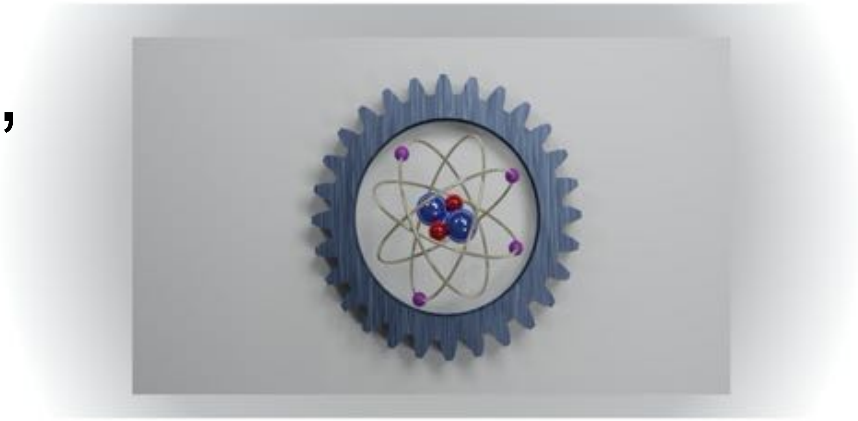
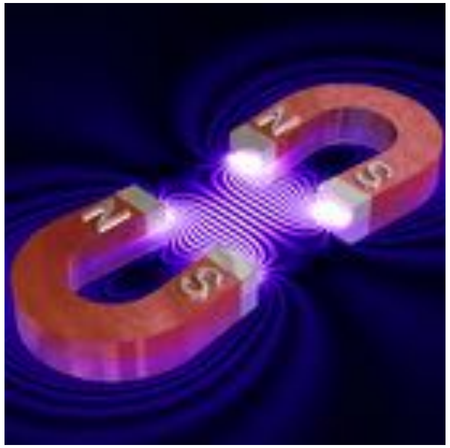
Magnetic levitation - cooling, spinning and overcoming eddy damping



Jason Twamley

OIST

OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY
沖縄科学技術大学院大学



http://www.bugman123.com/Physics/index.html

OIST Where is it?

Okinawa and the Quantum Machines Unit

CORAL REEFS/JUNGLE/BEACHES/FOOD/FOOD/FOOD

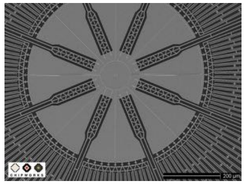
Hybrid Quantum Machines

WILL ALL QUANTUM MACHINES BE HYBRID

All modern technology brings together a enormous range of different sub-technologies and by making them work together one can produce amazing functionality

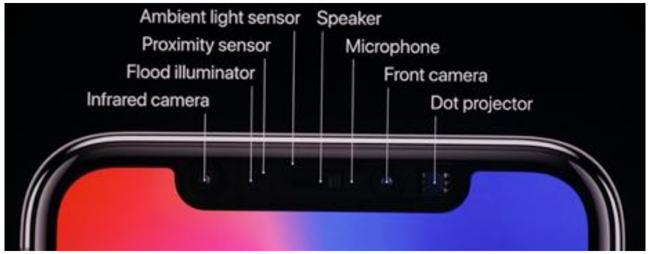
Tomorrow's quantum devices may also bring together different types of sub-systems in order to achieve an overall functionality not possible with a single sub-system alone.

Fingerprint Sensor



MEMS Gyro

Magnetometer



Array of cameras and optical sensors and mics

Four stories

SUMMARY

What’s so interesting about levitated systems?

Control of motional quality factor in magnetic levitation

How to use magnetic forces to generate large superpositions

Can we levitate liquids? Shapes of levitated liquid drops

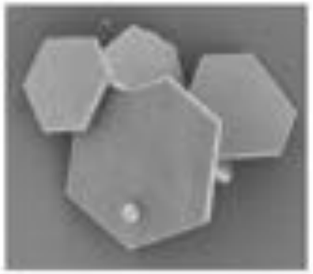
Spinning up levitated magnetic spheres to ultra-fast speeds

What’s so interesting about levitated systems?

WHY IS IT INTERESTING AND USEFUL?

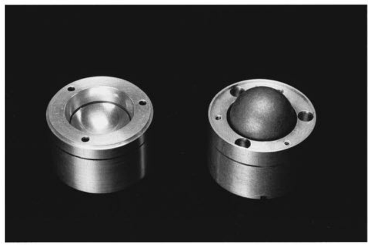
Mechanical systems which are levitated in vacuum can have ultra-low damping and can be useful for:

- **<u>Ultra-precise sensors</u>**: gravimeters, gyroscopes, inertial sensors, sensors for dark matter, magnetometers, gravity waves…
- **<u>Fundamental Science</u>**: generate really interesting mechanical quantum states – squeezed, Schrodinger Cats
- **<u>Gravity&Quantum</u>** : Massive systems – can explore the interaction of gravity with quantum!



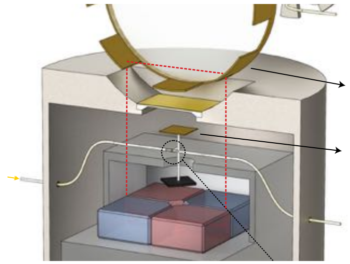
Optical Trapping of High-Aspect-Ratio NaYF Hexagonal Prisms for kHz-MHz Gravitational Wave Detectors

Geraci, et al, Phys. Rev. Lett. (2022)



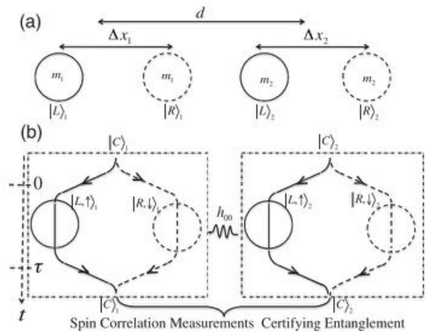
The superconducting gravimeter

J.M. Goodkind: Rev Sci Inst (1999)



Experiments with levitated force sensor challenge theories of dark energy

Du, et al, Nat Phys (2022)



Spin entanglement witness of quantum gravity

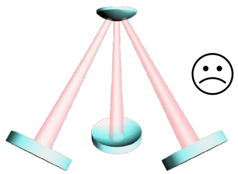
Bose, et al, Phys. Rev. Lett. (2017)

What's so interesting about levitated systems?

WHY IS IT INTERESTING AND USEFUL?

How can we levitate nano-micro sized objects?

Optomechanical Levitation

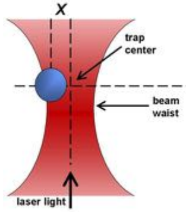


☹

Large laser powers! PRL (2013)

Optomechanical Optical Tweezers

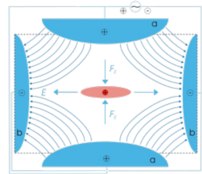
☹



Large laser powers! APL (1976)

Electrodynamic Trap

☹

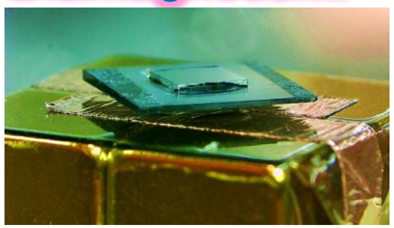


Micromotion, ZNA (1953)

Many forms of trapping/levitation are active – they use active power/controls to trap the object

Magnetic levitation is passive – can levitate a diamagnetic object forever with no power! Possibly ultra-quiet?

Diamagnetism!



$$\boldsymbol{F} \propto -\nabla|\boldsymbol{B} \cdot \boldsymbol{B}|$$

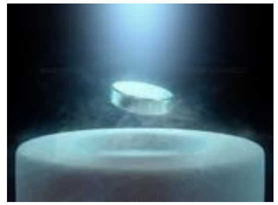
Magnetic Levitation

Diamagnetic Levitation

A flying frog!

Berry & Geim, Eur. J. Phys. (1997)

Meissner Repulsion



OIST

Four stories

SUMMARY

Control of motional quality factor in magnetic levitation

Priscila Romagnoli, OIST
Japan

Ruvi Lecamwasam, OIST
Japan

Shilu Tian, OIST,
Japan

James Downes, MQ,
Australia

JT, OIST

OIST

Appl. Phys. Lett. **122**, 094102 (2023)

Diamagnetic levitation

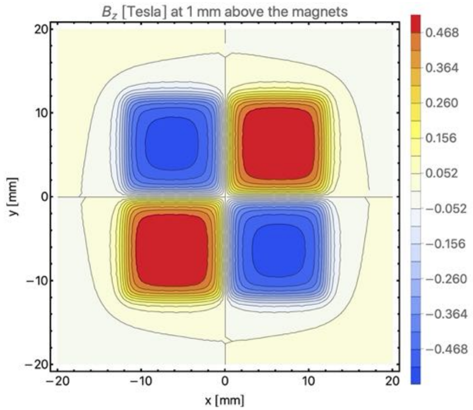
WHAT CAN WE LEVITATE AND HOW DOES IT VIBRATE?

- Highly Oriented Pyrolytic Graphite has largest diamagnetic response at room temp [anisotropic]
- No Cryogenics required
- Can levitate stably over checkerboard magnet array
- Can model vibrational and torsional oscillation frequencies

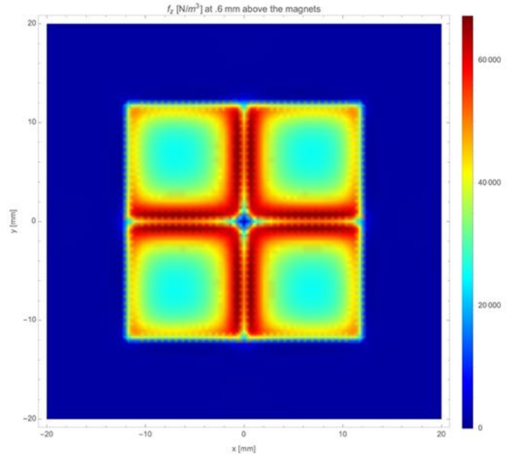
Material	Magnetic Susceptibility χ_v [× 10^{-5} (SI units)]
Superconductor	−105
Pyrolytic carbon	−40.9
Bismuth	−16.6
Mercury	−2.9
Silver	−2.6
Carbon (diamond)	−2.1
Lead	−1.8

Translational Mode	$\omega/2\pi$ [Hz]
ν_x	3.70551
ν_y	3.70552
ν_z	17.1166
ν_{xy}	3.7992
ν_{yx}	3.79916

Tilting Modes	$\omega/2\pi$ [Hz]
$\nu\tau_x$	16.8842
$\nu\tau_y$	16.894
$\nu\tau_{xy}$	16.8056



Bz magnetic field above the magnets



Vertical Force Density above the magnets

$$\mathbf{f} = (\mathbf{M}\cdot\nabla)\mathbf{B} = \frac{1}{2\mu_0}\nabla(\chi_x B_x^2 + \chi_y B_y^2 + \chi_z B_z^2),$$

$$\mathbf{M} = \frac{1}{\mu_0}\boldsymbol{\chi}\cdot\mathbf{B}.$$

$$\mathbf{F} = \int_V \mathbf{f}\,d\mathbf{V}$$

$$\boldsymbol{\tau} = \int_V \mathbf{M}\times\mathbf{B}\,dV + \int_V \mathbf{r}\times\mathbf{f}\,dV,$$

Low freq vibrations

Q-factor??

