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Evaluation of enhanced frame-dragging in the vicinity of a rotating niobium superconductor, liquid helium and a helium superfluid

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Abstract

To explain a reported Cooper-pair mass anomaly in niobium it has been predicted that rotating superconductors or superfluids might produce large non-classical frame-dragging fields. Anomalous gyroscope signals close to the measurement resolution in the proximity of rotating superconductors or liquid helium have also been reported while trying to investigate this theoretical concept. Based on lessons from various setups, we succeeded in building an experimental facility that allowed us to rotate a niobium superconductor, liquid helium, superfluid helium and low temperature matter with high accelerations at high speed exceeding all previous efforts. A military-grade SRS-1000 gyroscope at close proximity in different locations was used to measure any anomalous frame-dragging-like fields. No such anomalies were found within three times the noise level of our setup ($\pm 5 \times 10^{-8}$ rad s⁻¹). Measurements with an electric motor at speeds up to 5000 rpm enabled us to set low boundaries for any coupling or frame-dragging-like effect outside of a rotating niobium superconductor or liquid helium to 4×10^{-11} and for superfluids to 3×10^{-10} . Due to the high speeds used, these results are up to two orders of magnitude below any previous result.

(Some figures may appear in colour only in the online journal)

1. Introduction

Frame-dragging is a phenomenon in general relativity that causes rotating matter to drag space-time in its vicinity. According to Einstein's theory, this effect is so weak that it requires astronomical observations and precision tests with satellites to detect it [1]. Recently, to explain a reported Cooper-pair mass anomaly in niobium [2, 3] which remains unsolved at present [4], Tajmar and de Matos [5–8] predicted that rotating superconductors or superfluids might produce much larger non-classical frame-dragging fields. Other theoretical concepts were proposed supporting this conjecture [9–11]. Recently, McCulloch proposed that such frame-dragging-like fields may be linked to the Pioneer

anomaly [12]. Moreover, it was shown that such fields would be of great technological interest as they could enable the creation of artificial gravitational fields to enable, for example, microgravity research in an Earth-based laboratory [13].

Since 2003, several experiments have been performed at the Austrian Institute of Technology (AIT) [14–18] to detect greatly enhanced frame-dragging fields using accelerometers (dismissed early on due to high vibration sensitivity) and fiber-optic gyroscopes in close vicinity to rotating matter at low temperature, including steel, aluminum, Teflon, high and low T_c superconductors, liquid and superfluid helium. Initially, the sensors were mounted inside the cryostat inside a separate vacuum chamber, which provided the necessary thermal isolation to operate them at 25 °C. This chamber with the

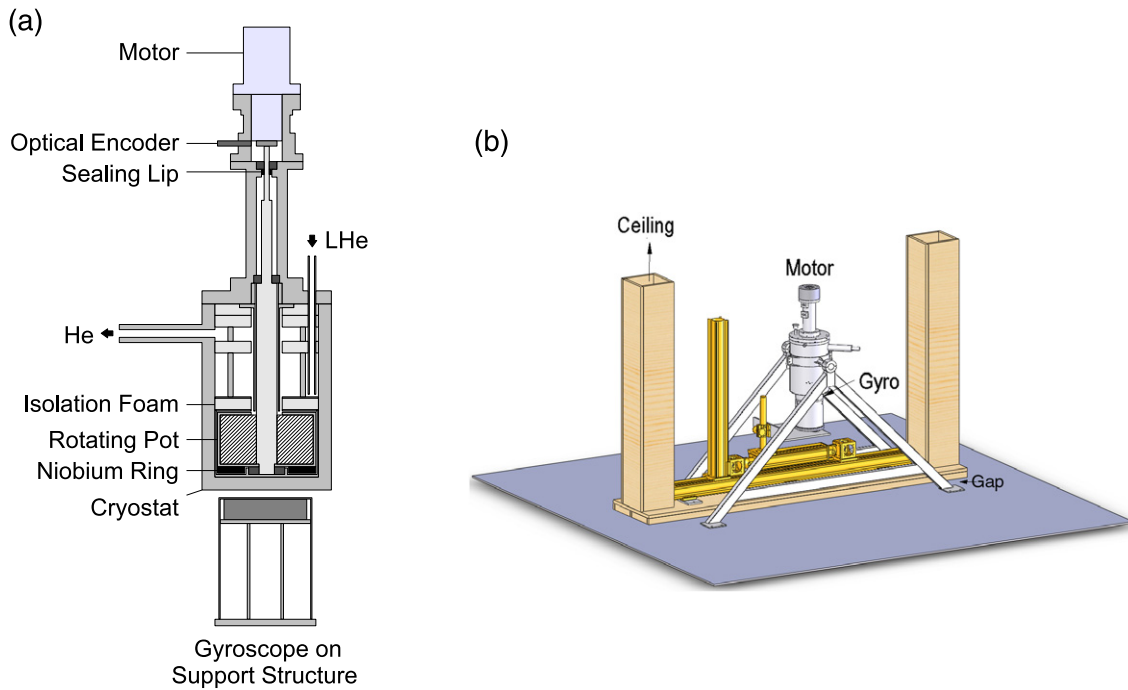


Figure 1. Experimental setup. (a) Detailed section and (b) overall experimental setup.

