

Nanoscale Anisotropy of SWCNTs Promotes Enhanced Diffusion in Heterogeneous Complex Fluids

Published as part of ACS Applied Nano Materials special issue "Early Career Forum 2026".

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Cite This: <https://doi.org/10.1021/acsanm.6c03452>



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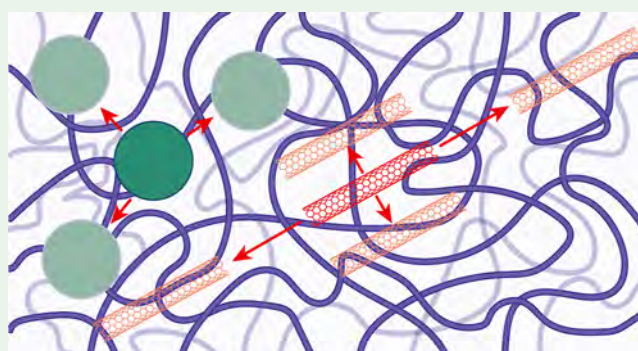
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ABSTRACT: Single-walled carbon nanotubes (SWCNTs) are anisotropic nanoparticles with unique mechanical, electrical, and optical properties. These properties have enabled applications in reinforcing nanocomposites, drug delivery, biosensing, and biomedical imaging, where their performance depends on transport through complex fluids. The mechanisms governing SWCNT transport in structured heterogeneous fluids, however, remain poorly understood because of their multiple characteristic length scales that can be smaller than or comparable to the structural length scales of the surrounding fluid. Here, we investigate the dynamics of SWCNTs in semidilute poly(ethylene oxide) solutions by systematically varying polymer concentration and molecular weight. We directly compare their transport with that of spherical nanoparticles (SNPs) with comparable characteristic dimensions to isolate the effect of particle anisotropy. SWCNTs exhibit substantially enhanced diffusivities up to 300× faster than Stokes–Einstein predictions. These deviations emerge at lower polymer molecular weights and are considerably larger than those observed for SNPs. SWCNT dynamics collapse onto a single curve when plotted as a function of the ratio of nanotube length to the polymer correlation length even well into the entangled regime, whereas SNPs exhibit a steeper power-law decrease that reflects coupling to entanglement dynamics. Moreover, SWCNTs exhibit pronounced non-Gaussian distributions of particle displacements, which confirm that SWCNTs experience different viscosities when transporting along or perpendicular to their length. Our results show that the nanoscale diameter of SWCNTs enables them to avoid constraints imposed by the polymer network and that their anisotropic geometry gives rise to distinct coupling to polymer microstructure and multiple diffusive modes. These findings reveal the mechanisms governing enhanced SWCNT transport and non-Gaussian statistics in structured complex media and provide a framework for predicting SWCNT dynamics in soft matter and biological environments.

KEYWORDS: nanoparticle dynamics, polymer solutions, single-walled carbon nanotubes, probe anisotropy, particle tracking



1. INTRODUCTION

Nanoparticles possess unique physicochemical characteristics arising from interfacial and quantum effects that are absent in bulk materials.¹ Because of these unique properties, nanoparticles are widely utilized in applications such as enhanced oil recovery,^{2–4} nanocomposite materials,^{5–7} and biomedical technologies including nanomedicine^{8–11} and biological imaging.^{12–14} In many of these applications, nanoparticles must transport through structurally heterogeneous complex fluids such as polymer solutions and melts, mucus, extracellular matrices, and the crowded cytoplasm. Understanding nanoparticle transport within these complex fluids is therefore essential for understanding and optimizing their performance.

In a homogeneous solution, the transport of spherical nanoparticles (SNPs) is classically described by the Stokes–Einstein (SE) equation $D = k_B T / 6\pi\eta R_{NP}$, which predicts the particle diffusivity D from its radius R_{NP} , the bulk viscosity of the

surrounding medium η , and thermal energy $k_B T$. In many of the aforementioned applications, however, the underlying assumption of the SE model no longer holds because the particle size becomes comparable to the characteristic length of the inhomogeneities in the medium. For SNPs, theoretical^{15–19} and experimental studies^{20–22} have shown that nanoparticle dynamics are decoupled from the bulk viscosity inside polymer matrices and instead dictated by either the segmental relaxations or the reptation of the polymer, depending on the ratio of nanoparticle size R_{NP} to polymer radius of gyration R_g , correlation length ξ , or tube diameter a_T . These size ratios therefore

Received: July 19, 2026

Revised: September 5, 2026

Accepted: September 6, 2026

dictate how isotropic probes move through heterogeneous solutions.

Anisotropic particles provide properties that are not accessible with isotropic spheres. Single-walled carbon nanotubes (SWCNTs) are a particularly attractive class of anisotropic nanoparticles due to their unique features. SWCNTs have a high elastic modulus, low density, and excellent electrical conductivity, making them promising reinforcing agents for nanocomposites.^{23–25} Their high surface area, tunable surface chemistry, and high drug-loading capacity make them ideal candidates for encapsulating and delivering therapeutic agents.^{26–29} Moreover, SWCNTs are highly photostable, demonstrating resistance to photobleaching and blinking.³⁰ Owing to these unique optical features as well as biocompatibility when wrapped with appropriate functionalization, SWCNTs are widely used in biosensing^{31–34} and biomedical imaging.^{35,36}

SWCNTs are characterized by multiple length scales—specifically their diameter d and length L —and therefore, theories developed for SNPs are not appropriate to predict their behavior. Prior studies of nanorods,^{37–39} stiff filaments,⁴⁰ and semiflexible rod-like viruses^{41,42} have demonstrated that anisotropic particles can exhibit substantially enhanced transport relative to SE predictions in complex fluids. These studies further showed that anisotropy gives rise to distinct transport modes, leading to anisotropic diffusion, non-Gaussian dynamics, and coupling to polymer microstructure and dynamics that cannot be described by a single particle length scale. Despite these studies, our understanding of the mechanisms underlying SWCNTs transport in structured complex fluids remains incomplete.

Here, we investigate how the anisotropy of SWCNTs influences transport in structurally heterogeneous polymer solutions by comparing their dynamics with those of SNPs of comparable characteristic dimensions. We systematically vary polymer concentration and molecular weight to independently tune the solution viscosity and polymer characteristic length scales and use single-particle tracking to quantify nanoparticle dynamics. We find that SWCNTs exhibit substantially enhanced transport relative to SE predictions, with deviations emerging at lower polymer molecular weights than for SNPs. Furthermore, the SWCNT dynamics collapse onto a master curve as a function of the ratio of nanotube length to the polymer correlation length and continue to follow this scaling within the entangled regime. By contrast, SNP dynamics deviate from the same scaling upon entering the entangled regime, highlighting a fundamental difference in how isotropic and anisotropic nanoparticles interact with polymer microstructure. Finally, SWCNTs exhibit pronounced non-Gaussian displacement distributions with extended tails and sharp peaks that increase in magnitude with polymer concentration, as opposed to the Gaussian distributions observed for SNPs. Together, these results demonstrate that SWCNT anisotropy facilitates dynamic coupling to the polymer network distinct from that of analogous spherical particles to promote enhanced diffusion. These findings establish a mechanistic framework for understanding and predicting the transport of SWCNTs in complex fluids.

2. MATERIALS AND METHODS

Raw high-pressure carbon monoxide (HiPco)-synthesized SWCNTs were purchased from NanoIntegris. Sodium deoxycholate (SDC) and glycerol were purchased from Thermo Scientific. Poly(ethylene oxide)

(PEO) of various molecular weights was purchased from Scientific Polymer and Sigma-Aldrich. Poly(methyl methacrylate) (PMMA) tracker particles with carboxyl-functionalized surfaces and a nominal diameter of 100–150 nm were purchased from PolyAn.