OIST

X. Chen *et al*, APL 116,(2020)

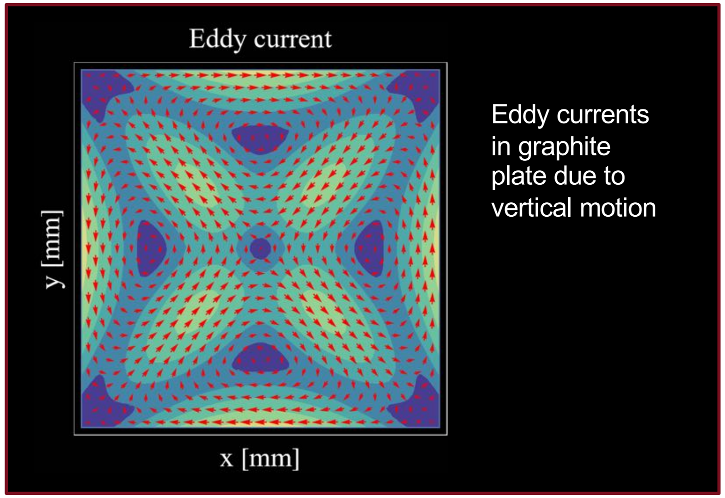
Eddy damping – low Q

EDDY DAMPING IS A DRAG!

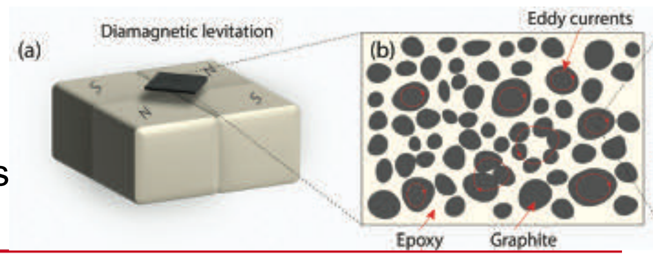
- Many highly diamagnetic materials are electrical conductors. Motion of a conductor in a magnetic field induces **eddy currents and loss** – graphite oscillation even in vacuum has low motional-Quality-factor.

- How to control this **– engineer the eddy currents in the graphite and control the motional Q without loosing too much diamagnetic lift?**

Material	Magnetic Susceptibility χ_v [× 10^{-5} (SI units)]	
Superconductor	−105	
Pyrolytic carbon	−40.9	Electrical Conductors
Bismuth	−16.6	Electrical Conductors
Mercury	−2.9	Electrical Conductors
Silver	−2.6	Electrical Conductors
Carbon (diamond)	−2.1	
Lead	−1.8	Electrical Conductors
Carbon (graphite)	−1.6	Electrical Conductors
Copper	−1.0	Electrical Conductors
Water	−0.91	



- One suggestion: composite- resin with micron sized graphite powder – reduces eddy currents but also reduces lift – does give high-Q !



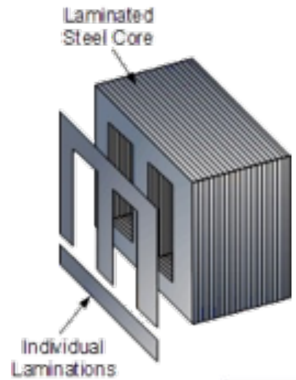
X. Chen *et al*, Adv Sci (2022)

OIST

Eddy damping – low Q

HOW TO ENGINEER THE EDDY DAMPING!

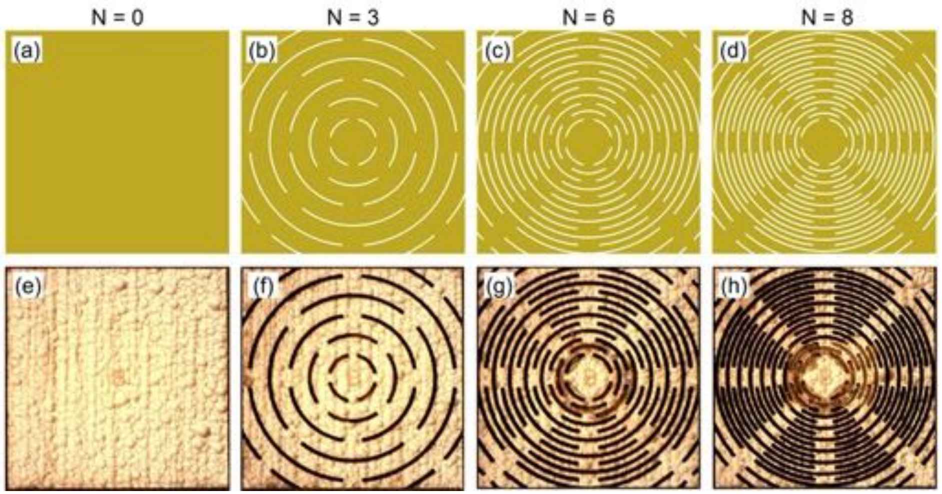
- Instead we follow route similar to how eddy currents are reduced in electrical transformers – physically interrupting the eddy currents.
- Interrupt the eddy currents by physically making tiny slots in the graphite slab



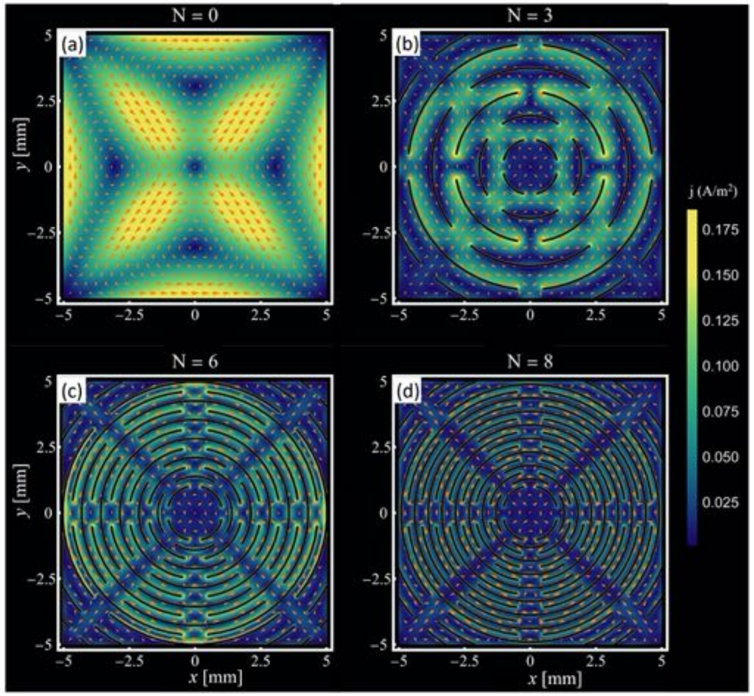
Laser Machining at OptoFab MQ Node

Design

Photo of machined graphite slab 10mm square



Eddy currents in slotted slabs greatly reduced

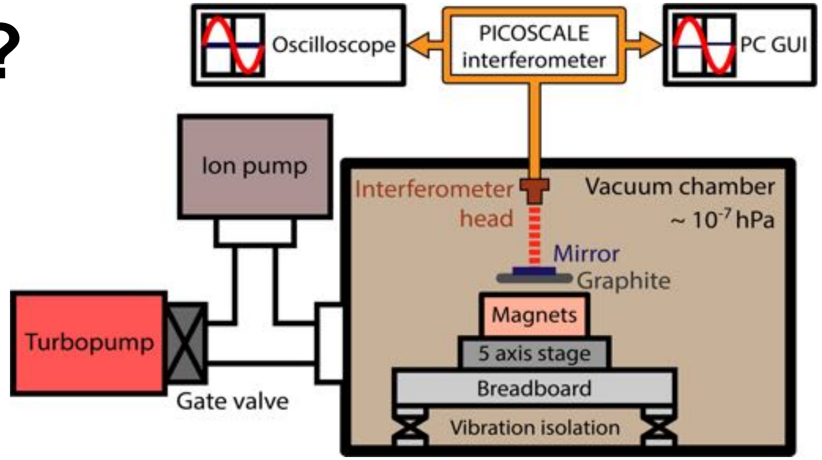


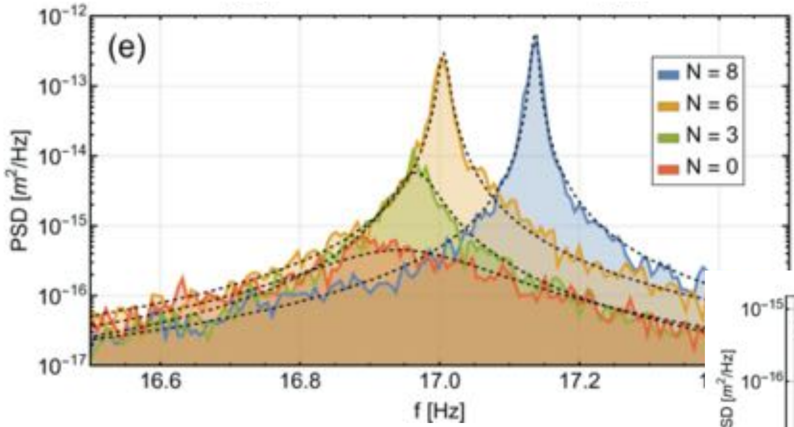
Eddy current simulations [Comsol/Mathematica]

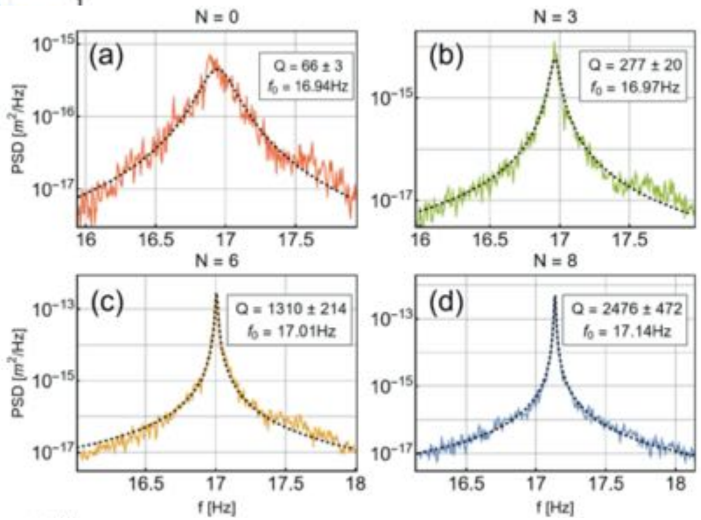
Measure Q of the levitated plate?

