Stable levitation and dynamics of ice particles at low pressures

Nicholas Kowalski, Bernard Xie, Colin V. Parker, and Cheng Chin∗
(Dated: April 14, 2015)

We demonstrate stable levitation and trapping of ice particles of 30∼200 µm at low background gas pressures in the presence of a temperature gradient. The thermophoretic force levitates the particles, which have long lifetimes of over an hour. The equilibrium position depends on the background pressure and temperature gradient, which is consistent with theoretical expectations. Furthermore, we investigate interesting launching and merging dynamics of the levitated particles, as well as the development of instability at high background pressures. Our system provides a robust platform to investigate the aggregation of floating ice particles in air, and potentially chemical and biological processes in a microgravity environment.

PACS numbers: 37.10.Mn, 37.10.Pq

I. INTRODUCTION

Levitation of particles in ground-based experiments provides an ideal situation for studying their dynamics and interaction in a pristine isolated environment, and has broad applications in fundamental and applied sciences. Electromagnetically levitated atoms, ions and molecules in vacuum have opened the field of quantum degenerate gases [1, 2], cold chemistry [3] and atom-based quantum information [4]. Optical levitation of micron-size objects [5] provides a new playground to investigate aerosols in atmosphere [6] and Brownian motion of microspheres [7].

Levitation of water and ice is of particular interest due to its wide applications in biological, chemical, atmospheric and even astro-chemical research. Several schemes to levitate droplets and ice particles have been realized based on electrodynamic balance [8], high magnetic field gradients [9, 10], acoustic waves [11, 12] and optical tweezers [13]. An interesting scheme was demonstrated recently to levitate ice particles in vacuum with a large temperature gradient between two surfaces: a hot surface at the bottom and a colder surface on the top. The so-called Knudsen compressor effect floats large dust aggregates about 1 mm above the hot surface [16], and thermophoretic force levitates ice particles 1 cm above the surface for several seconds [14].

We report an improved method to achieve fully stable levitation of ice particles, which provides a wide capture range and levitation stability that keeps ice particles confined for a very long time of ∼1 hour. The levitation is robust over a large range of background pressure from $P = 5 \sim 25$ Torr and temperature gradients from $170 \sim 200$ K/cm. The long levitation times allow us to observe the dynamical behavior of the ice particles in the trap, including launching, collisions and dynamical instability.

*Author to whom correspondence should be addressed. Electronic mail: c chin@uchicago.edu

II. EXPERIMENTAL APPARATUS

Our experimental apparatus is schematically shown in Figure 1. The system consists of two circular metal plates spaced by 10.5 mm housed in a vacuum chamber. The top plate of 25.4 mm diameter is the bottom of a stainless steel bucket cooled to 77 K by filling with liquid nitrogen; the lower copper plate of 33.7 mm diameter is temperature controlled by a Peltier cooler and monitored...
with a thermistor. We attribute the enhanced stability and the capture range in our setup compared with previous work [14] to the stronger temperature gradient and lower radiative emissivity of the metallic plates which improves the ratio of thermophoretic force to photophoretic force. The photophoretic force also levitates, but is frequently much stronger near the colder surface, and can thus destabilize the levitated particles [14]. The thermophoretic force, on the other hand, is stronger near the bottom surface and provides a stable levitation condition.

We introduce ice particles between the two plates by permitting a small amount of water vapor into the chamber via a needle valve. The vapor crystallizes on the top plate to form ice particles, which drop on the bottom plate either spontaneously or is forced to fall by vibrating the nitrogen bucket. The levitated ice particles are illuminated by light emitting diodes and their positions and dynamics recorded by a digital camera. The ice particles have irregular shapes and the quoted particle sizes are the geometric mean of the root-mean-square widths from Gaussian fits.