2.1. SWCNT Functionalization

SWCNTs are intrinsically hydrophobic and chemical functionalization is required to suspend them in aqueous solutions.⁴³ Pristine SWCNTs were dispersed in an SDC solution prepared in deionized (DI) water (1 wt %). A 10:1 mass ratio of SDC to SWCNTs in DI water was vortex-mixed and ultrasonicated using a 1/8" tapered microtip for 30 min at 40% amplitude (Sonics Vibracell VCX-130) to obtain a stable dispersion. The suspension was then ultracentrifuged at 63,000 rpm for 30 min at 10 °C (Optima L-100 XP, Beckman Coulter), and the top 80% of the supernatant was collected, while the pellet containing aggregates and impurities was discarded. A schematic illustration of the SWCNT dispersion and purification process is shown in Figure 1a. The concentration of the resulting SWCNT dispersion was determined to be 680 mg/L using UV–vis–NIR spectroscopy with an extinction coefficient of $A_{910} = 0.02554 \text{ L mg}^{-1} \text{ cm}^{-1}$ (Supporting Information, Figure S1).⁴⁴ Atomic force microscopy (AFM) measurements following similar surfactant assisted dispersion protocol for HiPco SWCNTs have reported an apparent nanotube diameter of 1–3 nm.⁴⁵ Moreover, previous work⁴⁶ used AFM to quantify the average length of these SWCNTs to be 120 nm with a range of 70–168 nm following functionalization and ultrasonication.

2.2. Sample Preparation

Semidilute solutions of PEO with molecular weights M_w ranging from 35 kDa to 4 MDa in water were prepared by adding polymer to deionized water at concentrations ranging from 1 to 30 c^* . The solutions were then homogenized on a roller for two weeks to ensure complete polymer dissolution. The overlap concentration was calculated as $c^* = 1/[\eta]$, where the intrinsic viscosity was obtained from the Mark–Houwink equation $[\eta] = KM_w^a$ with $K = 1.25 \times 10^{-2} \text{ mL g}^{-1}$ and $a = 0.78$.⁴⁷ The unperturbed radius of gyration was estimated as $R_{g,0} = (3M_w/4\pi N_A c^*)^{1/3}$, and the polymer correlation length was calculated as $\xi = R_g(c/c^*)^{-0.77}$. Resulting values of $R_{g,0}$ and ξ are provided in Supporting Information in Tables S1–S3. Spherical PMMA nanoparticles (SNPs) and SDC-wrapped SWCNTs were added to the solutions at a volume fraction of $\phi \approx 10^{-6}$ in 1 mL microtube vials and vortex-mixed for 2 min to ensure particle dispersion. The solutions were then added into glass slide chambers and sealed with epoxy to prevent evaporation following established protocols.⁴⁸ A schematic illustration of the sample preparation procedure is shown in Figure 1b. Under these conditions, strong electrostatic particle–polymer interactions are not expected. PEO is non-ionic, while both the carboxyl-functionalized PMMA nanoparticles and SDC-wrapped SWCNTs possess negatively charged carboxylate surface chemistries. No signs of strong attractive interactions with PEO are observed, which would manifest as dynamics slower than SE predictions. Similarly, no polymer-induced aggregation or phase separation was observed, as shown by representative sample snapshots in the Supporting Information (Figure S4), providing no evidence of strongly repulsive interactions between the polymer and particles. Thus, the interactions between particles and polymer chains in solution are expected to be effectively neutral. The SWCNT addition resulted in a residual SDC concentration of approximately 50 μM in the polymer solutions, well below its critical micelle concentration. SNP controls with and without 50 μM SDC exhibit nearly identical dynamics (Supporting Information, Figure S5), indicating that residual SDC has a negligible effect on probe transport.

2.3. Bulk Rheology

Rheology measurements were performed on a TA Instruments HR-20 rheometer using either a parallel plate geometry with a 20 mm diameter for high viscosity samples or a concentric cylinder setup with a 30 mm cup and 28 mm bob for low-viscosity samples. Viscosity measurements

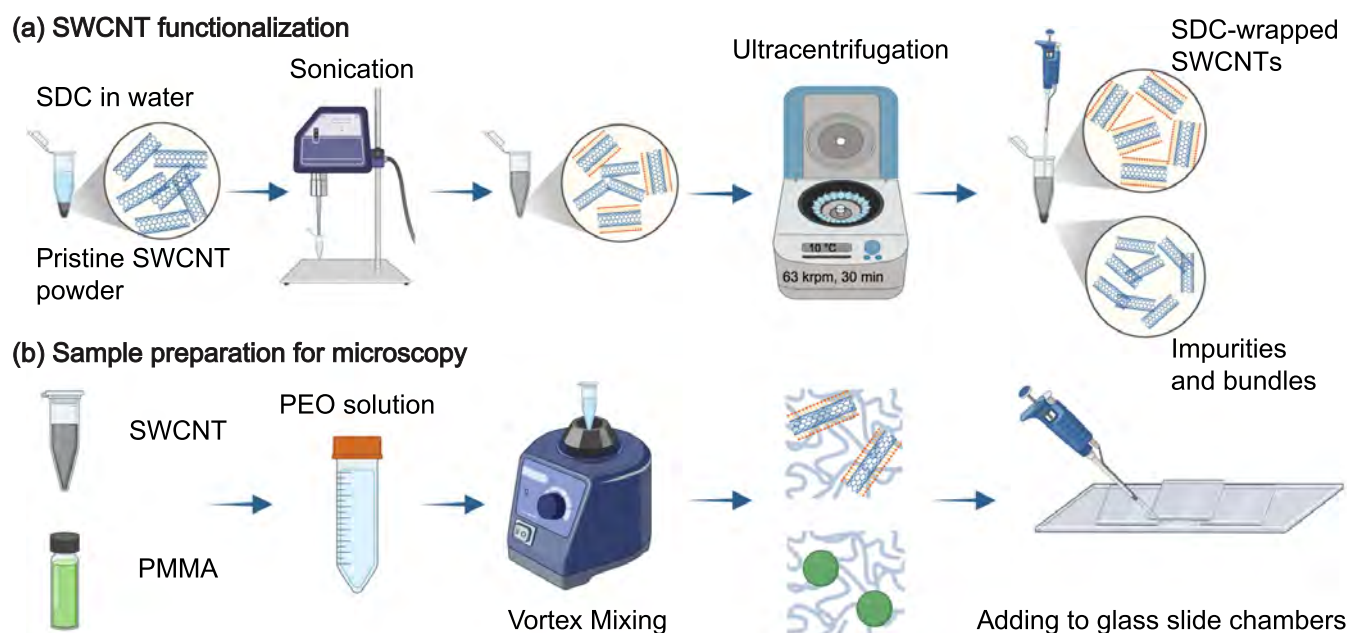


Figure 1. Schematic illustration of (a) SWCNT functionalization, in which pristine SWCNT powder was dispersed in 1 wt % SDC in DI water by sonication and purified by ultracentrifugation to remove bundles and impurities, yielding well-dispersed SDC-wrapped SWCNTs, and (b) sample preparation for imaging, in which SDC-wrapped SWCNTs or PMMA SNPs were dispersed in PEO solutions by vortex mixing before loading into glass slide microscope chambers.

were obtained from the zero-shear limit of a steady-shear flow sweep performed at 20 °C, in which the shear rate was varied from 0.01 to 100 s⁻¹. Example flow sweeps and solution viscosities are found in Supporting Information (Figures S2 and S3). Within experimental uncertainty, the viscosity collapses across molecular weights when plotted against c/c^* , consistent with polymer solution scaling theory.⁴⁹ The small deviations between molecular weights likely arise from polymer dispersity and scaling law estimates.

