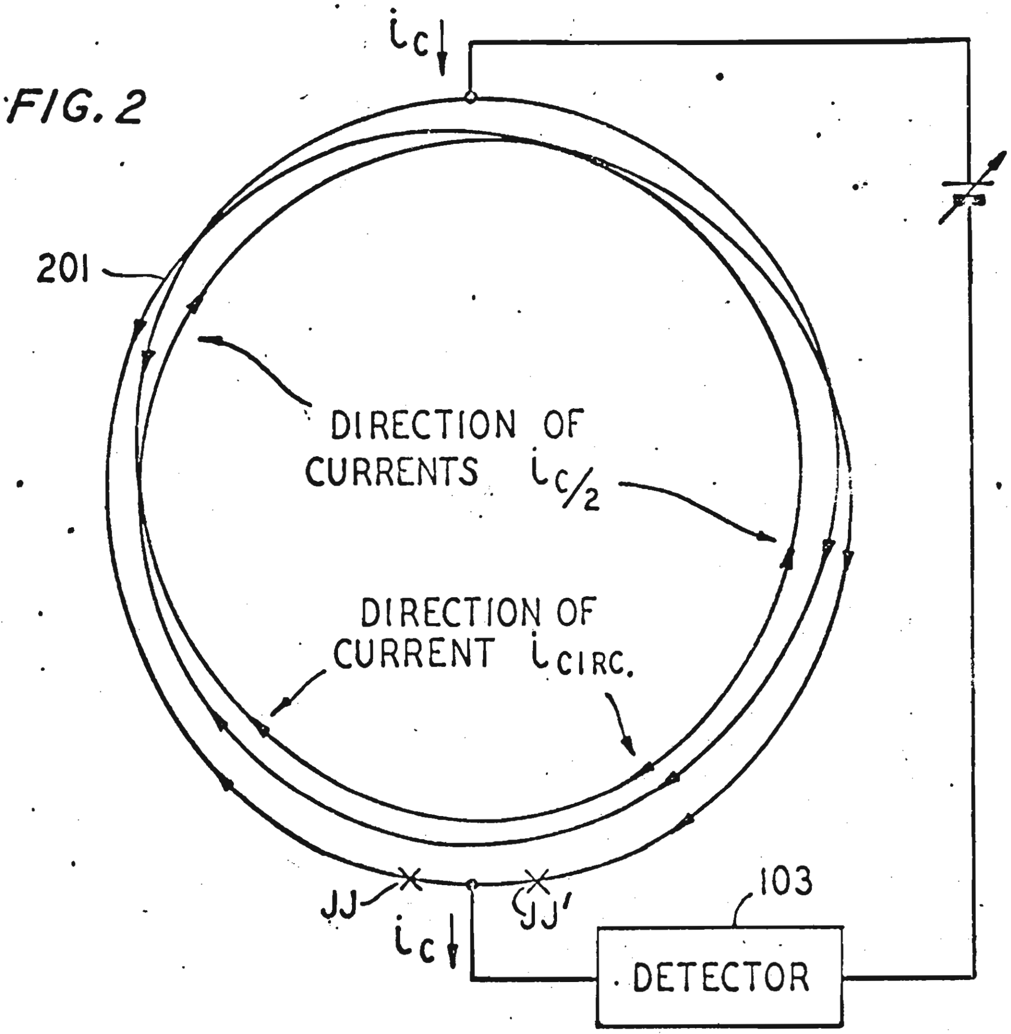

Figure 2
Three turn Superfluid Quantum Interferometer. Battery denotes variable constant current supply. Detector incorporates chemical potential difference detectors.