### III. LEVITATION OF ICE PARTICLES

Ice particles initially on the bottom plates assume various types of motion. Large aggregates over 200 μm spin or hover about 1 mm above the hot surface. The hovering behavior of the aggregates has been investigated and attributed to the Knudsen compressor effect [15–17]. The hovering particles shrink over time, due to sublimation of the ice [18]. Smaller ice particles of sizes 30 ~ 200 μm residing near the center of the copper plate have a higher chance to be levitated and can float near the mid-point between the top and bottom surfaces. Levitations of the particles is very stable and robust against temporary spatial excursions in all directions. We observe ice particles levitated for 45 minutes to 1 hour (our longest observation time) without discernable evaporation or loss of stability. We thus expect that the lifetime of the levitated particles is much longer than an hour.

The launch of ice particles occurs either immediately after an appropriately sized particle lands on the bottom plate, or after a particle on the plate sublimates to the appropriate size. A typical launch and levitation process is shown in Fig. 2. Following the launch, the particle reaches a stable levitation after about 10 sec.

The dynamics approaching the equilibrium position can be described by a damped harmonic oscillator with an oscillation period of 2.06(1) s and damping time of 1.45(1) s for the particle shown in Fig. 2. In the Fig. 2 inset, the two-dimensional trajectory recorded by the camera is shown, where \( x \) refers to the horizontal distance from the symmetry axis of the plates projected perpendicular to the imaging axis, \( h \) refers to the vertical distance from the bottom plate.

We study the condition required for levitation by varying the temperature gradient and background air pressure. Starting with a single levitated particle, we change the temperature of the copper plate with the Peltier cooling or the pressure with the leak valve slowly, and record the new levitation heights of the same particle after the new equilibrium is reached, see Fig. 3. Several experiments based on particles of different sizes are shown in the Fig. 3 insets.

Stable levitation of single particles is observed over the full range of the copper plate temperature \( T_{Cu} \) that we can access: 250 ~ 280 K. The temperature of the ice particles is estimated to be within the range of 150~170 K from linear interpolation of the top and bottom plate temperatures. Higher levitation positions are typically found for higher copper plate temperatures and smaller particle sizes, as shown in the inset of Fig. 2 (a) [19]. When the background pressure varies, we find robust levitation over the pressure range \( P = 5 \sim 25 \) Torr, and the height drops slightly at higher pressures, see Fig. 2 (b). Near the upper bound \( P = 25 \) Torr, a motional instability is developed, which we will discuss below. Below \( P = 5 \) Torr, the particles reach and stick to the upper plate.

We may understand the temperature and pressure dependence of the levitation position from the form of the thermophoretic force [20], the dominant levitation force in our system:

\[
F = -\eta f(\text{Kn}) \frac{\kappa A}{\sqrt{k_B T/m}} \nabla T, \tag{1}
\]

where \( A \) is the effective area of the particle, \( \kappa \) is the thermoconductivity of the background air, \( m \) is the mass
FIG. 3: Temperature and pressure dependence of the levitation. (a) Height of a single levitated particle at various temperatures of the copper plate $T_{Cu}$ as a function of time after temperature stabilization. Here particle size is $140 \mu m$ and pressure $P = 5$ Torr. Inset: heights of three particles of size $122 \mu m$ (blue), $120 \mu m$ (red) and $140 \mu m$ (black). Pressure is $P = 5$ Torr. (b) Levitation of a $60 \mu m$ particle at different pressure after pressure stabilization. Copper plate temperature is $T_{Cu} = 280.1$ K. Inset: averaged heights of two levitated particles $60 \mu m$ (black) and $50 \mu m$ (red). The errors show the height excursion.

of the air molecules, $f(Kn)$ parameterizes suppression of thermophoretic force in the hydrodynamic regime [20], the Knudsen number $Kn = l/a$ is the ratio between the mean-free path $l$ and the particle size $a$, and the parameter $\eta$ is given by the geometric details of the ice particle.