2.4. Optical Microscopy

Because of the different excitation and emission wavelengths of optically fluorescent spherical particles and near-infrared fluorescent SWCNTs, imaging was performed on two separate microscope systems. SNP solutions were imaged using a Leica DMi8 inverted microscope equipped with a Prime 95B scientific CMOS (sCMOS) camera and a green filter cube, using a 100× oil-immersion objective with a numerical aperture (NA) of 1.4. SWCNT solutions were imaged on an Olympus IX-73 inverted microscope using a 3 W 730 nm excitation laser and a 100× oil-immersion objective with an NA of 1.49. The corresponding diffraction-limited lateral resolutions for the two microscope systems were estimated using the Rayleigh criterion, $d_l = 0.61\lambda/\text{NA}$,^{50,51} where λ is the wavelength of the emitted light and NA is the numerical aperture of the objective lens. Using a representative green fluorescence emission wavelength for the SNPs and an average SWCNT emission wavelength of 1150 nm (corresponding to the 950–1350 nm emission range), the diffraction limits were estimated to be approximately 215 nm for SNP imaging and 470 nm for SWCNT imaging. For each sample, at least five videos were recorded in random locations to ensure sufficient statistical sampling. Videos were acquired at frame rates ranging from 1 to 30 Hz depending on particle dynamics. Snapshots of example videos are provided in the Supporting Information (Figure S4).

2.5. Particle Tracking

Particle tracking analysis was performed on captured videos via in-house MATLAB code, in which particle centroids were located and tracked over time.⁵² The tracking resolution was determined to be $\epsilon \approx 30$ nm on each microscopy. The resolution was quantified by fixing

SWCNTs and SNPs to the glass slide and measuring the resulting dynamics (Supporting Information, Figure S9). Following the analytical approach of our previous work,⁵³ we calculated various parameters from particle trajectories. First, the one-dimensional, ensemble-averaged mean-squared displacement (MSD) is calculated as a function of lag time $\Delta x^2(\Delta t) = (1/N) \sum_{i=1}^N [x_i(t + \Delta t) - x_i(t)]^2 - ((1/N) \sum_{i=1}^N [x_i(t + \Delta t) - x_i(t)])^2$, where $x_i(t)$ is the position of particle i at time t , N is the total number of displacement events included at each lag time Δt , and the second term corrects for bulk drift. The linear region of MSD versus lag time for each sample was fit to extract the diffusion coefficient D according to $\langle \Delta x^2(\Delta t) \rangle = 2D\Delta t$. Distributions of particle displacements⁵⁴ (DPDs) were calculated according to $G_s(\Delta x, \Delta t) = N^{-1} \sum_i \delta(x_i(t) - x_i(t + \Delta t) - \Delta x)$, where δ is the Dirac delta and N is the total number of particles. Finally, the non-Gaussian parameter α was calculated from these distributions according to $\alpha = \frac{\langle \Delta x^4(\Delta t) \rangle}{3\langle \Delta x^2(\Delta t) \rangle^2} - 1$.

3. RESULTS AND DISCUSSION

We begin by comparing the dynamics of comparably sized spherical nanoparticles (SNPs) and single-walled carbon nanotubes (SWCNTs). From particle tracking measurements in a Newtonian solution of 50% glycerol–water, we determine that the SNPs and SWCNTs have a translational diffusivity $D = 0.46 \pm 0.03 \mu\text{m}^2/\text{s}$ and $1.13 \pm 0.02 \mu\text{m}^2/\text{s}$, respectively (Supporting Information, Figure S6). Using the SE equation and the solution viscosity $\eta = 6.2$ mPa s, these diffusivities correspond to hydrodynamic diameters of $d_H = 150 \pm 10$ nm for the SNPs and $d_H = 61.3 \pm 1.1$ nm for the SWCNTs. We convert this measurement into an effective SWCNT length by approximating the nanotubes as rigid, slender rods ($L \gg d$) for which $d_H^2 = L^2/3$.⁴⁹ Under this assumption, we find that the SWCNTs have an effective length of $L = 106 \pm 2$ nm, which is comparable to the SNP hydrodynamic diameter and in good agreement with previous measurements from AFM.⁴⁶ For

anisotropic rods, however, a single translational diffusivity measurement provides a non-unique solution for L and d because rod-diffusion models depend on both dimensions. Alternative estimates for rod dimensions are provided in the Supporting Information (Figure S8) and are consistent with this hydrodynamic estimate when accounting for possible changes in the effective SWCNT diameter from the SDC wrapping and bound hydration layers. Under the assumptions of the SE prediction, we expect that SWCNTs and SNPs should exhibit similar diffusive dynamics in complex fluids because of their similar size.

To test this expectation, we investigate the dynamics of SNPs and SWCNTs in semidilute solutions of PEO at varying concentration and M_w . These solutions serve as model complex fluids in which the viscosity and length scales—such as the correlation length ξ , polymer radius of gyration R_g , and tube diameter a_T —can be tuned independently.^{20,49} For SNPs in polymer solutions at a fixed molecular weight of 600 kDa, nanoparticle mobility decreases with increasing polymer concentration due to the increase in viscosity (Figure 2a). At low polymer concentrations, the MSDs are linear with respect to time, indicating Fickian diffusion. At higher polymer concentrations (i.e., 20 c^* and 30 c^*), however, the SNP dynamics deviate from this linear scaling at short times and instead exhibit subdiffusive motion to scale as $\langle \Delta x^2(\Delta t) \rangle \sim t^\beta$ with $\beta < 1$. This two-step regime, which crosses over from subdiffusive to diffusive behavior on longer times, is commonly observed for SNPs inside polymer solutions^{55–58} when the particle size R_{NP} is comparable to the characteristic size of the polymer. These observations highlight the importance of the particle-to-polymer size ratio in governing nanoparticle transport through structurally heterogeneous polymer solutions.

To probe the effect of the particle-to-polymer size ratio, we investigate the dynamics of SNPs inside solutions with the same viscosity but different length scales. By varying polymer M_w from 35 kDa to 4 MDa at a constant c , we create a set of solutions with nearly identical viscosities but with $R_{g,0}$ varying from 8 to 140 nm (Supporting Information, Figure S3). As a result, we observe quantitatively similar particle dynamics for $M_w \leq 600$ kDa, with substantially faster SNP dynamics emerging only at higher M_w (i.e., 900 kDa and 4 MDa) (Figure 2b). Given the similar viscosity for all solutions, these enhanced dynamics indicate that particle dynamics decouple from the bulk solution viscosity when the nanoparticle is sufficiently small relative to the polymer. We quantify these enhanced dynamics by normalizing the SNP diffusivity by the diffusivity in pure solvent D_0 to remove explicit size dependence and compare to predictions from bulk rheology. As observed from the MSDs, we find that D/D_0 decreases with increasing polymer concentration and agree well with SE predictions for low M_w with significant deviations observed for higher M_w (Figure 2c). These deviations are consistent with our prior studies²⁰ and theoretical predictions,¹⁵ in which enhanced diffusivities arise from dynamic coupling of the nanoparticle to structural heterogeneities and segmental relaxations of the polymer.

To explore the effect of nanoparticle geometry, we next perform identical particle-tracking experiments with the rod-shaped SWCNTs. Similar to the observations for SNPs, SWCNT dynamics decrease with increasing polymer concentration at a fixed M_w of 600 kDa due to the increased bulk viscosity. The magnitude of this decrease and the short-time dynamics, however, differ substantially from those of SNPs. Specifically, we observe a much more modest reduction in

mobility with increasing polymer concentration, and the SWCNTs remain Fickian across all concentrations. Unlike the SNPs, we do not observe short-time subdiffusive dynamics. Moreover, at a fixed concentration of 20 c^* , we observe slow dynamics for the 35 kDa solution but significantly enhanced dynamics for $M_w \geq 300$ kDa (Figure 3b). In contrast to SNPs, where enhanced dynamics emerge only at the highest molecular weights, SWCNTs exhibit this transition at considerably lower M_w . More quantitatively, the relative diffusivities D/D_0 for SWCNTs exhibit deviations from bulk predictions at lower M_w (i.e., 300 kDa) and show significantly larger deviations from the SE relation compared to SNPs (Figure 3c). Given the comparable characteristic dimensions of the SNPs and SWCNTs, this contrast in particle dynamics implies that the nanoparticle geometry influences transport in structured polymer solutions.

