Motion Analysis of Self-Propelled Pt−Silica Particles in Hydrogen Peroxide Solutions

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Silica microspheres that are half-coated with platinum metal undergo self-propulsion in solutions of H2O2, with the average speed increasing with increasing H2O2 concentration. Microscopic observation of the particle motion, with segmentation of the image data, demonstrates that the particles move, on average, with the platinum-coated region oriented opposite to the direction of motion. Velocity autocorrelation and motion direction analyses show that the direction of motion is highly correlated with the particle orientation. The effect of the observation time interval on the measured translational diffusion coefficient and the apparent particle motion is analyzed.

Introduction

Self-propelled particles have been widely studied in biological systems, such as the actin polymerizing bacteria Listeria monocytogenes in cells and cell extracts and similarly behaving biomimetic polystyrene particles coated with the bacterial protein ActA.1–3 Recently, nonbiological micro- to nanoscale particles have been investigated that convert chemical energy into translational motion.4 These systems provide an opportunity to explore mechanisms of chemomechanical energy transduction and offer a link to self-propelled particles in living systems. In early studies, Whitesides and co-workers5 investigated the propulsion of millimeter-scale objects by the catalytic decomposition of hydrogen peroxide on a platinum surface. More recently, Mallouk and co-workers4,6–8 developed and characterized self-propelled asymmetric nanorods, prepared by the electrodeposition of Au and Pt. When the rods were suspended in dilute solutions of H2O2, video microscopy revealed that they were propelled generally in the direction of the Pt end of the rod. This propulsion direction was surprising in view of the study by Whitesides and co-workers,5 in which the motion generally occurred in a direction away from the Pt-coated region, with the propulsion depending on the production of O2 bubbles from the decomposition of H2O2. Mallouk and co-workers,4,6–8 proposed that the nanorods, composed of disparate metals in contact with one another, electrochemically generate a localized electrophoretic and proton field that induces motion of the rod through the surrounding fluid. Extensive studies by Mallouk, Sen, and co-workers,8–15 Ozin and co-workers,16–18 and Velegol and co-workers19,20 have identified a number of metallic nanorod systems that convert the fuel molecules hydrogen peroxide and hydrazine into translational and rotational motion.

A study of self-propelled, Pt-coated polystyrene particles was recently reported by Howse et al.,21 which showed that coating one hemisphere of the particle with Pt is sufficient for self-propulsion in dilute H2O2 solutions. The propulsion velocity obtained from the mean-squared displacement of the asymmetrically coated microspheres, also known as “Janus particles”, was found to increase with increasing hydrogen peroxide concentration. They proposed a mechanism involving diffusiophoresis, in which spatially asymmetric production of product molecules leads to propulsion of the particles.21–23 Theoretical studies of nanodimers by Rückner and Kapral24 showed that the propulsion can be understood in terms of a concentration gradient established by the catalytic production of product and a difference in the forces of molecular collisions with the catalytic and noncatalytic surfaces. In all of the studies of self-propelled particles, a common feature is a structural asymmetry that gives rise to a gradient of the product species.

Studies of self-propelled particles have focused primarily on particle velocity as a function of the concentration of reactant, usually H2O2, that fuels the propulsion. Tracking and motion analysis typically has been carried out at 36 frames per second (fps) or less. Optical microscopy of Pt−Au nanorods has allowed directionality coefficient analysis, which suggests that directionality is lost at low (<5.0%) hydrogen peroxide concentrations.4 The direction of motion relative to the orientation of the particle was not determined in the studies of asymmetrically Pt-coated polystyrene particles by Howse et al.21

We have carried out experiments with silica particles that are asymmetrically coated with Pt and immersed in H2O2 solutions, similar to the system studied by Howse et al.21 The focus of our study is on the particle orientation with respect to the direction of motion, which we investigate with velocity autocorrelation and propulsion direction analyses. We typically track about 20 particles, with images collected at 45–55 fps. An increase in average particle speed with increasing H2O2 concentration is found, in agreement with Howse et al.,21 where speed reflects the average distance traveled between video image frames. We find the velocity to be highly correlated on short time scales and the particle orientation to be highly correlated with the direction of motion.

