Mechanical dissipation below 1 \( \mu \)Hz with a cryogenic diamagnetic-levitated micro-oscillator

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Ultralow dissipation plays an important role in sensing applications and exploring macroscopic quantum phenomena using micro- and nano-mechanical systems. We report a diamagnetic-levitated mechanical oscillator operating at a low temperature of 3K with measured dissipation as low as 0.59 \( \mu \)Hz and a quality factor as high as \( 2 \times 10^7 \). To the best of our knowledge, the achieved dissipation is the lowest in micro- and nano-mechanical systems to date, orders of magnitude improvement over the reported state-of-the-art systems based on different principles. The cryogenic diamagnetic-levitated oscillator described here is applicable to a wide range of mass, making it a good candidate for measuring both force and acceleration with ultra-high sensitivity. By virtue of the naturally existing strong magnetic gradient, this system has great potential in quantum spin mechanics study.

Introduction. — Micro- and nano-mechanical systems have been developed as force sensors for detecting a wide range of weak signals, such as charge [1], spin [2], mass [3], etc. It has also been considered recently as potential tools for exploring force from new physics, such as a variety of dark matter models [4–6], wave-function collapse models [7,8], corrections to Newtonian gravity [13,14] and the high frequency gravitational wave [15]. In experimental realization, the signal understudy should be larger than the noise level of the force sensor that is characterized by noise power density:

\[
S_{FF}(\omega_0) = 4m\gamma k_B T, \tag{1}
\]

where \( \gamma \) is the mechanical dissipation character. One direct way to improve the performance is to make the oscillator mass \( m \) extremely small [10] so as to achieve the goal even at room temperature. However, for a wide range of applications, such as the force from gravity or acceleration, sufficient large mass is important, so low temperature environments and the lower mechanical dissipation \( \gamma \) are more useful in improving force sensitivity.

Besides sensing applications, dissipation is also paramount important for study quantum phenomena at macroscopic scale using micro- and nano-mechanical systems [17,18]. In order to control a macroscopic quantum state, such as generating spatial superposition, an important requirement is to overcome thermal decoherence. The finite-temperature oscillator’s thermal decoherence rate \( \gamma_{th} = \pi\gamma \) with \( \pi = k_B T/\hbar \omega_0 \) the thermal average phonon number [19]. Especially, in order to maintain quantum coherence within one oscillation period, we obtain the relation:

\[
\frac{\omega_0^2}{\gamma} > k_B T/\hbar. \tag{2}
\]

The left hand side is equal to the product of oscillator resonance frequency \( \omega_0 \) and quality factor \( Q = \omega_0 / \gamma \), known as \( \omega_0 Q \) product [19], so given \( \omega_0 \) and environmental temperature \( T \), a lower mechanical dissipation \( \gamma \) leads to better quantum coherence.

For a solid state mechanical resonator operating at high vacuum, the dissipation mainly comes from the direct coupling between the resonator and the substrate. In general, the dissipation of the solid-state mechanical system is inversely proportional to the oscillator’s mass. As the size decreases, it becomes a challenge to achieve very low mechanical dissipation. Efforts have been made to pursuit lower dissipation along different ways, such as employing novel improvement in material [20,21], geometry [22] and strain [22]. A dissipation down to the scale of mHz [22] has been reported. For a ultra-light mechanical resonator made of 1D or 2D materials with a mass of \( 10^{-18} \) g, a dissipation of 11Hz is achieved [24].

Different from solid-state mechanical systems, the dissipation of a levitated mechanical oscillator in ultra high vacuum is theoretically considered to be much lower [25]. In a recent experiment, a dissipation about...
FIG. 1. (Color online). Experiment setup. (a), The magneto-gravitational trap (MGT) is placed on the three-stage spring-mass suspension system which is used to isolate external vibration, the whole structure is mounted inside the chamber of a cryostat, a 633 nm laser light reaches the sample chamber through fiber and is focused loosely on the micro-sphere, and piezo positioners are used to control the position of trap so that scattered light is collected via lens. A CMOS camera is used to record the position of the micro-sphere, and an avalanche photodiode detector is used to measured the real-time intensity of the scattered light that is used to feedback cool or excite the motion of the micro-sphere via magnetic force via a magnetic field generated by a small coil near the MGT. (b), Vibration isolation system, the picture of spring-mass suspension structure and the MGT placement inside it, especially, soft copper braids are used to realize thermal connection between. (c) and (d), snapshots of the excited motion of the micro-sphere corresponding to two oscillation modes of different resonant frequencies (mode 1: 11.7 Hz, mode 2: 8.4 Hz) in x-y plane, where the exposure time is 200 ms, much longer than the period of oscillation (scale bar is 30 µm).