For a more direct comparison of SWCNT and SNP deviations from SE predictions, we calculate the enhanced diffusivity relative to SE predictions D/D_{SE} . For SNPs, D/D_{SE} remains close to unity for all concentrations of $M_w \leq 900$ kDa, indicating good agreement with SE predictions (Figure 4a). We observe pronounced increases in D/D_{SE} only for highly concentrated solutions of $M_w = 4$ MDa. By contrast, SWCNTs exhibit significantly enhanced dynamics at much lower molecular weights (i.e., $M_w \geq 300$ kDa). Specifically, SWCNTs exhibit diffusivities up to 300× faster than SE predictions (Figure 4b). The earlier onset and larger deviation of SWCNTs suggest that their structural anisotropy fundamentally alters coupling to the surrounding polymer microstructure and segmental relaxations.

Earlier theoretical work¹⁵ has shown that SNP diffusivities in semidilute polymer solutions scale as $D/D_0 \sim (R_{NP}/\xi)^{-2}$ because particle transport is governed by an effective local viscosity associated with polymer segmental relaxations rather than the bulk solution viscosity. Consistent with this framework, we observe that the normalized diffusivities of SNPs collapse onto a single master curve and follow the expected -2 scaling at low-to-intermediate values of R_{NP}/ξ (i.e., $R_{NP}/\xi < 4$) (Figure 5). At larger values of R_{NP}/ξ , however, the diffusivity deviates from the -2 scaling and exhibits a sharper power-law decay. This crossover occurs near the onset of the entangled regime in aqueous PEO solutions at $c_e \approx 5c^*$ according to our rheological measurements and literature reports.^{21,59} For entangled solutions, particle motion is constrained by chain entanglements relaxing through reptation, causing the particles to no longer couple to segmental relaxations. Such entanglement-controlled dynamics are predicted theoretically¹⁵ and confirmed experimentally.^{21,22}

For anisotropic nanoparticles with multiple characteristic dimensions, identifying the relevant length scale controlling dynamics is less straightforward. Prior studies on semiflexible rod-like viruses⁴¹ reported effective length scales intermediate between the particle length and radius. In our system, we find that the normalized diffusivities of SWCNTs collapse onto a single curve that agrees with the SNP collapse when plotted as a function of L/ξ (Figure 5). Similar to SNPs, the dynamics of SWCNTs follow the approximate -2 scaling, confirming that their dynamics couple to the segmental relaxations of the polymer mesh along the nanotube length. But, in contrast to SNPs, SWCNTs continue to follow this scaling even within the entangled regime. We hypothesize that this difference in coupling arises from the anisotropic geometry of SWCNTs. Because the SWCNT diameter (≈ 1 nm) remains substantially smaller than the polymer tube diameter a_T , the nanotubes are not localized by the entanglement network. As a result, polymer

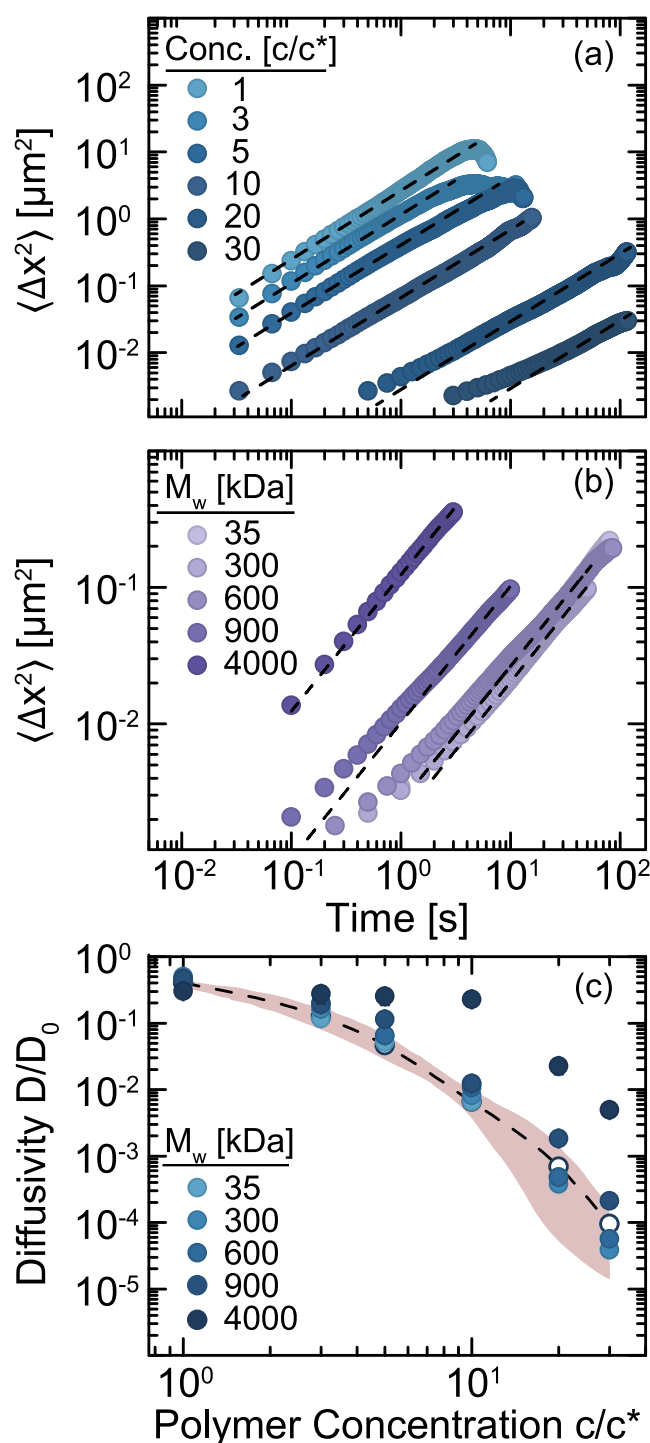


Figure 2. Mean-squared displacement ($\langle \Delta x^2 \rangle$, MSD) as a function of time for SNPs in solutions of (a) 600 kDa PEO at different polymer concentrations and (b) a concentration of 20 c/c^* for different M_w . Dashed lines represent linear scaling. (c) Normalized diffusivity D/D_0 of SNPs as a function of c/c^* for various M_w . Dashed line and open symbols represent the SE predictions and the shaded region represents uncertainty.

entanglements may play a less important role in governing the overall SWCNT transport. To investigate the transport mechanisms underlying these anisotropy-induced differences in dynamics, we next examine the distributions of particle displacements (DPDs) for SWCNTs and SNPs.

We normalize the DPDs by the square root of the MSD at a lag time Δt to enable comparison across samples with different particles, polymer concentrations, and molecular weights. For SNPs, the DPDs remain approximately Gaussian across all

polymer concentrations and M_w (Figure 6a,b), consistent with prior studies.^{20,41,48} The Gaussian DPDs suggest that SNPs couple uniformly to the surrounding polymer microstructure over the conditions examined and that increasing polymer concentration and molecular weight do not introduce qualitatively different transport mechanisms for SNPs.