Equation (1) suggests that the thermophoretic force points toward lower temperatures. This explains the vertical levitation, as well as the radial restoring force toward the center, which is colder than the surrounding chamber at the room temperature of 294 K. As the thermal conductivity of air increases with the temperature, the thermophoretic force is stronger at higher absolute temperature, and therefore decreases with height, leading to a stable balance with gravity at some particular height. As we warm up the lower plate and thus increase the temperature gradient, the levitation position rises. The lower levitation heights at higher pressures is more subtle, and comes from the hydrodynamic factor $f(Kn)$. At high pressures, the molecular mean-free path is small compared to the particle size $Kn << 1$. The levitation force reduces due to a more isotropic momentum transfer from the colliding molecules. A quantitative calculation of the levitation height is complicated by the irregular shape and porous nature of the ice particle, captured by the parameter $\eta$ in Eq. (1).

IV. DYNAMIC INSTABILITY AND AGGREGATION

Of particular interest in our study is the observed dynamic instability of levitated particles at high pressures. In Fig. 3 (b) oscillations of the levitation heights can be seen at pressures near and above 20 Torr. By increasing pressure, the oscillations of the particles significantly amplify and the particles are eventually lost above $P > 25$ Torr. Similar amplification of instability is also seen in the horizontal position of the particles $x(t)$, see Fig. 4 for two-dimensional trajectories. An elliptical motion of the levitated particles is clear above 15 Torr and becomes more complicated above 20 Torr.

A possible explanation for the instability of the levitated particles at higher pressure is the emergence of convection (Rayleigh-Bénard instability) in our gas cell. In fluid mechanics, the instability occurs with large temperature gradients and higher density, and the onset of the instability occurs at large values of the Rayleigh number,

$$Ra = \frac{g\beta}{\nu \alpha} (T_H - T_C) h^3,$$

(2)

FIG. 4: Development of motional instability at high pressure. Two-dimensional trajectories of the $60 \mu m$ particle shown in Fig. 3 (b) in the range of $t = 33 \sim 45$ s. Heights relative to the averaged values are shown and the horizontal positions are offset for clarity.
FIG. 5: Merging of three levitated ice particles at $P = 5$ Torr and $T_C = 254.5$ K. Starting with few levitated ice particles at time $t = 0$, we observe merging of 3 particles in subsequent dynamics. After collisions, the particles aggregate, indicated by the 2 arrows at times $t = 7.5$ and 11 s. The geometric sizes of the particles are 180 $\mu$m (red), 100 $\mu$m (black), 120 $\mu$m (blue), 210 $\mu$m (green) and 270 $\mu$m (cyan).

where $g = 9.8$ m/s$^2$ is the acceleration of gravity, $\beta$ is the gas thermal expansion coefficient, $\nu = \mu/\rho$ is the kinematic viscosity, $\mu$ is the dynamic viscosity, $\rho$ is the density, $\alpha = k/c_p$ is the thermal diffusivity, $c_p$ is the heat capacity, and $h = 1.05$ cm is the height of the system. For $\Delta T = 200$ K, viscosity and thermal conductivity for air evaluated at $T = 200$ K, and ideal gas properties for $c_p$ and $\beta$ we obtain $Ra = 0.2(P/Torr)^2$. Our observation of critical pressure $P = 25$ Torr corresponds to a Rayleigh number of $Ra=125$.

Another interesting dynamical behavior occurs when multiple ice particles are levitated simultaneously. We observe rich dynamics due to their interactions, which, in almost all cases we record, result in aggregation of the particles. An example of 3 particles interacting and merging is shown in Fig. 5. Here, ice particles 1, 2 and 3 are initially levitated and independent. Particles 1 and 2 collide and merge at $t = 7.5$ s, and the third particle joins at $t = 11$ s. The final aggregate, carrying the weights of all 3, is over 250 $\mu$m in size, but remains levitated stably afterwards. Surprisingly, the merging of particles does not have a significant effect on the equilibrium levitation position. This may be because the ice particles are porous, with a low enough filling factor that the effective area-mass ratio is unchanged after merging.

A common feature of the merging processes we observe is that the dynamics of merging happens most frequently in the vertical direction: One particle drifts to the top of the other particle and then falls down. When they collide, they merge and the combined particle sinks temporarily before eventually recovering to a new equilibrium position not far from the original equilibrium position. This dynamic is evident in both merging events in Fig. 5.

