Development of a diamagnetic levitation system for a macroscopic quantum measurement

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Abstract

- In order to observe quantum phenomena in the macroscopic scale low-noise oscillators are needed.
- Diamagnetic levitation can reduce thermal noise from a wire suspension, on the other hand eddy current thermal noise will emerge.
- I have been designing a ring magnet array and a ring graphite. I measured the energy dissipation and am planning to measure the quality factor.

Introduction

- Theorical predict that quantum mechanics holds true regardless of the mass scale.
- Quantum phenomena have not yet been observed in the macroscopic scale.
- One of the hypotheses of the cause is gravitational decoherence[1].
- A success of the observation will provide strong insight into the boundary between classical and quantum mechanics.

What is gravitational decoherence?

Macroscopic objects lose their quantum nature due to their own gravity.

$$\Delta E \cdot \Delta t \gtrsim \hbar$$

The lifetime of quantum nature Δt depends on its gravitational energy.

➢ Observations are needed at various mass scales to test this hypothesis.

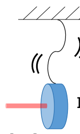
Objectives

- The main goal is the quantum measurement of a macroscopic oscillator using a laser interferometer.

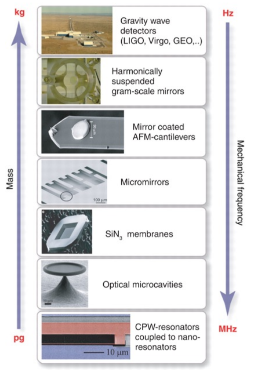
Classical noise must be below the SQL at around a certain frequency.

$$\Delta x_{\mathrm{cl}}(\omega) \leq \sqrt{\frac{2\hbar}{m\omega^2}}$$

However, wire thermal noise is larger than the SQL.



➢ An alternative method to trap the mass is needed.



[Cavity Optomechanics: Back-Action at the Mesoscale, T. J. Kippenberg, K. J. Vahala, 2008]

Method

- I adopt a diamagnetic levitation system to support mirrors.

$$\frac{\chi}{\mu_0}\boldsymbol{B}\nabla\boldsymbol{B} - \rho_m g \boldsymbol{e_z} = 0$$

μ_0 : Vacuum permeability
ρ_m : Density of floaters
χ : magnetic susceptibility

- I levitate a graphite plate and mount a mirror on it.

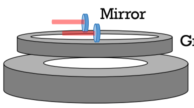
Advantage	**Disadvantage**
Sufficiently low χ	High electrical conductivity
⬇	⬇
Easily levitated using a commercial permanent magnets array	High eddy current thermal noise

Magnetic field gradient will produce eddy current thermal noise[2].

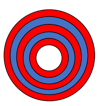
$$\gamma_e = \frac{\left(\frac{\partial B}{\partial r}\right)^2 r_0^2}{8\rho\rho_m}$$

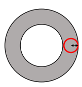
γ_e: Energy dissipation by eddy current
ρ : Electrical conductivity
r_0 : Eddy current radius

- Our proposal to reduce the eddy current thermal noise is to levitate a ring graphite on a ring magnet array.



Magnet and graphite seen from above





Narrow graphite rings can reduce eddy current thermal noise because eddy current radius is thought to depend on the width of a graphite ring.

- I verified some combinations of magnets and graphites could be levitated and measured their energy dissipation.

How to measure the energy dissipation

The circumferential damped oscillation of the graphite ring obeys the equation of motion:

$$I\ddot{\theta} = -\gamma I\dot{\theta} - k\theta$$

I : Moment of inertia
γ : Energy dissipation
k : Elastic constant

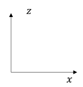
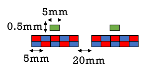
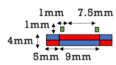
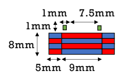
When torque as restoring force is 0,

$$\gamma = -\frac{\ddot{\theta}}{\dot{\theta}}$$

- I recorded the video of the rotation of a graphite ring and calculated.

Result

- The horizontal stability was not fully considered, and the system turned out to be unstable in some cases.
- Even when some combinations of magnets and graphite ring successfully levitated, the graphite ring often touched to the magnets due to the lack of the levitation height.

			
γ [Hz]	0.0403	0.1943	0.1294

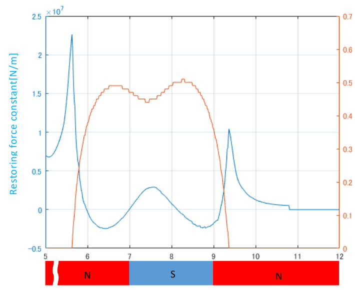
- The energy dissipation turned out to be larger than the target value[3] 2.9×10^{-6} to reach the quantum limit.
- Correlation between eddy current thermal noise and the graphite ring width cannot be confirmed.
- Taller magnets reduced non-uniformity in circumferential direction.

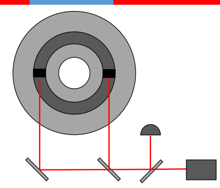
Discussion

- There is a tradeoff between the position of strong levitation force and the position of horizontal stability.
- The successfully levitated graphite was brittle and not uniform, which would have caused the rotation shift and the increase of the dissipation compared with a graphite with a larger width.
- Taller magnets seems to decrease the influence of the non-uniformity in the graphite and reduce eddy current thermal noise.
- Possible causes of the energy dissipation other than the eddy current damping include the air resistance and other external forces.

Progress

- We performed a detailed simulations and are trying to find a better design of the magnetic array.
- I am planning to develop an electrostatic actuator that provides restoring force, assemble an interferometer in a vacuum chamber, and measure quality factor.





References

[1] Roger Penrose. On gravity's role in quantum state reduction. General relativity and gravitation, Vol. 28, No. 5, pp. 581 – 600, 1996.

[2] Ryosuke Nakajima, Development of a magnetic suspension system for mirrors to verify macroscopic quantum mechanics, Master's Thesis, 2020.

[3] Jun Ogawa, Development of a method of supporting mirrors by magnetic levitation for verification of quantum mechanics in macroscopic systems, Master's Thesis, 2021