Our self-propelled particle system differs from previously studied systems in that the particle motion occurs effectively in two dimensions. The 1 µm Pt−silica particles in our experiments have a higher density than the aqueous H2O2 solutions and settle to the bottom of the thin layer of solution. We found that these 1 µm particles move freely, both as self-propelled Pt−silica particles in H2O2 solutions and as Pt−silica particles or silica particles undergoing Brownian motion in water.
in our control experiments. The particle speeds are likely affected by particle–surface interactions, as the 1 µm particles move in the boundary layer at the glass microscope slide surface. However, such interactions do not affect the correlation of particle motion with particle orientation, and the effectively two-dimensional motion allows accurate characterization of the particle movement and orientation. We note that larger 4 µm particles exhibited restricted movement or were stationary in our experiments.

**Experimental Section**

**Preparation of Silica Particles Half-Coated with Platinum.** A dilute aqueous suspension of washed 1 µm silica particles (Bangs Laboratories, 0.96 µm, 15% coefficient of variation) was deposited on a coverslip (1.8 × 1.8 cm²) that had been cleaned in Piranha solution (1:3 mixture of 30% H₂O₂ and 18 M H₂SO₄). After evaporation of the bead solution, a predominantly close-packed, single layer of particles was formed on the substrate. A layer of Pt ~5 nm thick was subsequently deposited onto the particles using e-beam evaporation (Temescal BJD-2000) at ~10⁻⁶ Torr, producing particles that are approximately half-coated with platinum metal. The half-coated particles were released from the coverslip by sonication in water.

**Reaction Mixture Preparation, Particle Tracking, and Data Analysis.** Small ~2 µL aliquots of the suspended particle solution were mixed with hydrogen peroxide solution to form particle suspensions with desired H₂O₂ concentrations. Particle motion was captured using an Olympus IX-81 optical microscope with a 100× oil objective, which was fitted with a Photronics Cascade 512B camera. In order to maximize frame capture rate, small regions were selected from the field of view that contained one or more particles. The particle motion was then captured at the highest possible frame rate. Images were background corrected and segmented using the software ImageJ. The particle motion was tracked using Video Spot Tracker software (v05.20), which provided the 2D position of the particle and the corresponding frame time.

**Results**

The dynamical behavior of the self-propelled particles is controlled by the rotational and translational contributions to the motion of the particles. We have monitored the autonomous motion of Pt–silica particles in hydrogen peroxide solutions using high-speed, high-resolution imaging (up to 150 fps) and frame-by-frame particle tracking in order to determine the particle orientation relative to the direction of motion. Image segmentation allows the Pt–silica particle symmetry axis to be identified in each frame.

An example of the particle motion analysis is shown in Figure 1A, in which three sequential bright-field optical micrographs of a 1 µm Pt–silica particle are superimposed. The particle is shown at time intervals of ~650 ms in three successive positions during its autonomous motion in a solution of 27.3% H₂O₂. The three images were chosen from a series of images taken at ~55 fps, with every 36th frame selected. The bright region of the particle is the result of a lensing effect of the Köhler illumination of the uncoated half of the silica microbead. The dark region stems from the high extinction coefficient of the Pt-coated half of the particle.

The surface plot in Figure 1B shows the intensity of light transmitted by the particle, with the Pt-coated and silica regions appearing as a valley and a peak, respectively. The orientation of the particle in a particular frame can be determined by considering the extrema of the valley and peak components to be the centers of the Pt-coated and silica regions. Using the background intensity as the reference intensity, each raw image is segmented into two images: one for the Pt-coated region, with intensities less than the reference intensity, and one for the uncoated silica region, with intensities greater than the reference intensity. The two sets of images are then independently tracked to generate an array of x−y location information at subpixel resolutions by kernel matching with interpolation.

Figure 1C shows segmented images from the raw image data in Figure 1A, with superimposed particle orientation and translation vectors for the motion analysis described below. The combined segmented images clearly show the Pt-coated (black) and the uncoated silica (light gray) regions of the particle. The Pt-coated region of the particle may be smaller due to the vapor deposition procedure; however, the apparent size may also be distorted by the lensing effect of the uncoated silica region. From the x−y position of the uncoated silica region of the particle and the time interval between sequential images, the frame-to-frame trajectory and angle of motion θ motion can be determined. In addition, the particle orientation angle θ axis is defined by a vector from the intensity minimum corresponding to the Pt-coated side of the particle to the intensity maximum corresponding to the uncoated silica side. The trajectory vectors provide the particle velocity, and the directional changes of the particle defined by the angle γ can be evaluated from sequential images. These quantities allow an analysis of the particle orientation with respect to its translational motion as a function of time.

