Colloids, Drops and Cells

胶体、液滴和细胞

By
Zhengdong Cheng
Liqun He
成正东 何立群 编著

University of Science and
Technology of China Press
中国科学技术大学出版社

当代科学技术基础理论与前沿问题研究丛书

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内 容 简 介

本书介绍了有关胶体及微流体的一些前沿研究内容，展示了最新的微、纳米水平上的实验和观察方法，有助于读者学习如何分析材料微观结构对宏观物理规律影响的现代研究方法。该书在内容上分为两部分，第一部分是胶体及微流体基本规律；第二部分介绍生物胶体的保存方法.

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编　委　会

总　　序

侯建国
（中国科学技术大学校长、中国科学院院士、第三世界科学院院士）

大学最重要的功能是向社会输送人才．大学对于一个国家、民族乃至世界的重要性和贡献度，很大程度上是通过毕业生在社会各领域所取得的成就来体现的．

中国科学技术大学建校只有短短的50年，之所以迅速成为享有较高国际声誉的著名大学之一，主要就是因为她培养出了一大批德才兼备的优秀毕业生．他们志向高远、基础扎实、综合素质高、创新能力强，在国内外科技、经济、教育等领域做出了杰出的贡献，为中国科大赢得了"科技英才的摇篮"的美誉．

2008年9月，胡锦涛总书记为中国科大建校五十周年发来贺信，信中称赞说：半个世纪以来，中国科学技术大学依托中国科学院，按照全院办校、所系结合的方针，弘扬红专并进、理实交融的校风，努力推进教学和科研工作的改革创新，为党和国家培养了一大批科技人才，取得了一系列具有世界先进水平的原创性科技成果，为推动我国科教事业发展和社会主义现代化建设做出了重要贡献．

据统计，中国科大迄今已毕业的5万人中，已有42人当选中国科学院和中国工程院院士，是同期（自1963年以来）毕业生中当选院士数最多的高校之一．其中，本科毕业生中平均每1,000人就产生1名院士和700多名硕士、博士，比例位居全国高校之首．还有众多的中青年才俊成为我国科技、企业、教育等领域的领军人物和骨干．在历年评选的"中国青年五四奖章"获得者中，作为科技界、科技创新型企业界青年才俊代表，科大毕业生已连续多年榜上有名，获奖总人数位居全国高校前列．鲜为人知的是，有数千名优秀毕业生踏上国防战线，为科技强军做出了重要贡献，涌现出20多名科技将军和一大批国防科技中坚．

为反映中国科大五十年来人才培养成果，展示毕业生在科学研究中的最新进展，学校决定在建校五十周年之际，编辑出版《中国科学技术大学校友文

库》，于2008年9月起陆续出书，校庆年内集中出版50种．该《文库》选题经过多轮严格的评审和论证，入选书稿学术水平高，已列为国家“十一五”重点图书出版规划．

入选作者中，有北京初创时期的毕业生，也有意气风发的少年班毕业生；有“两院”院士，也有IEEE Fellow；有海内外科研院所、大专院校的教授，也有金融、IT行业的英才；有默默奉献、矢志报国的科技将军，也有在国际前沿奋力拼搏的科研将才；有“文革”后留美学者中第一位担任美国大学系主任的青年教授，也有首批获得新中国博士学位的中年学者；……在母校五十周年华诞之际，他们通过著书立说的独特方式，向母校献礼，其深情厚意，令人感佩！

近年来，学校组织了一系列关于中国科大办学成就、经验、理念和优良传统的总结与讨论．通过总结与讨论，使我们更清醒地认识到，中国科大这所新中国亲手创办的新型理工科大学所肩负的历史使命和责任．我想，中国科大的创办与发展，首要的目标就是围绕国家战略需求，培养造就世界一流科学家和科技领军人才．五十年来，我们一直遵循这一目标定位，有效地探索了科教紧密结合、培养创新人才的成功之路，取得了令人瞩目的成就，也受到社会各界的广泛赞誉．

成绩属于过去，辉煌须待开创．在未来的发展中，我们依然要牢牢把握“育人是大学第一要务”的宗旨，在坚守优良传统的基础上，不断改革创新，提高教育教学质量，早日实现胡锦涛总书记对中国科大的期待：瞄准世界科技前沿，服务国家发展战略，创造性地做好教学和科研工作，努力办成世界一流的研究型大学，培养造就更多更好的创新人才，为夺取全面建设小康社会新胜利、开创中国特色社会主义事业新局面贡献更大力量．

