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Research Progress on Particle Behavior and Dynamics in Optical Tweezers

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Abstract: Optical tweezers technology utilizes the optical potential well generated by a focused laser beam to achieve precise manipulation of micro and nanoparticles. Based on the optical tweezers platform, the motion behavior and dynamic laws of particles are deeply studied, which can reveal the transport mechanism of complex systems. Based on summarizing the principles and experimental methods of optical tweezers technology, this article systematically summarizes the typical force characteristics of particles in optical tweezers, focusing on the dynamic research progress of single particle non-equilibrium state, double particle coupling, and multi-particle cluster system, laying a theoretical foundation for expanding the application of optical tweezers technology in physics, chemistry, biology, and other fields.

Keywords: Optical tweezers; Particle manipulation; Brownian motion; Non-equilibrium state; Coupling dynamics

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1. Introduction

Since its inception in 1986, optical tweezers technology has been widely used in micro nanoparticle manipulation and property characterization due to its unique non-contact manipulation capability and nanoscale spatial resolution. Especially in recent years, the combination of optical tweezers with pump-probe spectroscopy, microfluidic chips, and other technologies has provided new research ideas and experimental methods for studying the transport behavior of particles in complex environments and revealing their underlying dynamic mechanisms. Based on reviewing the development of optical tweezers technology, this article will focus on exploring the typical behavioral characteristics and dynamic models of particle systems in optical tweezers, to provide a reference for a deeper understanding of the physical mechanisms of particle manipulation and to expand the application of optical tweezers technology in cutting-edge interdisciplinary fields.

2. Principles and experimental methods of optical tweezers technology

2.1. Basic composition of optical tweezers system

The core of the optical tweezers system is a highly focused laser beam. When the laser beam is focused on a small particle, the refractive index difference between the particle and the surrounding medium causes the incident photon to interact with the particle, resulting in a change in momentum. According to the law of conservation of momentum, the particle will experience a force in the opposite direction of light propagation. When the optical tweezers force reaches equilibrium with the gravity of the particles, the particles are confined near the optical focal point, forming a stable three-dimensional optical potential well [1].

A typical optical tweezers system mainly consists of a laser, focusing objective lens, sample cell, position-sensitive detector, etc. The laser provides a continuous Gaussian laser beam, which is focused by the objective lens a few microns above the particles to be captured, forming an optical potential well. The particles are captured and suspended in the sample pool under the action of optical tweezers. By controlling the polarization state, power, wavelength, and other parameters of the incident beam, precise control of the particle capture position and force can be achieved [2].

2.2. Theoretical calculation model of optical tweezers force

In optical tweezers systems, accurately estimating the magnitude of the optical tweezer force acting on particles is crucial for achieving particle manipulation. According to the Mie scattering theory, when the particle size is much smaller than the wavelength of the incident light, the Rayleigh approximation can be used to describe the interaction between particles and the optical field. Assuming the polarizability of a single isotropic spherical particle is α, the environmental dielectric constant is ε, and the incident light intensity is *I*, the optical tweezer force *F* acting on the particle can be expressed as a gradient of light intensity: $\vec{F} = \frac{1}{2}\alpha\nabla\left(\frac{I}{c\varepsilon}\right)$ Where c is the speed of light.

The optical tweezer force exerted on particles in the Rayleigh region is directly proportional to the intensity of the incident light. When the particle size is equal to or larger than the wavelength, strict Mie scattering theory needs to be used for calculations, simplifying the incident light into an infinitely extended plane wave. When the light is incident on the surface of the particle, some of it is reflected, while the rest is refracted into the interior of the particle. Considering the absorption and multiple scattering effects of particles on light, the resultant force exerted on particles can be further decomposed into two components: scattering force directed towards the direction of light propagation and gradient force directed towards the direction of light intensity gradient. Scattering force drives particles to move along the direction of light propagation. Gradient force provides lateral constraint, trapping particles at the point of maximum light intensity, and the combined force of the two forces determines the equilibrium position of the particles in the optical tweezers system [3].

2.3. Experimental methods for particle capture and manipulation

Based on the optical tweezers system, precise manipulation of single and multiple particles can be achieved. Its core is to modulate the spatiotemporal distribution of the incident light field, apply precise and controllable optical tweezer forces, and guide the migration and assembly of particles.