sensors was fixed with stainless steel bars to the ceiling of the laboratory to remain fixed during the tests. When a ring sample cooled with liquid helium was rotated below the sensors, the gyroscope indeed seemed to follow the rotating ring with a coupling factor (gyroscope signal/ring angular velocity) of about 10^{-8} , mimicking a frame-dragging-like measurement. Also a parity violation was observed such that clockwise rotation yielded larger coupling factors than counter-clockwise rotation. The signal apparently did not decay over the distance of our vacuum chamber and was independent within a factor of two of the ring material used. It only decayed with the temperature of the ring (or with the liquid helium level in the cryostat) such that only temperatures close to liquid helium showed an effect. Although the gyroscope signal was very small, its magnitude was some 18 orders of magnitude above classical predictions. Of course, this warranted further investigation into the nature of the signals that we measured.

Because magnetic or temperature drift effects were soon ruled out, our main concern was vibration due to the motor and from the expansion of the liquid helium into gas during rotation. Our setup was gradually adapted by using low-noise cryomotors directly below the ring, a military-grade gyroscope with higher resolution and less vibration sensitivity as well as trying to move the gyroscope outside the cryostat for optimal vibration isolation. This resulted in lower rotation speeds and also smaller anomalous signals with coupling factors now in the range of 10^{-9} .

Also Graham *et al* [19] attempted to measure enhanced frame-dragging from a rotating lead disk at 4 K using the world's largest ring-laser gyro and failed to detect a signal within $1.7 \pm 3.8 \times 10^{-7}$ assuming a dipolar distribution, a sensitivity which is about two orders of magnitude worse than our design (their experimental values were re-assessed in [16])

and therefore could not rule out our anomalous gyroscope signals. Moulthrop [20] investigated frame-dragging-like signals from rotating superfluid helium and put an upper limit coupling factor of 0.05 which is seven orders of magnitude worse than our anomalies.

In order to finally settle the case, we built a new experiment, where the test sample inside the cryostat can be rotated at high speeds using an externally mounted motor. The gyroscope is mounted outside the cryostat, isolated from the ground, and attached to a structure that allows it to be mounted at different positions. Our latest setup allows us to rotate a niobium superconductor and a pot with liquid helium or superfluid helium at high speeds and accelerations in order to re-evaluate all theoretically predicted possibilities (whether the source of the effect is due to superconductivity, superfluid helium or the liquid helium itself).

2. Experimental setup

2.1. Overview

The main part of our experiment is a large custom-built cryostat made out of stainless steel (evacuated with multi-layer-insulation isolation) as shown in figure 1. The cryostat is mounted on a structure which allows it to be tilted along the Earth's north-south axis as we planned to tilt the cryostat in future experiments to investigate the influence of the Earth's spin. However, all experiments performed so far were done with the cryostat mounted vertically to our laboratory floor. Inside the cryostat is a pot made out of aluminum with a wall thickness of 3 mm, which can be filled with up to 1.71 l of liquid helium. Its outer and inner radii are 173 and 45 mm with a height of 98 mm. As shown in figure 2, the pot can only be

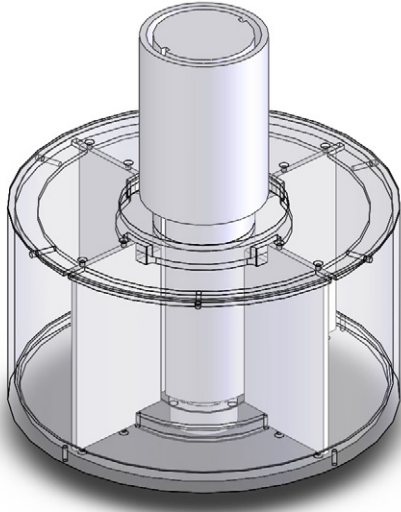


Figure 2. Rotating pot with fins (outer walls are transparent).

filled through a ring-shaped hole on the top and it has four fins that ensure that the liquid is homogeneously rotating with the same velocity. The fins have a 5 mm gap with respect to the outer wall and the inner rotating axis in order to allow closed loops for rotating superfluids to create vortices. In addition, a niobium ring with a thickness of 10 mm, an outer diameter of 173 mm and an inner diameter of 77 mm is attached at the bottom of the pot and fixed with screws.

The pot is mechanically attached to the main axle, which is stabilized with three ball bearings and extends up to a flexible coupling that allows any kind of external motor to be mounted to it. The lower and the middle bearings were low temperature bearings with solid MoS₂ lubricants made by KOYO. For our experiments, we used a compressed air motor (Düsterloh PMW 400 Z24) similar to one in our early experiments with maximum acceleration as well as a brushless servo motor (Torque Systems BNR3034). The axle also features an optical encoder to read out the speed as well as a sealing lip that was inserted during the superfluid measurements which required evacuation of the chamber. Silicon diodes (Lakeshore DT-670B-SD) were placed on the niobium disk as well as at the top of the inner cylindrical surface of the pot (readout via a slip ring close to the optical encoder as it is rotating with the pot) and on two positions inside the cryostat to monitor the filling level of the liquid helium and the temperatures. Great care was taken for good thermal isolation using Styropor isolation foam rings as well as protecting the liquid helium in the upper part of the cryostat from the rotating axle by a shielding tube to minimize heat and rotation sources, and hence the transition of liquid into gaseous helium. The helium gas exhaust was directly connected to a tube that extended through the windows of the laboratory so as not to influence our equipment.

