Meissner levitation of a permanent magnet within a superconducting radio frequency cavity

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Abstract

We report the first experimental demonstration of Meissner-effect levitation of a millimeter-scale neodymium magnet within a cm-scale superconducting aluminum coaxial quarter-wave stub cavity. The coaxial mode's resonance frequency shifts as a function of the levitation height of the magnet, giving an estimate of the magnet’s position and mechanical motion. The levitation height sensitivity is as large as 400 MHz/mm, where the total frequency shift is 1% of the bare cavity resonance. We observe levitation of magnets with remanences up to 140 times stronger than the critical field of the aluminum, and our experiments and simulations reveal that both the levitation height and levitation temperature increase with the strength of the magnet. This novel magnet-cavity system provides a means to couple the low-frequency mechanical motion of the magnet with other objects, such as magnons and transmons, which are used for quantum information processing.

Three-dimensional superconducting radio frequency (SRF) cavities have well-defined frequency spectra whose localized electric and magnetic fields provide unique opportunities to couple to other objects. Because of the physical positioning of the field distributions, the losses can be minimized allowing for a large quality factor [1--3]. These cavities are used in research for dark matter detection [4--6] and recently an experimental demonstration of the Casimir spring effect within a microwave cavity systems was published [7]. Cavities can be integrated with superconducting circuits for the purposes of preparing, controlling, storing, or measuring arbitrary quantum states [8], [9] and have been shown to be a promising platform for strong coupling to and ground state cooling of the mechanical resonator [10--12]. The coupling between light and matter enables applications like control of quantum systems and results in new quantum effects such as multimode entanglement and nontrivial ground states [13], [14].

Coupling to a levitated mechanical system has the potential advantage of reducing losses that come about from clamping and reduced thermal contact [15], [16]. Optical levitation inside a cavity and magnetic levitation over type II superconductors have been demonstrated [17--20]. The main challenges in optical levitation are maintaining stable trapping at high vacuum and reducing the mechanical trapping noise arising from photon recoil and heating [21]. Levitation of a magnet above a type II superconductor involves magnetic flux vortices and the flux motion introduces dissipation into the harmonic motion of the levitated magnet [22]. Meissner-effect levitation above type I superconductors is advantageous over the optical levitation and the flux pinning superconducting levitation because of the reduction in losses discussed above. In recent years, stable levitation of a permanent magnet above a punctured type I superconductor was demonstrated [23] and ultralow mechanical damping of Meissner levitation was also achieved [24].
In this letter we report on measurements of the shift in the resonance frequency of a SRF cavity as a function of temperature due to levitation of a permanent magnet within the cavity. We achieve levitation heights of 0.7 – 1.8 mm and measure a levitation height sensitivity as large as 400 MHz/mm where the total frequency shift is 1% of the bare cavity resonance. We investigate the dependence of levitation height and levitation temperature on the strength of the magnet and we observe that the levitation temperature and height both increase with permanent magnet strength. Similar cavities incorporating Josephson junction qubits are used for quantum information processing, and our work provides the opportunity to include a levitating magnet as a mechanical element within such a system [2], [25].

![Figure 1](image.png)

Figure 1: (a) Snapshot of a neodymium disc magnet inside of a plastic sleeve that fits over the stub. The potential energy landscape for the magnet as a function of position within the cavity is discussed in the supplementary materials. (b) Schematic of our experimental setup. A magnet is placed on the top of the stub and the cavity is probed with the vector network analyzer. The output signal is amplified by the HEMT and post amplifiers.

When a permanent magnet is placed near the superconducting boundary of a Type I superconductor, the superconductor exhibits a perfectly diamagnetic response. Supercurrents build up on the surface of the superconductor which fully screen the magnetic flux from its interior [26]. In the magnetic dipole approximation, the force arising from this interaction depends on the magnetic moment of the magnet, \( M \), and the distance to the boundary, \( r \), according to \( F \propto M^2 / r^4 \). The force is always repulsive, and can be large enough to lift macroscopic objects to some equilibrium height where the net force of the interaction combined with that due to gravity is zero [27]. Levitation persists as long as the magnetic field at the boundary is less than at the critical magnetic field of the superconductor [28].

The coaxial cylindrical cavity with one end open [Fig. 1(a)] is machined out of 6061 (97.9% pure) aluminum. The outer cylinder has a radius of 7 mm and a height of 55 mm. The inner stub cylinder has radius of 2 mm and height of 5 mm giving a quarter-wave resonance of \( f_0 = 10 \text{ GHz} \). The coaxial...
The stub cavity’s resonance frequency is determined by the height of the stub, \( l \), where \( f_0 \propto \frac{1}{4l} \) [2]. We use neodymium disc magnets of 1-mm diameter by 0.5-mm high, with a mass of 2.75 mg, and varying magnetic field strengths (remanence, provided by the manufacturer) of 1.22 T – 1.47 T. This corresponds to magnetic moments of 0.38-0.46 (mA)m², respectively.

