Variation of Susceptibility as Observed by Magnetic Levitation of Liquid Droplets

Toma Fujita, Ceco Dushkin, *† Masayoshi Nawa, and Seiichiro Nakabayashi
Department of Chemistry, Faculty of Science, Saitama University, 255 Shimo-ohkubo, Saitama, Saitama 338-8570;
†*Laboratory of Nanoparticle Science and Technology, Department of Inorganic Chemistry, Faculty of Chemistry, University of Sofia, 1 James Boucher Blvd., 1126 Sofia, Bulgaria*

(Received July 25, 2001; CL-010699)

The magnetic force is applied for the precisely controlled levitation of salt-containing water droplets in oil phase. This levitation phenomena analyses were achieved by the analytical calculation of the inhomogeneous space distribution of the field and force in the bore of a vertical superconducting magnet. The tiny effects on the droplet position are explained as variation of the diamagnetic susceptibility in the course of levitation.

Here we describe the application of a strong magnetic field to levitate a single water droplet (containing calcium chloride) suspended in an oil phase (benzyl ether) at various positions, where the magnetic force counterbalances the gravity force. Depending on the experimental conditions—droplet size and field strength—the droplets can locate at different heights within the zone of stable levitation, which is from z = 14.9 to 19.6 cm from the magnet center (Figure 1). Moreover, droplets of different sizes can reach different heights following complex trajectories of axial and radial motion from one quasi-equilibrium state to another one. Such levitating experiments differ very much from the stationary levitation of a liquid drop in air.[1–3] Their understanding and control are important for the engineering of ensembles of droplets[4] or other diamagnetic objects[5] in 3D-arrays. Another importance is coming from the possible changes of water-containing materials detected in a variety of systems imposed on magnetic or electromagnetic field (so called water memory effects).[6]

The experiments have been carried out in the inner side of a vertical superconducting magnet[7] JMTD-10T150 (Japan Magnet Technology) of bore diameter $2R_m$ = 15 cm and length L_m = 100 cm. The magnetic flux density B_0^0 at the magnet center z = 0, located 64.1 cm apart from the magnet top, can acquire a maximum value of 10 T.

To resolve the complexity of observed phenomena, two types of experiments have been carried out with droplets dropped from above in a glass cylinder of inner diameter 2.8 cm, coaxial to the magnet, containing 100 mL of oil: (i) Droplets with various volumes suspended in a magnetic field of fixed space distribution (constant B_0^0). After an oscillatory motion down and up certain quasi-equilibrium position is reached which seems to be dependent on the droplet size (Figure 2). Phenomenologically, this means increase of the apparent susceptibility $\Delta\chi$ with the position height z_0 in order to compensate the decrease of the local field $B_0(z)$ and, hence, of the magnetic force, $F(z) = (\Delta\chi V/\mu_0)B_0(dB_0/dz)$ and vice versa (Figure 2 inset). (ii) Droplet of fixed volume lifted up by the varying magnetic field B_0^0 (Figure 3). Each data point is collected after pre-equilibration of the system for at least 10 min from the establishment of the field value. Fluctuations around the quasi-equilibrium position z_0 make the data scattered, thus reflecting on the calculated values of $\Delta\chi$. Nevertheless, the size effect of minimum levitation position is readily seen for droplets of V ~1 mL (Figure 2); the droplets of V < 0.2 mL do not levitate.

The experiments (i) and (ii) reveal the susceptibility $\Delta\chi$ as apparent quantity, certainly dependent on the droplet volume and the magnetic field of levitation. The physico-chemical origin of apparent susceptibility anticipates the analogy with other quantities widely accepted in colloid chemistry such as the dynamic surface tension,[8] which may also play a role.[9] Indeed, the origin of size-dependent $\Delta\chi$ can be a surface term in the susceptibility, χ_{obj} or/and χ_{med}, stemming from the elongation of