We used an OPTOLINK SRS-1000 fiber-optic gyroscope, which is mounted on a support structure outside the cryostat allowing it to change its position and orientation all around the cryostat. In addition, a magnetic field sensor (Honeywell SS495A1), high resolution accelerometers (Colibrays

SiFlex1500 and SiliconDesigns 1221) and temperature sensors were mounted together with the gyroscope. All sensors are encapsulated under a high permeability magnetic shield (Permalloy) in order to reduce their magnetic sensitivity. The support structure was lifted off the laboratory floor by a stiff structure made out of wood that was connected to the ceiling of the laboratory as shown in figure 1(b). A gap of about 5 cm ensured good vibration isolation during rotation between the vibrating cryostat, which was fixed to the ground by screws and the actual gyro support structures. In addition, the gyro support structure was passively damped by rubber sheets between the gyro support and the wood structure. The gyroscope was moved along four positions during the experiment, labeled middle, side, off-axis and off-axis 2 as shown in figure 3, in order to investigate a possible field distribution of the anomalous signals.

2.2. Sensitivity and systematic effects

Since we are trying to measure very small rotation rates, it is important to know the minimum rotation rate that can be resolved by the fiber-optic gyroscope. For the SRS-1000 gyroscope, the upper limit of the minimal measured rotation rate, caused by polarization nonreciprocity of a light source with a Gauss spectrum, is expressed as [21, 22]

$$\Omega_{\min} \leq \frac{\lambda c p \epsilon}{DL} \sqrt{\frac{\lambda \sqrt{\ln 2} h L_p}{\pi \Delta \lambda}} \quad (1)$$

where $\lambda = 1.55 \times 10^{-6}$ m is the average wavelength of light, $\Delta \lambda = 50 \times 10^{-9}$ m is the width of the light spectrum, c is the speed of light in a vacuum, $D = 150 \times 10^{-3}$ m is the diameter of the fiber coil, $L = 1070$ m is the length of the fiber coil, $h = 1 \times 10^{-6}$ m⁻¹ is the polarization crosstalk of the fiber coil, $L_p = 2.5 \times 10^{-3}$ m is the beat length of the fiber coil, p is the residual degree of polarization of the light source and ϵ is the coefficient of the polarizer's extinction. For typical values of $p \approx 0.01$ and $\epsilon \approx 0.01$ (i.e. 40 dB), equation (1) gives an upper limit of $\Omega_{\min} \leq 4.1 \times 10^{-8}$ rad s⁻¹. This coincides with the bias drift value specified for the SRS-1000. We also tested the gyroscope on a piezo-activated nano-rotation table [23] and could resolve velocity steps of 1×10^{-7} rad s⁻¹ with an accuracy of 1.5×10^{-8} rad s⁻¹, which is just below the theoretically predicted resolution upper limit. No asymmetry has been seen between clockwise or counter-clockwise gyro responses.

The magnetic sensitivity along the gyro's axis is 4.8 ± 10^{-3} rad s⁻¹ T⁻¹. According to our Hall sensor mounted directly on the gyroscope, the magnetic field changes during rotation (influence from brushless servo motor and Barnett effect) were always less than 1 μ T. Therefore, the magnetic influence is about one order of magnitude below our minimum rotation rate resolution.

3. Experimental results

3.1. Calibration runs

Before going to liquid helium, the whole setup was first evaluated by filling the pot with liquid nitrogen (for a cold

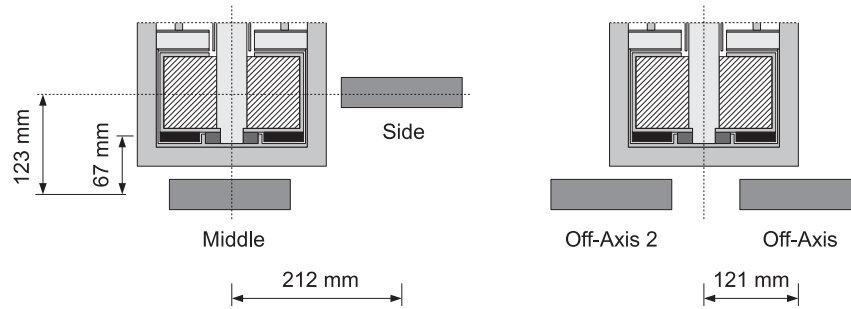


Figure 3. Gyroscope positions.

environment—but no superconductivity of the niobium ring or superfluidity) and then with ethanol as a general electrically non-conducting fluid at room temperature.