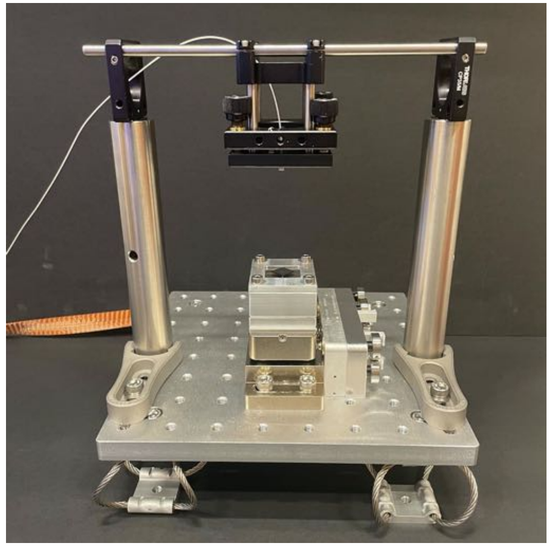
HOW TO CONFIRM THE IMPROVED DAMPING?

- Measure motion of plate (small mirror attached), using laser displacement interferometer – high vacuum – no pump vibrations using ion pump.









$$S(f) = \frac{8k_B T\gamma/m}{\left((2\pi f_0)^2 - (2\pi f)^2\right)^2 + (2\pi f\gamma/m)^2}$$

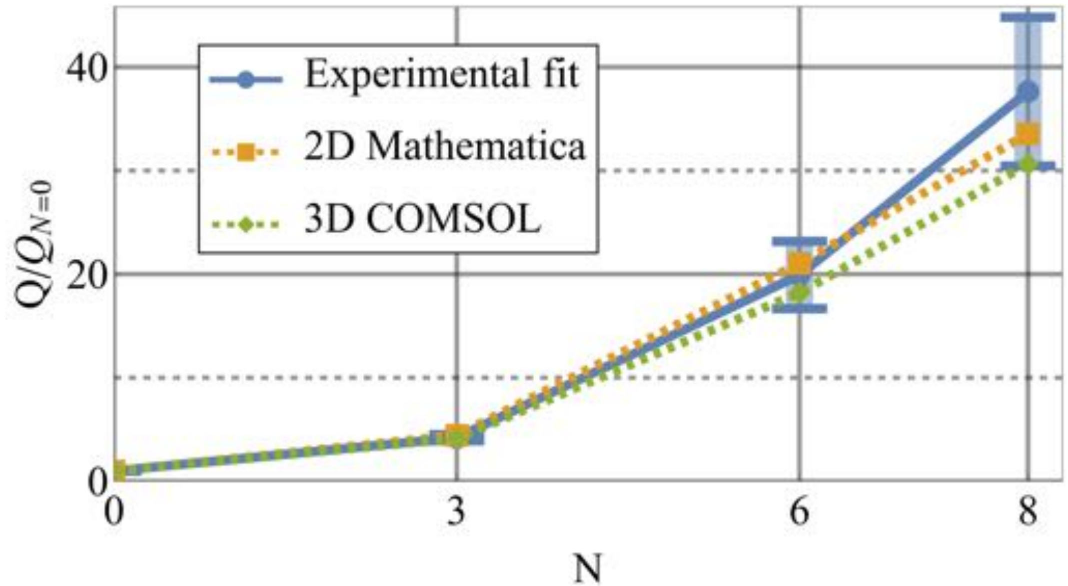
Q-factor increases

OIST

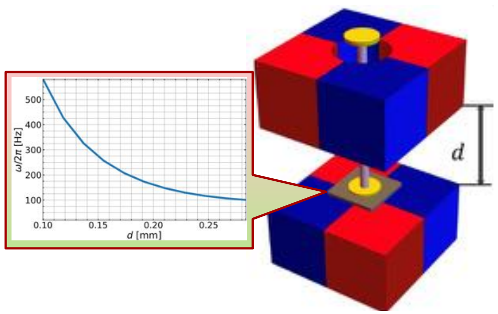
Measure Q of the levitated plate?

HOW TO CONFIRM THE IMPROVED DAMPING?

- Compare the Q-factor of the slotted plates with the solid plate with simulations done in Mathematica and COMSOL – very good agreement!
- Motional damping primarily due to eddy!
- Next – can we try some other diamagnetic materials to increase Q-factor and try feedback cooling?



Poster: Tatania Iakovleva



Use magnetically levitated cavity optomechanics to measure displacement to a resolution of

$$\Delta d \sim 10^{-21}\ \mathrm{m}$$


T. Iakovleva


B. Sarma

Appl. Phys. Lett. **122**, 094102 (2023)

arxiv.org/2302.06795

Four stories

SUMMARY

Sarath-Raman Nair, Australia

Shilu Tian, OIST, Japan

Gavin Brennen, Australia

Sougato Bose, UK

JT, OIST

How to engineer massive Schrodinger Katz?

https://arxiv.org/abs/2307.14553

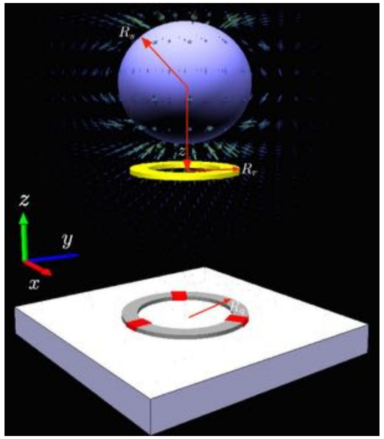
Schrodinger Cats with massive objects

MOTIVATION

- Long time interest – what is the boundary between quantum and classical worlds
- Generation of macroscopic quantum states of massive objects in two spatial positions
- Can be useful for ultra-sensitive sensors
- Can also be useful to probe the links between the quantum world and gravity!

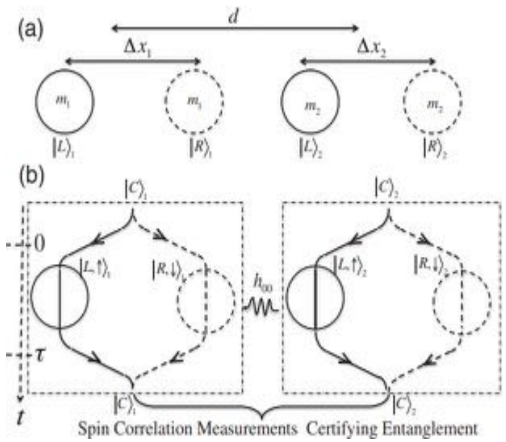
WITH MACROSCOPIC SUPERPOSITIONS OF MASSIVE OBJECTS

- Absolute gravimetry



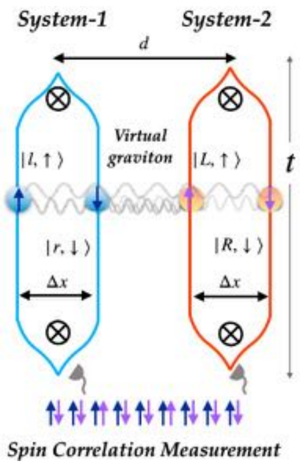
M. Johnsson et al., Sci. Rep. 6, 37495 (2016)

- Link between Quantum & gravity



S. Bose et al., Phys. Rev. Lett. 119, 2402401 (2017)

- Test quantum equivalence principle



S. Bose et al., arXiv:2203.11628 (2022)

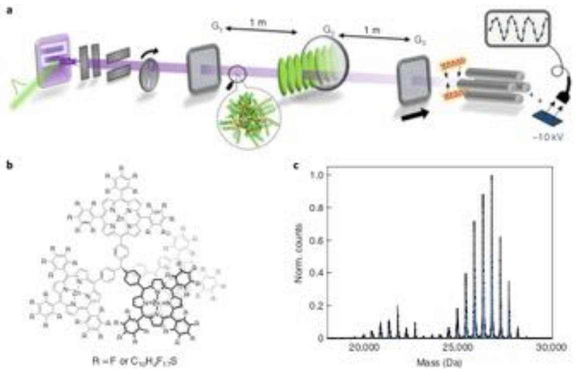
Quantum superpositions – what has been achieved?

REALIZED SUPERPOSITION

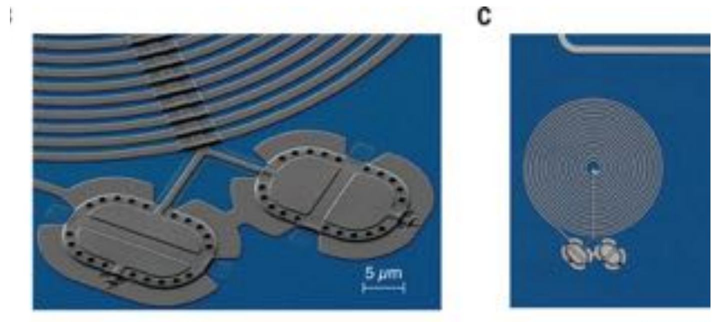
- Schrodinger’s cat

https://en.wikipedia.org/wiki/Schr%C3%B6dinger%27s_cat#/

- Superposition realization using matter-wave interferometer in electrons, neutrons, ions, molecules…



Superposition of particles with masses exceeding 25,000 Da



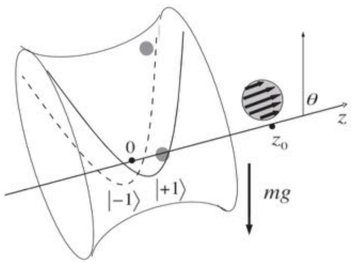
Entanglement of electromechanical drum modes, mass~70 pg

M. Arndt & K. Hornberger, *Nature Physics*, *10*(4), 271 (2014)
M. Zawisky et al, Nucl. Instrum. Methods Phys. Res. 481(1-3), 406 (2002)
C. Monroe et al., Science 272, 1131 (1996)
M. Arndt et al., Nature 401, 480 (1999)
S. Eibenberger et al., Phys. Chem. Chem. Phys 15, 14696 (2013)
Y. Y. Fein et al. Nat. Phys. 15, 1242 (2019)
T. Kovachy et al. Nature 528, 530 (2015)
S. Kotler et al, Science 372, 622 (2021)

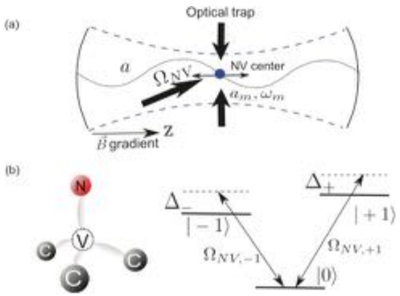
Macroscopic superposition

SOME PROPOSALS TO GENERATE MASSIVE SUPERPOSITIONS

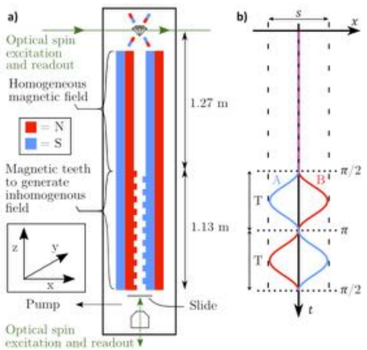
- Using NV-center diamond



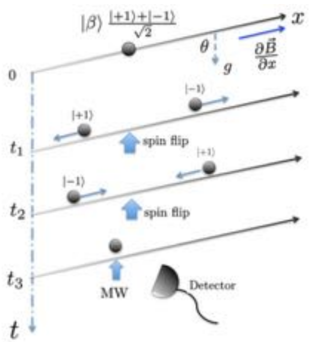
M. Scala et al., Phys. Rev. Lett. 111, 180403 (2013)



