

Evidence for Enhanced Tracer Diffusion in Densely Packed Interfacial Assemblies of Hairy Nanoparticles

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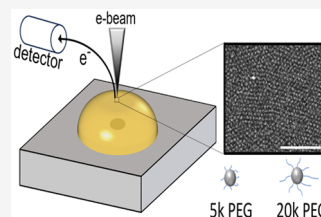
Article Recommendations



Supporting Information

ABSTRACT: Nearly monodisperse nanoparticle (NP) spheres attached to a nonvolatile ionic liquid surface were tracked by *in situ* scanning electron microscopy to obtain the tracer diffusion coefficient D_{tr} as a function of the areal fraction ϕ . The *in situ* technique resolved both tracer (gold) and background (silica) particles for ~ 1 – 2 min, highlighting their mechanisms of diffusion, which were strongly dependent on ϕ . Structure and dynamics at low and moderate ϕ paralleled those reported for larger colloidal spheres, showing an increase in order and a decrease in D_{tr} by over 4 orders of magnitude. However, ligand interactions were more important near jamming, leading to different caging and jamming dynamics for smaller NPs. The normalized D_{tr} at ultrahigh ϕ depended on particle diameter and ligand molecular weight. Increasing the PEG molecular weight by a factor of 4 increased D_{tr} by 2 orders of magnitude at ultrahigh ϕ , indicating stronger ligand lubrication for smaller particles.

KEYWORDS: electron microscopy, single particle tracking, colloidal glasses, nanoparticles, diffusion coefficient, ionic liquid



Transitions of particle packings from low density states, in which particles are disordered and highly mobile, to high density states, in which particle assemblies are glassy, jammed, or crystalline and nearly immobile, have long been a focus of materials science.^{1–12} For small, well-dispersed particles, ordering improves as particle density increases, accompanied by a shift from dominant single-particle dynamics to dominant multiple-particle or cooperative dynamics. In a broad scope, understanding the particle assembly mechanisms and associated structural transitions can impact numerous nanotechnologies, including bicontinuous jammed emulsions (bijeles),¹³ emulsion encapsulation,^{14,15} high throughput chemical Pickering emulsion catalysts,¹⁶ and high density photonic assemblies for optoelectronic devices.¹⁷ Directly visualizing nanoparticle (NP) dynamics in these contexts could have far-reaching consequences for medicine, composite mechanics, electrical devices, and sensors.^{13–15,18–20}

An important aspect of these dynamics is the tracer diffusion coefficient D_{tr} , which was measured here for NPs dispersed on a liquid surface across the full range of surface areal density ϕ . These measurements were facilitated by our recently developed scanning electron microscopy (SEM) method that offers *in situ* “open” single particle imaging of NPs residing on an ionic liquid (IL) surface.^{21–23} The local details of the assemblies can be visualized by SEM, a powerful advantage over optical microscopy, which can only track larger particles.^{24–27} The behaviors of NPs and colloidal particles are distinct due to the different relative length scales of interparticle interactions, which for NPs may extend over distances comparable to or greater than the particle diameter d . This difference in interaction length scales means that jamming

and caging behavior of NPs may be radically different than larger spheres. Adding ligands to the NPs (i.e., hairy NPs) further complicates these interactions and may lead to interesting and unexpected behavior, as these interactions become more important near jamming. The exquisite detail afforded by this SEM approach allows direct visual access to dense NP packings, where we hypothesize that stabilizing ligands on the NPs can greatly affect NP dynamics at ultrahigh ϕ .