All experiments were done using the same standardized speed profile which lasts about 200 s. The profile is subdivided into five sectors with pre-defined time intervals: rest, acceleration, maximum speed, de-acceleration and rest. Each profile was performed in clockwise direction (spin vector points downwards) and in counter-clockwise direction. Random noise was reduced by applying a 200 point digital moving average (DMA) filter to the gyro output and motor velocity. A sampling rate of 13 Hz ensured that the averaging window is always smaller than the maximum speed time interval of the profile. After the signal is acquired, it is normalized by subtracting the Earth’s rotation offset. The noise was further reduced by signal averaging of at least 10 (up to more than 50) profiles for each test case which also increases the statistical significance of our results. For the pneumatic air motor, the optical encoder data were used for the applied angular velocity, whereas in case of the brushless servo motor, the encoder velocity was used. Both were calibrated using reflection stripes on the axle and an external speedometer.

Figure 4 plots the gyroscope response mounted at the middle position during the rotation of both test fluids. The gyroscope shows only noise within a boundary of $\pm 5 \times 10^{-8} \text{ rad s}^{-1}$ which is close to the upper limit sensitivity and the bias drift. We should therefore consider this value as our noise limit in the further analysis.

3.2. Measurements with the electric motor

We used the brushless servo motor in order to evaluate the gyroscope response to different speeds rather than only maximum speed as in our earlier measurements. Two sets of measurements were taken: one for liquid helium and one with superfluid He⁴.

3.2.1. Liquid helium. The cryostat was filled with liquid helium and a series of measurements was taken with the maximum speed during our profile measurements varying from 1000 rpm (about 100 rad s^{-1}) up to 5000 rpm. At this temperature, the niobium ring at the bottom of the cryostat was also superconducting.

A summary of our measurements is shown in figure 5, where the average signal and standard deviation was evaluated

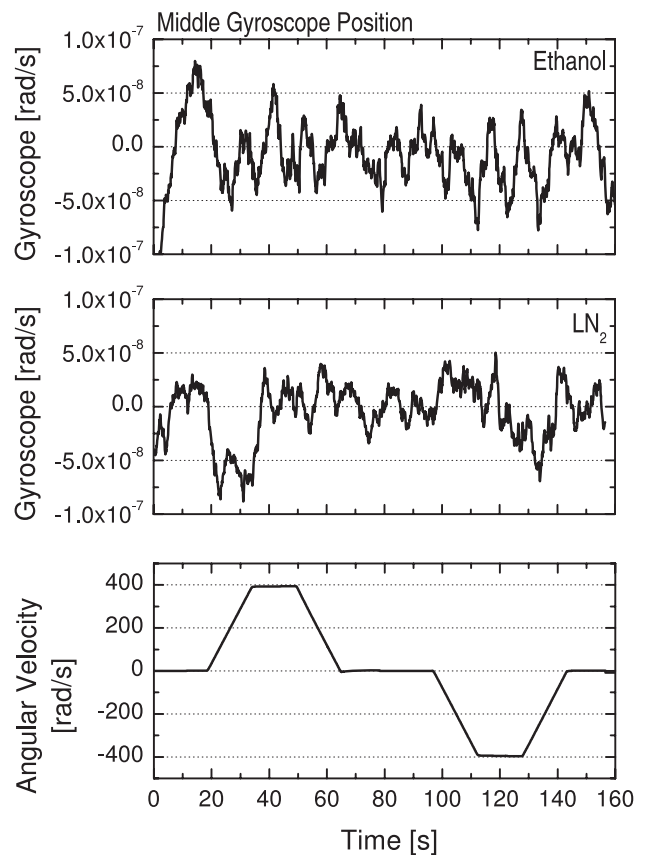


Figure 4. Calibration measurements with ethanol and liquid nitrogen: gyroscope output (middle position) and applied angular velocity.

during the maximum speed phase of our speed profile. Apart from the two last high speed points at 4000 and 5000 rpm (400 and 500 rad s^{-1}) in the counter-clockwise direction, all measurement data are within our noise limit of $\pm 5 \times 10^{-8} \text{ rad s}^{-1}$. The detailed plot of the 4000 rpm test run is shown in figure 6. The gyroscope signal during counter-clockwise rotation (negative velocities) does not fully follow the angular velocity profile, and its maximum signal is only about a factor of three above our gyroscope resolution.

A linear fit through the measurements in figure 5 sets a new limit for a possible coupling factor (or frame-dragging-like coupling) between the liquid helium/superconducting niobium