Z. Yin et al., Phys. Rev. A 88, 033614 (2013)

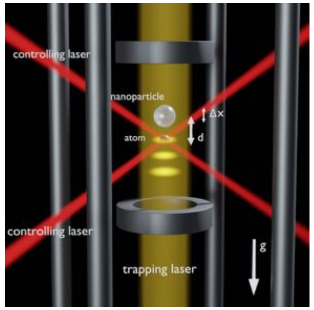


B. D. Wood et al., Phys. Rev. A 105, 012824 (2022)
S. Bose & G. W. Morley, arXiv:1810.07045 (2018)



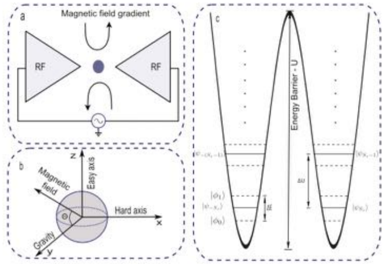
C. Wan et al., Phys. Rev. Lett. 117, 143003 (2016)
R. J. Marshman et al., arXiv:2105.01094 (2021)

- Atom-particle coupling



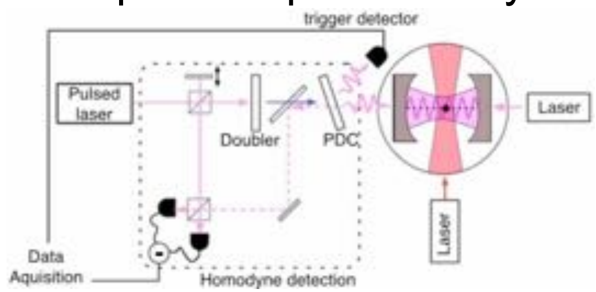
M. Toroš et al., Phys. Rev. Research 3, 033218 (2021)

- Ion trap and magnetic field



A T M A. Rahman, New J. Phys. 21, 113011 (2019)

- Optical trap and cavity

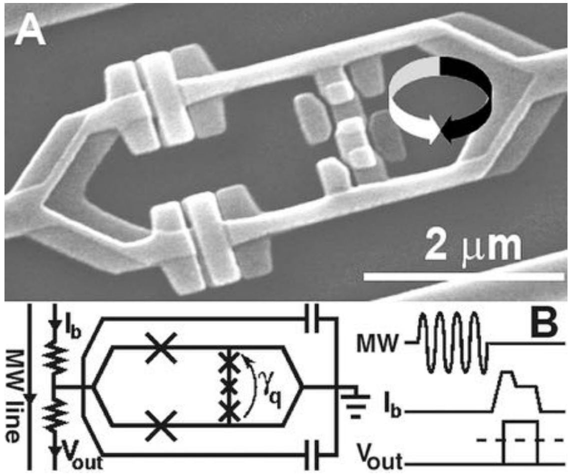


O. Romero-Isart et al., New J. Phys. 12, 033015 (2010)

Macroscopic superposition

OUR PLANS

- Using Quantum flux qubit



Large circulating current in quantum superpositions make quantum magnetic fields in superposition

We propose two schemes:

1. Superposition of Levitated Magnet

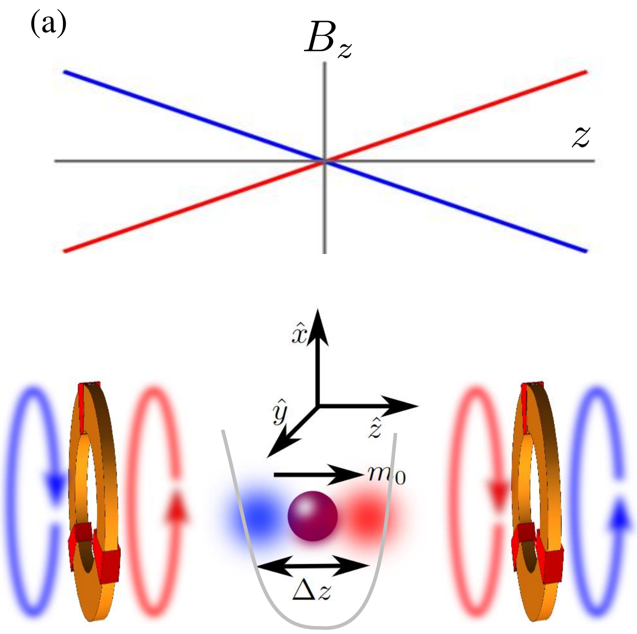
2. Superposition of Levitated Superconducting Flux Qubit

I. Chiorescu et al., Science, 299(5614), 1869 (2003)
J. R. Friedman et al., Nature, 406(6791), 43 (2000)

1. Superposition of Levitated Magnet

TRAPPED YIG SPHERE DISPLACED BY MAGNETIC FIELDS

- Consider Yttrium Iron Garnett (YIG), sphere trapped in 3D in a harmonic trap – can be MAGNETIC or OPTICAL trap
- YIG is a magnetic insulator – small remnant magnetization
- Position two ring flux qubits with oppositely circulating currents
- Magnetic field generated by Flux qubits form an anti-Helmholtz
  B field is zero midway and is linear
- Magnetic Interaction between YIG and B field causes the YIG to shift it's equilibrium to right by small distance
- Switch circulation of currents in Qubits and YIG shifts to the left
- Currents in Qubits can be in a superposition and thus YIG will be shifted into a superposition of two positions.



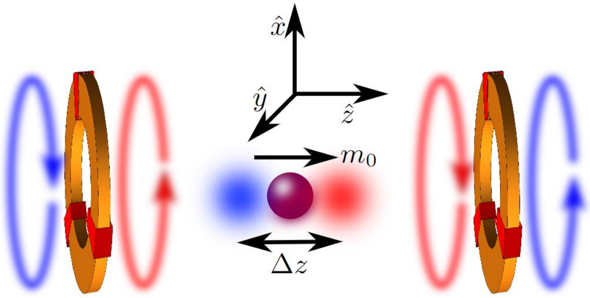
Superposition of Levitated Magnet

$$\chi \equiv \Delta z / z_{\mathrm{zpm}}$$

$$z_{\mathrm{zpm}} = \sqrt{\hbar/(2m\omega_z)}$$

HOW LARGE A SPATIAL SUPERPOSITION CAN WE GENERATE?

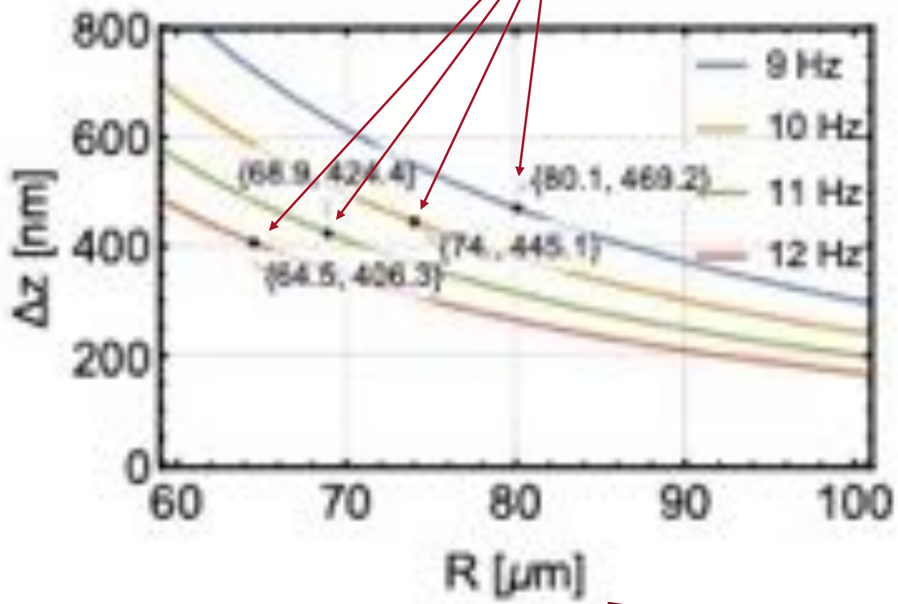
The spatial size of the superposition is INDEPENDENT of the size of the YIG sphere!



Siz
superp

Configs where $\chi \sim 10^6$

Motional Trap Freq



Radius of Flux Qubits

Can evaluate the displacement in terms of the zero point motional width δ. Can reach

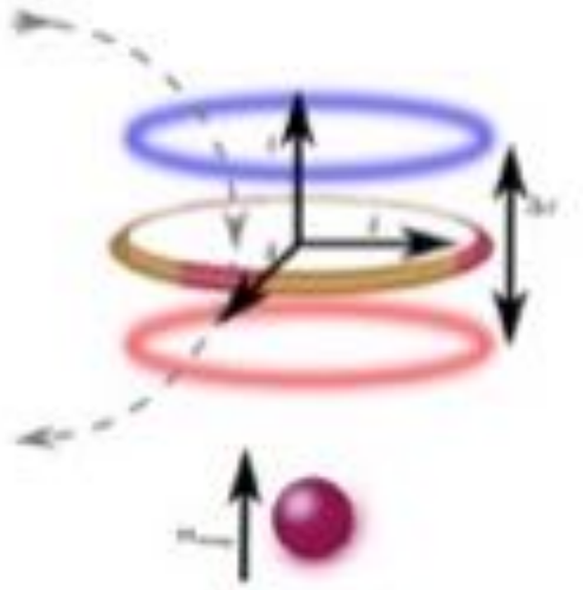
$$\Delta z / z_{\mathrm{zpm}} \sim 10^6$$