是为序．

2008年9月

Preface

Zhengdong Cheng

Model colloids, especially colloidal hard spheres are used as examples to introduce to the readers the fundamental questions, such as crystallization and glass transition that are being asked in soft-condensed matter physics and chemical engineering. Modern techniques for manipulating and probing colloids and cells, such as microfluidics, laser tweezers, microrheology are demonstrated, as well as the applications of colloids to nanotechnology, biotechnology and information technology. The storage is a vital process for study of biocolloids, such as living cells. We introduce here two routine approaches to long term preservation of biocolloids, low temperature storage and dry-state storage.

The readers intend to be undergraduate students who are interested in research in complex fluids, as well as young scientists and researchers. Most of the materials are extracted from the research field where the first author has performed his Ph. D and postdoctoral training at Princeton, Harvard, and ExxonMobil Research and Engineering Company, and is leading an active research group at Texas A & M University. He specially thanks his former advisors, Prof. Paul Chaikin, Bill Russel, David Weitz, and Tom Mason. Other materials of the biocolloids are extracted from the research conducted in the laboratory of the second author.

This book is a special dedication to USTC, where the first author, Zhengdong Cheng, graduated from the Modern Physics Department in 1993, and the other, Liqun He, is now working at the department of Thermal Science and Energy Engineering, in the occasion celebrating her 50th birthday.

Contexts

Preface to the USTC Alumni's Series ······ i
Preface ······ iii

Chapter 1 What Are Colloids? ······ 1
1.1 Colloids and the atoms: counting the atoms ······ 1
1.2 Micro-rheology—Probe the material properties at microscopic level ······ 3
1.3 Laser tweezers—Apply external force to nanoparticles ······ 6
1.4 Colloids ······ 9
1.4.1 Miniature of the physical world and tangible models of the atomic world ······ 9
1.4.2 "Inteligent" colloids ······ 13
Chapter 2 Colloids and Phase Transitions ······ 15
2.1 The hard sphere model ······ 17
2.1.1 The van der Waals picture of fluids ······ 17
2.1.2 Close packing of spheres as the principle of crystal structure ······ 18
2.1.3 Hard sphere model for disorder-order transition ······ 20
2.2 Model colloidal hard sphere systems ······ 21
2.2.1 Minimizing van der Waals interaction by refractive index matching ······ 21
2.2.2 Stabilization ······ 21
2.2.3 Model Colloidal Hard Spheres ······ 24
2.3 Properties of hard sphere dispersions ······ 24
2.3.1 Phase behavior ······ 24
2.3.2 Equation of state (continuing Perrin's measurement at higher

concentrations) ······ 28
2.3.3 Rheology of the fluid and metastable fluid states ······ 30
2.3.4 Crystal structures ······ 36
2.3.5 Crystallization kinetics ······ 38
2.4 Colloids in space ······ 41
2.4.1 Surprising observations ······ 41
2.4.2 Crystallization kinetics ······ 43
2.5 Confocal Imaging: Catch the critical nucleus ······ 45
2.6 How well do we understand nucleation? ······ 48
2.7 Applications of colloidal crystals ······ 50
2.8 Single crystal growth in a temperature gradient ······ 51
Chapter 3 Microfluidics ······ 54
3.1 Make emulsions drop by drop ······ 54
3.2 Emulsion crystallization to measure the nucleation rate of colloidal crystallization ······ 58
3.3 Living cell encapsulation ······ 61
3.3.1 Colloidosomes ······ 63
3.3.2 Layer by layer coating ······ 64
3.3.3 Agarose droplets generation ······ 65
3.3.4 Yeast cell encapsulation ······ 67
3.3.5 Tailor the transport property of the microencapsules by LbL coating ······ 68
3.3.6 Enhancement of the mechanical stability of the microencapsules by nano-particle coating (Colloidosomes) ······ 69
3.4 Cell manipulation by microfluidics ······ 71
Chapter 4 Biocolloids ······ 73
4.1 Biocolloids ······ 73
4.2 The cell volume change before freezing ······ 76
4.2.1 The equilibrium volume of a cell ······ 77
4.2.2 The non-equilibrium volume of a cell ······ 80
4.3 The change of cell volume during cooling/freezing ······ 82
4.3.1 Rapid cooling ······ 83
4.3.2 Slow cooling ······ 85
4.3.3 Optimal cooling ······ 85
4.3.4 Modeling the volumetric response of a cell to freezing ······ 86
4.4 Other mechanisms of cryoinjury ······ 89