By contrast, SWCNTs exhibit pronounced non-Gaussian behavior characterized by sharp peaks near $\Delta x = 0$ and extended tails at large displacements (Figure 6c,d). At fixed M_w ,

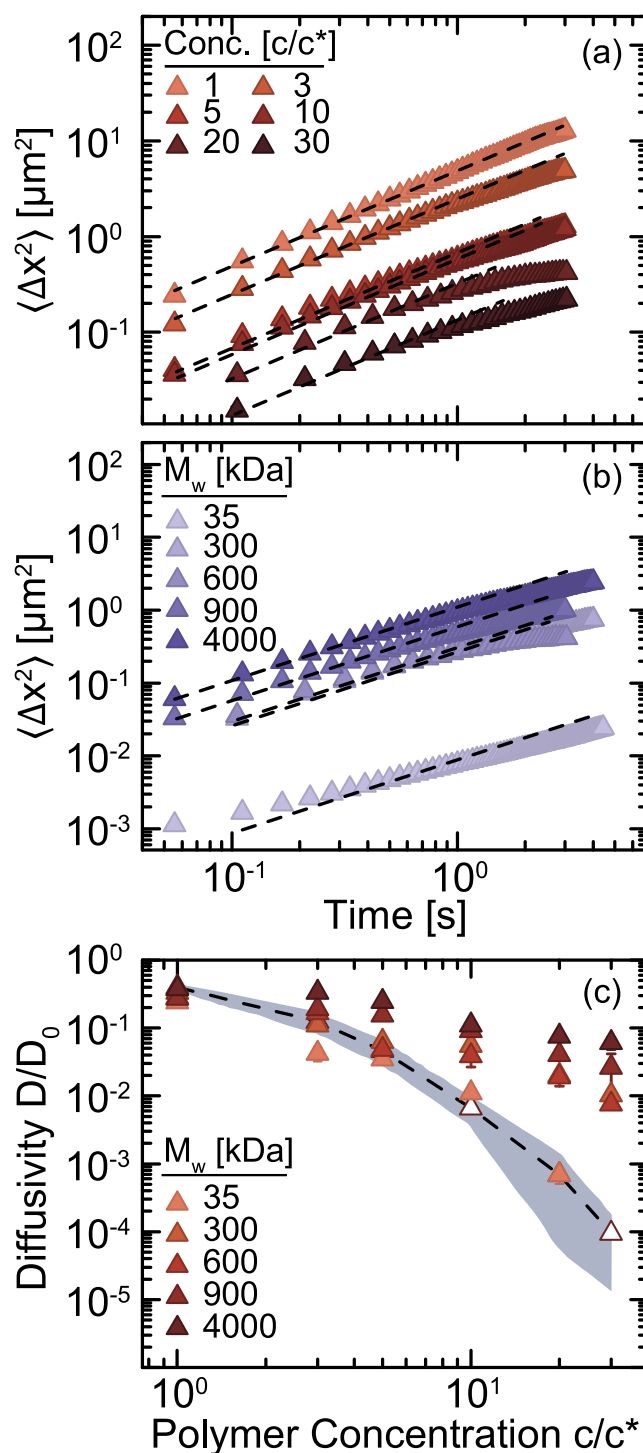


Figure 3. Mean-squared displacement ($\langle \Delta x^2 \rangle$, MSD) as a function of time for SWCNTs in solutions of (a) 600 kDa PEO at different c/c^* and (b) at a concentration of $20 c/c^*$ for different M_w . Dashed lines represent linear scaling. (c) Normalized diffusivity D/D_0 for SWCNTs as a function of polymer concentration c/c^* for various M_w . Dashed line and open symbols represent the SE predictions and the shaded region represents uncertainty.

these non-Gaussian characteristics increase with polymer concentration. The non-Gaussian behavior is observed across all molecular weights, with the strongest deviations occurring near $M_w = 600$ kDa. The sharp peak near $\Delta x = 0$ implies an increased probability of small displacements, whereas the extended tails indicate an increased probability of large displacements relative to a Gaussian distribution. Importantly, analysis of the individual particle diffusivity distributions

(Supporting Information, Figure S10) shows no distinct population with D near the tracking resolution limit, confirming that the enhanced probability of small displacements arises from transiently localized rather than permanently stuck particles. To quantify these observations, we calculate the non-Gaussian parameter α . Consistent with the Gaussian DPDs, α remains close to zero for SNPs across nearly all conditions (Figure 7a). By contrast, SWCNTs exhibit values greater than zero across all

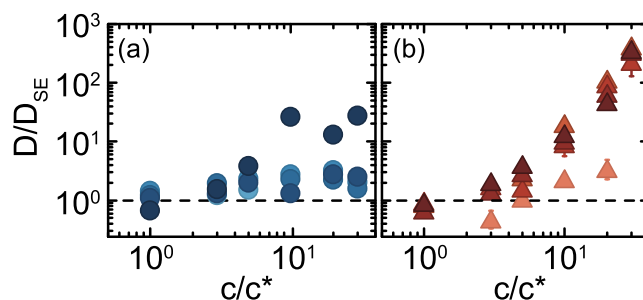


Figure 4. Enhanced diffusivity D/D_{SE} as a function of polymer concentration c/c^* for (a) SNPs and (b) SWCNTs. The color gradient from light to dark represents increasing M_w from 35 kDa to 4 MDa. Dashed line denotes $D/D_{SE} = 1$, corresponding to agreement with SE predictions.

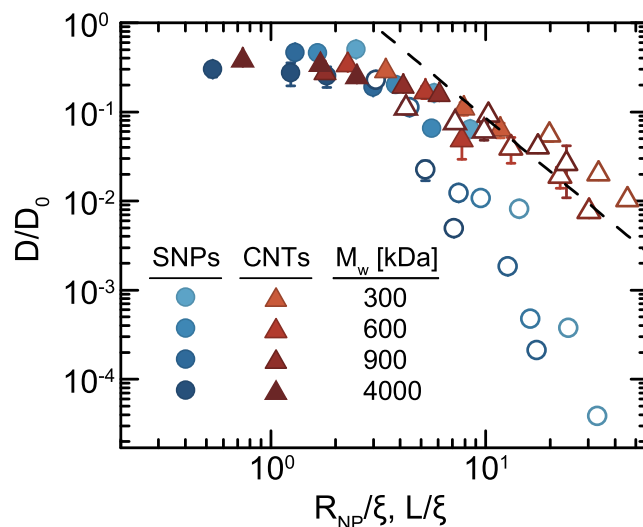


Figure 5. Normalized diffusivity D/D_0 as a function of normalized length scale R_{NP}/ξ for SNPs and L/ξ for SWCNTs. Dashed line represents the predicted -2 scaling from Ref. [15]. Open symbols denote data corresponding to the entangled regime.

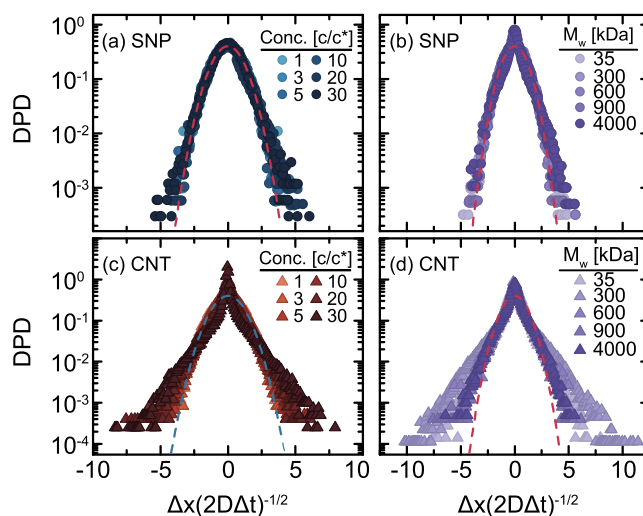


Figure 6. Distribution of particle displacements (DPDs) as a function of displacement normalized to diffusion distance $\Delta x(2D\Delta t)^{-1/2}$ at a lag time $\Delta t = 1$ s for (a,b) spherical nanoparticles and (c,d) SWCNTs. Panels (a,c) show DPDs in 900 kDa solutions for varying polymer concentrations and panels (b,d) show DPDs in solutions of 20 c/c^* for varying M_w . Dashed lines indicate Gaussian predictions.

conditions, with a pronounced maximum near $M_w = 600$ kDa for all concentrations (Figure 7b).