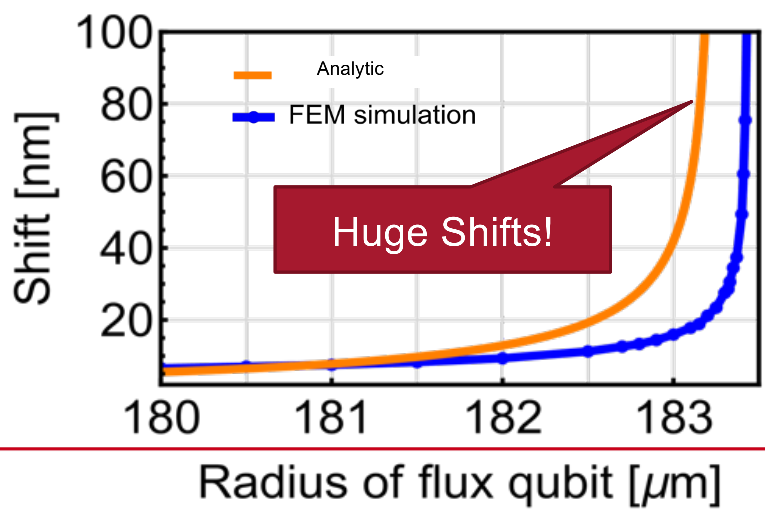
OIST

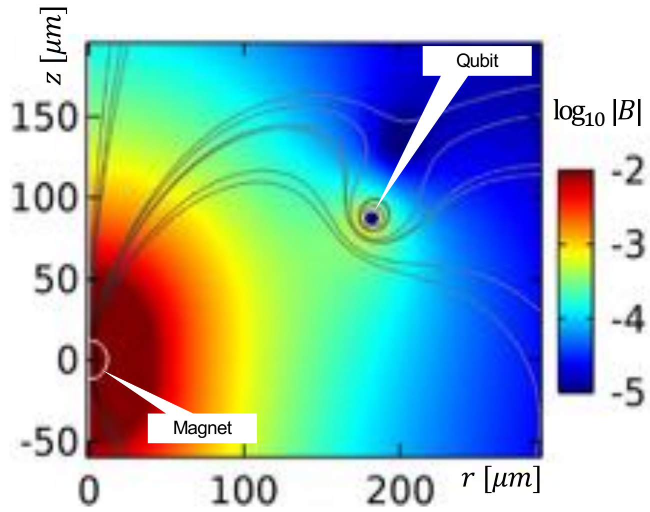
Floating an entire Flux Qubit

MASSIVE SUPERPOSITIONS

- Use single magnet to levitate AN ENTIRE SUPERCONDUCTING FLUX QUBI – Meissner levitation of the superconducting ring
- FQ can be driven inductively – no contact needed –Take care of backaction onto magnetic field
- Depending on currents flowing in FQ massive shifts in equilibrium height.
- Levitated ring is also stable in horizontal direction and to tilts
- Both setups could have very high motional Q factors!







$$\Delta z / z_{\mathrm{zpm}} \sim 10^6$$

https://arxiv.org/abs/2307.14553

Four stories

SUMMARY

Isha Sanskriti,
OIST

Daehee Kim,
OIST

JT, OIST

Levitation of Liquids and what shape do they take?

On arxiv soon – help!

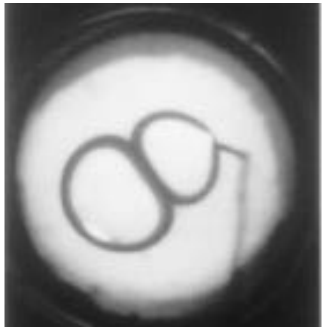
Why levitate liquids

MOTIVATION

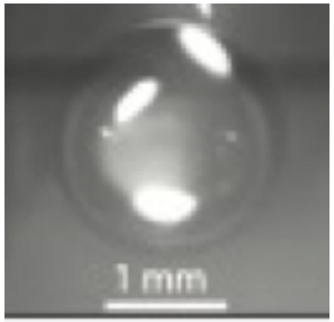
- Super fun – interesting!
- Can simulate micro-gravity within the liquid – study novel fluid dynamics and surface tension
- Can be used as a sensor eg. density, magnetic susceptibility of fluids
- Can be used in hybrid devices eg. photonics, liquid optical resonators and lasers

LEVITATION OF LIQUIDS

- Liquid Helium

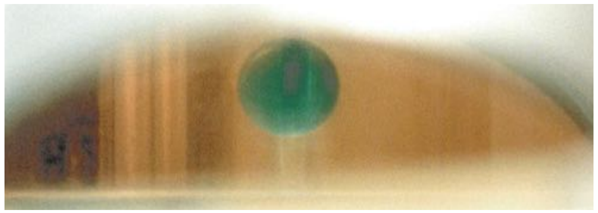


Using superconducting Solenoid – Weilert, Whitaker, Maris, Seidel, PRL (1996)



Using superconducting Solenoid, evaporation and WGM – Brown, Wang, Namazi, Harris, Uysal, Harris, PRL (2023)

- Aqueous



Levitated ball of CuSO4 solution in a 10 Tesla superconducting magnet

Using superconducting Solenoid, Making water levitate – Ikezoe, Hirota, Nakagawa, Kitazawa, Nature (1998)

Seems to require very strong magnetic fields and gradients!

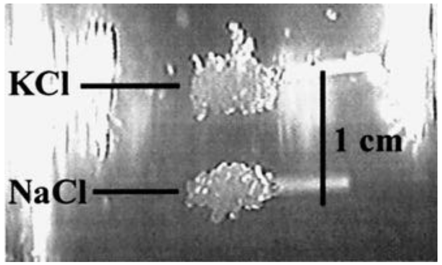
$$|B\,(\mathrm{d}B/\mathrm{d}z)| > 500\,\mathrm{T}^2/\mathrm{m}$$

Can we find a way to magnetically levitate with lower magnetic fields?

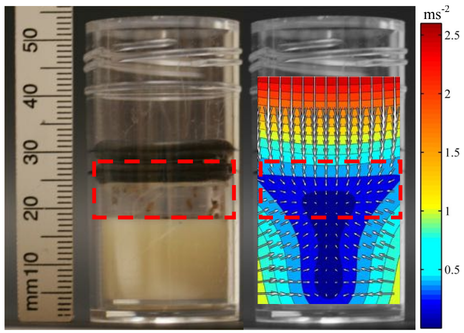
Why levitate solids and liquids

MAGLEV APPLICATION IN CHEMISTRY, BIOLOGY AND MAT SCI

- Magneto-Archimedes Levitation of solids and liquids
- Float diamagnetic objects in a paramagnetic liquid
  Increased lift due to larger magnetic susceptibility contrast and buoyancy
- Can be used as a very sensitive measurement of density and magnetic susceptibility of small quantities of particles

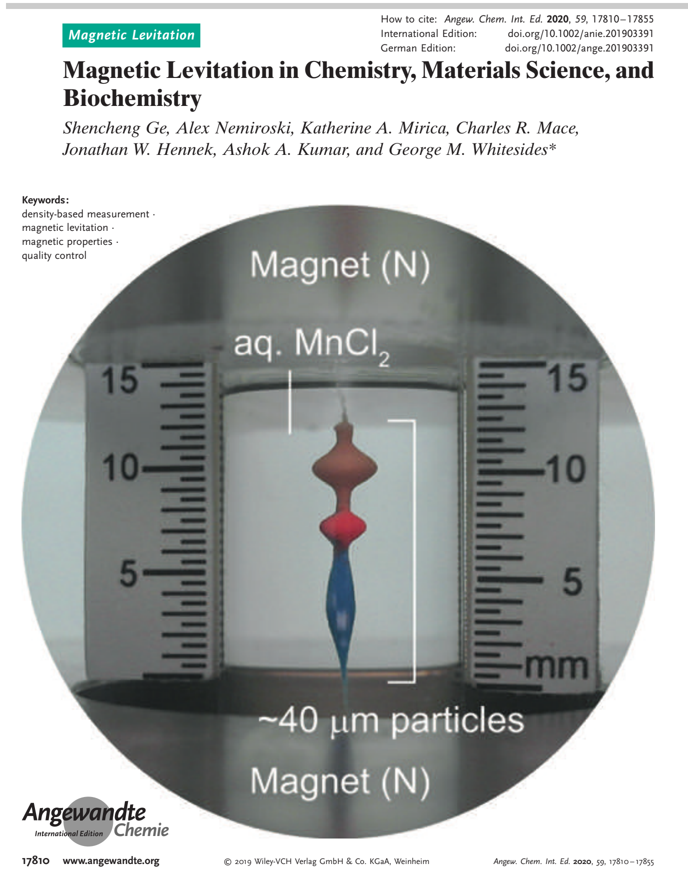


Levitation separation of chemicals
RIKEN, Japan (2002)



Simulate microgravity environments on earth. E.g. genetic transcription of fruit flies effected by microgravity

BMC Genomics, 2012 (CSIC, Spain)



How to cite: Angew. Chem. Int. Ed. 2020, 59, 17810–17855
International Edition: doi.org/10.1002/anie.201903391
German Edition: doi.org/10.1002/ange.201903391

Magnetic Levitation

Magnetic Levitation in Chemistry, Materials Science, and Biochemistry

*Shencheng Ge, Alex Nemiroski, Katherine A. Mirica, Charles R. Mace, Jonathan W. Hennek, Ashok A. Kumar, and George M. Whitesides**

Keywords:
density-based measurement ·
magnetic levitation ·
magnetic properties ·
quality control

Angewandte Chemie International Edition
17810 www.angewandte.org

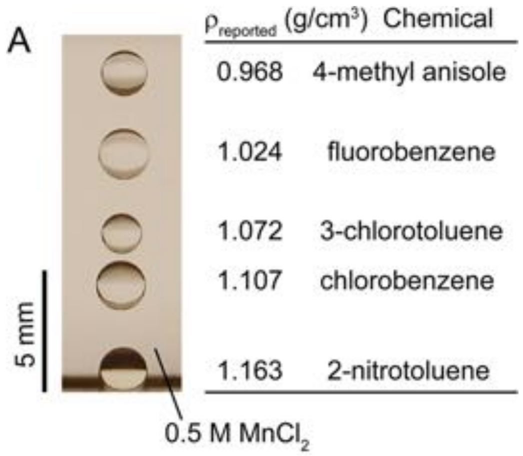
Angew. Chem. Int. Ed. 2020, 59, 17810–17855

Mostly used for solids (particles) but some examples of liquid levitations

Magneto-Archimedes MagLev of liquids

EXAMPLES OF MAGLEV OF LIQUIDS

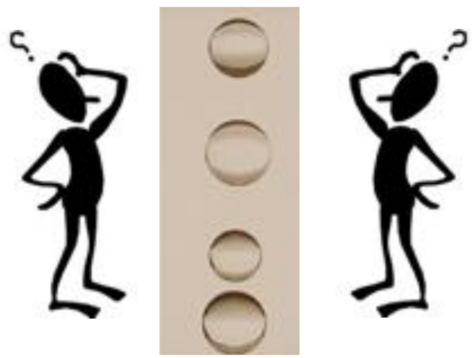
- Magneto-Archimedes Levitation of liquids
- Uses strong permanent magnets
- Uses diamagnetic organic liquids which do not mix in aqueous solvents
- Uses paramagnetic salt aqueous solutions to increase contrast



"Axial" Magnetic Levitation Using Ring Magnets Enables Simple Density-Based Analysis, Separation, and Manipulation
Anal. Chem. 2018, 90, 12239−12245

LET US STUDY THE STATIC SHAPE DEFORMATION OF MAGNETICALLY TRAPPED DROPLETS

- The magnetic force changes the stationary height of these diamagnetic particles/droplets
- Droplets can deform in shape –
  How do they deform in response to the magnetic forces?
- Deformation SMALL or LARGE?
- Can we use this deformation for something useful ? **MAGNETOMETRY!**



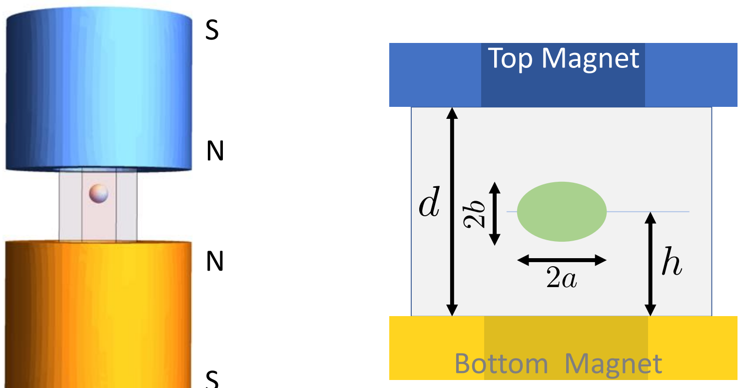
Spherical?