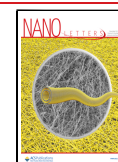
Similar interfacial particle systems have previously been studied by ensemble-average methods, including microrheology,^{2,28–30} grazing incidence or small-angle X-ray scattering and reflectivity,^{31–33} Langmuir–Blodgett techniques,^{32,34,35} and thermal approaches,^{9,29} yielding important insights into the density-driven transitions of two-dimensional NP packings. However, these methods cannot follow the simultaneous changes in the organization and motion of individual NPs or NP packing heterogeneities. Another distinct advantage of our SEM method is that the NP motions are restricted to the two-dimensional (2D) interface, which allows for increased fidelity in tracking without the concern of diffusion out of plane. Less traditional imaging methods such as liquid cell TEM,^{36–38} liquid AFM,³⁹ super-resolution optical microscopy,^{40–42} and variable pressure SEM have been used to visualize such

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nanoscale assemblies but have weaknesses in their geometrical constraints, spatiotemporal resolution, or artifacts induced from outside perturbations. SEM imaging circumvents these problems by taking advantage of the negligible vapor pressure and innate conductivity of ILs, which enable large-scale open imaging of the liquid surface without evaporation or charging.

The packing and diffusion of small spheres at a liquid surface have been examined frequently,^{25–27,43–57} with studies variously focused on impacts of contact angle, interfacial fluid dynamics, interfacial tension, and changes to interfacial viscosity. In the present study D_{tr} was measured by SEM for PEGylated tracer gold NP spheres as a function of ϕ , tracking NP motions/displacements at an IL–vacuum interface containing a backdrop of neighboring silica NPs with 5000 g/mol PEG ligands. The orientational ($\langle\psi_6\rangle$) and translational (T^*) order parameters of the NPs and the pair correlation function were determined for all ϕ .^{21–23,58,59} Previous studies of sphere diffusion at liquid surfaces typically used larger particles, and nearly all are terminated at densities well below jamming, limiting the variation of D_{tr} measured and missing any phenomena close to jamming. Archer et al. studied similar soft NPs in the bulk at ultrahigh ϕ and showed that these composite materials can counter NP jamming under the appropriate conditions (e.g., NP diameter to ligand size ratio).^{60,61} Our SEM method uniquely positioned us to visualize tracer NP diffusion across all ϕ and uncover the role ligands play at ultrahigh ϕ .

When dispersed on the IL (1-ethyl-3-methylimidazolium ethyl sulfate) interface at low ϕ , the NPs displayed 2D interactions closely resembling those of hard spheres.^{21,23} Although their ligand configurations could not be characterized *in situ*, small-angle neutron scattering of PEG dissolved in similar ILs yielded a Flory exponent of 0.55–0.60,⁶² suggesting moderate-to-good solvent conditions. Salerno and co-workers examined PEGylated NPs,⁶³ and their modeling indicated that a 5000 g/mol PEG ligand layer was ~ 2 – 3 nm thick in a good solvent. A 5 nm correction was thereby made to d in calculating ϕ , a correction most robust at low ϕ where NP–NP contacts were infrequent. At high ϕ , ligand–ligand interactions were prevalent, so the ligand coronae were likely compressed. In these cases, the Alexander–de Gennes brush model better approximates the interparticle potential.^{22,64}

Each tracer NP was matched to a nontracer NP of nearly the same d , and the matched pair are referenced by their nominal diameter expressed in nanometers: 100 nm (for 101 nm d), 130 nm (for 132 nm d), 160 nm (for 158 nm d), and 240 nm (for 238 nm d). Tracer particles were used because the NPs can displace a distance greater than their center–center spacing in the time between frames for moderate-to-high ϕ packings and could not be distinguished, a problem avoided with the tracer NP strategy. All NPs had less than ~ 11 – 13% dispersity in d , and all bore the same dense PEG ligand layer, which drove the NPs to the IL surface due to the low surface energy of PEG, ~ 43 mN/m, compared to that of IL, ~ 48 mN/m.²³ The ligand layer thickness for all samples was much less than d , so at low ϕ the layers primarily acted as nonsticky short-range “bumpers”, precluding aggregation of NPs in the liquid or at its surface. The PEG ligands also afforded all particles the same surface chemistry and the same contact angle, and nothing indicated that the interior compositional difference between tracer and background NPs affected their interactions. Figure 1 shows NPs in a monolayer, prepared as described in the Methods section, as the drop volume was

