Modeling Diffusion of Nano-meter Sized Colloids in Confined Spaces

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Abstract:

Imaging and analyzing trajectories of single particles undergoing Brownian motion provides information on the diffusion coefficients of these particles. In many applications, the individual particles diffuse within confined spaces, for example, biomolecules within organelles of a cell or small molecules within interstitial spaces of macromolecular crystals. To understand how the geometry and the size of the confining space affects diffusion, we have used a high-sensitivity EM-CCD camera to image trajectories of fluorescently tagged 100*nm*-size colloidal particles trapped within micron-sized defects of colloidal crystals. The colloidal crystals were fabricated with 1.5μm or 1.9μm latex spheres using the “horizontal” evaporation method; the crystals were found to have a variety of micron-size defects. We have flooded these large-sphere crystals with a colloidal solution of 100*nm* latex spheres that diffused and got trapped within the defects. The analysis of these nano-particle trajectories shows that their diffusion coefficient drops substantially within the confined space, in a manner analogous to prior experiments studying particle confinement within a sandwich of two glass slides. Since the particles are non-interacting, we interpret the drop in diffusion as a consequence of hydrodynamic effects (e.g., non-slip boundary layers of a Newtonian fluid) near the geometric boundaries.

Main Goal:

Measure how the diffusion coefficient of particles changes depending on their confinement.

Diffusion:

- Relates to random motion of molecules and other small particles in solutions
- $\langle x^2\rangle = 2Dt$
  - $\langle x^2\rangle$ is the variance in position of the diffusing particle
  - D is the diffusion coefficient specific to particles of given radii in a solution of a given viscosity
  - t is the time between measurements of displacement

Method:

- Fabricate a crystal with balls of diameter 1500*nm* or 1900*nm*
- Flood the crystal with balls of diameter 100*nm*
- Find a place in the crystal where a small ball is trapped but still moving
- Take a movie of the ball
- Analyze the movie and find D

Finding the Coefficient, *D*:

- Track a particle
- Find the change in x, Δx, for a given change in time, Δt
- Make a frequency plot of Δx
- Fit a Gaussian curve to the plot and find $\langle x^2\rangle$
- Plot a graph of $\langle x^2\rangle$ vs. t
- From the slope we can find D