How to magnetically trap and squish!

EXPERIMENT

❖ Consider ”Axial” design for Magneto-Archimedes levitation – opposing strong magnetic fields from strong ring magnets

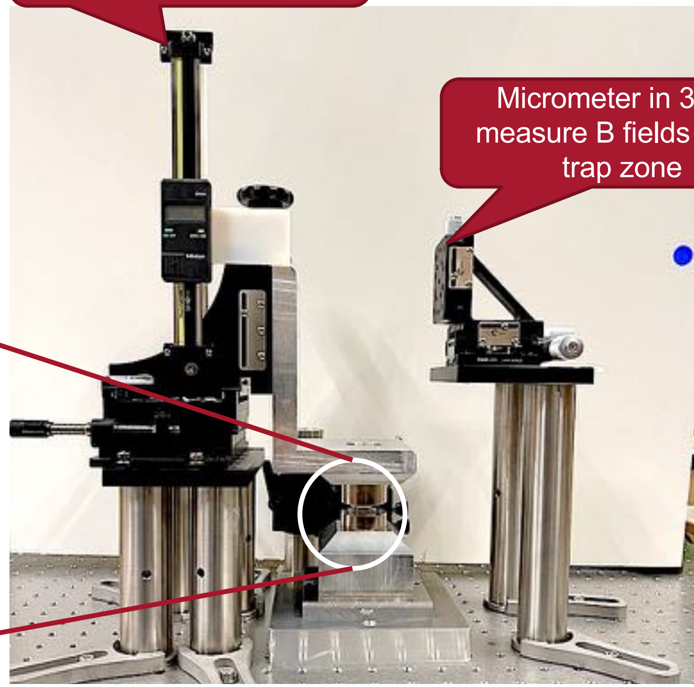
❖ Droplet of diamagnetic organic immiscible SAMPLE fluid trapped at a certain height in a cuvette of paramagnetic MEDIUM fluid



$$e = \sqrt{1 - (b/a)^2}$$

Micrometer to measure magnet separation

Micrometer in 3D to measure B fields in the trap zone



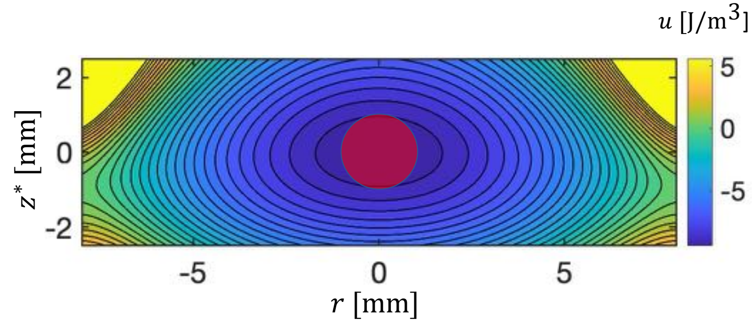
OIST

How to magnetically trap and squish!

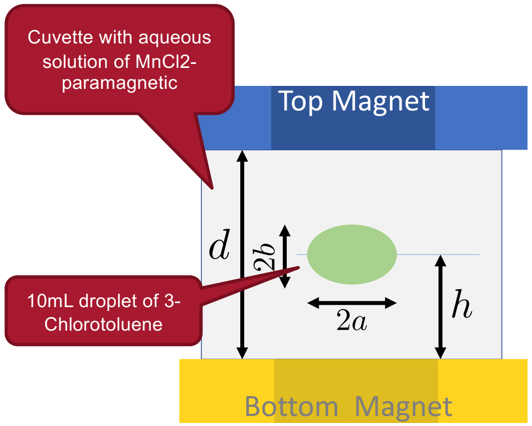
$$u(\vec{r}) = (\rho_s - \rho_m) g z - \frac{1}{2\mu_0}(\chi_s - \chi_m)|\vec{B}(\vec{r})|^2 ,$$

EXPERIMENT

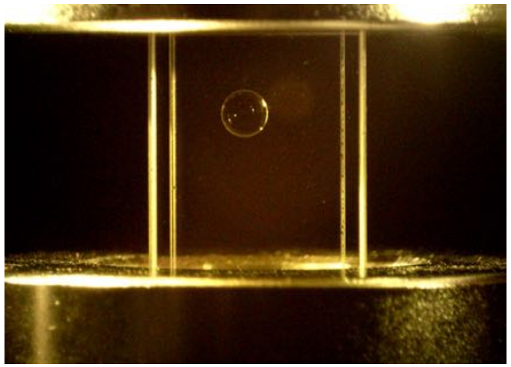
- Consider "Axial" design for Magneto-Archimedes levitation – opposing strong magnetic fields from strong ring magnets
- Droplet of diamagnetic organic immiscible SAMPLE fluid trapped at a certain height in a cuvette of paramagnetic MEDIUM fluid
- **How does the static shape of the droplet change as we bring the magnets closer together?**



Potential Energy of the trap – Red Ball is the droplet – for intermagnet separation of 7 mm

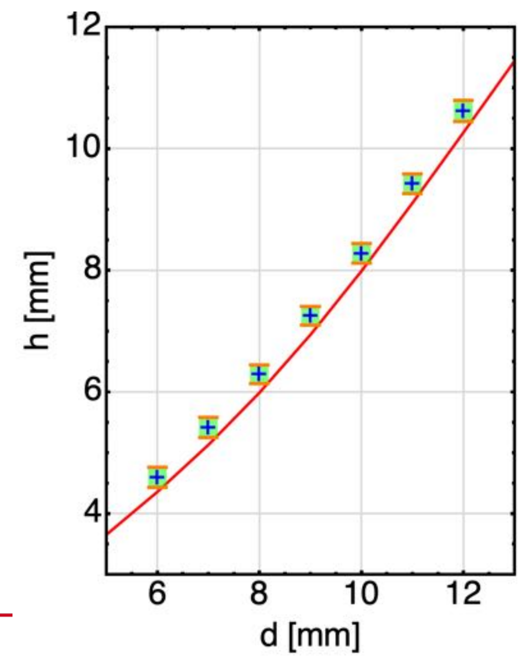


$$e = \sqrt{1 - (b/a)^2}$$



Measure droplet height as we vary the magnet separation and compare with theory –

NO FITTED PARAMETERS!



OIST

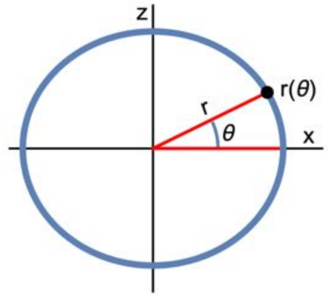
How to magnetically trap and squish!

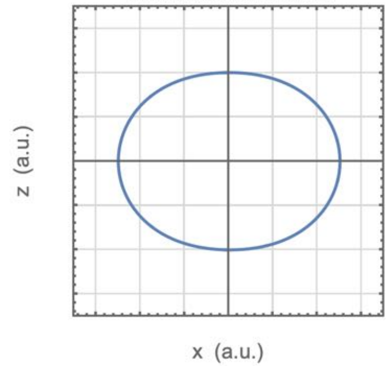
$$u(\vec{r}) = (\rho_s - \rho_m) g z - \frac{1}{2\mu_0}(\chi_s - \chi_m)|\vec{B}(\vec{r})|^2 \ ,$$

SHAPE OF THE DROPLET

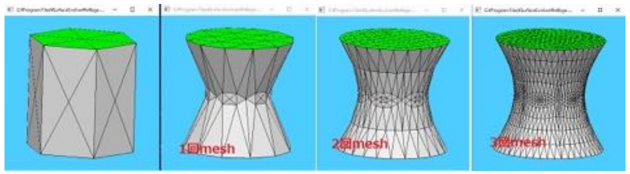
- Take photomicrograph - image analysis – polar coordinates - fit Fourier series – extract largest and smallest radii and get eccentricity

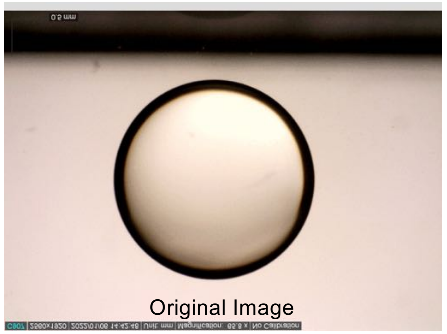
$$e = \sqrt{1 - (b/a)^2}$$



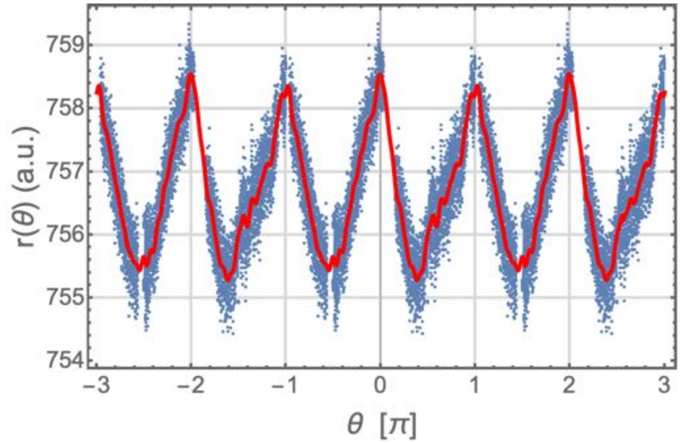


- Numerically predict eccentricity by using finite element method to relax to the minimal surface shape in the presence of force density and surface tension = **Surface Evolver**





$$de = \left(\frac{b^2}{a^3}\right)\frac{\delta a}{e} + \left(\frac{b}{a^2}\right)\frac{\delta b}{e}$$



$$e = 0.093 \pm 0.018$$

$$d = 9\,\mathrm{mm}$$

Application as a Gradiometer?