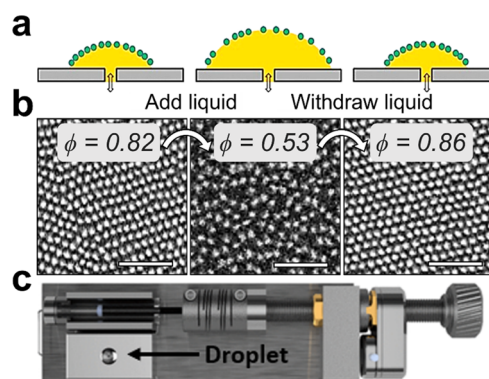


Figure 1. SEM liquid cell. (a) Sequential addition/withdrawal of liquid to adjust drop size. (b) SEM images of NP arrangements after addition/withdrawal of liquid from drop. Initial and final arrangements are nearly jammed (scale bars: 1 μ m). (c) Liquid cell component layout displaying specimen stage and supported drop (lower left), motorized syringe (upper right), and connecting fluid path (upper left). Reproduced in part from ref 22.

manipulated at ϕ close to NP jamming. Precise control over ϕ was directed by the increase/decrease of the IL volume, which changes the total surface area of the droplet (e.g., when IL is added ϕ decreased, and when IL is removed ϕ increased). NP arrangements before and after the ϕ change were indistinguishable, establishing structural reversibility upon interfacial expansion/compression and a means to increase ϕ .

Tracking was performed in a similar manner to our previous work.^{21–23,58} Briefly, imaging was performed at room temperature near the drop apex to minimize the impact of interfacial curvature on NP motion, as well as the distortions emanating from 2D imaging of a curved interface. Gold-coated silica NP tracers were used; therefore, the small difference in inertia between tracer and background NPs is minor. The interfacial NPs, due to their small masses, did not produce gravity-induced menisci, and the IL surface surrounding them was, therefore, nearly planar. To maintain the $\sim 14^\circ$ contact angle θ under this constraint,²¹ NP centers lay well below the surface. Because SEM secondary electron imaging mode reveals only the topmost 20–50 nm of the surface structure,²³ the more deeply submerged portions of NPs, including NP–NP contacts, were not visualized, and the NPs appeared as white circular caps surrounded by a dark, continuous IL matrix (Figure 1). Further details on the imaging protocol can be found in the Supporting Information.

Figure 2a presents typical SEM-imaged trajectories of 160 nm NPs for ϕ equal to 0.78, 0.65, and 0.33. Initially, all tracers displayed time-invariant irregular motions. At $\phi = 0.78$, these motions were mostly caged over the period monitored, rendering the trajectories much more compact than those at lower ϕ . Intermittent caging was evident at $\phi = 0.65$, whereas no caging was noted at $\phi = 0.33$. The trajectories of Figure 2a are provided in Supporting Information Movies SM1–SM3, while Figures S2–S5 offer images for several d and ϕ along with associated movies (Movies SM4–SM6). Movie SM7 provides snapshots of an increase in ϕ using 160 nm NPs, demonstrating ϕ can be manipulated *in situ*. While successive frames could be captured over thousands of seconds, NP motions beyond ~ 100 s time steps displayed an inconsistent slowing down of dynamics, a feature attributed to beam-induced IL cross-linking from radiolysis. Lowering beam current and increasing scan speed decreased the cross-linking,