4.4.1 Cryoinjury during the Storage Period ··· 89
4.4.2 Cell injuries in the warming process ··· 90
4.4.3 "Cold Stock" Injury ··· 90
4.5 Banking cells at their dried state ··· 91
4.5.1 Brief History of Freeze Drying ··· 91
4.5.2 Freeze-Drying Process and Its Control ··· 94
4.5.3 Some cells having been dried ··· 95
Reference ··· 100

Chapter 1 What Are Colloids?

1.1 Colloids and the atoms: counting the atoms

For most of us, the first thing to learn in school is to *count*. Let's consider to account small things such as molecules. The idea that matter was composed of minute components (atoms) that was not capable of subdivision without limit goes back to the Greek philosophers Leucippus and Democritus. The unit for counting the amount of substance in International System of Units is the mole. The number of carbon atoms in 12 grams of unbound carbon - 12 is 1 mol, which is called Avogadro's constant. In 1811, Avogadro published a paper in French on determining the relative masses of the elements and their proportions by which they enter into their compounds, he coined the word *molecule* (diminutive of the Latin *mole*, a mass) for the smallest particle that normally exists in a free state. Avogadro's hypothesized that equal volumes of all gases at the same temperature and pressure contain the same number of molecules. He applied this principle to the determination of the relative masses of gas molecules; the ratios of the masses of the molecules are the same as the ratios of the densities of the different gases at the same temperature and pressure. Avogadro's Constant $N_A = (6.022,141,79 \pm 0.000,000,30) \times 10^{23}\ mol^{-1}$. This number equals the ratio of the molar mass to the molecular mass. Its great importance is that it provides a link between the properties of individual atoms or molecules and the properties of the bulk matter. For example, it links the energies of individual atoms and molecules, which can be determined from spectroscopy, to the thermodynamic energies of bulk matter which are obtained from calorimetric experiments.

The number of particles in a given volume of an idea gas is $n_0 = RT/P$, equals to $(2.686,777,3 \pm 0.000,004,7) \times 10^{25}\ m^{-3}$ at 273.15 K and 101.325 kPa with T the temperature and P the pressure. The gas constant R is related to the Avogadro constant by the Boltzmann constant, $R = N_A k_B$. One way to measure Avogadro's constant is using the Brownian motion of colloids, which won the 1926 Nobel Prize for Perrin.

Figure 1.1 Robert Brown (1773 - 1858), discoverer of Brownian motion①

The kinetic theory of Brownian motion was developed by Einstein[5] and Smoluchowski.[6] Einstein did a statistical analysis of molecular motion and its effect on particles suspended in a liquid. From this analysis he calculated the mean square displacement of these particles. He argued that observation of this displacement would allow an exact determination of atomic dimensions. He also recognized that failure to observe this motion would be a strong argument against the molecular-kinetic theory of heat. In 1908 Perrin[7,8] first used this theory to determine Avogadro's constant. Now, a undergraduate level experiment using automated-computer based video microscopy of 1.02 micron Polystyrene particles can be used to obtain an estimate of Boltzmann's constant k_B which is good to within 5%.[9]

Perrin was the first person to exploit model colloids.[10] The word "colloid" derives from the Greek for glue by Thomas Graham in 1861.[11] In 1909, Perrin let nearly equal-sized emulsion droplets suspended in water to reach sedimentation equilibrium in gravity. He prepared these monodisperse

① Robert Brown[3] (Dec. 21, 1773 - June 10, 1858) is a British botanist. In 1827, while examining pollen grains and dust suspended in water under a microscope, Brown observed the minute particles executing a continuous jittery motion. Although he himself did not provide a theory to explain the motion, the phenomenon is now known as Brownian motion in his honor. The suspended particles do not play an essential part in the movement, but only make manifest the internal agitation of the liquid, provide a direct and visible proof of the real exactness of our hypothesis concerning the nature of heat (Gouy, 1888[4]). You can explore Brownian motion via the following website: http://www.aip.org/history/einstein/brownian.htm.

colloids of a gum (gamboges) by elaborate fractional centrifuging. By direct observation in a microscope, he verified that the density profile of this "atmosphere" of these colloidal particles obeyed the Boltzmann distribution

$$n(z) = n(0)e^{-\frac{mgz}{k_B T}},$$

where $n(z)$ is the number of particles at elevation of z in Earth gravity g.