A comparison can be made between the particle orientation and the direction of motion from the angle information given by θ axis and θ motion in Figure 1C. Figure 2 shows a plot of the normalized distribution of the minimum absolute difference between the two angles, δθ = |θ axis − θ motion|. The value of δθ gives the deviation of the translation direction from the orientation direction of the Pt–silica particle. In the case where the particle travels in a direction exactly in line with its orientation, with the Pt-coated region to the rear, δθ = 0. The occurrence plot in Figure 2 shows that θ axis and θ motion coincide to a remarkable degree, consistent with our video observations and the velocity autocorrelation analysis described below. We note that there is little difference in this analysis between the occurrence distribution for particles in 15.0% and 27.3% H₂O₂ solutions.

The distribution of the directional angle γ for uncoated silica particles and Pt–silica particles in water and Pt–silica particles
same or nearly the same direction in the subsequent image frame, and the probability of the directional motion increases with increasing H₂O₂ concentration. For Pt–silica particles in 27.3% solutions of H₂O₂, the probability of continuing to travel in nearly the same direction is about 3 times as likely as for these particles in water. The probability of moving at right angles ($\pi/2$ or $-\pi/2$) is about half as likely, and the probability of moving in the opposite direction ($\pi$) is very unlikely. Figure 3d–f shows the distribution of the directional angle $\gamma$ for Pt–silica particles in 27.3% solutions of H₂O₂ with increasing observation time interval $\Delta t$. The distribution of $\gamma$ broadens as $\Delta t$ is increased, indicating that the apparent motion becomes more Brownian-like as the observation time interval becomes comparable to or larger than the rotational diffusion time $\tau_R$, as discussed below.

An analysis of the velocity autocorrelation function is consistent with the directional angle distributions. The normalized velocity autocorrelation function for three silica particles and three Pt–silica particles in water and H₂O₂ solutions is shown in parts a and b of Figure 4, respectively. The velocities of these particles exhibit little if any correlation, with the autocorrelation function quickly falling to zero. The velocity autocorrelation function for half-coated Pt–silica particles in 15.0% and 27.3% solutions of H₂O₂ is shown in parts c and d of Figure 4, respectively. The analysis is again carried out for three particles in each case. In contrast to the behavior of particles in water, we now see very strong correlations in the particle velocities, with a general trend of the autocorrelation function decreasing to zero at $\sim 0.5$ s. In both cases, the autocorrelation function decreases to slightly negative values after a falloff from large positive values, consistent with our observations of looping behavior at long times described below. In each experiment, a particle was observed for $\sim 5$ s, with a camera frame rate of $\sim 50$ fps.

The average speed of the three half-coated Pt–silica particles in water and in 15.0% and 27.3% H₂O₂ solutions is shown in Figure 5. The speed is determined by the distance traveled between image frames, which, in agreement with the studies of Howse et al., increases with increasing H₂O₂ concentration. The average speed of the uncoated silica particles in water is also shown for comparison, which is very close to the speed of

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**Figure 2.** Plot of normalized occurrence distribution of $\delta \theta = \theta_{\text{final}} - \theta_{\text{initial}}$ for half-coated Pt–silica particle motion in 15.0% (C) and 27.3% w/w H₂O₂ (○) solutions. Plot constructed from over 2000 and 1300 frames of tracked motion, respectively.

**Figure 3.** Distribution of directional angle $\gamma$ for uncoated silica and half-coated Pt–silica particles in water and H₂O₂ solutions. (a) Silica particles in water; (b) half-coated Pt–silica particles in water; (c) half-coated Pt–silica particles in 15.0% w/w H₂O₂ solution; (d–f) half-coated Pt–silica particles in 27.3% w/w H₂O₂ solution. For each solution, 3000 frames were analyzed for the particle motion. The observation time interval $\Delta t = 0.021$ (a), 0.022 (b), 0.019 (c), and 0.018 s (d). The effect of observation time interval is shown in (e) with $\Delta t = 0.36$ s and (f) with $\Delta t = 0.73$ s for half-coated Pt–silica particles in 27.3% w/w H₂O₂ solution.

