Chemical Energy to Mechanical Motion Through Catalysis

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Abstract

We have demonstrated that one can build nanomotors "from scratch" that mimic biological motors by using catalytic reactions to create forces based on chemical gradients. These motors are autonomous in that they do not require external electric, magnetic, or optical fields as energy sources. Instead, the input energy is supplied locally and chemically. Depending on the shape of the object and the placement of the catalyst, different kinds of motion can be achieved. Additionally, an object that moves by generating a continuous surface force in a fluid can, in principle, be used to pump the fluid by the same catalytic mechanism. Thus, by immobilizing these nanomotors, it is possible to developed micro/nanofluidic pumps that transduce energy catalytically.

Introduction

Nano and microscale moving systems are currently the subject of intense interest due in part to their potential applications in nanomachinery, nanoscale assembly, robotics, tribology, fluidics, and chemical/biochemical sensing. Most of the research in this area has focused on using biological motor proteins in artificial systems, or using "molecular motors" such as rotaxanes that are powered externally. These have serious limitations with regards to fuel source, stability, and adaptability. As described below, we have demonstrated that one can build nanomotors "from scratch" that mimic biological motors by using catalytic reactions to create forces based on chemical gradients.

Results

In designing catalytic nanomotors and devices derived from them, it is important to understand the principles that govern their motion in the micrometer and nanometer regimes. We have established that electrokinetics is the dominant mechanism for the spontaneous motion of bimetallic nanorods and microgears suspended in hydrogen peroxide (H_2O_2) solutions (see Figs. 1 and 2) [1].

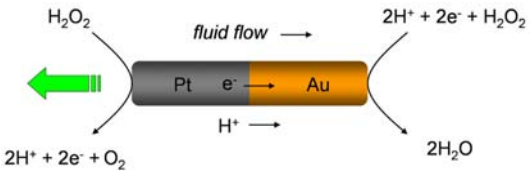

Figure 1. A schematic illustrating self-electrophoresis. Hydrogen peroxide is oxidized to generate protons in solution and electrons in the wire on the platinum end. The protons and electrons are then consumed with the reduction of H_2O_2 on the gold end. The resulting ion flux induces motion of the particle relative to the fluid, propelling the particle towards the platinum end with respect to the stationary fluid [1].

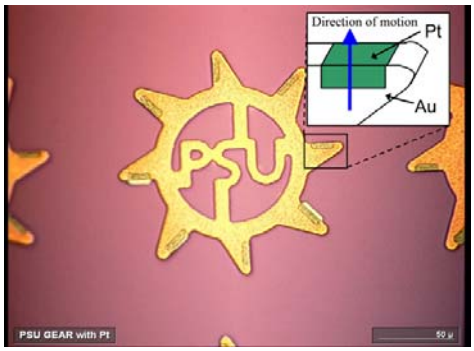

Figure 2. 100 μm diameter gold "microgears" with platinum "teeth" can rotate ~360°/sec in aqueous hydrogen peroxide systems [1].

In addition to controlling the motion of the hydrogen peroxide-driven systems by geometric design of moving structures, motion may also be controlled magnetically [2]. For example, hydrogen peroxide-powered nanorods that contain magnetic segments could be aligned when an external magnetic field is applied (Fig. 3). Nickel segments with a

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length shorter than the segment radius were used to ensure the easy axis of magnetization was orthogonal to the direction of motion. The rod motion was propelled by the hydrogen peroxide decomposition (and not by attraction to the magnet) and their direction could be remotely controlled using relatively weak magnetic fields. This motion is analogous to the behavior of motile bacteria that align themselves with Earth's weak magnetic field, and in fact these magnetotactic bacteria have magnetic moments on the same order as the nickel-containing rods.

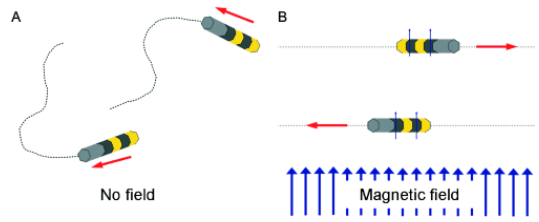

Figure 3. Schematic illustrating movement of Pt/Au/Ni/Au/Ni/Au rods without applied magnetic field (**A**), and with applied field (**B**) in aqueous H_2O_2. Note that rods align *perpendicular* to the applied magnetic field resulting in rod motion ~90 degrees to the applied field [2].