The neodymium magnet is placed inside a coaxial microwave stub cavity, which was attached to the base plate of a dilution refrigerator, Fig. 1(b). The refrigerator is cooled down to approximately 50 mK (well below the zero-field critical temperature of aluminum) and vacuum pressure is maintained at 10⁻⁷ mbar. A microwave signal (~0 dBm) is coupled into the cavity to probe the quarter wave mode via a pin antenna that extends into the body of the cavity near the region with the strongest electric field. Transmission measurements (\( S_{21} (\omega) \)) are performed with an over-coupled cavity which results in a loaded cavity Q on the order of 2500 to ensure that the mode can be tracked on a vector network analyzer (VNA). N-type cryogenic grease is used to maximize thermal contact between the cavity and the base plate of the dilution refrigerator and to make the cavity stable during the cooldown.

![Figure 2](image)

Figure 2: (a) The expected frequency shift with the position of the magnet. When there is no magnet present (a bare cavity), the resonance frequency is fixed and shown by the blue curve. If the magnet rests on the bottom of the cavity, the resonance frequency is higher than that of the bare cavity (green curve). If the magnet rests on top of the stub, its resonance is less than that of the bare cavity as shown by the orange curve. (b) Finite element calculations (COMSOL Multiphysics) of magnetic levitation from the surface of the stub. In these calculations, the magnet is placed at different positions on the surface of the stub. The frequency change is the difference in frequency between that of the bare cavity and the cavity with the magnet. The size and shape of the magnet and the cavity are the same as in the experimental work.

Fig. 2 (a) illustrates the expected changes to the resonance frequency of the cavity during levitation experiments. Any perturbation within the coaxial region of the cavity changes the shape of the cavity mode and its frequency [29]. When a magnet is placed on the surface of the stub, it increases
the effective height of the stub and decreases the frequency of the cavity. The amount of frequency downshift corresponds to the interaction of the magnet with the electric field of the cavity mode, which is concentrated toward the edges of the stub. Conversely, when the magnet is placed on the bottom of the cavity it raises floor of the cavity. This reduces the effective length of the stub which causes the resonance frequency to increase. As the magnet levitates above one of the surfaces, the resonance shifts towards that of the bare cavity (cavity without any magnet).

Finite element calculations (COMSOL Multiphysics) help interpret the movement of the magnet during levitation [Fig. 2 (b)]. For example, when the magnet is still in contact with the stub ($z = 0$), lateral movement of the magnet towards the edge of the stub produces a frequency downshift of -50 MHz/mm. According to our calculations the largest height sensitivity is expected for a magnet positioned at the edge of the stub (1.75 mm) where the sensitivity is -400 MHz/mm for levitation heights of 0-0.1 mm. As can be seen in the overlapping traces in Fig. 2 (b), once the levitation height exceeds $z=0.7$ mm, the levitation sensitivity no longer depends strongly on lateral position. The expected frequency shifts from these simulations are used to estimate the levitation height in the experimental data. These simulation patterns matched with the room temperature experiments discussed in [30] and a discussion of a room temperature experiment for lateral movement of the magnet is presented in the supplementary material.
Figure 3: (a) Change in frequency as a function of temperature for N35, N42, N50, and N52 magnets. Data is taken between 5 K (above $T_c$) and 50 mK (base temperature). The data taken as the experimental chamber is cooled from 1.25 K to 50 mK is displayed. $\Delta f=0$ represents the frequency of the bare cavity from 5 K to 50 mK. (b) Comparison of frequency shift pattern of N50 disc magnet (gold color) with the N50 cylindrical magnet (blue color). The inset shows the dimensions of the two magnets. The frequency shift before levitation for the cylindrical magnet (around 130 MHz) is higher than that of the disc magnet (around 80 MHz) due to the difference in magnet size and uncertainty in the exact position of the magnet on the top of the stub.

Figure 3 (a) displays experimental results taken at low temperatures, focusing on the frequency shift between 1.25 K and 50 mK. When the bare cavity (with the plastic sleeve surrounding the stub) is cooled through the superconducting transition of aluminum at 1.2 K we observe a negligible frequency shift of a few KHz due to a change in the penetration depth. These small shifts at low temperatures, along with larger shifts ($\sim$20 MHz) due to thermal contraction as the system cools from room temperature, are reproducible in all of our measurements. The bare cavity’s resonance at $\sim$5K is used as the reference frequency for all levitation experiments.