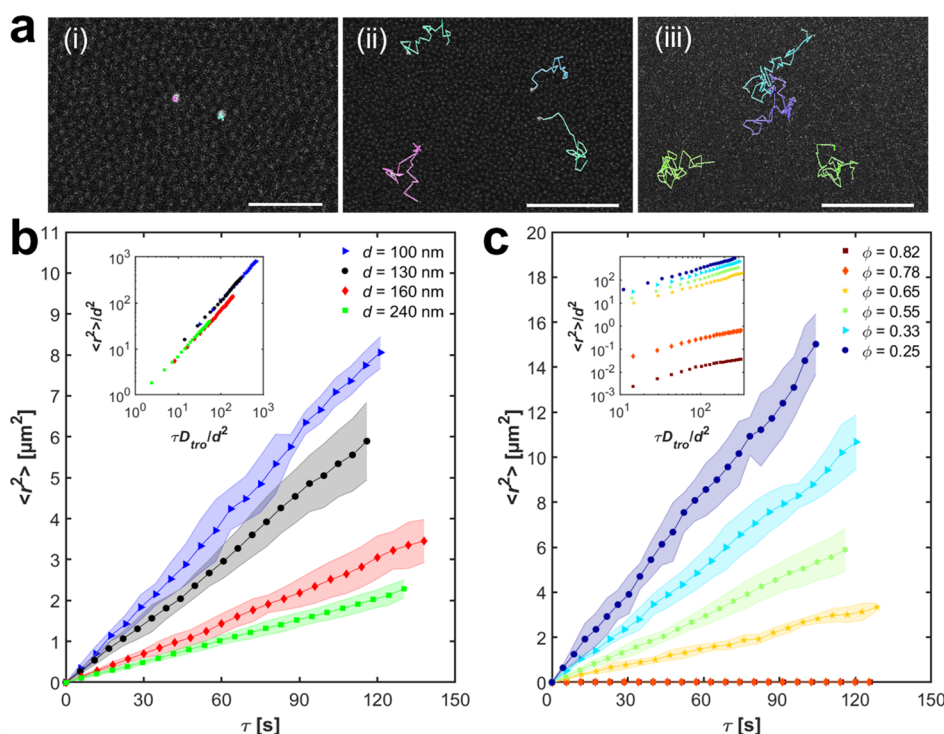


Figure 2. (a) Trajectories of 160 NPs for $\phi =$ (i) 0.78, (ii) 0.65, and (iii) 0.33. As reflected by scale bars of (a) 1 μm , (b) 3 μm , and (c) 5 μm , magnification was adjusted to highlight NP motion. (b) Mean-square-displacement $\langle r^2 \rangle$ vs time lag τ for all d at $\phi \sim 0.55$ and (c) select ϕ for $d = 130$ nm. The shaded regions in (b) and (c) indicate one standard deviation away from the mean values. Insets show the same data normalized by the characteristic length scale d and time scale d^2/D_{tro} .

but imaging contrast and quality were concurrently diminished. Except at ϕ close to jamming, the initial period of stable dynamics was long enough to capture NP excursions comparable or larger than d .

At least three independent measurements and 15 individual NP trajectories, such as those in Figure 2a, were used to construct plots of mean-square displacement $\langle r^2 \rangle$ vs time lag τ for each d and ϕ . Figure 2b provides plots of $\langle r^2 \rangle$ vs τ for $\phi = 0.55$ for all d , and as anticipated for moderate ϕ , $\langle r^2 \rangle$ decreased as d increased, indicating decreased mobility. The inset shows the same data in terms of normalized variables $\langle r^2 \rangle / d^2$ and $\tau D_{\text{tro}} / d^2$, where D_{tro} is D_{tr} for an infinitely dilute system (i.e., ϕ extrapolated to zero; see Figure 4). Because the underlying dynamics are scale invariant, the data collapse, tracing a slope close to unity with reasonable linearity. These results are consistent with the analogous normalized data for larger hard sphere colloids.²⁶ Deviations, especially at longer times, for large ϕ are attributed to caging effects. Figure 2c, which presents $\langle r^2 \rangle$ vs τ for 130 nm NPs, shows the transition from ordinary but congested Brownian motion to persistently caged Brownian motion, as vaguely reflected in the significant drop in $\langle r^2 \rangle$ for $\phi \gtrsim 0.65$. When ϕ rose above $\phi \simeq 0.70$, approximately the onset of 2D colloidal crystalline ordering, the characteristic time for NP escape from cages became significantly greater than the characteristic time d^2/D_{tro} than at slightly lower ϕ , reflecting a sharp break toward short-term diffusion (inset Figure 2c). Caging is visually obvious in all NP trajectories collected for $\phi \gtrsim 0.65$ and in the $\langle r^2 \rangle$ vs τ plots. Figures S6–S9 display the analogous plots for all d across the same ϕ range alongside fits to Fickian and Fickian with drift models (Supporting Information) for calculating D_{tr} . While some of

these trends are unsurprising, they validate that real-time *in situ* SEM tracking can provide D_{tr} for interfacial NPs.