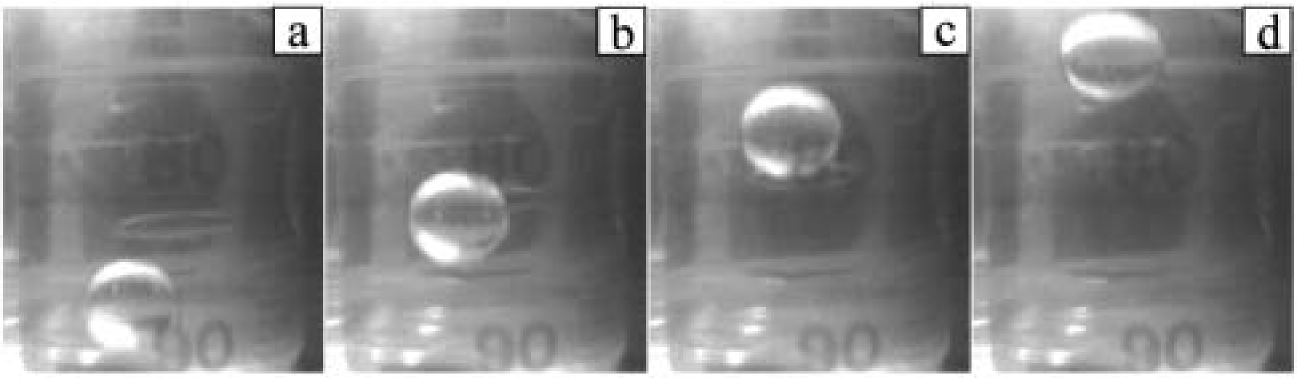

Figure 1. Photograph of a water droplet of volume V= 0.3 mL (mean radius R = 0.42 cm) levitating in oil. The successive photos are at different height z_0 from the magnet center at increasing magnetic field B_0^0: (a) z_0 = 18.5 cm, B_0^0 = 6.58 T (B_0 = 3.75 T); (b); z_0 = 19.3 cm, B_0^0 = 6.64 T (B_0 = 3.56 T); (c) z_0 = 20.0 cm, B_0^0 = 6.71 T (B_0 = 3.39 T); (d) z_0 = 20.7 cm, B_0 = 6.96 T (B_0 = 3.31 T). The CCD camera for monitoring the droplet motion is located in the magnet bore aside from the glass cylinder.

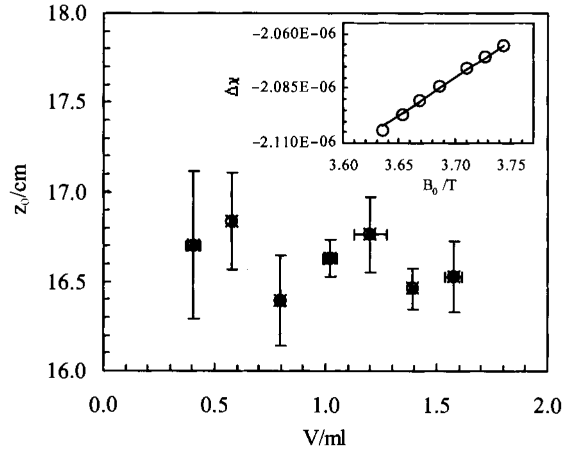

Figure 2. Vertical positions z_0 of water droplets of different volume V in magnetic field $B_0^0 = 5.675$ T (○ data point, × calculated value; V is measured by pipette and from video image). The bars represent statistical errors from three independent droplets of nearly the same sizes. The inset plots the calculated apparent susceptibility $\Delta\chi$ versus the local magnetic field $B_0(z_0)$ (errors to $\Delta\chi$ between 0.013×10^{-6} and 0.052×10^{-6}, not shown in the plot). The line is the data fit $\Delta\chi = -3.3539\times10^{-6}+3.4427\times10^{-7}B_0$ (in SI units; the dimensional coefficient is in T^{-1}).

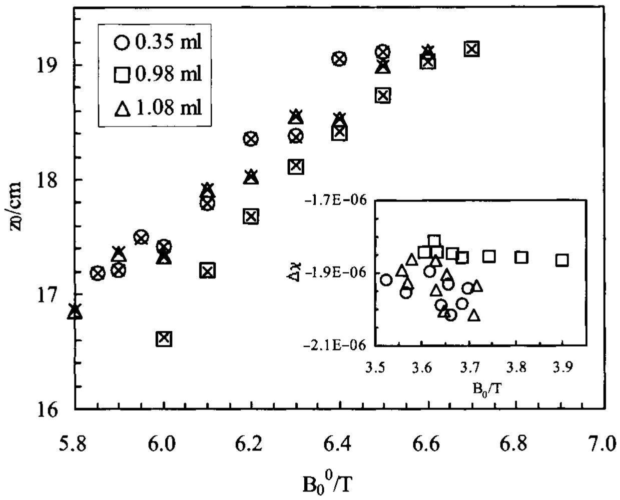

Figure 3. The positions of three droplets of different volumes plotted as a function of the central magnetic field B_0^0. The inset is the apparent susceptibility $\Delta\chi$ versus the local magnetic field B_0.

droplets in the direction of applied magnetic field (z-coordinate axis), proved already for ferromagnetic liquid drops.[9] In addition, inhomogeneous and alternating magnetic field can create eddy currents and induced magnetic moment in the charged moving droplets.[10] The detailed study whether these effects could explain the results (i) and (ii) is ongoing in this laboratory. It should address also the radial motion of droplets toward the magnet wall accompanying the axial levitation in case (ii).