So, he provided the first reasonably direct estimate of Boltzmann's constant k_B. Perrin's beautiful experiment clearly recognized that colloidal suspensions are "thermodynamic systems" in which thermally induced Brownian motion plays a central role. Colloidal particles behave like very large atoms.

Back in 1905, many scientists, such as Mach and Ostwald, considered energy the fundamental physical reality and regarded atoms and molecules as mathematical fictions. Perrin's observations enabled him to estimate the size of water molecules and atoms. This was the first time the size of atoms and molecules could be reliably calculated from actual visual observations. Perrin's work helped raise atoms from the status of useful hypothetical objects to observable entities whose reality could no longer be denied.[12]

1.2 Micro-rheology

— Probe the material properties at microscopic level

Rheology is the study of the deformation and flow of matter[13] under the influence of an applied stress.[14] The term *rheology* was coined 1920 by Eugene Bingham, a professor at Lehigh University from a suggestion by a colleague Markus Reiner. The term was inspired by Heraclitus' famous expression *panta rei*, "everything flows". The geological viscous flow of solid Earth materials is known as rheids. Hemorheology is the study of blood flow which has an enormous medical significance. Rheology modifiers are a key element in the development of paints and help get the oil out of the ground. Rheology also characterizes the property of the spider silk, the strength of a single carbon nanotube.

Einstein was the first to understand that the basic quantity in Brownian motion was not the average velocity of the particles,[15] but their mean square displacement in a given time $[R^2(t)]$. The mean displacement $[R(t)]$ of a large number of particles is zero in the case of a truly random walk (Fig. 1.2), so it is the mean square which is the meaningful quantity. Let's use Paul Langevin's derivation here.[16] According to the theorem of the equipartition of the kinetic energy among the various degrees of freedom of a system in thermal equilibrium, there is an average kinetic energy $RT/2N_A$ for motion in a given direction at temperature T. A particle moving with in a liquid at the speed $\frac{dx}{dt}$ experiences a viscous resistance that equals to $6\pi\mu a\frac{dx}{dt}$ according to Stokes' law, where μ is the viscosity of the liquid, a is the radius of the particle. The equation of motion in the x direction is

$$m\frac{d^2x}{dt^2} = -6\pi\mu a\frac{dx}{dt} + F.$$

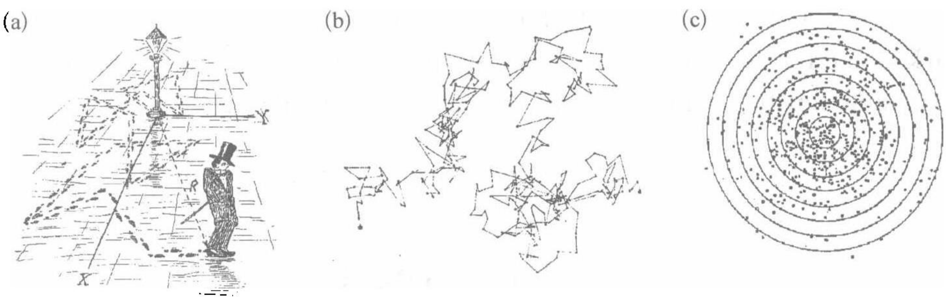

Figure 1.2 Random walk and Brownian motion

(a) Random walk according to Gamov.[1] (b) a trajectory of a Brownian particle. (c) statistical distribution of displacements.[2]

Where m is the mass of the particle, F is the fluctuation force. Multiplied by x, this equation may be written as

$$\frac{m}{2}\frac{d^2x^2}{dt^2} - m\left(\frac{dx}{dt}\right)^2 = -3\pi\mu a\frac{dx^2}{dt} + xF.$$