The ϕ dependence of D_{tr} will coincide with changes in NP organization, which SEM captured across all ϕ . To characterize organization, the centers of background NPs were first obtained by procedures essentially the same as those for tracer NPs (see the Methods section). Delaney triangulation then produced Voronoi diagrams from which the hexagonal orientational order parameter $\langle \psi_6 \rangle$, translational order parameter T^* , number of nearest neighbors z , and pair correlation function $g(r)$ were calculated.^{22,59,65} Figures 3a–d provide the first two of these characterizations for 160 nm NPs at ϕ equal to 0.33 and 0.80, and Figures 3e and S10 offer the other characterizations for $0.1 \leq \phi \leq 0.83$. Across all ϕ , NP organization was fully consistent with literature reports for 2D sphere packings,^{59,64,66} with hexatic and crystal phases observed at conditions expected for hard spheres.

For 2D Brownian motion conforming to Fick's law, D_{tr} is calculated from the slope of $\langle r^2 \rangle$ vs τ and analyzing NP tracking data in terms of eqs S1 and S2; Figures 4a and 4b offer D_{tr} as a function of ϕ for all d . Unsurprisingly given the trends discussed for Figure 2, all $D_{\text{tr}}(\phi)$ show about a 1 order of magnitude decrease in D_{tr} before the onset of ordering, while a 4 orders of magnitude decrease is incurred afterward. Similar observations have been made by Dozier et al.⁶⁷ for electrostatically repelling colloids in the bulk. However, the SEM method was able to resolve tracer NP positions to ± 10 nm, and D_{tr} as small as $\sim 5 \times 10^{-7} \mu\text{m}^2/\text{s}$ could be measured. Thus, D_{tr} could be assessed for fully caged but unjammed (jamming emerges at $\phi \simeq 0.82$ – 0.85)^{44,57,65} NPs at $\phi \gtrsim 0.70$, where Archer et al. observed liquid-like behavior in solventless hairy NP assemblies.^{60,61} In the log–linear format of Figure 4b, D_{tr}

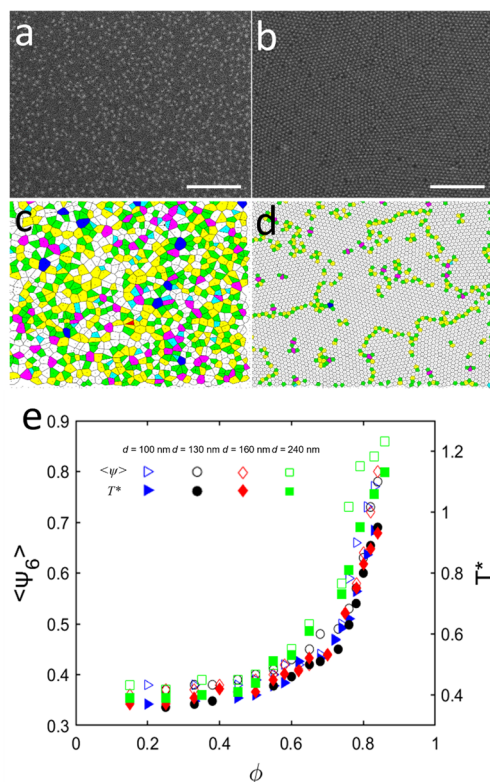


Figure 3. SEM image of 160 NPs at (a) $\phi = 0.33$ and (b) $\phi = 0.80$. Scale bars: 2 μm . Corresponding Voronoi tessellations (c) and (d) for SEM images in (a) and (b). Color map: $z = 3$ (red), 4 (light blue), 5 (green), 6 (white), 7 (yellow), 8 (pink), and 9 (dark blue). (e) Order parameters $\langle\psi_6\rangle$ (closed symbols) and T^* (open symbols) for all d as a function of ϕ , showing good overlap and an upturn at $\phi \approx 0.72$ – 0.76 ; 100, 130, 160, and 240 NPs are represented by blue triangles, black circles, red diamonds, and green squares, respectively.

trends at ultrahigh ϕ are highlighted, and they display an inflection point with a d dependence not expected with only

hard sphere interactions. For these interactions, the normalized data in the inset of Figure 4b should superimpose across all ϕ , as noted except at the highest ϕ region.

