DOI: 10.1002/anie.200803021

Nanomotors

A Freight Train of Nanotubes for Cargo Transport on the Nanoscale

*Marko Burghard**

actuators · molecular electronics · molecular functional units · nanomotors · nanotubes

The targeted transport of nanoparticles or molecules on the micrometer or nanometer scale is an active interdisciplinary area of research[1] that promises numerous applications, such as the defined insertion of nanoprobes or pharmaceutically active compounds into cells[2] and applications in biosensing[3] and microfluidics.[4] The transport can in principle be driven by light, as well as by thermal or chemical energy. An initial strategy comprises the coupling of the nanoobject to a catalytic nanomotor that can move autonomously within a liquid medium. For example, when bimetallic nanorods consisting of a gold and a platinum segment are introduced into an aqueous solution of H_2O_2, local decomposition of the peroxide takes place on the platinum surface with the formation of oxygen (Figure 1 a).[5] Model calculations suggest that the variation in the metal/liquid interfacial tension along the rod associated with the resulting oxygen concentration gradient is responsible for the propulsion with speeds of a few micrometers per second.[5,6] However, the precise mechanism is still the subject of current investigations. Among the alternative mechanisms under discussion are ion currents at the rod surface[7] and the release of oxygen bubbles.[8] In a recent study, polymer microparticles were bound to one end of Pt/Au nanorods by electrostatic or protein–ligand interactions.[9] Although the attachment of the cargo makes the bimetallic motors slower, they can transport particles with a considerable diameter of up to about 1 μm in a solution of H_2O_2. The transport takes place in a targeted manner within a hydrogen peroxide gradient towards the concentration maximum, a type of "chemotaxis" that had been documented previously for unloaded motors.[10] Moreover, the interposition of short nickel segments into the motor enabled the directed movement of the motor/particle hybrids in a magnetic field.

SiO_2 microparticles whose surface is coated with a molecular catalyst for the decomposition of H_2O_2 serve as alternative catalytic nanomotors. Until now, such particles have been provided with a fluorescent marker to enable better localization;[11] however, they should be equally suitable for the transport of larger cargos. A further highly promising nanomotor was created by the covalent coupling of two different enzymes to carbon nanotubes.[12] The principle behind its function is that H_2O_2 produced by one enzyme (glucose oxidase) in an aqueous glucose medium is then decomposed by another enzyme (catalase); the oxygen thus generated provides the drive.

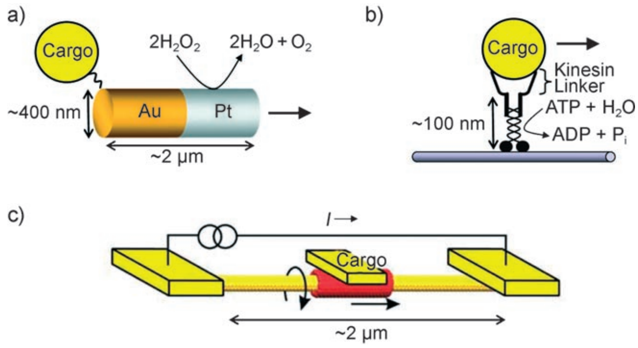

Figure 1. Three types of motor for the transport of a cargo on the micro- or nanometer scale. a) A segmented gold–platinum nanorod whose movement is caused by the local catalytic decomposition of hydrogen peroxide.[5] b) A kinesin biomotor whose movement, driven by the hydrolysis of adenosine triphosphate (ATP), is directed along a microtubule. P_i: phosphate, ADP: adenosine diphosphate. c) An electrically driven nanomotor composed of a nanotube sheath which moves along a coaxial nanotube.[21] The motion of the sheath is purely rotational, purely translational, or like that of a nut along a screw.

A second strategy is the ex vivo utilization of protein nanomachines as transport vehicles.[13] These systems offer the advantage that the cargo can be transported unidirectionally along a nanostructured track (Figure 1 b). The biomotor kinesin, which is powered chemically by ATP hydrolysis to move along microtubules (cylindrical polymers of the protein tubulin with a diameter of 25 nm and a length of many micrometers), has been investigated in detail.[14] Substrate-bound kinesin enables the transport of microtubules, which can be directed in defined directions through suitable channels.[15] Conversely, stationary microtubules enable the transport of kinesin. The tubules can be aligned with identical polarity (each cylinder has a "plus" and a "minus" end) by surface flow, so that the motors move uniformly in a fixed preferred direction.[16] Both kinesin and microtubules have been used to transport a cargo, for example, particles of different materials of several micrometers in size[17] or DNA

[*] Dr. M. Burghard
Max-Planck-Institut für Festkörperforschung
Heisenbergstrasse 1, 70569 Stuttgart (Germany)
Fax: (+49) 711-689-1662
E-mail: m.burghard@fkf.mpg.de

molecules[18] on substrates. In this way, objects can be moved over several millimeters with speeds of up to 1 μm s^{-1}.[17] Current studies are concerned with the use of microtubules for the sorting of proteins in microfluidic cells[19] or as shuttles that can transport objects between defined sites on a substrate surface.[20]

A common feature of all of these transport systems is that they are functional solely in a liquid medium. A novel electrically driven motor created recently from carbon nanotubes for the transport of nanoobjects may be integrated into solid structures.[21] The motor was prepared by attaching two gold electrodes to a multiwalled nanotube and patterning a nanostructured gold plate (side lengths ≈ 500 nm) on the nanotube by electron-beam lithography. The tube was heated by applying an electrical current, which led to the ablation of the outer wall(s), with the exception of the section protected by the metal plate. In the last step, the substrate was etched between the electrodes to produce a self-supporting structure composed of a short (ca. 500 nm) cargo-carrying nanotube sheath around a longer (ca. 2 μm), firmly anchored nanotube axis (Figure 1 c). A current flow through the axis could then be used to transport the plate over a distance of more than 1 μm. A speed of up to 1 μm s^{-1} was possible, which corresponds approximately to the speeds attained with the kinesin biomotors.[13]