We will consider a large number of identical particles and take the mean value of each term in the equation, using $\langle xF\rangle = 0$ and $\left\langle m\left(\frac{dx}{dt}\right)^2\right\rangle = \frac{RT}{N_A}$

$$\frac{m}{2}\frac{d\left\langle\frac{dx^2}{dt}\right\rangle}{dt} + 3\pi\mu a\left\langle\frac{dx^2}{dt}\right\rangle = \frac{RT}{N_A}.$$

The general solution is

$$\left\langle \frac{\mathrm{d}x^2}{\mathrm{d}t} \right\rangle = \frac{RT}{N_A} \frac{1}{3\pi\mu a} + ce^{-\frac{6\pi\mu a}{m}t}.$$

At the time regime that the Brownian motion is observed, $t \approx 10^{-8}$ seconds

$$\left\langle \frac{\mathrm{d}x^2}{\mathrm{d}t} \right\rangle = \frac{RT}{N_A} \frac{1}{3\pi\mu a}.$$

Hence for a time interval τ

$$\langle x^2 \rangle - \langle x_0^2 \rangle = \frac{RT}{N_A} \frac{1}{3\pi\mu a}\tau.$$

Since $x = x_0 + \Delta_x$ for the displacement Δ_x

$$\langle \Delta_x^2 \rangle = \frac{RT}{N_A} \frac{1}{3\pi\mu a}\tau.$$

which is the result first derived by Einstein.

For diffusion

$$\langle \Delta_x^2 \rangle = 2D\tau.$$

Where, D is the diffusion coefficient for the particle in the liquid. Therefore we arrive at the Stokes-Einstein equation

$$D = \frac{k_B T}{6\pi\mu a}$$

Let's rewrite it as

$$\mu = \frac{k_B T}{6\pi D a} = \frac{k_B T}{3\pi \frac{\langle \Delta_x^2 \rangle}{\tau} a}.$$

This formula states that we can measure the viscosity (rheology properties) of the liquid in which the particles are suspended by observing the mean square displacement as a function of time. This is the starting point of a modern technique called microrheology.[17-19] (Fig. 1.3).

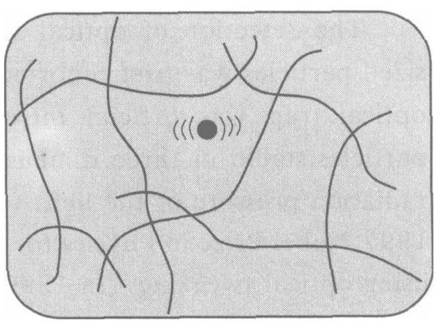

Figure 1.3 Microrheology

Tracking motions of tracer particles embedded in a complex fluid, analysis yields viscoelastic properties of the fluid.

In conventional rheology, millimeter-or centimeter-size plates, cylinders, and other geometries are used to apply deformations and measure stress. In the passive microrheology, thermal agitation spontaneously generate stress locally, and the nanometer-scale deformation are monitored by dynamic light scattering[17] or by laser interferometry.[20] In the second category of microrheology, the active microrheology, optical traps or other external forces are used to apply oscillatory forces onto probe particles. The displacements of these particles allow the frequency-dependent viscoelasticity of the micrometer-scale environment to be measured.[20] Among the applications of microrheology, we can explore the micro-world inside the living cells.[21, 22]

1.3 Laser tweezers

— Apply external force to nanoparticles

Laser tweezers[23] provide the unique ability to manipulate microscopic particles dispersed in a liquid medium and to measure small forces on those particles in a non-intrusive and non-destructive manner. They use the forces exerted by a tightly focused beam of light via a high numerical number lens to trap and move objects ranging in size from tens of nanometres to tens of micrometres. Laser tweezers can stably trap thin coinlike microdisks in 3D with an edge-on orientation.[24, 25] Scattered light forms a streak which can be tracked using a fast camera to measure the disk's angular displacement. Circularly polarized tweezers rotate the disk and streak, yielding a colloidal lighthouse (Fig. 1.4, adopted from[23]).