In many contexts a semiempirical model for D_{tr} can be helpful in distinguishing subtle effects immediately prior to the onset of ordering. For an isolated hard sphere diffusing at a planar fluid interface, D_{tr} can be expressed in a modified Stokes–Einstein form

$$D_{tr} = \frac{32k_B T}{3\pi\eta_0 d [16 + 9 \cos \theta - 2.224 \cos^2 \theta + O(\cos^3 \theta)]} \quad (1)$$

following calculations from Dörr et al.,⁵³ who analytically determined D_{tr} via a geometric perturbation approach. Here k_B is the Boltzmann constant, T is the temperature, and η_0 is the fluid viscosity. For a ligand-decorated NP surface, η_0 could further depend on the spreading/interaction of ligands, especially at approach to jamming. For a bulk suspension of hard spheres, the Krieger–Dougherty model⁵⁴ closely tracks the volume fraction ϕ dependence of suspension viscosity

$$\eta_0 = \eta \left(1 - \frac{\phi}{\phi_{\max}} \right)^{-B} \quad (2)$$

where η is the IL viscosity, $\phi_{\max}$ is the maximum achievable volume fraction, and B is an empirical exponent. Setting $\phi_{\max}$ to the inflection point ($\phi = 0.76$), constraining B to a single value ($= 3/2$ for 2D interfaces), and substituting eq 2 into eq 1 produces the solid curves drawn through the data sets shown in Figure S11. Agreement between curves and data is surprisingly good but loses accuracy for low d and high ϕ . Interestingly, when B is adjusted to fit the data separately for each d , values of 1.5, 1.45, 1.35, and 1.2 are obtained in the order of descending d (fits in Figure 4). This decreasing trend in the exponent value may be related to increased ligand lubrication and decreased interfacial viscosity.

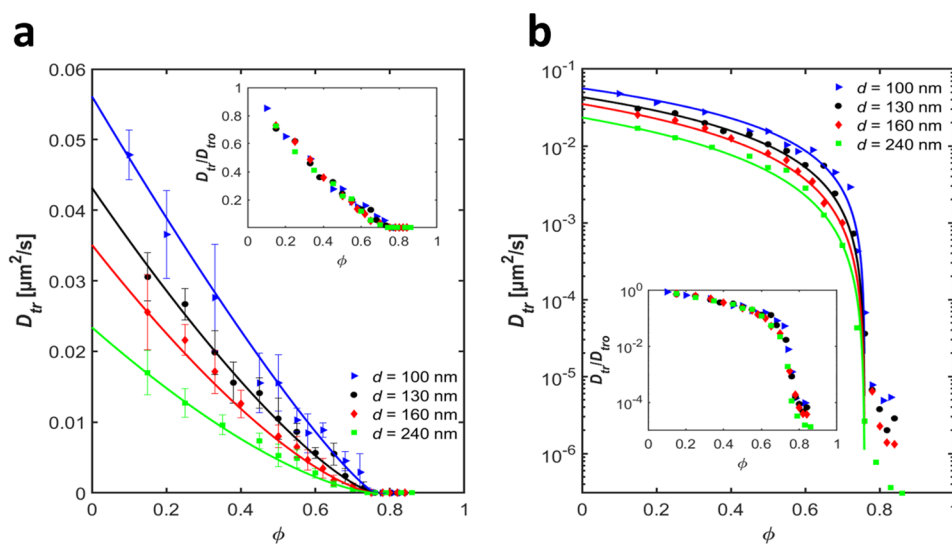


Figure 4. D_{tr} as a function of ϕ for all d . (a) Data are displayed in linear–linear format in the main plot, and the inset shows the same data plotted in linear–linear format after D_{tr} is normalized by $D_{tr,0}$. (b) Data are displayed in log–linear format in the main plot, and the inset shows the data displayed in log–linear format after the same division of D_{tr} . Normalization collapses the ϕ dependence except at large ϕ . The data are fit to a phenomenological model provided by Dörr et al. (see eq 1). A star marker is used for the diffusion coefficient of 100 nm particles with 20000 PEG ligands.