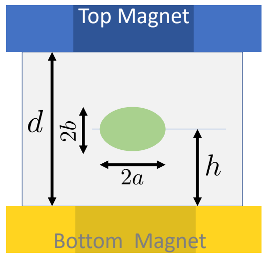
$$u(\vec{r}) = (\rho_s - \rho_m) g z - \frac{1}{2\mu_0}(\chi_s - \chi_m)|\vec{B}(\vec{r})|^2 \ ,$$

COMPARE AND APPLICATION AS A MAGNETIC GRADIOMETER

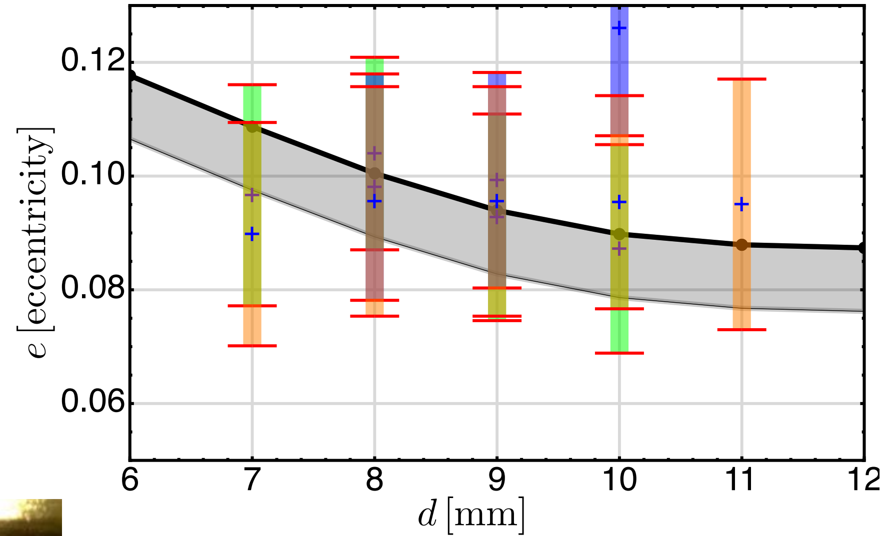
- Experiments and theory ok match
- Measuring shape of the droplet needs to improve

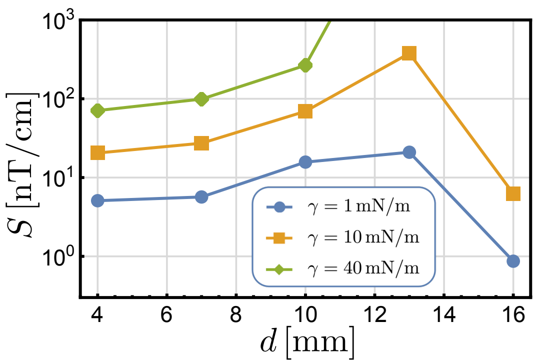
- Can use the eccentricity of the droplet as a gauge of the local magnetic fields and gradients – can find for low surface tensions – 1 mN/m – may be able to sense magnetic field gradients as small as

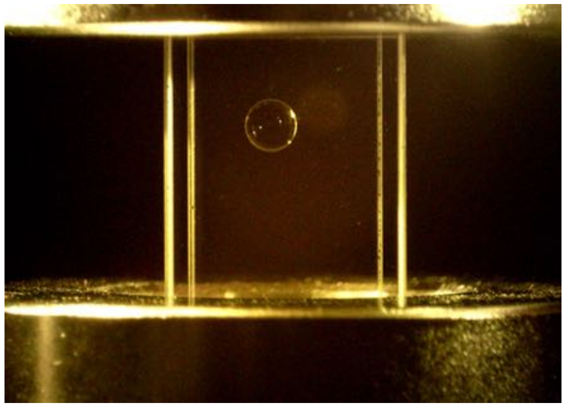
$$\mathcal{S} \sim 1\,\mathrm{nT/cm}$$



$e = \sqrt{1-(b/a)^2}$







On arxiv – help!

Four stories

SUMMARY

Kani Mohamed,
OIST Japan

Fernando
Quijandria,
OIST Japan

JT, OIST

Spinning up levitated magnetic spheres to ultra-fast speeds

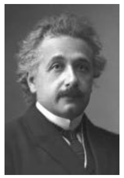
OIST

Phys. Rev. Lett. 129, 257201 (2022)

Who has tried spinning up things? How fast?

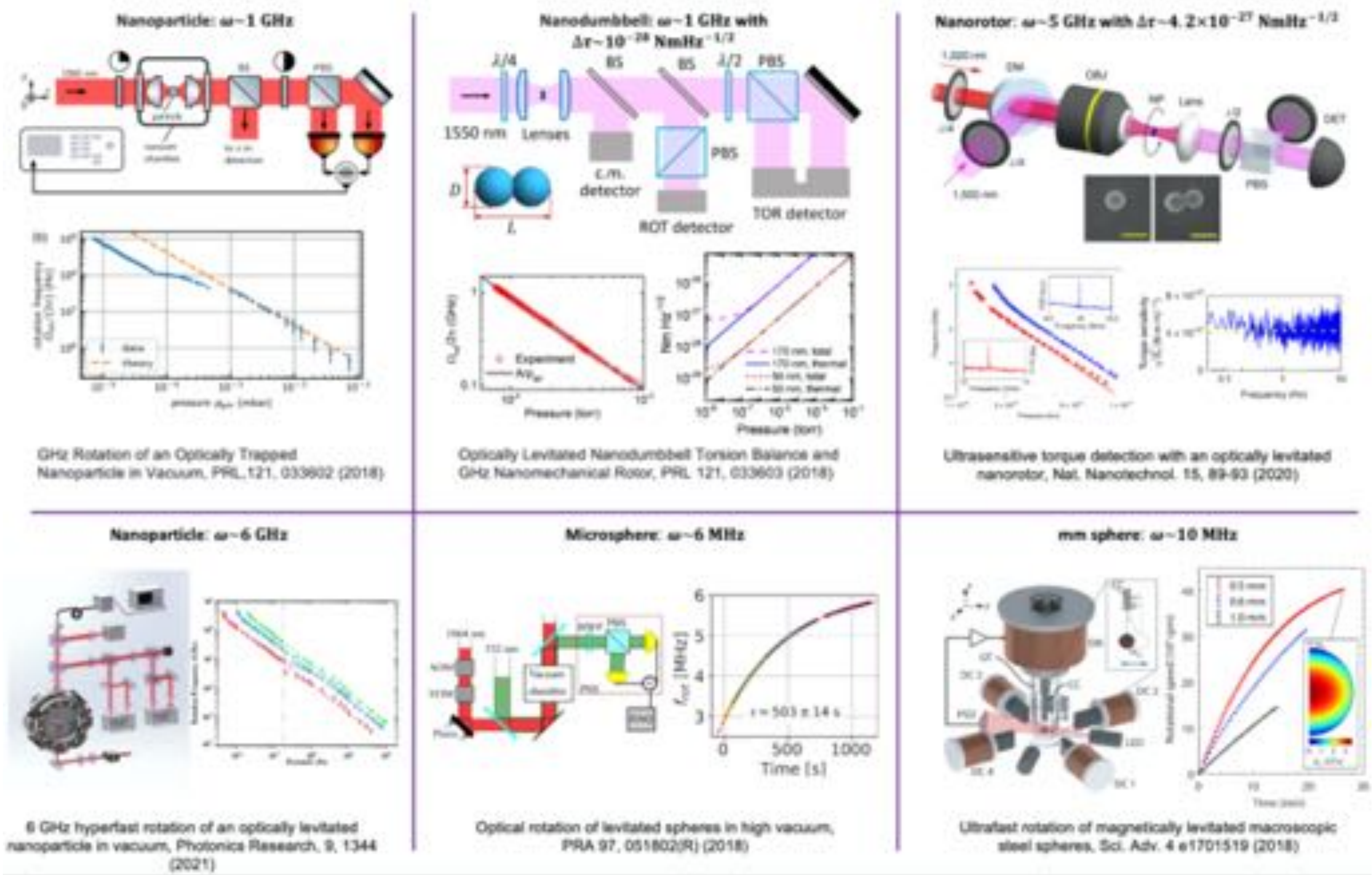
A LOT OF INTEREST IN SPINNING UP OBJECTS…

- Can we use magnetization to rotate an object?
- Yes!
- The Einstein-de Haas effect



Albert Einstein

Wander Johannes de Haas



What is the EdH effect?

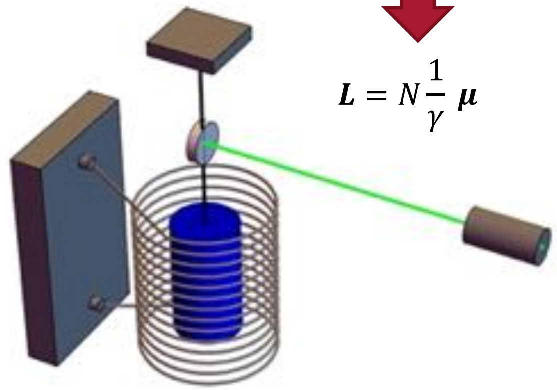
MAGNETIZATION CAUSES MECHANICAL ROTATION

- Total Angular Momentum is conserved
- Spins possess angular momentum and in a demagnetized magnetic material they all point in random directions so net AM is zero
- If you apply an external B field to align (magnetize) the spins the net spin AM is non-vanishing and for total AM to be conserved the object acquires mechanical/orbital AM.
- Very challenging to demonstrate experimentally (alignment).
- Spins in a solid are NOT isolated – coupled together – collective dynamics called **SPIN WAVES…**
- Quantized spin waves are called **Magnons.**

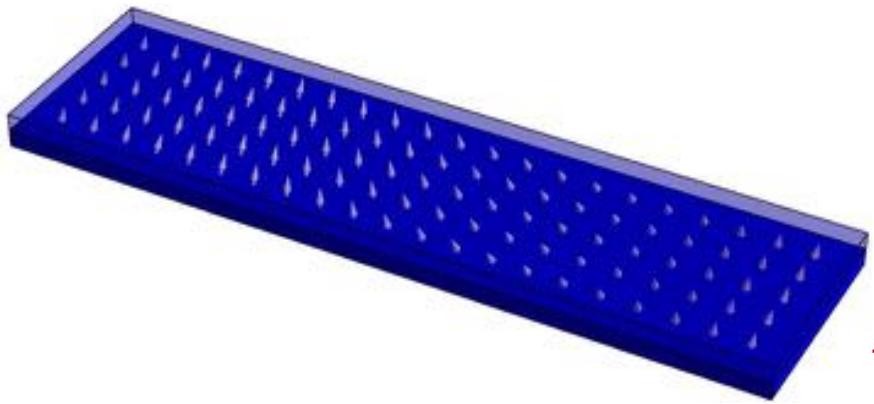
$$\boldsymbol{S} = -\frac{1}{\gamma}\,\boldsymbol{\mu}$$

$$\boldsymbol{S} = 0 \;\rightarrow \boldsymbol{S} = -N\frac{1}{\gamma}\,\boldsymbol{\mu}$$

$$\boldsymbol{L} = N\frac{1}{\gamma}\,\boldsymbol{\mu}$$



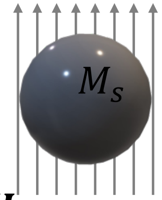
Mechanical rotation by magnetization



Magnons in a spherical insulating magnetic crystal

COLLECTIVE WAVES IN A CRYSTAL HAVE MODES

- Magnetization dynamics obeys the Landau-Liftshitz Eqn: $\frac{d\,\boldsymbol{M}(\boldsymbol{r},t)}{dt} = -\gamma\mu_0\,\boldsymbol{M}(\boldsymbol{r},t)\times\boldsymbol{H}(\boldsymbol{M},\boldsymbol{r},t)$



- $\boldsymbol{H}$ includes the field generated by the collective moments so LL Eqn is nonlinear.