For single particle systems, directional transport of particles can be achieved by controlling the polarization state of the incident beam and utilizing the anisotropy of the optical tweezers potential well. If radially polarized light is used to form an asymmetric optical tweezers array in the horizontal plane of the sample cell, it can induce particles to migrate in a specific direction [4].

For multi-particle systems, spatial light modulators can be used to dynamically control the incident light wavefront. Real-time modification of the shape, size, and arrangement of the optical tweezers array enables precise assembly and manipulation of particles. For example, computer-generated holograms can be used to modulate the incident Gaussian light wave, projecting light intensity distributions of any shape such as circular or spiral on the surface of the sample pool, thereby controlling the spatial arrangement and combination of particles. Constructing microstructures with specific patterns, introducing time-dependent terms to incident light using acousto-optic modulators, and dynamically controlling the assembly process of particles in real-time [5]. Machine vision feedback is also an important means to improve the spatiotemporal resolution of particle manipulation. Real-time particle motion images are collected by high-speed CCD cameras and combined with digital image processing algorithms to track particle position and velocity in real-time, obtain information such as particle spatiotemporal trajectories, and integrate visual feedback signals into closed-loop control systems. By adjusting the magnitude and direction of the optical tweezers force in real-time, precise servo control of individual and multiple particles can be achieved, enabling them to move along predetermined trajectories and significantly improving the spatiotemporal resolution of particle manipulation [6].

3. Typical behavioral characteristics of particles in optical tweezers

3.1. Brownian motion and fluctuations of particles

Small particles in the suspended liquid will be randomly impacted by the thermal motion of surrounding solvent molecules, exhibiting irregular Brownian motion. Even if a single particle is confined in an optical tweezers potential well, it will still undergo restricted Brownian motion near the center of the potential well. Its position and velocity fluctuate over time, and the movement of particles is influenced by the combined effects of solvent viscosity resistance, optical tweezers binding force, and random collisions of solvent molecules. By analyzing these factors, we can better understand the restricted Brownian motion characteristics of particles in potential wells and provide a theoretical basis for related research.

Solving the stochastic differential equation can obtain the root mean square value of the particle displacement χ, which reflects the amplitude of the fluctuation of the particle around the binding center: $\sqrt{\langle x^2 \rangle} = \sqrt{\frac{k_B T}{\kappa}}$. It can be seen that the fluctuation amplitude of particles is directly proportional to the square root of the system temperature and inversely proportional to the square root of the stiffness of the optical tweezers. By analyzing the time series of particle displacement, it can characterize the characteristics such as the binding strength of the optical tweezers potential well, and can also be used to detect the spatiotemporal fluctuations of local environmental temperature [7].

The restricted diffusion motion of particles in the potential well also satisfies the Einstein-Smoluchowski relationship: $D = \frac{k_B T}{\gamma} = \frac{k_B T}{6\pi\eta a}$ Among them, D is the diffusion coefficient of the particle, η is the fluid viscosity, and α is the particle radius. By measuring the change of the particle's mean azimuthal shift with time, the diffusion coefficient of the particle can be directly calculated, and the microenvironment parameters of the local fluid can be quantitatively characterized, providing a new idea for quantitative analysis of particle fluid interactions.

3.2. Interaction forces between particles

When capturing multiple particles, additional interaction forces are generated between adjacent particles due to the interaction of the scattering field. For two spherical dielectric particles with a radius of a and a distance of *r*, the classical dipole approximation theory provides that the interaction potential energy *U(r)* between particles can be expressed as: $U(r) =- \frac{A}{r^6} + \frac{B}{r^{12}}$ The first term is the attractive potential caused by dispersion force, the second term is the repulsive potential, and A and B are constants related to particle properties.

This potential energy form is similar to the Lanner-Jones potential, with an equilibrium distance where two particles are balanced and form a stable bound state. By adjusting the particle spacing, the particles can be induced to self-assemble and form composite structures such as dimers [8].

When the particle spacing is small to a certain extent, the high-order multipole moment effect of the scattering field becomes non-negligible. The latest research shows that high dielectric constant particles will excite significant beam self-focusing effect inside the particles under the action of a strong focusing laser field, resulting in uneven distribution of the scattering field, which induces the particles to produce additional dipole moments and exhibits excellent scattering force characteristics along the optical axis. Theoretical analysis shows that this force is proportional to the fourth power of the particle radius and plays a key role in the stable confinement of submicron particles. The multiple polar moment interactions induced by scattering fields have become a new factor affecting the stability of complex particle systems [9].