Because SNPs are isotropic, their transport is well described as a random walk with a single diffusive mode, such that particles have equal probability of moving in any direction. As a result,

their displacement distributions remain Gaussian and α stays near zero across the conditions investigated,⁶⁰ even in the presence of viscoelasticity and structural heterogeneity. The observed non-Gaussian displacement distributions for SWCNTs can arise through a number of mechanisms, including

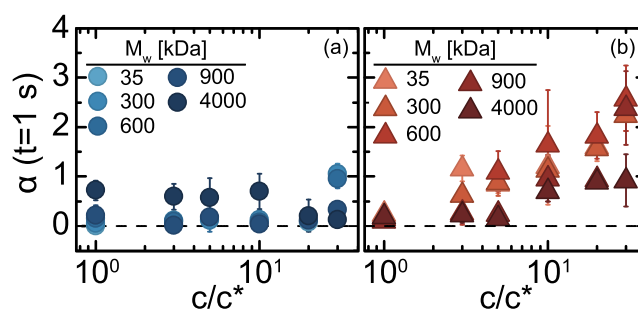


Figure 7. Non-Gaussian parameter α of (a) spherical nanoparticles and (b) SWCNTs at $\Delta t = 1$ s as a function of c/c^* for different M_w . Dashed line indicates $\alpha = 0$, representing Gaussian distributions. Error bars represent standard deviations across at least 5 videos for each sample.

length polydispersity, bundling, or heterogeneity in the local environment. We observe minor contributions from length polydispersity with $\alpha \approx 0.22$ when measured in a homogeneous, Newtonian fluid of a 50% glycerol–water solution (Supporting Information, Figure S7). Thus, length polydispersity alone cannot explain the pronounced non-Gaussian distributions observed in PEO solutions. Significant bundling is also unlikely. Bundles would have a larger hydrodynamic size and therefore diffuse more slowly but we do not observe SWCNT dynamics slower than SE predictions. Environmental heterogeneity may also contribute to the observed distributions, but SNPs remain approximately Gaussian under the same PEO conditions, suggesting that sample heterogeneity alone does not account for the strong non-Gaussian behavior of SWCNTs.

Instead, the relevant distinction is that anisotropic nanorods in complex fluids can exhibit substantially faster motion parallel to their length than perpendicular to it.^{37,40,61} We therefore attribute the non-Gaussian DPDs and elevated α values observed for SWCNTs to differences in transport along these two directions.^{62,63} Because the SWCNT length and diameter couple differently to the surrounding polymer microstructure, motion parallel and perpendicular to the nanotube axis experience different hydrodynamic constraints, resulting in a distribution of diffusivities. The maximum in α near $M_w = 600$ kDa further supports this interpretation. At lower molecular weights, the polymer length scales remain small compared to the nanotube length, leading to strong differences between transport parallel and perpendicular to the nanotube axis. As the polymer molecular weight increases beyond 600 kDa, the characteristic polymer length scales become increasingly comparable to the SWCNT length so that transport perpendicular to the SWCNT length can also decouple from bulk viscosity. As a result, both perpendicular and parallel dynamics deviate from SE predictions, reducing the difference between these transport modes and resulting in a decrease in α with M_w . Our results demonstrate that the observed non-Gaussian behavior of anisotropic nanoparticle dynamics originates from the presence of multiple transport modes arising from the multiple characteristic length scales of SWCNTs. This mechanistic picture provides a physical basis for the enhanced transport and distinct scaling behavior of SWCNT dynamics relative to those of SNPs.

4. CONCLUSIONS

We investigated the effect of nanoparticle anisotropy on transport in semidilute polymer solutions by comparing the dynamics of SWCNTs and SNPs with comparable characteristic dimensions. SWCNTs exhibit substantially enhanced transport,

with deviations from Stokes–Einstein predictions emerging at lower polymer molecular weights and increasing more strongly with polymer concentration than what is observed for SNPs. These differences indicate that SWCNTs couple to the surrounding polymer microstructure differently than isotropic nanoparticles. We find that SWCNT transport is governed by the nanotube length relative to the characteristic polymer length scales. Unlike SNPs, SWCNTs continue to exhibit enhanced transport in the entangled regime. The distributions of particle displacements and non-Gaussian parameters further show that SWCNT transport is facilitated by multiple transport modes that arise from anisotropic motion parallel and perpendicular to the nanotube axis. Together, these results provide a mechanistic picture for the enhanced transport of SWCNTs in complex fluids. This understanding may enable the use of SWCNTs as sensitive microrheological probes of local structure and dynamics in soft matter and biological environments,^{64–69} as well as providing useful insights for targeted drug delivery in crowded media.⁷⁰

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsanm.6c03452>.

Structural length scales, rheological characterization and zero-shear viscosities, representative flow curves, example microscopy images and particle tracking, SWCNT size characterization, nanoparticle dynamics in a Newtonian glycerol solution, individual particle diffusivity distributions, and additional statistical analyses (PDF)

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<https://pubs.acs.org/doi/10.1021/acsanm.6c03452>

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was supported in part by the Grants #CBET-1844536 (D.R.) and #CBET-2339052 (R.P.S.) from the National Science Foundation and Cottrell Scholar Award #CS-CSA-2025-033 from Research Corporation for Science Advancement (R.P.S.). TOC graphic and schematics were created using [BioRender.com](https://www.biorender.com) software.