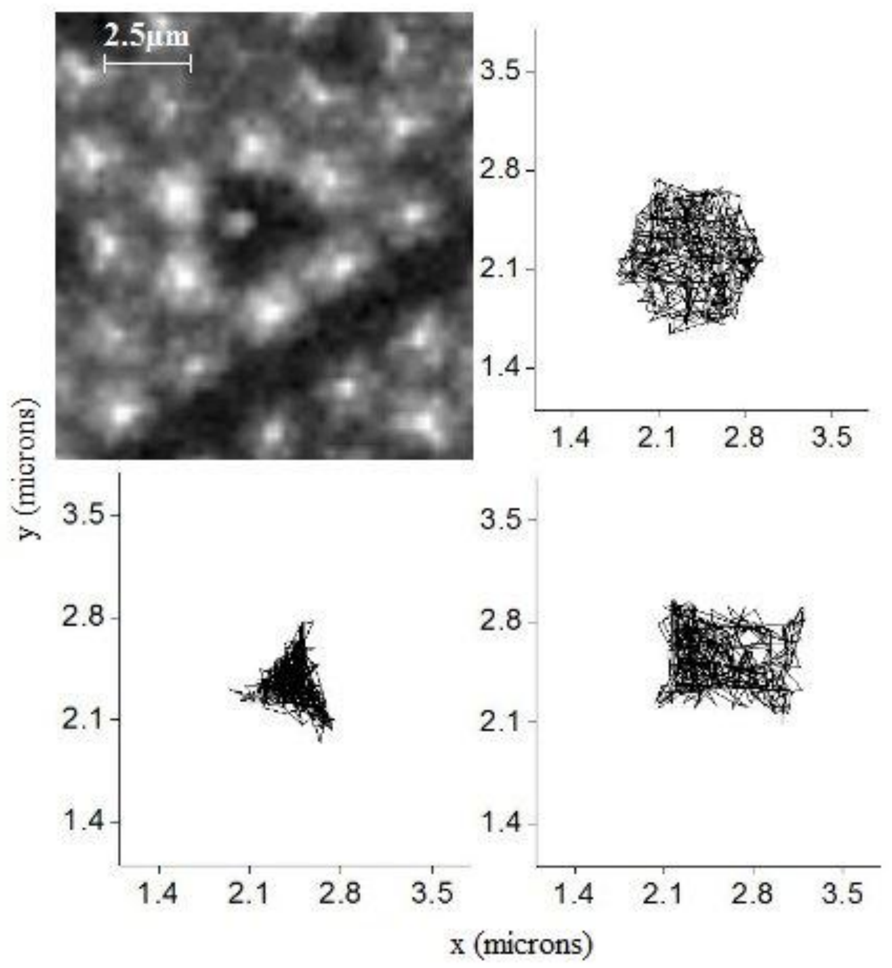

Figure 1: Track plots of latex spheres.
The image in the top left corner displays a latex sphere of diameter 100*nm* trapped in a triangular defect which confines the ball’s diffusion. The next three plots are representations of typical tracks of such spheres.

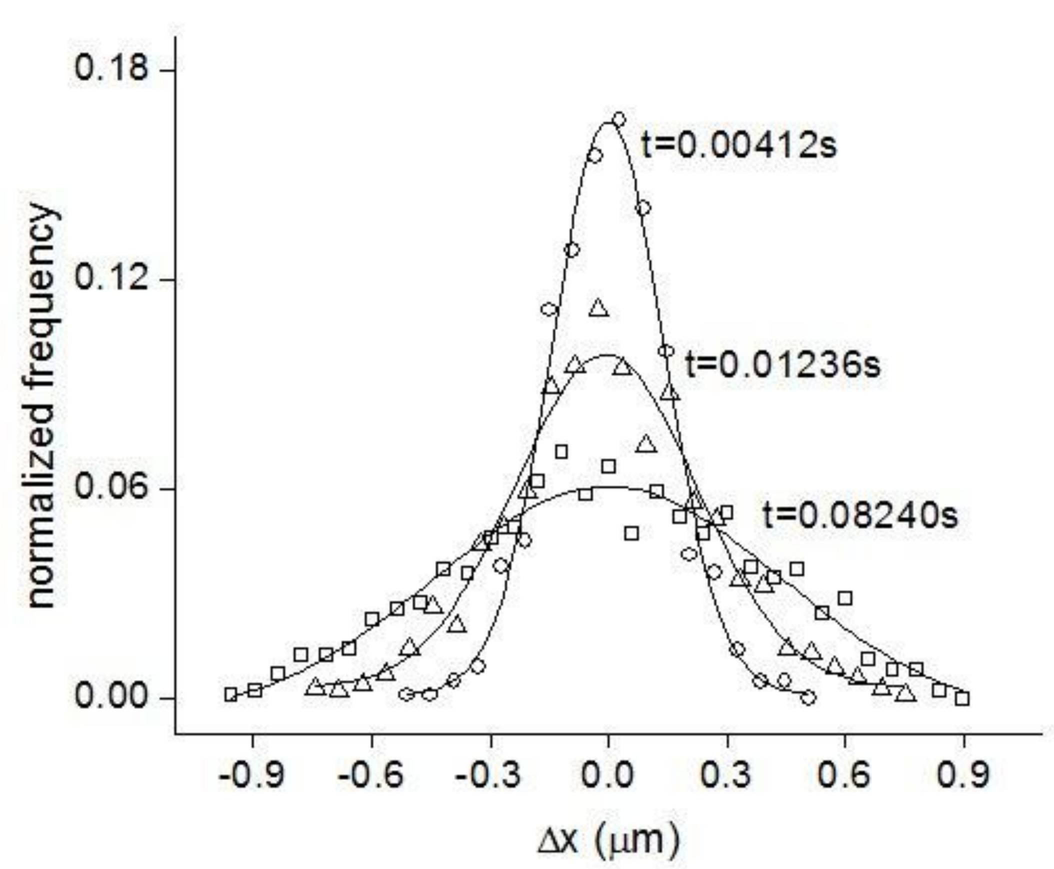

Figure 2: Finding variance.
The plot shows three different Gaussian curves at different Δt for one sphere of radius 100*nm*.