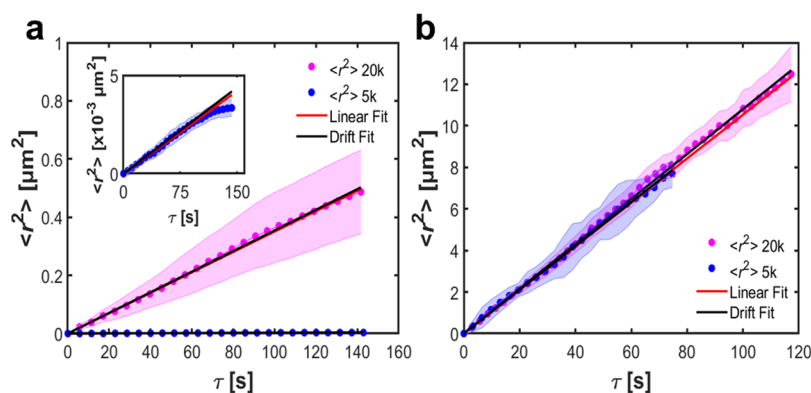


Figure 5. $\langle r^2 \rangle$ vs τ for 100 nm NPs at (a) $\phi = 0.8$ and (b) $\phi = 0.33$ for both 5k (blue) and 20k (magenta) PEG ligands with fits to extract D_{tr} . Inset shows the zoomed in $\langle r^2 \rangle$ vs τ for the 5k PEG ligands. The shaded regions in (a) and (b) indicate one standard deviation away from the mean values.

The D_{tr} dependence on ϕ before ordering is attributed to defect annihilation. The packing of background NPs was decorated with numerous defects, vacancies, and grain boundaries, and packing defects along grain boundaries were increasingly annihilated across $0.73 < \phi < 0.78$, exactly where normalized D_{tr} fell most abruptly. The d dependence of D_{tr}/D_{tro} above the inflection point cannot be explained by the same argument. This dependence must arise from ligand-mediated NP interactions because packing defects were rare and diffusion within cages prevailed. In this scenario, the ratio of ligand thickness to NP size becomes important, and NPs can no longer be treated as hard spheres. Under these circumstances, Figure 4b shows that D_{tr}/D_{tro} declined as the ratio of d to ligand layer thickness increased. For smaller d NPs, ligands fill a larger fraction of the interstitial area between NPs and consequently can better lubricate displacements when the NPs are nearly in contact. Archer et al. reported that neat, ligand-coated NPs can even flow as bulk liquids, demonstrating that appropriate ligands can counter NP jamming in three-dimensional sphere packings.^{60,61} If the same holds for these 2D monolayers, then D_{tr}/D_{tro} is sensitive to ligand chemistry, ligand length, and ligand grafting density at $\phi \gtrsim 0.76$.

To highlight the impact of ligand length, 100 nm NPs were functionalized with 20000 g/mol (20k) PEG ligands. Quadrupling the ligand length would be expected to increase the ligand layer thickness by ~ 2.3 times ($4^{3/5}$), indicating a roughly 5.75 nm brush, a value used in calculating ϕ . Movie SM8 shows the motion of 100 nm particles with 20k ligands at $\phi = 0.8$. In comparison to the motion of the analogous particles with 5000 g/mol (5k) ligands (Movie SM9) faster diffusion is visually apparent. To distinguish the difference in D_{tr} quantitatively, $\langle r^2 \rangle$ for the 20k PEGylated NPs was compared to that for the 5k counterparts. At $\phi = 0.8$, Figure 5a shows a 2 orders of magnitude increase in slope, corresponding to an increase in diffusion coefficient from $\sim 5.94 \times 10^{-6} \mu\text{m}^2/\text{s}$ for the 5k PEGylated NPs to $8.75 \times 10^{-4} \mu\text{m}^2/\text{s}$ for the 20k PEGylated NPs. The larger ligand molecular weight drastically improves the lubricated motion of the NPs and results in enhanced diffusion of the NPs. Figure 5b shows the same comparison between the 20k and 5k PEGylated NPs at $\phi = 0.33$, where there was no significant change in the measured D_{tr} . These findings suggest that ligand effects can impact NP dynamics above $\phi \gtrsim 0.76$, with little effect at low ϕ .