The detection of optical scattering and gradient forces on micrometer sized particles was first reported in 1970 by Askin from Bell Labs.[26] The optical trap was official introduced in 1986[27] which capable holding particles stable in three dimensions when the gradient force wins over the radiation pressure of the light (see Fig. 1.4). Steven Chu was awarded the 1997 Nobel Prize in Physics for his research on cooling and trapping of atoms using optical tweezing. In 1990s, Carlos Bustamante, James Spudich, and Steven Block pioneered the use of optical trap force spectroscopy to characterize molecular-scale biological motors at the single-molecule level, leading to a better understanding of the stochastic nature of these force-generating molecules.

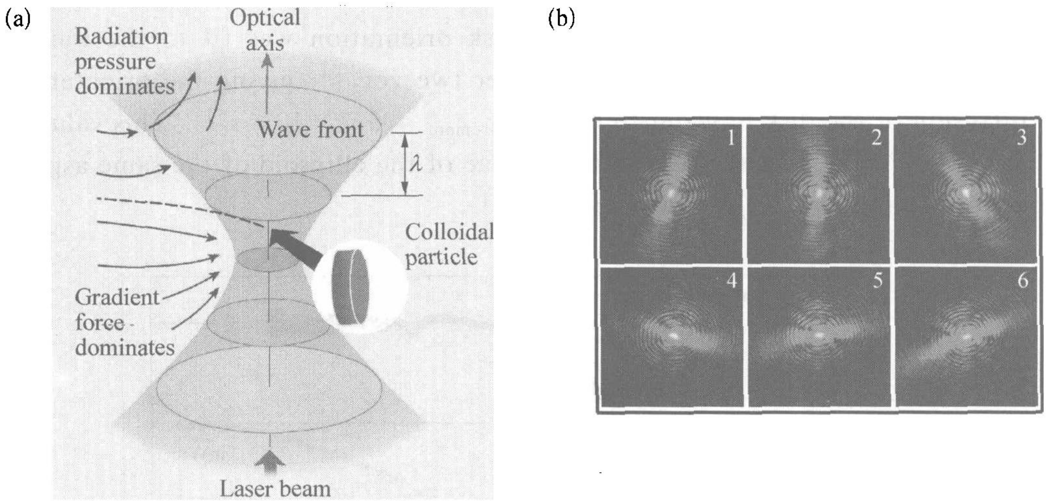

Figure 1.4 Colloidal lighthouse (refer to the Color Page 1)

Rotation of a microdisk in a laser tweezer. Separation between frames is 1/6 second.

Linearly polarized tweezers rotationally trap a birefringent disk, of which the harmonically-bound Brownian rotation was measured over a few decades in time. As seen from Fig. 1.5, the refracted laser light from the disk forms a two "wings" extending from disk to the outer space in parallel to the body of the disk. By defining the axial central line of the refracted light, a natural optical lever was found to measure the disk's orientation θ_{α}, the angle

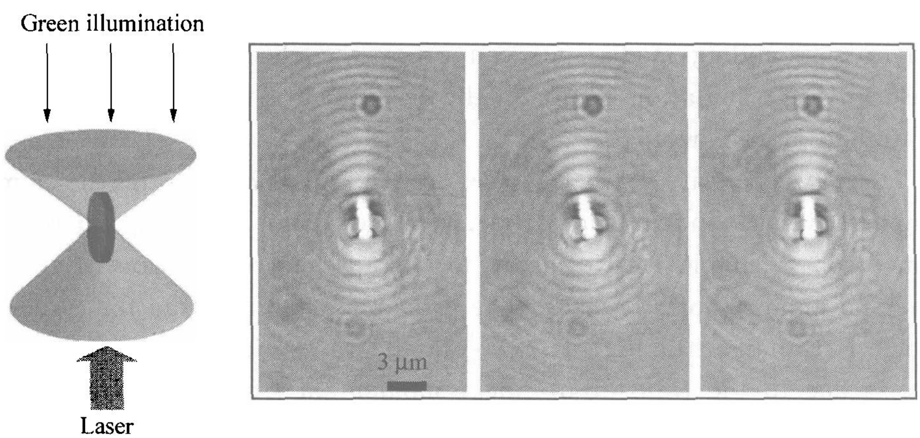

Figure 1.5 A colloidal disk trapped in a linearly polarized light (refer to the Color Page 1)

The right three micrographs were the top-views of the trapped disk. The polarization of the laser was vertical and parallel to the page.