**Figure 4.** Normalized velocity autocorrelation function for uncoated silica and half-coated Pt–silica particles in water and H₂O₂ solutions. (a) Silica particles in water; (b) Pt–silica particles in water; (c) Pt–silica particles in 15.0% w/w H₂O₂ solution; (d) Pt–silica particles in 27.3% w/w H₂O₂ solution. In each case, the motion of three different particles is analyzed, as shown by the black, blue, and green curves.

in H₂O₂ solutions is shown in Figure 3. Here $\gamma$ is defined as positive for clockwise changes in direction, $\gamma \in (0, \pi]$, and negative for counterclockwise changes in direction, $\gamma \in (-\pi, 0]$, with $\gamma = 0$ corresponding to no directional change. We see that there is virtually no directional preference for silica particles or Pt–silica particles in water (Figure 3a,b), reflecting the random selection of directional changes that accompanies Brownian motion. In contrast, there is a distinct directional preference for half-coated Pt–silica particles in 15.0% and 27.3% solutions of H₂O₂ (Figure 3c,d), with a narrowing distribution for the solution with the higher concentration. These distributions show that the self-propelled particle travels in the
the Pt–silica particles in water. Also plotted is the average time at which the velocity autocorrelation function falls to zero in each case. These values represent the approximate times when the particle velocities become uncorrelated, with the Pt–silica particles in H$_2$O$_2$ solutions showing significantly longer correlation times. The corresponding time for the uncoated silica particles in water is also shown, which is essentially the same as the time for the Pt–silica particles in water. These correlation times are very close to zero.

The interpretation of the directional angle and velocity autocorrelation analyses described above becomes more intuitive in terms of the high-speed video images. Figure 6 shows an overlay of images of a self-propelled Pt–silica particle in 10.0% H$_2$O$_2$ taken at a rate of ~56 fps. A lower H$_2$O$_2$ concentration was utilized in this experiment in order to capture Brownian-like motion in one frame area. The composite image shows that the particle typically travels in the same direction in the subsequent frame and continues in the same general direction for several more and sometimes many more frames. Large directional changes occur infrequently but give rise to major changes in the overall particle trajectory. This behavior is in agreement with the directional angle analysis shown in Figure 3. We also see that the particle velocity is correlated on short time scales, as shown in the analysis of the velocity autocorrelation function in Figure 4; however, on long time scales, the particle turns in wide angles and may travel in the opposite direction. The loss of correlation at ~0.5 s described in Figures 4 and 5 can be seen in the composite image in Figure 6 over sequences of approximately 25–30 frames.

**Discussion**

Suspensions of half-coated Pt–silica particles in H$_2$O$_2$ solutions are easily prepared and offer a convenient experimental system for studies of particle self-propulsion. Our study has utilized particles in which effectively two-dimensional motion is exhibited along the surface of a glass slide. While the overall particle speeds are no doubt affected by the frictional forces, this configuration allows an accurate characterization of correlations between the orientation axis of the particle and the direction of translational motion. The high extinction coefficient of the thin metal coating together with the illumination focusing by the uncoated silica allows the particle orientation to be continuously monitored during its self-propelled motion. With the location of the particle determined frame to frame, the measurements permit a detailed analysis of the particle orientation and direction of motion.

We note that our measurements do not allow us to directly determine the “turning angle” of a particle, i.e., the change in direction that accompanies reorientation of the particle. Our measurements determine the particle position and orientation at each instant a video image is captured, and because directional changes may occur between the moments two successive image frames are captured, the measurements simply correlate the orientation of the particle with the direction of motion. We note below that the observation time interval also affects the value of the translational diffusion coefficient when the time scale of the observation is shorter than the characteristic rotational diffusion time.

The directional angle measurements shown in Figure 3 offer insights into the effect of the observation time interval on the apparent motion of the particle. The distributions of the directional angle $\gamma$ for silica and Pt–silica particles in water and Pt–silica particles in 15.0% and 27.3% H$_2$O$_2$ solutions demonstrate that, with an observation time interval of $\Delta t \sim 0.02$ s, the self-propelled motion is highly directional compared to the Brownian motion. The particles in water display virtually no motion directionality, with an almost uniform distribution of the directional angle $\gamma$ (Figure 3a,b). The motion directionality is random for this purely Brownian behavior. The distribution of the directional angle $\gamma$ is distinctly different for the self-propelled particles in H$_2$O$_2$ solutions (Figure 3c,d), with the distribution becoming increasingly centered around small values of $\gamma$ with increasing concentration. These distributions for the self-propelled particles indicate that the rotational diffusion time $\tau_R$ is larger than the observation time interval $\Delta t$. The directional angle distributions in Figure 3e,f become more uniform with increasing observation time interval $\Delta t$ for the self-propelled particles. These distributions utilize the same data set for Pt–silica particles in 27.3% H$_2$O$_2$ solutions in Figure 3d, with measurements at ~55 fps. The image sequence was decimated by taking every 20th image for Figure 3e and every 40th image for Figure 3f. We see that the distribution of $\gamma$ becomes less centered and, at the largest $\Delta t$, exhibits characteristics of Brownian motion with a relatively uniform distribution. Hence, with an observation time interval $\Delta t$ that is about 40 times larger
than that for observing Brownian motion of Pt\textsuperscript{-}silica particles in water (Figure 3b) or propelled motion in H\textsubscript{2}O\textsubscript{2} solutions (Figure 3d), the same particles exhibit Brownian-like motion in H\textsubscript{2}O\textsubscript{2} solutions (Figure 3f).