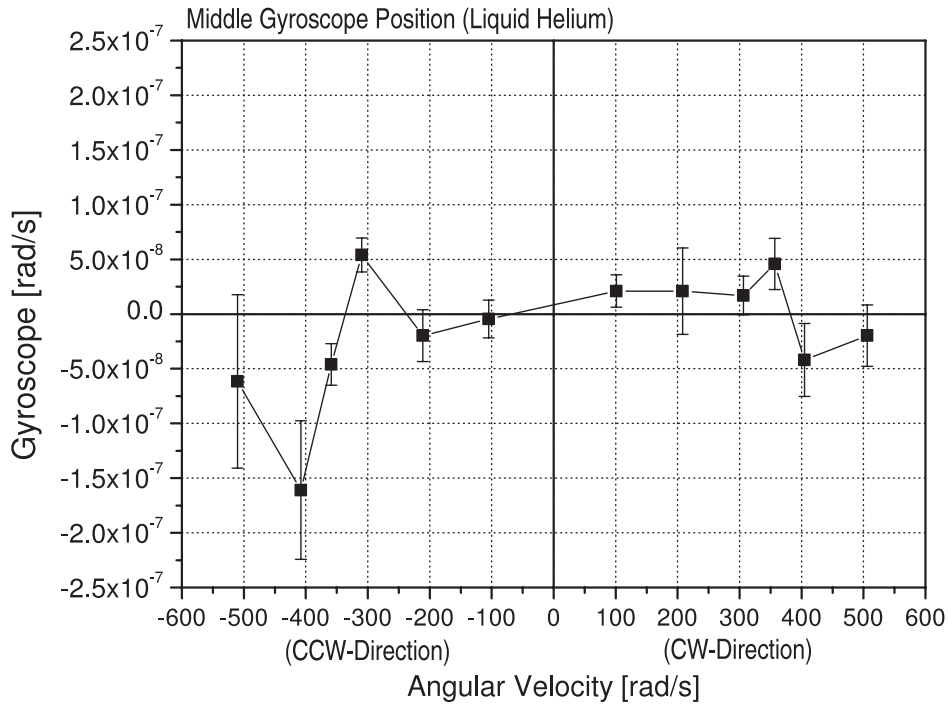


Figure 5. Liquid helium measurement with electric motor: gyroscope output (middle position) versus applied angular velocity.

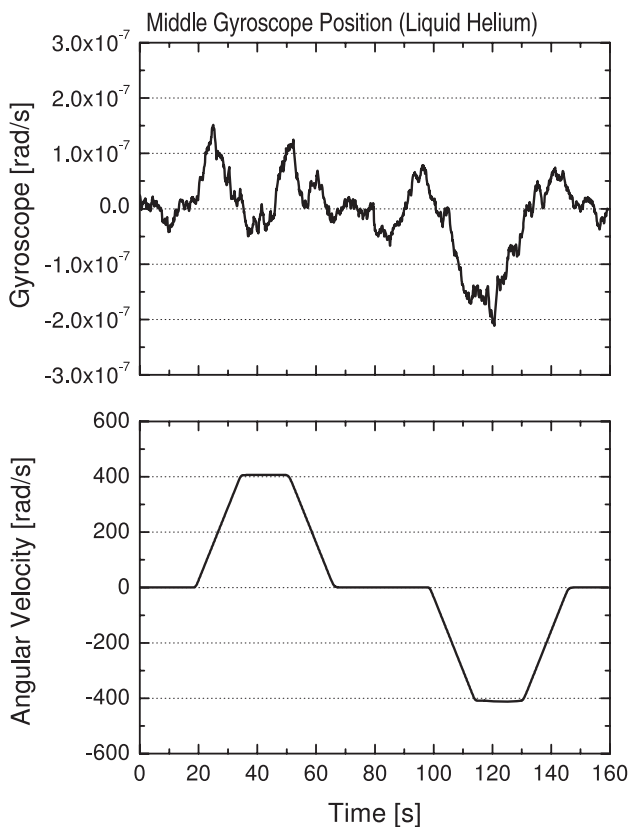


Figure 6. Liquid helium measurement example at 4000 rpm: gyroscope output (middle position) versus applied angular velocity.

and a gyroscope in close proximity as $1.9 \pm 4 \times 10^{-11}$, which is nearly two orders of magnitude below previous measurements [17].

3.2.2. *Superfluid helium.* We also performed test runs with superfluid helium by filling the cryostat with liquid helium with the sealing lip on the main axle and subsequently pumping on it. We could reach a temperature down to 1.8 K in our pot, well below helium’s lambda point at 2.17 K. The test runs were done at three maximum speeds ranging from 500, 750 to 1000 rpm, which is an order of magnitude higher than our previous superfluid helium measurement [18]. Above 1000 rpm we could not keep the temperature below the lambda point during rotation.

The summary plot is shown in figure 7 and shows a similar picture to the one obtained with the liquid helium only. The data points are mostly within our noise level with one exception in the clockwise direction at 750 rpm which is again about a factor of three above our gyroscope resolution. The detailed plot from this particular speed is shown in figure 8.

Also here we can perform a linear fit through the measurements in figure 7 and set a new limit for a possible coupling factor (or frame-dragging-like coupling) between the superfluid helium and a gyroscope in close proximity as $1.6 \pm 3 \times 10^{-10}$.

3.3. *Measurements with an air motor*

We then performed measurements using the pneumatic air motor providing very high accelerations and a maximum angular velocity of around 4300 rpm which is comparable to the highest speeds that we achieved with the electric motor. Moreover, it has no electromagnetic noise which may influence the gyroscope. On the other hand, only one fixed speed is possible; however, we performed measurements at different locations as outlined in figure 3.