Finding Average Radius of Trap:

- There is a maximum displacement, Δx, the ball reaches for any Δt, given by the trap size
- This is seen as the asymptote on the plot of $\langle x^2\rangle$ vs. t
- We fit this curve with the equation[1]

$$\langle x^2\rangle = a^2\left(1-\frac{8e^{\left[-\frac{\alpha^2 t}{\tau}\right]}}{\alpha^2(\alpha^2-1)}\right)$$

- a is the average radius of the trap

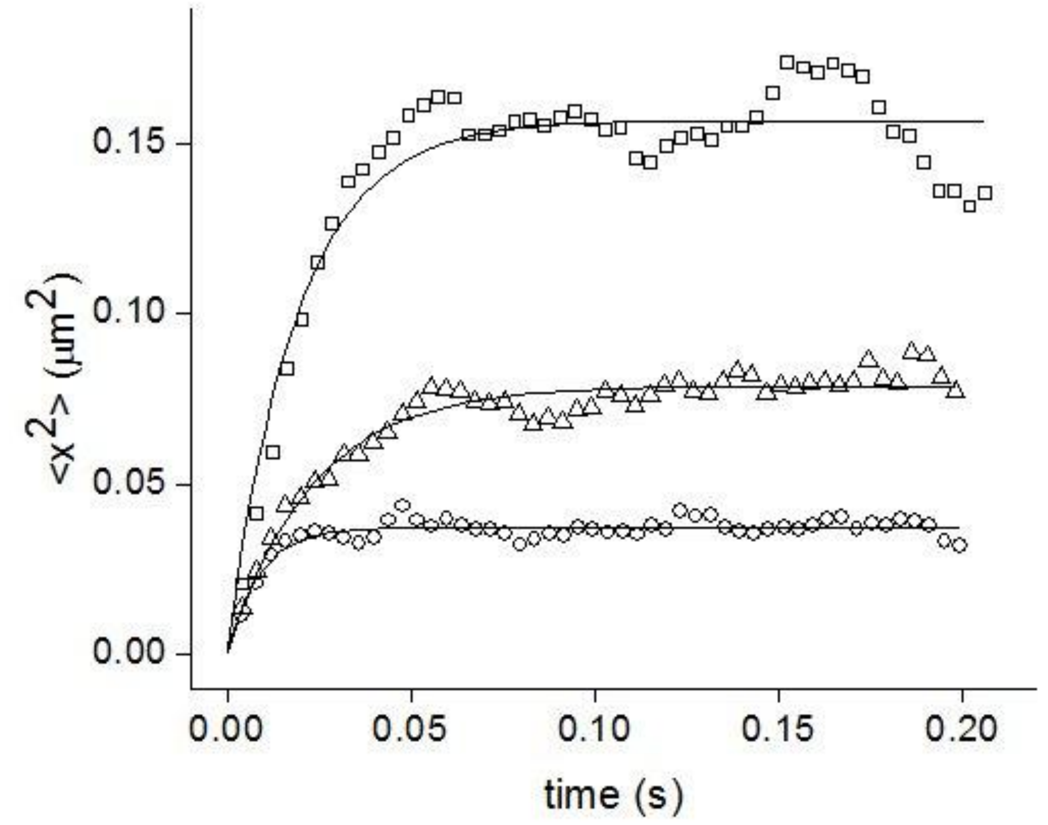

Figure 3: Finding average radius of a trap.
These plots are x^2 vs. t of a sphere of radius 100*nm* in three different traps. Due to the trap, the maximum jump a ball is able to take is restricted.