REFERENCES

- (1) Yao, Y.; Hong, B.; An, Y. Nanoparticles in Concrete: Data-Driven Visualization, Collaboration, and Trends. *ACS Appl. Nano Mater.* **2025**, *8*, 668–692.
- (2) Zhou, W.; Xin, C.; Chen, Y.; Mouhouadi, R. D.; Chen, S. Nanoparticles for Enhancing Heavy Oil Recovery: Recent Progress, Challenges, and Future Perspectives. *Energy Fuels* **2023**, *37*, 8057–8078.
- (3) Kandel, Y. E.; Attia, G. M.; Metwalli, F. I.; Khalaf, R. E.; Mahmoud, O. Nanoparticles in Enhanced Oil Recovery: State-of-the-Art Review. *J. Pet. Explor. Prod. Technol.* **2025**, *15*, 66.
- (4) Akbari, A.; Nikraves, H.; Kazemzadeh, Y. Applications of Nanoparticle in Enhanced Oil Recovery: A Comprehensive Review, History, and Future Prospects. *Can. J. Chem. Eng.* **2026**, *104*, 138–168.
- (5) Saha, S.; Das, S.; Rahman, M. Z. Hybridization in Natural Fiber Composites: Enhanced Performance and Sustainability. *Compos. B Eng.* **2026**, *308*, 112986.
- (6) Senses, E.; Tyagi, M.; Pasco, M.; Faraone, A. Dynamics of Architecturally Engineered All-Polymer Nanocomposites. *ACS Nano* **2018**, *12*, 10807–10816.
- (7) Kao, J.; Thorkelsson, K.; Bai, P.; Rancatore, B. J.; Xu, T. Toward Functional Nanocomposites: Taking the Best of Nanoparticles, Polymers, and Small Molecules. *Chem. Soc. Rev.* **2013**, *42*, 2654–2678.
- (8) Doane, T. L.; Burda, C. The Unique Role of Nanoparticles in Nanomedicine: Imaging, Drug Delivery and Therapy. *Chem. Soc. Rev.* **2012**, *41*, 2885.
- (9) Devaraji, M.; Thanikachalam, P. V.; Elumalai, K. The Potential of Copper Oxide Nanoparticles in Nanomedicine: A Comprehensive Review. *Biotechnol. Notes* **2024**, *5*, 80–99.
- (10) Boisselier, E.; Astruc, D. Gold Nanoparticles in Nanomedicine: Preparations, Imaging, Diagnostics, Therapies and Toxicity. *Chem. Soc. Rev.* **2009**, *38*, 1759.
- (11) Saha, S.; Trivedi, D.; Rengan, A. K.; Yu, A. Polyurethane Nanoparticles as Versatile Tools in Nanomedicine: A Review. *ACS Appl. Nano Mater.* **2024**, *7*, 5729–5744.
- (12) Han, X.; Xu, K.; Taratula, O.; Farsad, K. Applications of Nanoparticles in Biomedical Imaging. *Nanoscale* **2019**, *11*, 799–819.
- (13) Kim, D.; Kim, J.; Park, Y. I.; Lee, N.; Hyeon, T. Recent Development of Inorganic Nanoparticles for Biomedical Imaging. *ACS Cent. Sci.* **2018**, *4*, 324–336.
- (14) Algar, W. R.; Massey, M.; Rees, K.; Higgins, R.; Krause, K. D.; Darwish, G. H.; Peveler, W. J.; Xiao, Z.; Tsai, H.-Y.; Gupta, R.; Lix, K.; Tran, M. V.; Kim, H. Photoluminescent Nanoparticles for Chemical and Biological Analysis and Imaging. *Chem. Rev.* **2021**, *121*, 9243–9358.
- (15) Cai, L.-H.; Panyukov, S.; Rubinstein, M. Mobility of Nonsticky Nanoparticles in Polymer Liquids. *Macromolecules* **2011**, *44*, 7853–7863.
- (16) Dell, Z. E.; Schweizer, K. S. Theory of Localization and Activated Hopping of Nanoparticles in Cross-Linked Networks and Entangled Polymer Melts. *Macromolecules* **2014**, *47*, 405–414.
- (17) Yamamoto, U.; Schweizer, K. S. Theory of Nanoparticle Diffusion in Unentangled and Entangled Polymer Melts. *J. Chem. Phys.* **2011**, *135*, 224902.
- (18) Yamamoto, U.; Schweizer, K. S. Spatially Dependent Relative Diffusion of Nanoparticles in Polymer Melts. *J. Chem. Phys.* **2013**, *139*, 064907.
- (19) Yamamoto, U.; Schweizer, K. S. Microscopic Theory of the Long-Time Diffusivity and Intermediate-Time Anomalous Transport of a Nanoparticle in Polymer Melts. *Macromolecules* **2015**, *48*, 152–163.
- (20) Poling-Skutvik, R.; Krishnamoorti, R.; Conrad, J. C. Size-Dependent Dynamics of Nanoparticles in Unentangled Polyelectrolyte Solutions. *ACS Macro Lett.* **2015**, *4*, 1169–1173.
- (21) Xue, C.; Shi, X.; Tian, Y.; Zheng, X.; Hu, G. Diffusion of Nanoparticles with Activated Hopping in Crowded Polymer Solutions. *Nano Lett.* **2020**, *20*, 3895–3904.
- (22) Guo, H.; Bourret, G.; Lennox, R. B.; Sutton, M.; Harden, J. L.; Leheny, R. L. Entanglement-Controlled Subdiffusion of Nanoparticles within Concentrated Polymer Solutions. *Phys. Rev. Lett.* **2012**, *109*, 055901.
- (23) Moniruzzaman, M.; Winey, K. I. Polymer Nanocomposites Containing Carbon Nanotubes. *Macromolecules* **2006**, *39*, 5194–5205.
- (24) Coleman, J. N.; Khan, U.; Gun'ko, Y. K. Mechanical Reinforcement of Polymers Using Carbon Nanotubes. *Adv. Mater.* **2006**, *18*, 689–706.
- (25) Byrne, M. T.; Gun'ko, Y. K. Recent Advances in Research on Carbon Nanotube–Polymer Composites. *Adv. Mater.* **2010**, *22*, 1672–1688.
- (26) Mulvey, J. J.; Villa, C. H.; McDevitt, M. R.; Escorcia, F. E.; Casey, E.; Scheinberg, D. A. Self-Assembly of Carbon Nanotubes and Antibodies on Tumours for Targeted Amplified Delivery. *Nat. Nanotechnol.* **2013**, *8*, 763–771.
- (27) Liu, Z.; Cai, W.; He, L.; Nakayama, N.; Chen, K.; Sun, X.; Chen, X.; Dai, H. In Vivo Biodistribution and Highly Efficient Tumour Targeting of Carbon Nanotubes in Mice. *Nat. Nanotechnol.* **2007**, *2*, 47–52.
- (28) Sonowal, L.; Gautam, S. Advancements and Challenges in Carbon Nanotube-Based Drug Delivery Systems. *Nano-Struct. Nano-Objects* **2024**, *38*, 101117.
- (29) Das, S.; Roy, S.; Dinda, S. C.; Bose, A.; Mahapatra, C.; Basu, B.; Prajapati, B. Carbon Nanotubes in Brain Targeted Drug Delivery: A Comprehensive Review. *Results Chem.* **2025**, *15*, 102206.
- (30) Nadeem, A.; Lyons, S.; Kindopp, A.; Jamieson, A.; Roxbury, D. Machine Learning-Assisted Near-Infrared Spectral Fingerprinting for Macrophage Phenotyping. *ACS Nano* **2024**, *18*, 22874–22887.
- (31) Ackermann, J.; Metternich, J. T.; Herberich, S.; Kruss, S. Biosensing with Fluorescent Carbon Nanotubes. *Angew. Chem. Int. Ed.* **2022**, *134*, e202112372.
- (32) Basu, S.; Bisker, G. Near-Infrared Fluorescent Single-Walled Carbon Nanotubes for Biosensing. *Small* **2025**, *21*, 2502542.
- (33) Nadeem, A.; Rahmani, M.; Wang, Y.; Yari, S.; Lopez, R. M.; Kim, M.; Roxbury, D. Spectral Fingerprinting of Engineered Nanomaterials for Precision Biosensing. *ACS Nano* **2026**, *20*, 3921–3943.
- (34) Rahmani, M.; Van Gorden, K.; Peyton, S. R.; Roxbury, D. In Vitro Detection of Breast Cancer Cell Types Using Machine Learning-Assisted Spectral Fingerprinting of SWCNTs. *bioRxiv* **2026**.
- (35) Liu, Z.; Yang, K.; Lee, S.-T. Single-Walled Carbon Nanotubes in Biomedical Imaging. *J. Mater. Chem.* **2011**, *21*, 586–598.