3.3. Particle migration induced by optical tweezers potential well

Based on the asymmetry of optical tweezers force, optical tweezers technology can be used to manipulate the directional migration of particles. According to the Maxwell stress tensor method, the optical force acting on particles can be expressed as the integral of the electromagnetic field on the particle surface: where T is the Maxwell stress tensor and S is any closed surface surrounding the particle.

For an ideal symmetric optical field, the particle experiences zero resultant force and is in a state of force equilibrium, but in practical optical tweezers systems. When the focused light field is transmitted in a medium, distortion occurs, and the axial light intensity distribution becomes asymmetric, resulting in additional scattering forces along the direction of light propagation on the particles. When the pushing effect of the scattering force exceeds the binding effect of the gradient force, the particles will detach from the potential well and migrate along the direction of light propagation.

To achieve flexible and controllable direction and rate of particle migration. Dynamic control of the spatial distribution and polarization state of the incident light field is required, such as using a liquid crystal spatial light modulator to spiral phase modulate the wavefront of a Gaussian beam, forming a vortex optical trap array with rotational symmetry of light intensity distribution in the sample plane. The captured particles will migrate along a circular orbit under the action of rotational light torque, and the migration speed can be dynamically controlled by adjusting the light intensity and polarization state.

4. Research progress on particle dynamics of optical tweezers

4.1. Single particle non-equilibrium dynamics

By binding a single particle in an optical tweezers potential well and modulating the binding potential over time, the particle can move away from the thermodynamic equilibrium state and exhibit unique transport behavior. Theoretical studies have shown that in a potential well where the stiffness of the optical tweezers is periodically modulated over time. The motion of particles satisfies the generalized Langevin equation:$m \cdot \frac{d^2x(t)}{dt^2} =- \gamma \cdot \frac{dx(t)}{dt} - \kappa \cdot x(t) + \sqrt{2k_B T\gamma} \cdot \zeta(t)$ The potential well stiffness $\kappa(t)$ exhibits a periodic function.

Numerical simulations have found that there is a synchronization phenomenon between the migration direction of particles and the modulation frequency of the driving force. At a specific frequency, particles mainly undergo directional migration along the stiffness gradient direction of the optical tweezers, and there is an optimal modulation frequency at which the particle transport efficiency is highest. Unbalanced modulation optical tweezers provide a new driving mechanism for particle transport [10].

Further research has shown that periodic modulation optical tweezers can also induce random resonance phenomena in particles by periodically modulating the electric field component of incident polarized light. A bistable potential well that evolves can be constructed, and under appropriate noise intensity, the transition rate of particles between bistable states is synchronized with the driving modulation, thereby significantly enhancing transport efficiency. The synergistic effect of non-equilibrium driving and noise can greatly amplify the weak transport response inherent in the system, which provides a new idea for using optical tweezers to construct artificial brown noise environments and study the stochastic resonance effect of particle transport.

4.2. Double particle coupled motion behavior

When capturing two particles in adjacent optical tweezers potential wells, the dual particle system exhibits distinct linkage behavior compared to a single particle due to the interaction of scattering fields and the coupling effect of surrounding fluids. Experimental studies have found that when two identical micron-sized polystyrene spheres are captured in dual-beam optical tweezers at a certain angle. The two spheres exhibit synchronous periodic oscillations along the optical axis, and their oscillation amplitude and frequency are closely related to the angle between the light beams.

Theoretical analysis shows that when two beams of light overlap in space, the scattered light field produces a significant self-focusing effect between the two microspheres. Causing additional light pressure, thereby inducing oscillatory motion between the two balls.

The fluid coupling effect in the dual particle system is also an important factor affecting the dynamic behavior of particles. The latest research used optical tweezers technology to study the Brownian motion of two colloidal microspheres in viscoelastic fluids and found that when the two microspheres approach a certain distance [11]. Their Brownian motions are no longer independent of each other, but show a clear correlation, exhibiting a synergistic diffusion phenomenon. The motion of each microsphere will excite viscoelastic stress waves in the surrounding fluid. When two microspheres are very close, the stress waves will couple with each other, transferring momentum between the two microspheres, thus causing the correlation between the motion of the two microspheres. By measuring the cross-correlation function of particle displacement, microrheological parameters such as the viscoelastic relaxation time of fluid media can be quantitatively extracted. The dual particle system has opened up new research ideas for the micro-viscoelastic characterization of complex fluid materials.