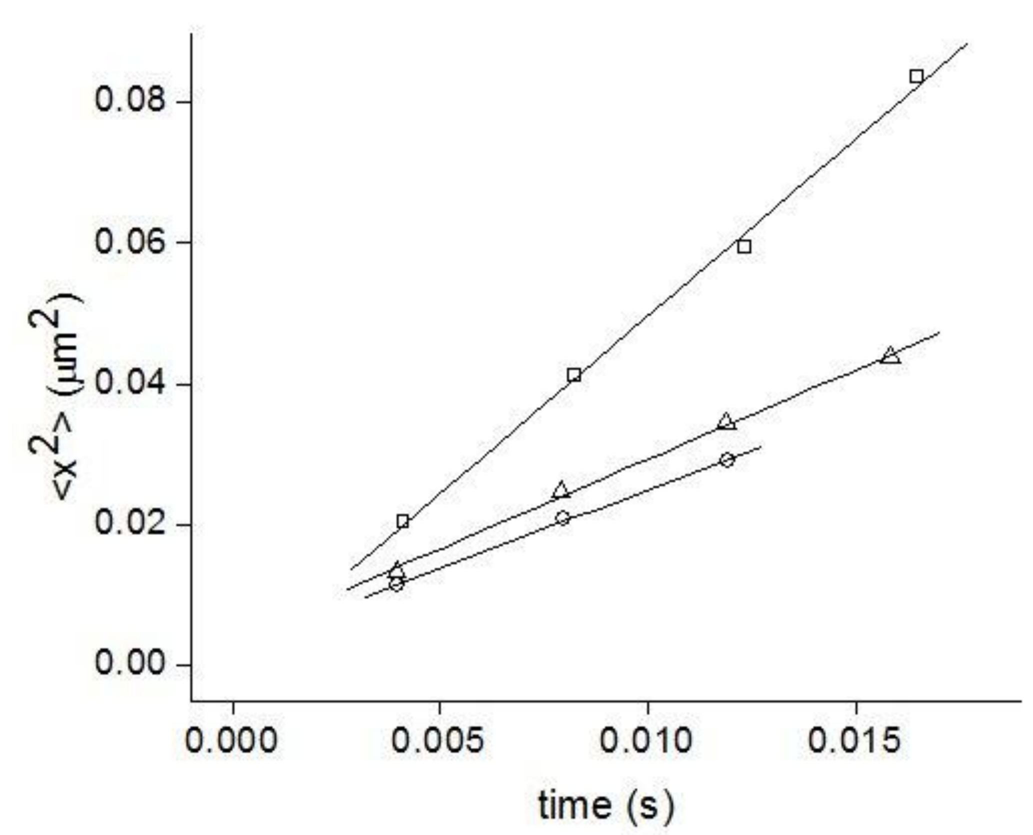

Figure 4: Finding D
These plots are the first several data points of figure 3. Before the effect of the trap takes over, the plots are linear, so we can find D from the slope.