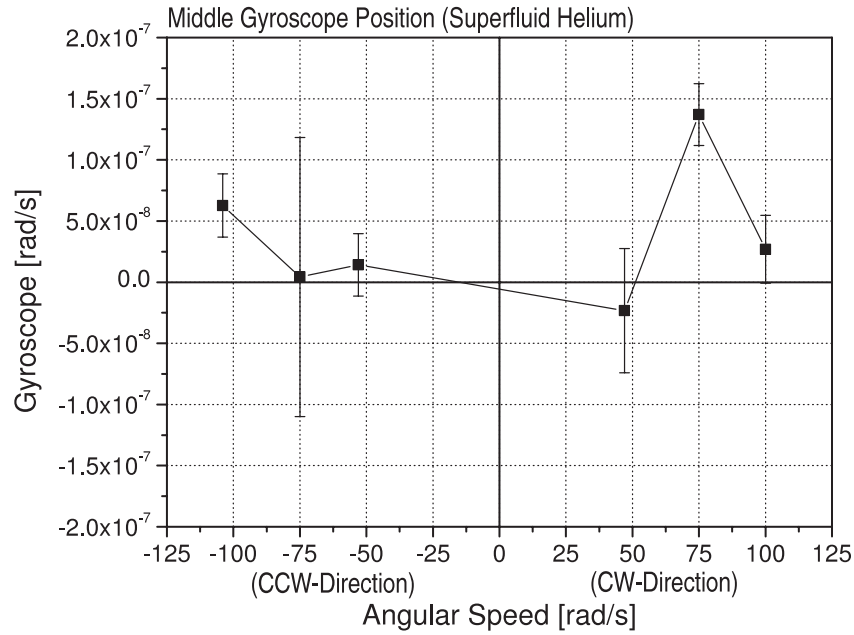


Figure 7. Superfluid helium measurement with electric motor: gyroscope output (middle position) versus applied angular velocity.

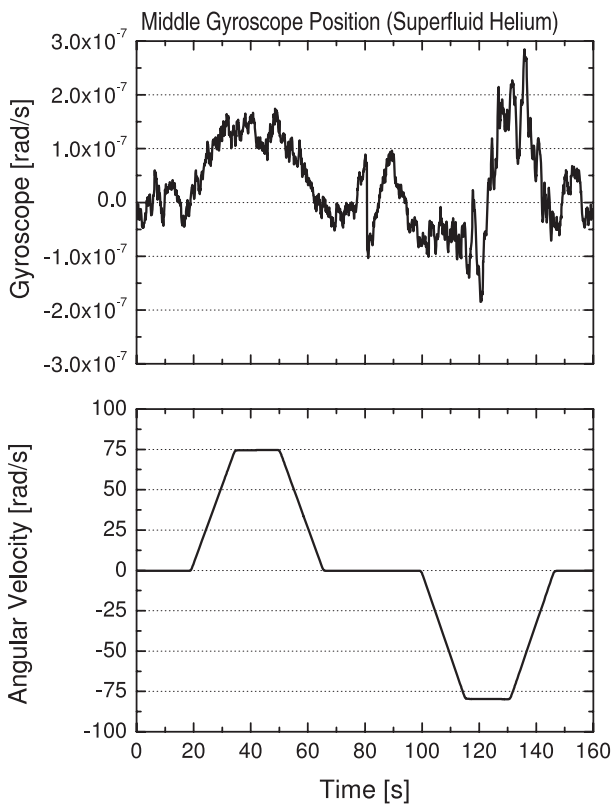


Figure 8. Superfluid helium measurement example at 750 rpm: gyroscope output (middle position) versus applied angular velocity.

Two summary plots in figures 9 and 10, respectively, show the results from our air motor measurement on all different positions for the liquid helium as well as for helium gas

(summarizing temperatures from 6 K up to room temperature) which we were running as non-liquid helium reference test runs. Whereas the helium gas reference measurements with error bars are really all within our noise limit of $\pm 5 \times 10^{-8} \text{ rad s}^{-1}$, the offset positions for the liquid helium case appear to show some room for anomalous signals. Also, the maximum anomalous signal strengths are within three times our noise level, which is not sufficient. Moreover, the anomalous signal is not consistent, because for the off-axis position it is positive and for the off-axis 2 position it is negative. A similar sign would have been expected for any frame-dragging-like field at these two locations due to rotational symmetry. Detailed plots for all gyro positions during the liquid helium test runs are shown in figures 11 and 12, respectively.

4. Discussion and conclusion

Our latest setup enabled us to perform high acceleration and high angular rotation of a niobium superconductor, liquid and superfluid helium together with a military-grade fiber-optic gyroscope mounted outside the cryostat and isolated from vibration. No anomalous signals were found up to within three times the noise level of our gyroscope ($\pm 5 \times 10^{-8} \text{ rad s}^{-1}$) which puts new bounds on any coupling or frame-dragging-like effect from superconductors, superfluids or low temperature matter. In addition, our accelerometers (mounted in tangential, radial and vertical directions) did not record any anomalous result within a noise band of $\pm 10 \mu\text{g}$.