An alternative approach to the mean-squared displacement for determining the translational diffusion constant $D_{\text{tran}}$ is to examine the step length distribution of a particle in the $x$ and $y$ directions for a given observation time interval $\Delta t$.\textsuperscript{27} This approach allows us to take advantage of frame-to-frame measurements of the particle displacement to gain insights into the effect of $\Delta t$ on the apparent motion of the particle. The probability density for a 1D displacement $\Delta$ is given by

$$P(\Delta) = A \exp(-\Delta^2/2\sigma^2)$$

where $\sigma = (2D_{\text{tran}}\Delta t)^{1/2}$. The value of $D_{\text{tran}}$ can therefore be determined by fitting eq 1 to a normal distribution of the step length $\Delta$ for a particular observation time interval $\Delta t$. We demonstrate with this approach that the self-propelled particles exhibit a Gaussian distribution of 1D step length over a wide range of the observation time interval $\Delta t$.

Figure 7 shows step length distributions for silica and Pt\textsuperscript{-}silica particles in water and Pt\textsuperscript{-}silica particles in 15.0% and 27.3% H\textsubscript{2}O\textsubscript{2} solutions, with an observation time interval $\Delta t \approx 0.02$ s. The red curves show Gaussian fits for the four cases, with values of $D_{\text{tran}}$ from Figure 7a--d of 0.42 $\pm$ 0.04, 0.46 $\pm$ 0.03, 0.60 $\pm$ 0.06, and 0.66 $\pm$ 0.04 $\mu$m$^2$/s, respectively. The dependence of the value of $D_{\text{tran}}$ on the observation time interval $\Delta t$ was investigated by developing new data sets from the data sets for Figure 7 according to $\Delta t_n = \Delta t(n + 1)$ for $n = 1, 2, 3$, etc. The probability density for 1D displacements $\Delta$ was plotted for each data set corresponding to the incremented observation time interval. The Gaussian fits of these plots, similar to those in Figure 7, provide values of $D_{\text{tran}}$ as a function of $\Delta t$.

The dependence of the translational diffusion constant $D_{\text{tran}}$ on the observation time interval $\Delta t$ is shown in Figure 8 for silica and Pt\textsuperscript{-}silica particles in water and Pt\textsuperscript{-}silica particles in 15.0% and 27.3% H\textsubscript{2}O\textsubscript{2} solutions. The red line in each plot represents the effective translational diffusion constant for Brownian motion. In (c) and (d), an approximate value of $\tau_R$ is given by the value of $D_{\text{tran}}$ when it becomes constant, indicating the behavior is Brownian-like with $\Delta t \geq \tau_R$. The relative values of $D_{\text{tran}}$ in each plot are given in Table 1.

**Figure 7.** Distribution of the step length $\Delta$ for (a) silica and (b) Pt\textsuperscript{-}silica particles in water and (c) Pt\textsuperscript{-}silica particles in (c) 15.0% w/w and (d) 27.3% w/w H\textsubscript{2}O\textsubscript{2} solutions. The distributions are plotted for frame-to-frame step lengths in the $x$ and $y$ directions and normalized by dividing by the total number of steps (3000). The bar width is 0.02 $\mu$m in each distribution, and the observation time interval $\Delta t = 0.021$ (a), 0.022 (b), 0.018 (c), and 0.019 s (d). The Gaussian fit is shown by the red line, and the values of $D_{\text{tran}}$ ($\mu$m$^2$/s) from each fit are (a) 0.42 $\pm$ 0.04, (b) 0.46 $\pm$ 0.03, (c) 0.60 $\pm$ 0.06, and (d) 0.66 $\pm$ 0.04.

**Figure 8.** Translational diffusion coefficient $D_{\text{tran}}$ as a function of the observation time interval $\Delta t$ for (a) silica and (b) Pt\textsuperscript{-}silica particles in water and Pt\textsuperscript{-}silica particles in (c) 15.0% w/w and (d) 27.3% w/w H\textsubscript{2}O\textsubscript{2} solutions. The red line in each plot represents the effective translational diffusion constant for Brownian motion. In (c) and (d), an approximate value of $\tau_R$ is given by the value of $D_{\text{tran}}$ when it becomes constant, indicating the behavior is Brownian-like with $\Delta t \geq \tau_R$. The relative values of $D_{\text{tran}}$ in each plot are given in Table 1.