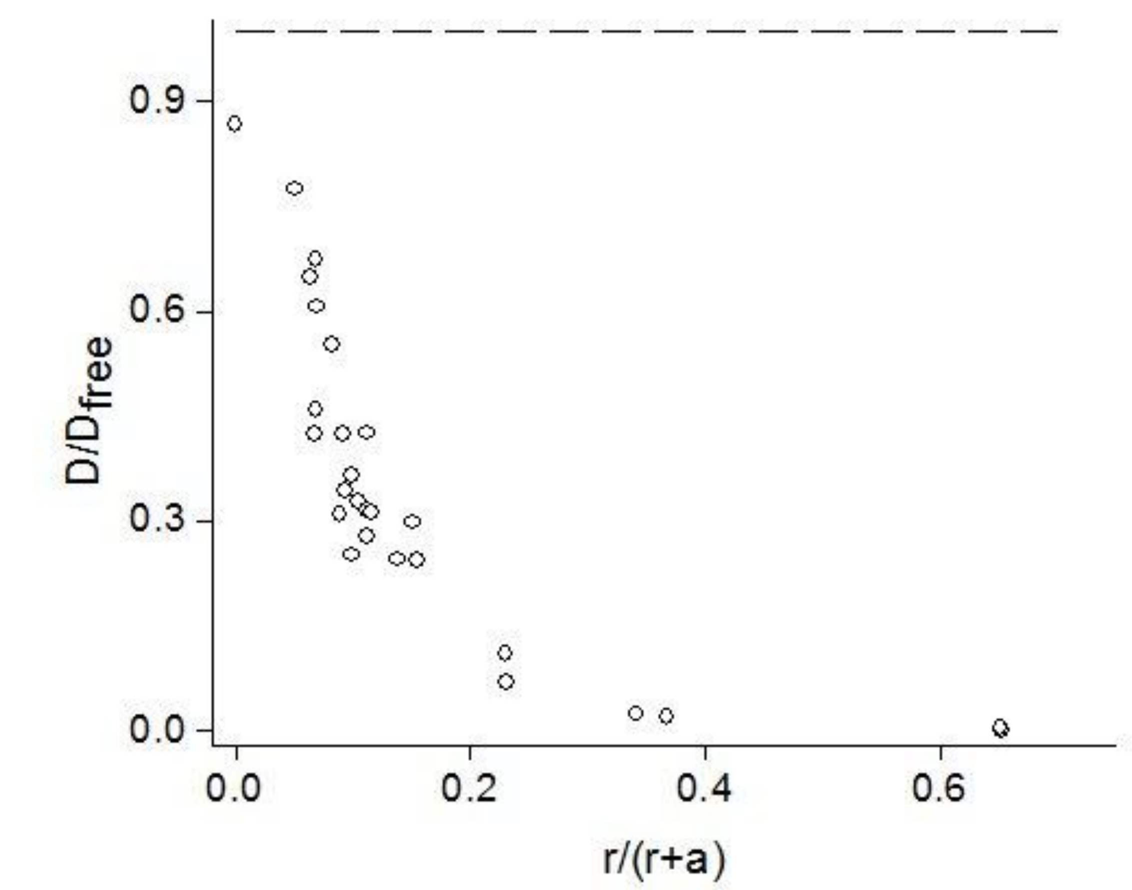

Figure 5: Effect of the confinement size on particle diffusion.
The diffusion coefficient decreases as trap size decreases.

Results:

The results show that as trap size increases, the diffusion constant of the ball approaches the diffusion constant of free diffusion. This means that the movement of a ball in a small trap would seem sluggish to the movement of a ball of equal radius in a larger trap.

This result can be explained due to hydrodynamic effects. As a consequence of the trap, it is more difficult for a ball to displace the water in which it is moving, because the water is harder to move when it there is a barrier in the way.
Similar observations have been made in previous studies in which it was noted that the diffusion coefficient of a particle decreases depending on its distance from a slide[3]. Similarly, experiments have been done in which particles were confined between two glass slides and again the diffusion coefficient decreased due to this confinement.[4]

For future work, it would be beneficial to take more data of balls in traps, especially in the region where $r/(r+a) > 0.2$ and then find a fit to the data.

References:

1. Bickel, Thomas. "A Note on Confined Diffusion." *Physica A: Statistical Mechanics and its Applications* 377.1 (2007): 24-32.
2. Nelson, Philip. Biological Physics : Energy, Information, Life. 2nd ed. New York: Worth, Incorporated, 2003.
3. Benesch, Thorben, and Sotira Yiacoumi. "Brownian Motion in Confinement." *Physical Review* 68.2 (2003): 021401-1-21401-5.
4. Lin, Binhua, Jonathan Yu, and Stuart A. Rice. "Direct Measurements of Constrained Brownian Motion of an Isolated Sphere between Two Walls.

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