To predict the profile of the magnetic field at the droplets positions we calculated the axial and radial magnetic field along the entire magnet using as the core equation that for a thick solenoid:

$$\frac{B_0(z)}{\tilde{B}_0} = (1+\zeta)\ln\frac{\tilde{\rho}+\sqrt{(1+\zeta)^2+\tilde{\rho}^2}}{\rho+\sqrt{(1+\zeta)^2+\rho^2}} + (1-\zeta)\ln\frac{\tilde{\rho}+\sqrt{(1-\zeta)^2+\tilde{\rho}^2}}{\rho+\sqrt{(1-\zeta)^2+\rho^2}}$$

Here, $\zeta = 2z/\tilde{L}_m$, $\rho = 2R_m/\tilde{L}_m$, and $\tilde{\rho} = 2\tilde{R}_m/\tilde{L}_m$, , where $\tilde{L}_m$ and $(\tilde{R}_m - R_m)$ are the effective length and width of the superconducting solenoid itself and.

$$\tilde{B}_0 = (B_0{}^0/2)/\ln[(\tilde{\rho}+\sqrt{1+\tilde{\rho}^2})/(\rho+\sqrt{1+\rho^2})].$$

The radial field dependence and values of model parameters will be published elsewhere. Then the droplet position z_0 is reconstructed from the numerical solution of the equations for B_0, F and G (Figure 4) at: $\mu_0 = 4\pi\times10^{-7}$ N/A^2, gravity force, $G = (\rho_{obj} - \rho_{med})gV$, gravity acceleration $g = 981$ cm/s^2, droplet density $\rho_{obj} = 1.047$ g/cm^3 (0.552 mol dm^3 water solution of $CaCl_2$) and oil medium density $\rho_{med} = 1.0318$ g/cm^3 (temperature 25 °C). Calcium salt is chosen due to the biological importance of Ca^{2+} ions in liquid compartments.[6] The difference, $\Delta\chi = \chi_{obj} - \chi_{med}$, above referred to as apparent susceptibility, is the adjustable parameter of calculations, with χ_{obj} and χ_{med} being the magnetic susceptibilities of levitating object (droplet) and continuous medium (oil phase), respectively.

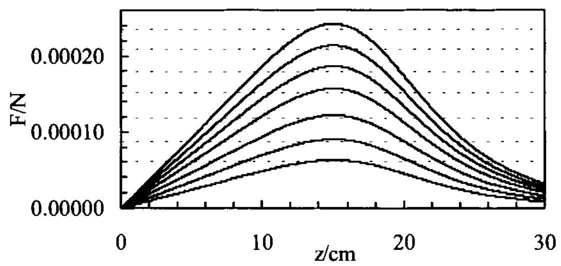

Figure 4. Illustration of the calculation procedure for obtaining z_0 as the crossing points of the magnetic force curves (solid) with the gravity force lines (dashed) for different droplets from Figure 2. From bottom to top, V is 0.41, 0.58, 0.8, 1.02, 1.2, 1.39 and 1.58 mL.

We gratefully acknowledge the RFTF (Research for the Future) program of the Japan Society for Promotion of Science for the financial support.

References

1 Y. Ikezoe, N. Hirota, J. Nakagawa, and K. Kitazawa, *Nature*, **393**, 749 (1998).
2 K. Kitazawa, Y. Ikezoe, H. Uetake, and N. Hirota, *Physica B*, **294-295**, 709 (2001).
3 E. Beaugnon, D. Fabregue, D. Billy, J. Nappa, and R. Tournier, *Physica B*, **294-295**, 715 (2001)
4 T. Fujita and S. Nakabayashi, in: Proc. Fourth Symposium on New Magnetoscience, Nov. 13-15, 2000, Omiya, Japan, p 421.
5 J. S. Brooks and J. A. Cothern, *Physica B*, **294-295**, 721 (2001).
6 M. Colic and D. Morse, *Colloids Surf. A*, **154**, 167 (1999).
7 S. Nakabayashi, R. Aogaki, U. Iguchi, and M. Nawa, *Chem. Lett.*, **1998**, 591.
8 Tz. H. Iliev and C. D. Dushkin, *Colloid Polym. Sci.*, **273**, 370 (1995).
9 S. Banerjee, M. Fasnacht, S. Garoff, and M. Widom, *Phys. Rev. E*, **60**, 4272 (1999).
10 L. M. Holmes, *J. Appl. Phys.*, **49**, 3102 (1978).