Before availability of this SEM method, NP tracking at nondilute conditions in or on liquids was problematic. The

tracer method used here has provided quantitative insights into diffusion processes across the full range of ϕ , highlighting the different behavior observed for small NPs at ultrahigh ϕ . A decrease in D_{tr} by almost 5 orders of magnitude was found, with the largest drop noted at ϕ too high for visualization/tracking by any other method. The same approach can be applied to smaller spheres, $d < 100$ nm, where ligand lubrication is expected to be even greater, but additional imaging refinements and better understanding of beam artifacts will be needed to improve contrast. While dense NP assemblies display many properties analogous to those of larger particles, they also possess their own characteristic features; for example, NPs typically are coated with ligand layers thick enough to greatly impact dynamics as was uncovered here. Further optimization of imaging methods and the implementation of mixed systems (i.e., spheres, rods, cubes, etc.) will also allow for time-evolving compositional and alignment variations at the nanoscale, which may greatly improve our understanding of structural variations in existing and future nanotechnologies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.3c02989>.

Movie SM1: diffusion of 160 nm NPs (MP4)

Movie SM2: diffusion of 160 nm NPs (MP4)

Movie SM3: diffusion of 160 nm NPs (MP4)

Movie SM4: various other ϕ and d (MP4)

Movie SM5: various other ϕ and d (MP4)

Movie SM6: various other ϕ and d (MP4)

Movie SM7: snapshots of a continuous increase in ϕ using 160 nm NPs (MP4)

Movie SM8: motion of 100 nm NPs with 20k ligands at $\phi = 0.8$ (MP4)

Movie SM9: motion of 100 nm NPs with 5k ligands at $\phi = 0.8$ (MP4)

Text describes NP and ligand interactions at the interface and detailed sample preparation and imaging conditions; mean-square displacement equations for Brownian diffusion and diffusion with drift models; nanoparticle organization and structure are described using the hexagonal orientational order parameter $\langle \psi_6 \rangle$, the translational order parameter T^* , and the pair correlation function $g(r)$; Figure S1: TEM images of

tracer NPs used; Figure S2: snapshots of 100 nm NPs in a zoomed-in area of different ϕ ; Figure S3: snapshots of 130 nm NPs in a zoomed-in area of different ϕ ; Figure S4: snapshots of 160 nm NPs in a zoomed-in area of different ϕ ; Figure S5: snapshots of 240 nm NPs in a zoomed-in area of different ϕ ; Figure S6: mean-square-displacement $\langle r^2 \rangle$ vs time lag τ for 100 nm NPs; Figure S7: mean-square-displacement $\langle r^2 \rangle$ vs time lag τ for 130 nm NPs; Figure S8: mean-square-displacement $\langle r^2 \rangle$ vs time lag τ for 160 nm NPs; Figure S9: mean-square-displacement $\langle r^2 \rangle$ vs time lag τ for 240 nm NPs; Figure S10: number of nearest neighbors and pair correlation function analysis for all 160 NPs; Figure S11: D_{tr} as a function of ϕ for all d fit using eqs 1 and 2 where $B = 3/2$ (PDF)

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Author Contributions

Z.F.: conceptualization, investigation, formal analysis, methodology, writing—original draft, and writing—review and editing; P.Y.K.: methodology, software, and writing—review and editing; S.S.: investigation and writing—review and editing; A.E.R.: methodology, resources, and writing—review and editing; D.A.H.: conceptualization, funding acquisition, supervision, resources, and writing—review and editing; T.P.R.: conceptualization, funding acquisition, supervision, resources, and writing—review and editing. The manuscript was written through contributions of all authors.

Notes

The authors declare no competing financial interest.

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