Our electric motor measurements at different speeds enabled setting very low standard deviation boundaries for external coupling effects (space-time like dragging of rotating matter) for superconductors and liquid helium to 4×10^{-11} and for superfluids to 3×10^{-10} outside their boundaries. This is orders of magnitude below both previous theoretical

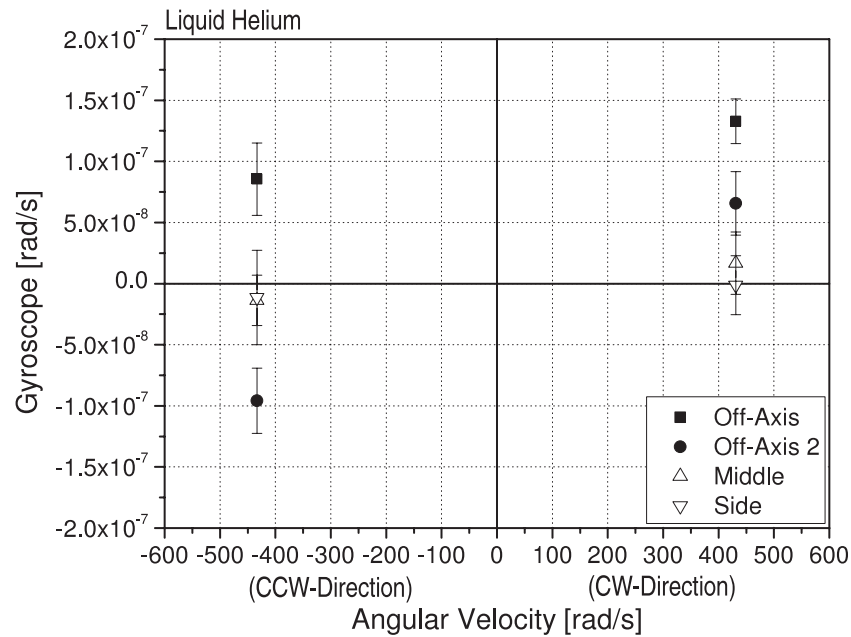


Figure 9. Liquid helium measurements with an air motor: gyroscope output at different positions versus applied angular velocity.

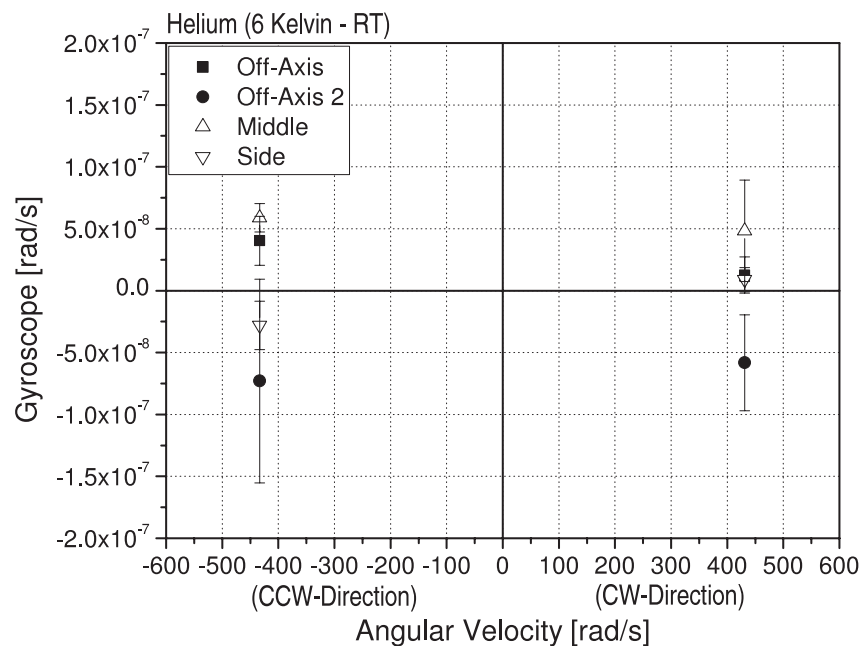


Figure 10. Helium gas measurements with an air motor (reference): gyroscope output at different positions versus applied angular velocity.

predictions and measurements. A short comparison is given as follows:

- We speculated earlier that a frame-dragging-like field could account for a reported Cooper-pair mass anomaly in niobium. A coupling factor of the order of magnitude of 10^{-4} was predicted [6] in this case. In accordance with our previous measurements, such a possibility can be ruled out by some seven orders of magnitude.
- Another prediction was that superfluid helium may produce frame-dragging-like fields with an even higher coupling factor of the order of unity [6]. Although

Moulthrop [20] had already ruled out a coupling factor down to 0.05, we can rule out such a possibility by some 10 orders of magnitude.

- All previous measurements which were performed outside the cryostat (setup C [17] and setup D [18]) recorded anomalous signals up to $1.5 \times 10^{-7} \text{ rad s}^{-1}$ similar to the maximum signals that we have seen in the present tests. However, the tests in this paper were performed at nearly 50 times the speed in our previous setups. Since the anomalous signals did not increase at higher speeds, they are most probably noise and data analysis artifacts.