4.3. Dynamics model of multi-particle cluster

Under the action of a strong focusing optical tweezers field, a large number of particles spontaneously form complex cluster structures under the interaction of multiple scattering forces and gradient forces [12]. In the experiment, a large number of polystyrene microspheres were captured by an optical tweezers array, and it was found that the microspheres moved randomly in the potential well, gradually aggregated, and finally formed island-shaped cluster structures.

Theoretical analysis reveals that the fluctuations in particle density satisfy the Cahn-Hilliard equation:

$\frac{\partial \phi}{\partial t} = \nabla \cdot [M \cdot \nabla \mu]$ Among them, φ is the particle density, *M* is the mobility, and μ is the chemical potential. Further consideration is given to the interaction force exerted by optical tweezers on particles and the density fluctuations caused by Brownian motion. The dynamic process of particle cluster formation can be quantitatively described. Studies have shown that by optimizing the optical field distribution parameters of the optical tweezers array, the morphology of the cluster structure formed by particle self-assembly can be controlled, providing a new approach for the preparation of functionalized colloidal materials.

Introducing active particles into the optical tweezers system provides a new approach for constructing thermodynamic open systems. By modifying the surface of the particles with light-driven molecular motors, the particles can continuously absorb energy from the environment under illumination, overcoming viscous dissipation. To maintain the system in a steady state far from equilibrium, the dynamic behavior of this active particle system can be quantitatively described by a continuum model as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

$$\rho \left(\frac{dv}{dt} + v \cdot \nabla v \right) = -\nabla p + \eta \nabla^2 v + f$$

Among them, ρ is the particle density field, v is the velocity field, ρ is the pressure, η is the viscosity, and f is the random force including self-driving force and noise, in a steady state. The density and velocity fluctuation spectra of particle clusters are directly related to the statistical characteristics of particle self-driving velocity and noise. Active particle systems exhibit novel dynamic behaviors that differ from classical Brownian particle systems, such as sustained directional transport, large density fluctuations, and self-organizing pattern formation. Optical tweezers technology is an ideal model for studying statistical physical laws far from equilibrium systems. It provides a powerful tool for constructing and manipulating thermodynamic open systems at the microscale and is expected to deepen people's understanding of the physical mechanisms of non-equilibrium phenomena commonly present in living systems as shown in **Figure 1**.

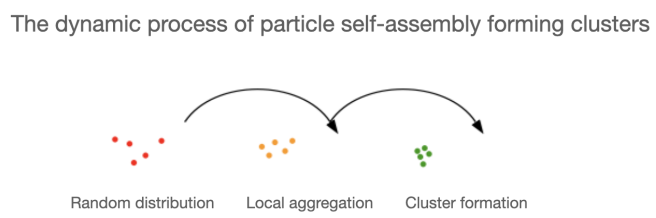

Figure 1. Schematic diagram of the formation process of multi-particle clusters under the action of optical tweezers

5. Conclusion

Optical tweezers technology, with its unique single particle manipulation and ultra-high spatial resolution imaging capabilities, has become a powerful tool for studying particle dynamics behavior. Based on a review of the development of optical tweezers technology, this article focuses on exploring the typical characteristics of particle forces in optical tweezers. Summarizing the research progress in single particle non-equilibrium transport, dual particle coupled motion, and dynamic models of multi-particle systems, these research works greatly expand people's understanding of the transport mechanism of complex particle systems, provide new ideas for developing new colloidal materials, constructing intelligent drug delivery systems, and revealing the working mechanism of intracellular molecular motors.

Looking ahead to the future, the integration of optical tweezers technology with micro-nano processing, surface plasmon resonance, microfluidic chips, and other technological means is expected to achieve multi-field coupling control of particle dynamics behavior, achieve integrated and intelligent particle manipulation, and promote innovative applications of optical tweezers in interdisciplinary fields such as physics, chemistry, and biology. Introducing optical tweezers into novel physical environments such as mixed dimensional systems and active substance systems provides a new research paradigm for studying non-equilibrium statistical physics developing biomimetic intelligent materials, and the development of optical tweezers technology. It will undoubtedly encourage people to reveal the laws of motion of the material world, manipulate the structure and function of matter at the micro and nano scales, and continuously expand the cognitive boundaries of humanity towards the microscopic world.

Disclosure statement

The author declares no conflict of interest.

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