10 µHz has been realized using optical levitation in high vacuum [26–28], and a dissipation as low as about 81 µHz has been realized in an electric trap [29]. Typically, optical and electrical levitated oscillators work at room temperature due to the required power input, while on the other hand, magnetic levitated oscillators, either Meissner levitated [30, 31] and diamagnetic levitated [32, 33], are fully passive with no energy inputs and so naturally suitable for low temperature operation, and have recently been demonstrated to have mechanical dissipations at the order of magnitude of 10 µHz [31, 33]. However, realization of a diamagnetic levitated oscillator operating at low temperature is still elusive [32, 34].

In this letter, we report a diamagnetic levitated micro-mechanical oscillator working at low temperature. The levitation is realized with a magneto-gravitational trap, where a diamagnetic micro-sphere of mass of 540 pg (1 pg = 10^-12 g) is stably levitated. We observed a ultra-low mechanical dissipation with damping rate γ/2π of 0.59 ± 0.11 µHz at resonance frequency of 11.7 Hz, the corresponding quality factor (Q) is 2 × 10^7.

The reported mechanical dissipation is more than three orders of magnitude lower than traditional solid-state oscillators [20, 23], and one to three orders lower than reported optical levitated oscillators [26, 28], Meissner levitated [30, 31] and electrical levitated oscillators [29], and also about an order of magnitude improvement over previous experiments based on the same principle but working at room temperature [32, 35], the reported mechanical dissipation is even slightly smaller than the start-of-art milligram-scale pendulum oscillator [36, 37]. The behavior of this system used as force and acceleration sensors is evaluated and its potential applications to realizing quantum spin-mechanics systems are discussed.

**Experimental system.** — The experimental setup is shown in Fig. 1. A magneto-gravitational trap (denoted as MGT hereafter) are placed in low-temperature and high-vacuum environment. The low temperature is generated by a cryogen-free cryostat. To overcome the strong vibration generated by the operation of the cryostat, a special designed string-mass suspensions system, as shown in Fig. 1 (a), is used to isolate vibration noise. The suspension structure consists of three stages, with each stage corresponds to a suspension load mass as well as character frequency. The designed isolation at frequency 8 Hz is 54 dB and is expected to be better at resonance frequency of diamagnetic levitated micro-mechanical oscillator (see Table I for parameter of suspension structure).

The magneto-gravitational trap is similar to the one
FIG. 2. (Color online). Measured mechanical dissipation. (a), Logarithmic plot free ring-down of normalized oscillation energy $X(t)^2/X(0)^2$ corresponding to oscillation mode with resonance frequency 11.7 Hz as function of time. Green and blue dots are results with statistic errors measured under high purity helium gas and vacuum. Solid curve lines are fit to the exponential decay given by Eq. (4) (b), Same as (a) but for the oscillation mode with resonance frequency 8.7 Hz, with dark yellow the helium gas and red the vacuum. (c) The mechanical dissipation $\gamma/2\pi$ and the corresponding oscillator mass for a variety of mechanical systems based on different mechanisms. Red star is dissipation of 11.7 Hz mode in this experiment, rhombuses are solid-state oscillator [20–24], squares are optical levitated oscillator [26–28], the pentagon is electrical levitated oscillator [29], triangles are Meissner levitated oscillator [30, 31] and circles is pendulum oscillator with milligram-scale [36, 37].

| Stage | Mass (kg) | Character frequency (Hz) | Isolation (dB) |
|-------|-----------|--------------------------|---------------|
| 1st   | 7         | 1.4                      | 29            |
| 2nd   | 1.6       | 2.5                      | 19            |
| 3rd   | 0.08      | 4.6                      | 6             |

TABLE I. Designed parameters of the vibration isolation system. The characteristic frequency is the mass-spring suspension resonance frequency at vertical direction (z axis) which is significantly larger than the frequency in horizon (x, y), isolation give actuation in square of vibration amplitude response at frequency 8Hz.

Measurement method and results. — To obtain the mechanical dissipation of the micro-oscillator, we start from the equation of motion of the a micro-oscillator used at room temperature [33] but with modifications in geometry. It is generated by a set of SmCo magnets with octagonal bilayer geometry as shown in Fig. 1(b). The oscillator is a microsphere of polyethylene glycol which is loaded into the trap by a home-built nebulizer, the charge on the micro-sphere is eliminated by following a standard procedure [33]. After pumping the sample chamber into vacuum, the system is cooled down to and the sample chamber is then maintained at 3K during the experiment. The temperature of the magneto-gravitational trap, due to its weak thermal connection to cold plate of sample chamber, has a higher temperature about 7K.