A precise model for the merging dynamics would have to take into account particle shape, as well as the thermophoretic force at intermediate Knudsen number Kn [20], and is beyond the scope of this work. Previous work on interactions between aggregates hovering on a hot surface[16] attributed interactions to gas flow from the Knudsen compressor effect within the aggregate. We speculate that these flows are still present for porous levitated ice particles, although without a surface nearby to build pressure against the situation is somewhat different. Nonetheless, the Knudsen compressor effect could lead to an inward flow of gas at the top of the lower particle, attracting the upper particle.

V. CONCLUSION AND FUTURE

In summary, we investigate levitation of ice particles based on the thermophoretic force. An experimental apparatus is employed which provides very robust levitation over a large range of pressure and temperature gradient. A stronger levitation is observed at higher temperature gradient and lower pressure, consistent with theory. Rich dynamics are observed at higher pressure when the particles experience dynamical instability, as well as when multiple ice particles interact, which results in collisions and merging. A detailed investigation of the motional instability may reveal critical behavior of Rayleigh-Bénard instability in a rarified gas.

Our experiment both provides an excellent platform to study the dynamics and formation of ice particles, and offers three-dimensionally trapped samples of solid water, in which other materials could be injected for potential chemical or biological study. Finally, the tunable pressure and temperature gradient in our system may also provide a desktop simulation of ice and snow dynamics in the atmosphere.

Acknowledgments

The authors wish to thank Joshua Nascimento and Li-Chung Ha for image analysis, and Logan Clark for careful reading of the manuscript. This work was supported by NSF MRSEC Grant No. DMR-1420709.

[1] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Science 2693, 198 (1995).
[2] K. B. Davis, M. -O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn and W. Ketterle, Phys.
Rev. Lett. 75, 3969 (1995).
[3] R.V. Krems, Phys. Chem. Chem. Phys. 10, 4079 (2008).
[4] D. Kielpinski, C. Monroe and D. J. Wineland, Nature 417, 709 (2002).
[5] A. Ashkin and Dziedzic J. M. Dziedzic, Appl. Phys. Lett. 19 283 (1971).
[6] C. Mund and R. Zellner, Chem. Phys. Chem. 4, 630 (2003).
[7] S. Kheifets, A. Simha, K. Melin, T. Li, and M. G. Raizen. Science 343 6178 (2014).
[8] V. Dhariwal, P. G. Hall, A. K. Ray, J. Aerosol. Sci. 24, 197209 (1993).
[9] M. V. Berry and A. K. Geim, Eur. J. Phys. 18 307 (1997).
[10] Y. Ikezoe, N. Hirota, J. Nakagawa and K. Kitazawa, Nature 393 749 (1998).
[11] R. E. Apfel, J. Acoust. Soc. Am. 49 145 (1971).
[12] E. G. Lierke, Acta Acustica united with Acustica 82 220 (1996).
[13] A. Ashkin and J.M. Dziedzic, Science 187 1073 (1975).
[14] T. Kelling, G. Wurm and C. Dürmann, Rev. Sci. Instrum. 82, 115105 (2011).
[15] M. Knudsen, Ann. Phys. (Leipzig) 336, 205 (1909).
[16] T. Kelling and G. Wurm, Phys. Rev. Lett. 103, 215502 (2009).
[17] G. Aumatell and G. Wurm, Monthly Notice of the Royal Astronomical Society, 437 690 (2014).
[18] G. Aumatell and G. Wurm, Monthly Notice of the Royal Astronomical Society 418 L1 (2011).
[19] A special case shown in Fig. 2 (a) inset is the 122 µm particle which floats higher than the 120 µm particle. A careful analysis of their sizes show that the aspect ratio of the 122 µm particle $\Delta x/\Delta h = 0.97$ is higher than that of the 120µm particle $\Delta x/\Delta h = 0.88$. The wider horizontal size of the 122 µm particle could explain its higher levitation height.
[20] F. Zheng, Adv. Colloid Interface Sci. 97, 255 (2002).