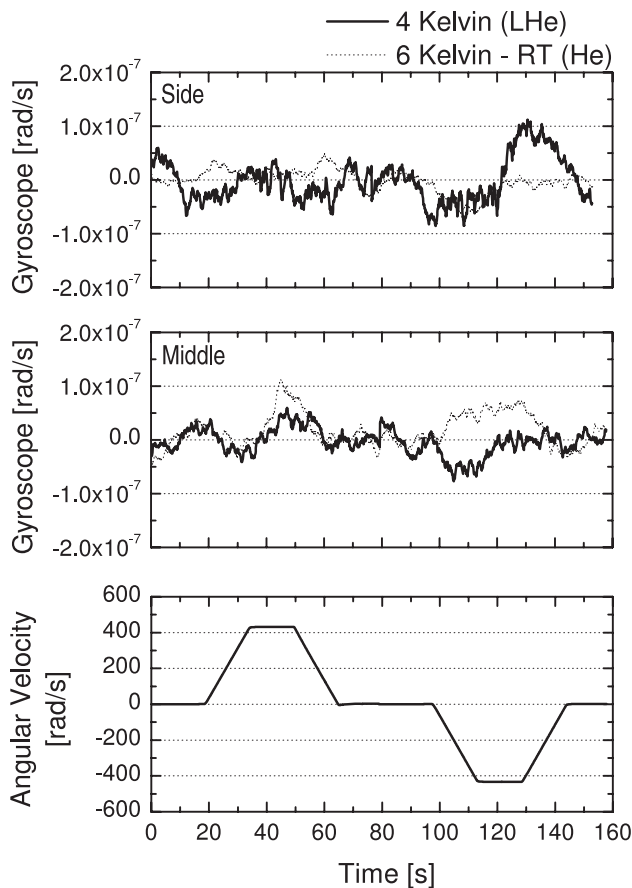


Figure 11. Liquid helium measurements with an air motor: gyroscope output at middle and side position versus applied angular velocity.

Although conclusions can be drawn for all results obtained previously and now outside the cryostat, an explanation for the large anomalous signals with up to $1.4 \times 10^{-5} \text{ rad s}^{-1}$ reported from gyroscopes inside the cryostat (setup A and B in [17]) is still missing. Our results, however, suggest, that the liquid helium expansion during rotation created an acoustic noise environment that may have influenced the gyroscopes. This needs to be confirmed by future measurements.

This leaves the following conclusions:

- Since our earlier speculation about non-classical frame-dragging fields from superconductors and superfluids can be ruled out, the starting point of the reported Cooper-pair mass anomaly in niobium is still not solved. That leaves the possibility for a weak-equivalence-principle (WEP) violation of Cooper-pairs or an unknown experimental error that was not accounted for in the setup from Tate *et al* [2, 3]. Both possibilities should be pursued and first theoretical concepts [24] as well as experimental assessments for WEP violation in superconductors [25] have been reported in the meantime. Tate's experiment should be repeated in order to further investigate the Cooper-pair mass anomaly.
- Attempts to replicate our frame-dragging experiment should concentrate on our earlier setups A and B [17] with the gyroscope embedded around a cold environment in order to either confirm them or identify the source of error.

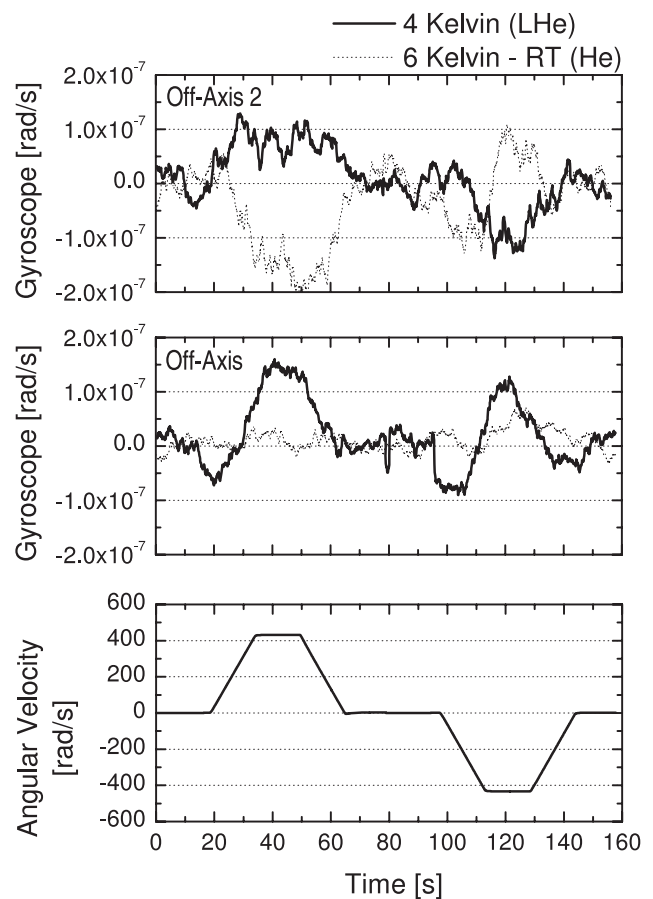


Figure 12. Liquid helium measurements with an air motor: gyroscope output at offset positions versus applied angular velocity.

Recent theoretical work points to the necessity for a cold environment to measure the effect [12].

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