Most recently, we have discovered that the platinum/gold nanorods also exhibit chemotaxis (Figure 4) [3], traditionally defined as the movement of "organisms" toward or away from a chemical attractant or toxin by a biased random walk process. Again, this is the first example outside living systems. Our work also reveals that chemotaxis does not require "temporal sensing" mechanism commonly attributed to bacteria. This behavior provides a novel way to direct particle movement towards specific targets. Chemotaxis also offers a new method of sorting and separating particles of similar mass and size. Only those that are catalytically active move in response to the chemical gradient. From a fundamental standpoint, our work can be a starting point for the design of new motors for collective functions, such as catalytically driven swarming and pattern formation.

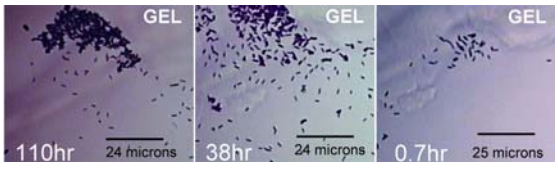

Fig. 4. The changing distribution of platinum-gold rods in a hydrogen proxide concentration gradient. The gel (soaked in 30% hydrogen peroxide) appears in the upper left part. The images were taken at 0.7 hour, 38 hours, and 110 hours [3].

One noteworthy aspect of the work involving hydrogen peroxide and metallic structures relates to immobilizing the catalyst onto a fixed surface. While freely suspended metal nanorods move with respect to the bulk solution, by Galilean invariance an immobilized metal structure in the presence of hydrogen peroxide will induce fluid flows at the interface between the structure and the fluid. We have demonstrated this fluid pumping effect on a gold surface patterned with silver, another known hydrogen peroxide decomposition catalyst (Fig. 5) [4]. When aqueous hydrogen peroxide containing colloidal tracer particles was deposited onto these bimetallic surfaces, the tracers either followed a convection-type fluid flow towards the micron-sized silver surface or formed patterns as they were pushed away from the catalyst, depending on the zeta potential of the tracer (Figure 10).

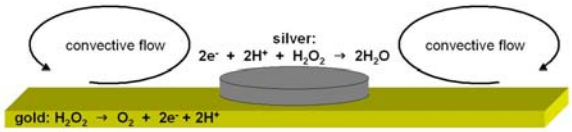

Figure 5. A catalytic micropump consisting of a silver disk on a gold substrate. The electrochemical decomposition of hydrogen peroxide establishes a weak electric field. This field causes tracer particles to migrate *towards* or *away* from the silver depending on their *surface charge*. Particles migrating towards the silver follow *electroosmotic convection* (arrows) near the catalyst surface [4].

Future Directions

The small scale and local conversion of chemical to mechanical energy may find use, among other applications, as micropumps and motors for micro/nanomachinery. The catalytically induced electrokinetic phenomenon could find use in microfluidics and lab-on-a-chip applications where the use of pressure gradients or externally generated electric fields may be difficult or undesirable.

In addition to micropump applications, the ability of particles that are both catalytic and asymmetric to locally convert chemical to mechanical energy offers the possibility of designing and controlling micro- and nanoscale machines that can interact with biological systems, such as individual cells. The idea of designing and developing devices that can interact intimately with

biological systems at the cellular level is an exciting one, and will benefit from addressing two aspects of biocompatibility: one that allows the device to work properly in biological systems, and one that will not interfere in an undesirable way with the biological host. This will require developing new approaches (or adapting current ones) to allow for biocompatible and bioavailable materials and fuels.

The examples in this paper demonstrate the fulfillment of the minimum requirements for nanoscale machines, namely initiating motion and, to a lesser degree, controlling the direction of that motion at the micron and nanometer scales. If, in addition to a motor and a director, one could incorporate a device to perform some useful operation, such as carrying cargo, entirely new classes of micro and nanoscale devices become possible. By incorporating materials that selectively adsorb or desorb a substance upon action of some stimulus, from either the immediate environment or a remote source, such devices could be engineered to deliver small-scale amounts of therapeutic agents, or other payload, to specific regions in the human body.
In charting future directions, two major areas will need to be addressed. First, while we know that catalysts can be used to impart motion to otherwise inanimate objects, we need to more fully understand and develop the mechanisms of chemical to mechanical energy transduction.

References

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