- (36) Gong, H.; Peng, R.; Liu, Z. Carbon Nanotubes for Biomedical Imaging: The Recent Advances. *Adv. Drug Deliv. Rev.* **2013**, *65*, 1951–1963.
- (37) Wang, J.; O'Connor, T. C.; Grest, G. S.; Zheng, Y.; Rubinstein, M.; Ge, T. Diffusion of Thin Nanorods in Polymer Melts. *Macromolecules* **2021**, *54*, 7051–7059.
- (38) Baynosa, M. M. B.; Mukhopadhyay, A. Transient Interactions and Local Heterogeneity Drive Rotational–Translational Decoupling of Nanorods in Semidilute Mucin Solutions. *Soft Matter* **2025**, *21*, 9203–9212.
- (39) Mukhopadhyay, A. Nanorheology of a Reconstituted Mucin Gel. *Macromolecules* **2025**, *58*, 968–979.
- (40) Fakhri, N.; MacKintosh, F. C.; Lounis, B.; Cognet, L.; Pasquali, M. Brownian Motion of Stiff Filaments in a Crowded Environment. *Science* **2010**, *330*, 1804–1807.
- (41) Smith, M.; Poling-Skutvik, R.; Slim, A. H.; Willson, R. C.; Conrad, J. C. Dynamics of Flexible Viruses in Polymer Solutions. *Macromolecules* **2021**, *54*, 4557–4563.
- (42) Safi Samghabadi, F.; Slim, A. H.; Smith, M. W.; Chabi, M.; Conrad, J. C. Dynamics of Filamentous Viruses in Polyelectrolyte Solutions. *Macromolecules* **2022**, *55*, 10694–10702.
- (43) Nadeem, A.; Kindopp, A.; Junge, E.; Rahmani, M.; Roxbury, D. Enhancing Optical Properties and Stability of DNA-functionalized Carbon Nanotubes with Cryoprotectant-Mediated Lyophilization. *Carbon* **2026**, *248*, 121159.
- (44) Jena, P. V.; Safaei, M. M.; Heller, D. A.; Roxbury, D. DNA–Carbon Nanotube Complexation Affinity and Photoluminescence Modulation Are Independent. *ACS Appl. Mater. Interfaces* **2017**, *9*, 21397–21405.
- (45) Usrey, M. L.; Strano, M. S. Controlling Single-Walled Carbon Nanotube Surface Adsorption with Covalent and Noncovalent Functionalization. *J. Phys. Chem. C* **2009**, *113*, 12443–12453.
- (46) Safaei, M. M.; Gravely, M.; Rocchio, C.; Simmeth, M.; Roxbury, D. DNA Sequence Mediates Apparent Length Distribution in Single-Walled Carbon Nanotubes. *ACS Appl. Mater. Interfaces* **2019**, *11*, 2225–2233.
- (47) Bailey, F. E.; Kucera, J. L.; Imhof, L. G. Molecular Weight Relations of Poly(Ethylene Oxide). *J. Polym. Sci.* **1958**, *32*, 517–518.
- (48) Slim, A. H.; Poling-Skutvik, R.; Conrad, J. C. Local Confinement Controls Diffusive Nanoparticle Dynamics in Semidilute Polyelectrolyte Solutions. *Langmuir* **2020**, *36*, 9153–9159.
- (49) Rubinstein, M.; Colby, R. H. *Polymer Physics*; Oxford University Press, 2003.
- (50) Rose, K. A.; Molaei, M.; Boyle, M. J.; Lee, D.; Crocker, J. C.; Composto, R. J. Particle Tracking of Nanoparticles in Soft Matter. *J. Appl. Phys.* **2020**, *127*, 191101.
- (51) Rayleigh, L. On the Theory of Optical Images, with Special Reference to the Microscope: London, Edinburgh. *Dublin Philos. Mag. J. Sci.* **1896**, *42* (255), 167–195.
- (52) Crocker, J. C.; Grier, D. G. Methods of Digital Video Microscopy for Colloidal Studies. *J. Colloid Interface Sci.* **1996**, *179*, 298–310.
- (53) Keane, D. P.; Constantine, C. J.; Mellor, M. D.; Poling-Skutvik, R. Nanoparticle Transport in Biomimetic Polymer-linked Emulsions. *AIChE J.* **2024**, *70*, e18307.
- (54) Van Hove, L. Correlations in Space and Time and Born Approximation Scattering in Systems of Interacting Particles. *Phys. Rev.* **1954**, *95*, 249–262.
- (55) Ge, T. Scaling Perspective on Dynamics of Nanoparticles in Polymers: Length- and Time-Scale Dependent Nanoparticle–Polymer Coupling. *Macromolecules* **2023**, *56*, 3809–3837.
- (56) Nath, P.; Mangal, R.; Kohle, F.; Choudhury, S.; Narayanan, S.; Wiesner, U.; Archer, L. A. Dynamics of Nanoparticles in Entangled Polymer Solutions. *Langmuir* **2018**, *34*, 241–249.
- (57) Foreman, K.; Tran-Ba, K.-H. Single-Particle Tracking in Poly(Ethylene Glycol) Diacrylate: Probe Size Effect on the Diffusion Behaviors of Nanoparticles in Unentangled Polymer Solutions. *J. Phys. Chem. B* **2023**, *127*, 7091–7102.
- (58) Park, J.; Bailey, E. J.; Composto, R. J.; Winey, K. I. Single-Particle Tracking of Nonsticky and Sticky Nanoparticles in Polymer Melts. *Macromolecules* **2020**, *53*, 3933–3939.
- (59) Del Giudice, F.; D'Avino, G.; Greco, F.; De Santo, I.; Netti, P. A.; Maffettone, P. L. Rheometry-on-a-Chip: Measuring the Relaxation Time of a Viscoelastic Liquid through Particle Migration in Microchannel Flows. *Lab Chip* **2015**, *15*, 783–792.
- (60) Valentine, M. T.; Kaplan, P. D.; Thota, D.; Crocker, J. C.; Gisler, T.; Prud'homme, R. K.; Beck, M.; Weitz, D. A. Investigating the Microenvironments of Inhomogeneous Soft Materials with Multiple Particle Tracking. *Phys. Rev. E: Stat., Nonlinear, Soft Matter Phys.* **2001**, *64*, 061506.
- (61) Chen, Y.; Xiang, Z.; Ren, H.; Guo, F.; Ganesan, V.; Liu, J. Anisotropic and Non-Gaussian Diffusion of Thin Nanorods in Polymer Networks. *Macromolecules* **2024**, *57*, 5105–5118.
- (62) Wang, B.; Anthony, S. M.; Bae, S. C.; Granick, S. Anomalous yet Brownian. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106*, 15160–15164.
- (63) Hapca, S.; Crawford, J. W.; Young, I. M. Anomalous Diffusion of Heterogeneous Populations Characterized by Normal Diffusion at the Individual Level. *J. R. Soc. Interface* **2009**, *6*, 111–122.
- (64) Godin, A. G.; Varela, J. A.; Gao, Z.; Danné, N.; Dupuis, J. P.; Lounis, B.; Groc, L.; Cognet, L. Single-Nanotube Tracking Reveals the Nanoscale Organization of the Extracellular Space in the Live Brain. *Nature Nanotech* **2017**, *12*, 238–243.
- (65) Paviolo, C.; Ferreira, J. S.; Lee, A.; Hunter, D.; Calaresu, I.; Nandi, S.; Groc, L.; Cognet, L. Near-Infrared Carbon Nanotube Tracking Reveals the Nanoscale Extracellular Space around Synapses. *Nano Lett.* **2022**, *22*, 6849–6856.
- (66) Lee, A.; Simon, A. A.; Boyreau, A.; Allain-Courtois, N.; Lambert, B.; Pradère, J.-P.; Saltel, F.; Cognet, L. Identification of Early Stage Liver Fibrosis by Modifications in the Interstitial Space Diffusive Microenvironment Using Fluorescent Single-Walled Carbon Nanotubes. *Nano Lett.* **2024**, *24*, 5603–5609.
- (67) Reuel, N. F.; Dupont, A.; Thouvenin, O.; Lamb, D. C.; Strano, M. S. Three-Dimensional Tracking of Carbon Nanotubes within Living Cells. *ACS Nano* **2012**, *6*, 5420–5428.
- (68) Strano, M. S.; Jin, H. Where Is It Heading? Single-Particle Tracking of Single-Walled Carbon Nanotubes. *ACS Nano* **2008**, *2*, 1749–1752.
- (69) Basu, S.; Hendler-Neumark, A.; Bisker, G. Dynamic Tracking of Biological Processes Using Near-Infrared Fluorescent Single-Walled Carbon Nanotubes. *ACS Appl. Mater. Interfaces* **2024**, *16*, acsami.4c10955–54975.
- (70) Lenders, V.; Koutsoumpou, X.; Phan, P.; Soenen, S. J.; Allegaert, K.; De Vleschouwer, S.; Toelen, J.; Zhao, Z.; Manshian, B. B. Modulation of Engineered Nanomaterial Interactions with Organ Barriers for Enhanced Drug Transport. *Chem. Soc. Rev.* **2023**, *52*, 4672–4724.