We measure the behavior of the cavity-magnet system for a sequence of four magnets having the same shape and mass but having different magnetic strengths. The magnets are placed on top of the stub but the exact positioning on the stub is undetermined. Since the stub has minor imperfections it is not perfectly symmetric and the frequency downshift due to the presence of the magnet varies depending upon the exact position of the magnet (see the supplementary material). For example, at 5K, the frequency shift due to the N35 (1.22 T) and N42 (1.32 T) magnets is $\sim$120 MHz, but the frequency shift for the N50 (1.44 T) and N52 (1.47 T) magnets is just $\sim$90 MHz. Multiple cooling and heating cycles are performed for each magnet.

Table I: The total frequency shift ($\Delta f$), the range of temperature where the motion of the magnet was observed ($T_{motion}$), and the levitation temperature ($T_{Lev}$) are tabulated for the five magnets used in the experiment.
For each trace in Fig. 3(a), one observes four features as the temperature drops (see Table I). Initially the frequency is constant while the magnet rests on the surface of the stub. Secondly there is a fluctuation region where the frequency varies from the high temperature value by ~20 MHz. Thirdly, at intermediate temperatures there is a transition region characterized by sudden transitions of >30 MHz with plateaus. And fourthly, there is a final levitation region. As an example, consider the case of the weak N35 magnet. The frequency remains constant at about -120 MHz as the temperature drops from 1.25 K to 600 mK. Between 600 mK and 300 mK the fluctuation region exhibits variations between -120 MHz and -100 MHz. Sudden large step transitions (>30 MHz) occur in the range of 300 mK down to 150 mK. Finally, the measured frequency remains steady below 100 mK. All of the magnets exhibit the four features, but magnets providing larger magnetic fields display them at higher temperatures.

For comparison in Fig. 3(b) we performed the same experiment with a N50 cylindrical neodymium magnet having a height of 1 mm and a radius of 0.375 mm. This magnet has the same remanence (1.44 T) as the N50 disc magnet, but the mass of this magnet is nearly twice (4 mg) that of the disc magnet. The same SRF cavity was used. For both magnets, the transition temperature was close to 650 mK. The levitation height (which was measured from the center of mass of the magnet) for the cylindrical magnet (2.50 mm) was higher than for the disc magnet (1.56 mm). The height which was due to the larger volume (and thus larger magnetic moment) of the cylindrical magnet.

| Type of the magnet | Total Δf (MHz) | $T_{\text{motion}}$ (mK) | $T_{\text{lev}}$ (mK) |
|--------------------|----------------|---------------------|----------------------|
| N35 (1.22T)        | 102 (Run1) 99 (Run2) | 600-300 (Run1) 500-165 (Run2) | 100 (Run1) 165 (Run2) |
| N42 (1.32T)        | 108 (Run1) 105 (Run2) | 700-400 (Run1) 800-550 (Run2) | 350 (Run1) 545 (Run2) |
| N50 (1.44T)        | 79 (Run1) | 900-700 (Run1) | 640 (Run1) |
| N52 (1.47T)        | 80 (Run1) 80 (Run2) | 900-700 (Run1) 900-740 (Run2) | 695 (Run1) 740 (Run2) |

Figure 4: Levitation height as a function of remanence.
Figure 4 shows that magnets producing a larger magnetic field attain a larger levitation height and exhibit a higher levitation transition temperature compared with magnets producing a smaller magnetic field. This is surprising because prior to levitation, when the magnet rests directly on the surface of the aluminum, the magnetic field strength at the interface is larger than the critical field of the aluminum (10 mT at 1.2 K). Prior to levitation, because of the large magnetic field produced by the magnet, there exists a normal conducting region that has a depth of 1-2 mm directly below the magnet whose depth varies with the strength of the magnet. The normal region shrinks as the temperature drops and the critical field increases, while the levitation force depends quadratically on the magnetic moment of the magnet used. Below the levitation temperature the Meissner effect produces a force whose magnitude is sufficient to overcome the force due to gravity and allow the magnet to levitate. We find that the uncertainty in our measurement of levitation height also decreases as the levitation force increases [31].

To summarize, we have characterized the levitation of mm-sized permanent magnets within a type-I SRF cavity. We obtain levitation heights of 0.7-1.8 mm for commercially-available neodymium magnets. These levitation heights are in a range where the SRF cavity’s resonance frequency varies with magnet position. Levitation temperatures for aluminum cavities range from 100-700 mK, which is obtainable in dilution refrigerator systems. Such electro-mechanically coupled systems, if stabilized, can be used to introduce the low-frequency mechanical motion of the magnet with other objects whose quantum states can be probed and manipulated in SRF cavities, such as magnons and transmons [25]. In addition, the levitated high Q mechanical oscillator enables application in ultra-sensing [32–36] and gravitational wave detection [37].

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