<table>
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<tr>
<th>TABLE 1: Values of $D_{\text{tran}}$, $\tau_R$, and $V$ from Step Length Probability Distribution</th>
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<tr>
<td>$D_{\text{tran}}$ (µm$^2$/s)</td>
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<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>SiO$_2$/water</td>
</tr>
<tr>
<td>Pt--SiO$_2$/water</td>
</tr>
<tr>
<td>Pt--SiO$_2$/15.0% H$_2$O$_2$</td>
</tr>
<tr>
<td>Pt--SiO$_2$/27.3% H$_2$O$_2$</td>
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SiO$_2$/water and Pt--silica particles in water and Pt--silica particles in 15.0% and 27.3% H$_2$O$_2$ solutions were investigated by developing new data sets from Figure 7 according to $\Delta t_n = \Delta t(n + 1)$ for $n = 1, 2, 3$, etc. The probability density for 1D displacements $\Delta$ was plotted for each data set corresponding to the incremented observation time interval. The Gaussian fits of these plots, similar to those in Figure 7, provide values of $D_{\text{tran}}$ as a function of $\Delta t$. The dependence of $D_{\text{tran}}$ on the observation time interval $\Delta t$ is shown in Figure 8 for silica and Pt--silica particles in water and Pt--silica particles in 15.0% and 27.3% H$_2$O$_2$ solutions. The red line in each plot represents the effective translational diffusion constant for Brownian motion. In (c) and (d), an approximate value of $\tau_R$ is given by the value of $D_{\text{tran}}$ when it becomes constant, indicating the behavior is Brownian-like with $\Delta t \geq \tau_R$. The relative values of $D_{\text{tran}}$ in each plot are given in Table 1.
The value of $V$ can be calculated from the relation $D_{\text{tran}} = D + \frac{1}{4} V^2 \tau_R$, where $D$ is the diffusion constant for purely Brownian motion of the Pt–silica particles in water. We see that the value of $D_{\text{tran}}$ rises dramatically for the Pt–silica particles in H$_2$O$_2$ solutions compared to the value of $D_{\text{tran}}$ for the particles in water, and that the value increases with increasing H$_2$O$_2$ concentration. The value of $V$ also increases with increasing H$_2$O$_2$ concentration, while the value of $\tau_R$ changes only slightly. For comparison, the values of $D_{\text{tran}}$, $\tau_R$, and $V$ obtained from measurements of the mean-squared displacement are listed in Table 2.

### Table 2: Values of $D_{\text{tran}}$, $\tau_R$, and $V$ from Mean-Squared Displacement

<table>
<thead>
<tr>
<th>Solution</th>
<th>$D_{\text{tran}}$ ($\mu$m$^2$/s)</th>
<th>$\tau_R$ (s)</th>
<th>$V$ ($\mu$m/s)</th>
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<tbody>
<tr>
<td>SiO$_2$/water</td>
<td>0.48 ± 0.01</td>
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<tr>
<td>Pt–SiO$_2$/water</td>
<td>0.75 ± 0.03</td>
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<tr>
<td>Pt–SiO$_2$/15.0% H$_2$O$_2$</td>
<td>5.48 ± 0.10</td>
<td>0.53</td>
<td>6.14</td>
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<tr>
<td>Pt–SiO$_2$/27.3% H$_2$O$_2$</td>
<td>9.80 ± 0.32</td>
<td>0.59</td>
<td>7.77</td>
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Conclusion

Self-propelled Pt–silica particles in H$_2$O$_2$ solutions offer a convenient system for the characterization of chemically powered translational motion. In this study, we have found that the observation time scale may correspond to a regime of Brownian-like motion, where the observation occurs on a longer time scale than the rotational diffusion time, or to a regime of directed propulsion, where the observation occurs on a shorter time scale than the rotational diffusion time. This crossover in observed behavior with observation time interval allows important parameters to be determined, such as the rotational diffusion time $\tau_R$, the effective translational diffusion coefficient $D_{\text{tran}}$, and the velocity derived from the chemical propulsion $V$.

or viscosity gradients. In addition, the system offers an opportunity to compare the features of nonbiological chemical propulsion to those of self-propelled particles in living systems.

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References and Notes

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