The pivotal developments with respect to rotors created from nanotubes, which were described in 2004,[22] are the second degree of freedom (translation) and the drive mechanism. Whereas the rotor was controlled electrostatically, the current fed into the motor produces Joule heat, which leads to intense heating of the nanotube. As the heat is dissipated effectively at the metal contacts, a thermal gradient of approximately 1000 °C in the middle of the tubes to almost ambient temperature at the contacts is generated. The force which drives the sheath to the closest electrode is ascribed to the current of phononic excitations along the temperature gradient. The nature of the movement of the sheath along the coaxial nanotube depends upon the structure of the two nanotubes. The character of the atomic interaction potential between the two walls determines whether the sheath preferentially undergoes pure translation, pure rotation, or a combination of both, rather like the rotational movement of a nut along a screw. In this way, steps in the subnanometer range are possible, that is, considerably smaller steps than the 8 nm steps with which kinesin moves along microtubules.[4] A further advantage of the nanotube motor is the longer lifetime expected relative to that of biomotors used ex vivo, which are subject to denaturation within a few days.[13]

The nanotube motors should enable fundamental knowledge to be gathered on atomic frictional processes in nanomachines. However, a number of barriers stand in the way of their use in practice, for example, for the transport of liquids or as nanopipettes for the controlled release of medicines. The current high temperature of the nanotubes is particularly problematic, but could be decreased by using shorter sheaths. To produce a desired type of movement, a synthetic method would have to be developed which yields nanotubes of specific layers. The implementation of back and forward movement would also be needed for many applications.

Published online: September 24, 2008

Translated by Dr. David Le Count, Congleton

[1] V. Vogel, H. Hess, *Lect. Notes Phys.* **2007**, *711*, 367.
[2] G. D. Bachand, S. B. Rivera, A. Carroll-Portillo, H. Hess, M. Bachand, *Small* **2006**, *2*, 381.
[3] S. Ramachandran, K. H. Ernst, G. D. Bachand, V. Vogel, H. Hess, *Small* **2006**, *2*, 330.
[4] C. T. Lin, M. T. Kao, K. Kurabayashi, E. Meyhofer, *Small* **2006**, *2*, 281.
[5] a) W. F. Paxton, K. C. Kistler, C. C. Olmeda, A. Sen, S. K. St. Angelo, Y. Y. Cao, T. E. Mallouk, P. E. Lammert, V. H. Crespi, *J. Am. Chem. Soc.* **2004**, *126*, 13424; b) W. F. Paxton, S. Sundararajan, T. E. Mallouk, A. Sen, *Angew. Chem.* **2006**, *118*, 5546; *Angew. Chem. Int. Ed.* **2006**, *45*, 5420.
[6] N. Bala Saidulu, K. L. Sebastian, *J. Chem. Phys.* **2008**, *128*, 074708.
[7] Y. Wang, R. M. Hernandez, D. J. Bartlett, J. M. Bingham, A. Sen, T. E. Mallouk, *Langmuir* **2006**, *22*, 10451.
[8] N. L. Kovtyukhova, *J. Phys. Chem. C* **2008**, *112*, 6049.
[9] S. Sundararajan, P. E. Lammert, A. W. Zudans, V. H. Crespi, A. Sen, *Nano Lett.* **2008**, *8*, 1271.
[10] T. R. Kline, W. F. Paxton, T. E. Mallouk, A. Sen, *Angew. Chem.* **2005**, *117*, 754; *Angew. Chem. Int. Ed.* **2005**, *44*, 744.
[11] N. Heureux, F. Lusitani, W. R. Browne, M. S. Pshenichnikov, P. H. M. van Loosdrecht, B. L. Feringa, *Small* **2008**, *4*, 476.
[12] D. Pantarotto, W. R. Browne, B. L. Feringa, *Chem. Commun.* **2008**, 1533.
[13] M. G. L. van den Heuvel, C. Dekker, *Science* **2007**, *317*, 333.
[14] J. Howard, A. J. Hudspeth, R. D. Vale, *Nature* **1989**, *342*, 154.
[15] S. G. Moorjani, L. Jia, T. N. Jackson, W. O. Hancock, *Nano Lett.* **2003**, *3*, 633.
[16] R. Yokokawa, S. Takeuchi, T. Kon, M. Nishiura, K. Sutoh, H. Fujita, *Nano Lett.* **2004**, *4*, 2265.
[17] K. J. Böhm, R. Stracke, P. Muhlig, E. Unger, *Nanotechnology* **2001**, *12*, 238.
[18] S. Diez, C. Reuther, C. Dinu, R. Seidel, M. Mertig, W. Pompe, J. Howard, *Nano Lett.* **2003**, *3*, 1251.
[19] C. T. Lin, M. T. Kao, L. Kurabayashi, E. Meyhofer, *Nano Lett.* **2008**, *8*, 1041.
[20] C. Brunner, C. Wahnes, V. Vogel, *Lab Chip* **2007**, *7*, 1263.
[21] A. Barreiro, R. Rurali, E. R. Hernandez, J. Moser, T. Pichler, L. Forro, A. Bachtold, *Science* **2008**, *320*, 775.
[22] B. Bourlon, D. C. Glattli, C. Miko, L. Forro, A. Bachtold, *Nano Lett.* **2004**, *4*, 709.