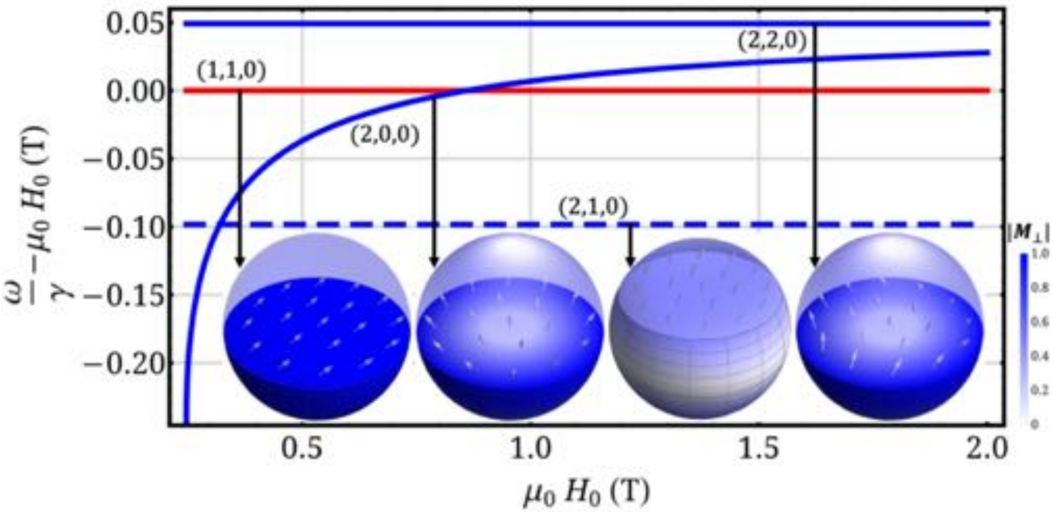
- Typically spin waves are assumed as a small deviation from the macroscopic magnetization $\boldsymbol{M} = M_s\boldsymbol{e}_z + \boldsymbol{m}(\boldsymbol{r},t)$

- Magnon modes in a sphere have different resonance frequencies and spatial textures

$$\widehat{\boldsymbol{m}}_{n,m,0} = M_0\frac{\rho^{m-1}z^{n-m}}{R^{n-1}}\left(\boldsymbol{e}_x + i\boldsymbol{e}_y\right)e^{-i(1-m)\varphi}\hat{\boldsymbol{s}} + H.c.$$

For $m = n$ and $m = n$-1

- These modes are OAM eigenmodes with l=1−m



Phys. Rev. Appl. 12, 014061 (2019).
Phys. Rev. B, 101, 125404 (2020).
Phys. Rev. B, 101, 014439 (2020)

Spinning up the sphere

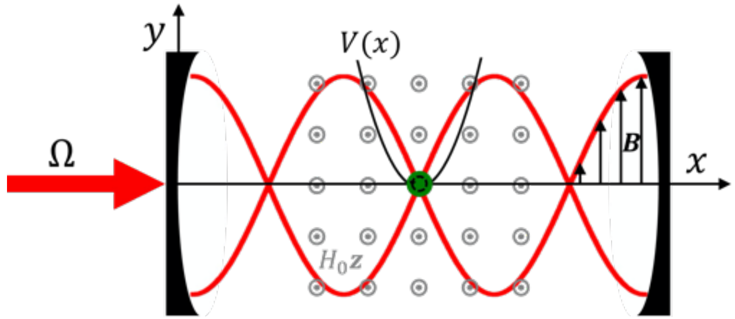
EXCITE A MAGNON MODE WHICH HAS OAM

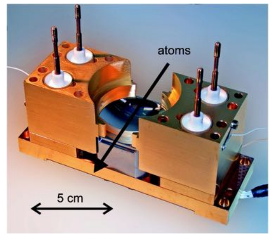
- Trap a YIG sphere in a driven Microwave cavity
- Magnetic interaction with B field of the MW cavity   no net force but a net torque on the sphere when the OAM modes are excited e.g. magnon mode (2,2,0)

$$\mathcal{H} = \Delta_a \hat{\boldsymbol{a}}^\dagger \hat{\boldsymbol{a}} + (\Delta_s - \omega_R)\hat{\boldsymbol{s}}^\dagger \hat{\boldsymbol{s}} + g\left(\hat{\boldsymbol{a}}\hat{\boldsymbol{s}}^\dagger + \hat{\boldsymbol{a}}^\dagger \hat{\boldsymbol{s}}\right) + \Omega\left(\hat{\boldsymbol{a}} + \hat{\boldsymbol{a}}^\dagger\right)$$

MW photon | Magnon | Coupling | MW Drive

- As OAM magnon excited mechanical torque created – but as the sphere spins the Barnett effect – mechanically rotating spins create an effective B field – the magnon freq shifts – reducing the torque: **HUGE ROTATIONAL SPEEDS**
- But if we can measure speed we can alter bias B field to compensate for Barnett effect





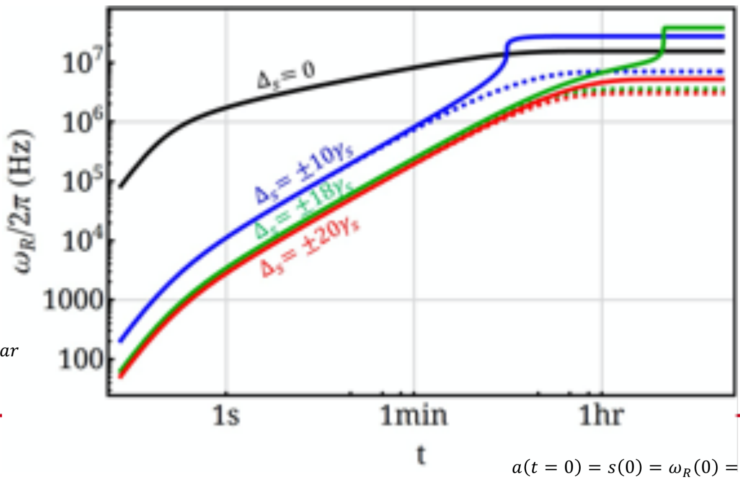
High-Q superconducting Microwave cavity

Appl. Phys. Lett. **90**, 164101 (2007).

$R = 1\ \mu m$

$p = 10^{-4} mbar$

$P = 10\ \mu W$



$a(t=0) = s(0) = \omega_R(0) = 0$

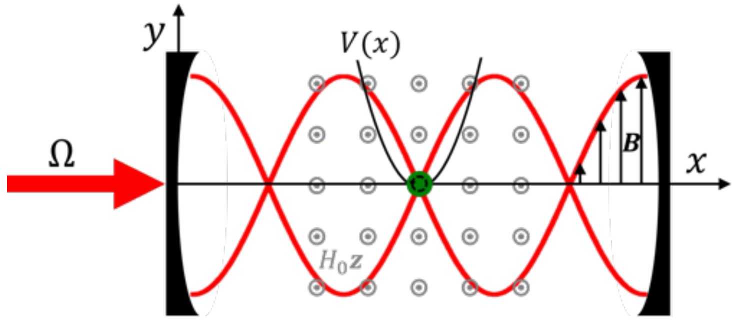
Spinning up the sphere

EXCITE A MAGNON MODE WHICH HAS OAM

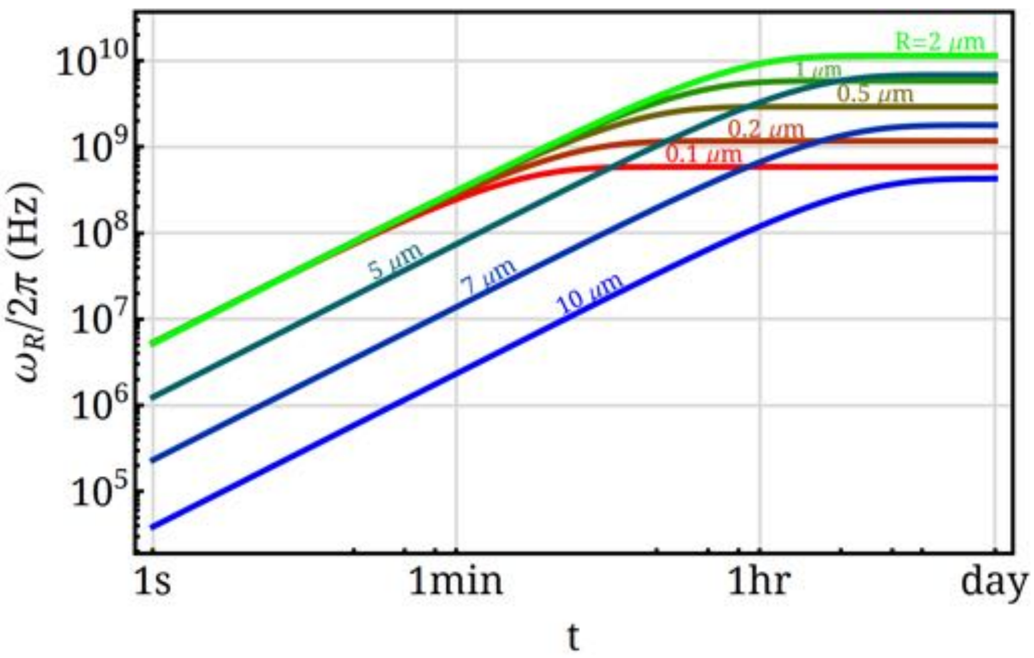
- When Barnet compensated :

Mega-Ultra-Hyper-Super fast rotation!

- Limited by gas pressure and bursting speed/max tensile stress of the material
- Can spin up any sized YIG sphere but as the sphere size but damping increases with size.



At the optimal detunings



OIST

Phys. Rev. Lett. 129, 257201 (2022)

Final Word

QUANTUM MACHINES ARE FUN!

- **Diamagnetic levitation** has great potential
- **Can we levitate entire superconducting qubits** to generate large superpositions?
- **Liquid Magnomechanics** – what new applications and study some fundamentals for fluids
- **YIG - magnons** – room temperature internal spin system with strong coupling – lots of potential but linewidth a mystery

.

PhD students
Internships