To obtain the position and the dynamics of the levitated micro-sphere, a weak 633 nm laser with power less than 50 $\mu$w is sent into the chamber via single mode fiber and is loosely focused on the microsphere, and the scattered light from the microsphere is collected vertically via a lens and comes out of the cryostat via windows. To realize feedback cooling and excitation of the micro-sphere, an avalanche photodiode detector (APD) is firstly used to measure the intensity of scattered light that contains the real time information of the microsphere position, then the electrical signal of the detector is amplified and sent to a computer where its amplitude and phase corresponding to the oscillator resonance frequency are calculated, and a program based feedback circuit is used to control the arbitrary waveform generator which generated the feedback signal. Typically, the feedback bandwidth is of the scale of 0.1 Hz which is fast enough for our system. The output electric signal goes back to the sample stage via a small coil near the micro-sphere and generating a weak magnetic field. Combined with the magnetic field gradient of the MGT finally, it becomes a feedback force applied on the microsphere. Due to the limitation of the dynamic range of APD, we used a CMOS camera instead so that the absolute position of the microsphere was directly recorded. Fig. 1(c) and (d) is typical images of micro-sphere excited motion corresponding to two resonance modes.
of math $m$ of one oscillation mode with a resonance frequency of $\omega_0/2\pi$:

$$m\ddot{x} + n\gamma\dot{x} + m\omega_0^2 x + m\epsilon x^3 = F_{\text{fluc}}(t),$$

(3)

where the second term describes the dissipation the oscillator with a damping rate $\gamma/2\pi$, the fourth term is the Duffing nonlinearity, and $F_{\text{fluc}}(t)$ is the total fluctuation force, including thermal fluctuation, external vibration etc. The motion can be written in the form $x(t) = X(t) \cos(\omega_0 t + \varphi(t))$ with $X(t)$ and $\varphi(t)$ the slow-varying amplitude and phase, respectively. There are several commonly used experimental methods to determine the dissipation $\gamma$. One is to measure the system's frequency response. For harmonic oscillator, the corresponding linewidth equals to $\gamma/\pi$, but in the presence of nonlinearity, the measured linewidth is broadened significantly, even when it is driven by solely the thermal fluctuation [26, 33]. We obtained $\gamma$ by energy autocorrelation proportional to $\langle X(t)^2 X(0)^2 \rangle$, with $X(t)$, as it has been shown that energy autocorrelation is insensitive to nonlinearity [38]. In the actual realization, we directly measure the free decay of $X(t)^2$, to do this we first excited the oscillator to initial amplitude $X(0)$ that is much higher (more than 10 times) than the background stochastic motion amplitude $\langle X_{\text{ba}} \rangle^2$ driven by the fluctuation force $F_{\text{fluc}}(t)$, and the theoretical evolution can be written as:

$$X(t)^2 = X(0)^2 e^{-t\gamma}$$

(4)

with error less than a few percent [33, 38]. Under our experimental conditions, $X(t)^2$ were obtained using a CMOS camera based on the method in Ref. [37]. The position of the microsphere was recorded for a duration so as to obtain an average of $X(t)^2$ and its statistical deviation. The measured data were then fitted with Eq. (4) to give the dissipation rate $\gamma$. Then the dissipation rate is obtained by fitting the measured data with Eq. (4).

The diameter of the micro-sphere used in this experiment is 9.8 ± 0.9 $\mu$m, which is obtained in advance from the dissipation $\gamma$ measured at high purity helium gas environment with pressure $2 \times 10^{-6}$ mbar. As the helium gas at a temperature of 3K can still be considered as a idea gas, the diameter is simply related to the microsphere oscillation damping rate and the pressure as a result of background gas collisions [25]:

$$\gamma = (16/\pi)(P/\nu R \rho),$$

with $P$ and $\nu$ the pressure and the mean speed of the background gas, respectively, and $\rho$ the density of the micro-sphere. Then we turned off the helium gas and pumped the chamber to high vacuum with background pressure $3.3 \times 10^{-7}$ mbar (measured at room temperature), which is maintained stable during the experiment. Fig. 2 (a) and (b) shown the normalized damping curve as $X(t)^2/X(0)^2$, and the results is summarized in Table II for the vibrational mode of resonance frequency 11.7 Hz (mode 1), we observed a ultra-long damping time $\tau = 1/\gamma$ of $2.7 \times 10^5$ s (about 70 hours), corresponding to a mechanical dissipation of $\gamma/2\pi = 0.59 \pm 0.11$ $\mu$Hz and a quality factor $Q = 2.0 \pm 0.4 \times 10^7$. For the vibrational mode of resonance frequency 8.7 Hz (mode 2), the mechanical dissipation is $\gamma/2\pi = 2.6 \pm 0.1$ $\mu$Hz, about 4 times larger than that of mode 1. A possible origin of such a difference may come from boundary effects of residual helium gas [39] in carrying out our experiment. Fig. 2 (c) plots the comparison of our results with currently reported micro- and nano-mechanical using different principle. It clearly shows that our system performs with significant lower dissipation in a wide range of mass, and is even comparable to those milligram-scale mechanical system whose mass is larger by about 7 orders of magnitude [36, 37].

**TABLE II.** Measured mechanical dissipation at low temperature and high vacuum. The diameter of the oscillator is 9.8 ± 0.95 $\mu$m, and the corresponding mass is 540 ± 160 pg. The errors show the statistic deviation at the 95% confidence level.

| Mode | $\omega_0/2\pi$ (Hz) | $\gamma/2\pi$ ($\mu$Hz) | $Q (10^7)$ |
|------|----------------------|-------------------------|------------|
| 1    | 11.7                 | 0.59 ± 0.11             | 2.0 ± 0.4  |
| 2    | 8.4                  | 2.6 ± 0.1               | 0.34 ± 0.02|

**Discussion and summary.** — The potential performance of our diamagnetic-levitated oscillator used for force and acceleration sensing can be evaluated from the dissipation achieved in our experiment. The

![FIG. 3. (Color online). Estimation of performance of force and acceleration sensing. Left axis, force sensitivity as function of mass at environment temperature of 3K (light blue solid line) and 10 mK (light blue dash line), force from single electron spin (dark blue solid line) and single proton spin (dark blue dash line) are shown for comparison. Right axis, same as left but of acceleration sensitivity. The experimentally measured dissipation $\gamma/2\pi = 0.59$ $\mu$Hz and the magnetic gradient $G = 10^4$ T/m are adopted in the estimation.](image-url)
sensitivity of force sensor is given by Eq. (1), and the sensitivity of acceleration is characterized by noise power density $S_{\text{a}}(\omega_0) = 4\gamma k_B T/m$, which differs from that of the force in that large mass is advantageous. In principle, a magneto-gravitational trap can levitate particles of a very wide range of mass of the order of magnitude of $10^{-14}$ to $10^{-3}$ g. Fig. 3 shows the force and acceleration at 3K which corresponding to this experiment and 10 mK which can be reached by a commercial dilution refrigerator. At 3K, we see that the force sensitivity is enough to detect a single electron when the oscillator’s mass is smaller than $4 \times 10^{-9}$ g. In the estimation, a magnetic gradient $G = 10^4$ T/m from a typical magneto-gravitational trap is adopted. A single proton spin is also detectable when the oscillator’s mass is smaller than 100 fg. On the other hand, for a mass of $10^{-6}$ g, the acceleration sensitivity reaches $\sqrt{S_{\text{a}}(\omega_0)} < 10^{-10} g/\sqrt{\text{Hz}} (g = 9.8 \text{ m/s}^2)$ at 3K, comparable to the state-of-art method reported so far [10].

The potential of application of this system to the study of macroscopic quantum process can be estimated by assuming an oscillator resonance frequency $\omega_0/2\pi \approx 100 \text{ Hz}$ and at a 10 mK environment temperature. We find that $\omega_0 Q/2\pi \approx 10^{10} \text{ Hz} \gg k_B T/(2\pi h)$ and Eq. (2) is well satisfied. Therefore, the quantum coherence of the system could last for many oscillation periods. Especially, it is interesting to consider applying the system to the realization of quantum spin-mechanics dynamics [11, 12]. Considering the interaction between electron spin, the spin-mechanical coupling strength $\gamma = G x_{\text{pl}} \mu_e/\hbar$, where $x_{\text{pl}} = \sqrt{\hbar/m \omega_0}$ is the zero point motion and $\mu_e$ is the electron spin magnetic moment, for oscillator with mass of $10^{-13}$ g, we have $\lambda/2\pi \approx 10 \text{ kHz}$, which is four orders of magnitude larger than the decoherence rate $1/T_2$ of electron spin at low temperature [13], and four orders of magnitude larger than thermal decoherence rate $\gamma_{\text{th}}$ of the oscillator. The cooperativity here is $C = \lambda^2 T_2 Q/\hbar(k_B T) \approx 10^8$, which marks the onset of highly coherent quantum effects.

In summary, we report the realization of a cryogenic diamagnetic-levitated micro-mechanical system with a recorded low dissipation value, which provides a new way to achieve high-performance sensing and quantum control of macroscopic mechanical dynamics.

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